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FUTURE WATER REQUIREMENTS FOR RICE IRRIGATION IN THE PARDO RIVER BASIN (BRAZIL)

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1 ABSTRACT

The objective of this research was to estimate the future water requirements for rice paddy irrigation in the Pardo River Basin (Brazil) taking into account the changes in cultivation systems that are likely to occur in the near future in that region. After identifying the major trends in the rice cultivation systems, different scenarios were set and the water requirements for these scenarios were estimated using mathematical modelling and geoprocessing techniques. Census data indicate that the rice-growing area in the Pardo River Basin is expanding. However, the use of water per hectare is decreasing, as a result of increasing water use efficiency. The main agent behind this higher efficiency is land-levelling, which allows for a reduced volume of water required for flooding the paddies. Despite this improvement however, the overall water demands in future scenarios will still be greater than the current demands due to the expansion of the farmed area. However, these demands can be minimized if land-levelling is adopted more intensively across the entire Basin. Otherwise, there will be a need for either controlling the expansion of the rice-growing area, or increasing water availability through construction of additional reservoirs to minimize potential conflict amongst water users in the near future.

Keywords: rice, water requirements, irrigation, GIS, water availability demand

2 INTRODUCTION

Rice paddy irrigation in the Pardo River Basin (3,636 km^2), located in the South of Brazil, accounts for 87% of the total annual water usage and for 97% of the total summer water usage in the basin (Ecoplan, 2005a). The latest harvest data indicate that the cultivation area has been continuously growing in that region, posing a serious threat to other water users, including households (Instituto Rio Grandense do Arroz, 2005). During public consultations in 2005 to establish prioritisation of water usage, respondents ranked the use of water for rice irrigation second, with 24% of responses, just behind the use of water for households, with 31% (Ecoplan, 2005a). However, in the rural areas which are mostly occupied by rice farms, the use of water for rice irrigation was ranked equally to that for human supply. These facts clearly demonstrate the importance of the riziculture, as well as the public concern towards the sustainability of the activity in that region. In addition, due to the existence of extensive lowland areas as yet unused for riziculture (Helfer & Louzada, 2005), the potential for further expansion of rice farming has been creating further pressure on the water resources of the Pardo River Basin. These factors indicate that the region will need to either increase the

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availability of water, or minimize water use if it is to guarantee the potential future demand for water.

In this context, the objective of this study was to quantify the future water requirements of rice paddy irrigation across the Pardo River Basin, taking into account the predicted changes in the rice production systems. This research has three key objectives: i) to estimate the size of the rice-growing area across the Pardo River Basin for the year 2016, which is the projection adopted in the Pardo Basin Plan; ii) to determine the future rice cultivation scenarios in the Pardo River Basin for 2016; and iii) to calculate the water demands for these future scenarios using geoprocessing tools and mathematical modelling.

3 STUDY AREA

The Pardo River Basin is one of the nine catchments that form the hydrological region of Lake Guaiba in the south of Brazil. With an area of 3,636 km^2, it represents 1.3% of the total area of Rio Grande do Sul, the southernmost state in that country. The Pardo and Pardinho rivers are the Basin’s main watercourses and extend for 200 km and 90 km respectively. The lower lands of the Pardo River Basin are extensively occupied with irrigated rice farms, one of the main agricultural activities in that region. Approximately 8,500 hectares are cultivated annually with irrigated rice, which account for an annual productivity of around 65,000 tons (Ecoplan, 2005a).

4 METHODOLOGY

4.1 Rice-growing area in 2016

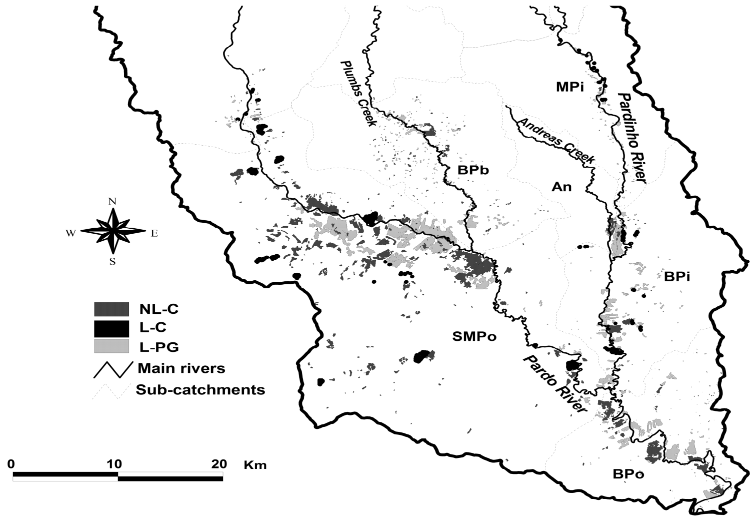
The year of 2016 was chosen by the Pardo River Basin Committee for the development of the long-term Basin Plan (Ecoplan, 2005a; 2005b), and so was adopted in this study for the water demand projections. To begin with, an equation was adjusted to historical harvest data available for each city in the Basin (Instituto Rio Grandense do Arroz, 2005). The future rice-growing area was then calculated using this equation, taking into account the availability of suitable soils for the activity. These soils were identified after compiling geographical information related to soil type, soil use, topography and permanent preservation areas using GIS software.

4.2 Future scenarios in 2016

The future scenarios were established based on trends predicted in the cultivation systems used in riziculture, which may affect the future irrigation requirements. Each rice cultivation system has unique features, which may result in distinct water demands. These features are the soil topography, which determines the height of water ponding, soil moisture conditions maintained during the sowing season, and rice varieties, which determine the evapotranspirative demand (Sociedade Sul Brasileira de Arroz Irrigado, 2007). Therefore, the scenarios in this study consisted of different combinations of rice cultivation systems across the Basin, which altogether involve distinct water demands due to the different features associated with each system.

The following abbreviations were used to represent the main rice cultivation systems in the Pardo River Basin: L-PG = Levelled soil + pre-germinated system/ L-C = Levelled soil + conventional system / NL-C = Non-levelled soil + conventional system. Figure 1 shows the current distribution of the rice cultivation systems across the Pardo River Basin, as well as the area and the percentage of occupation of each of those systems in six sub-catchments in the Basin.

The main institution for irrigated rice research in Brazil - IRGA (Instituto Rio Grandense do Arroz) - along with local rice producers and entities, were the main sources of information to help build the future scenarios, which were later approved by the Basin Committee. According to Instituto Rio Grandense do Arroz (2006), the latest available harvest data show that 60% of the rice-growing farms in the Pardo River Basin use land-levelling, which comprises a non-existent slope between paddy bunds, and consequently, less volume of water for water ponding. Of these, 55% use the pre-germinated system and 5% use the conventional system of rice cultivation. Non-levelled rice farms using the conventional system of rice cultivation occupy 40% of the total rice area in the Pardo River Basin.



Sub-catchment	Total Cultivated Area	Unit	L-PG	L-C	NL-C
An	185	Ha	104.6	0	80.4
BPb	643.2		409.2	0.4	233.6
BPi	880.1		667	57.7	155.4
BPo	1309.4		647	0	662.4
MPi	141.1		110	13.4	17.7
SMPo	5272.9		2235.4	315.8	2721.7
Pardo basin	**8431.7**		**4173.2**	**387.3**	**3871.2**
An	2.2%	%	1.2%	0.0%	1.0%
BPb	7.6%		4.9%	0.0%	2.8%
BPi	10.4%		7.9%	0.7%	1.8%
BPo	15.5%		7.7%	0.0%	7.9%
MPi	1.7%		1.3%	0.2%	0.2%
SMPo	62.5%		26.5%	3.7%	32.3%
Pardo basin	100.0%		49.5%	4.6%	45.9%

Figure 1. Rice cultivation systems in the Pardo River Basin (An = Andreas Creek / BPb = lower Plumbs Creek / BPi = lower Pardinho River / BPo = lower Pardo River / MPi = middle Pardinho River / SMPo = middle Pardo River). Source: author, through reclassification of satellite image and field validation (2006)

As for rice varieties, 50% of the rice producers use late maturation varieties (136 to 150-day cycle), 30% use medium cycle varieties (121 to 135 days) and 20% use early maturation varieties (106 to 120-day cycle). The most common rice varieties in the Pardo River Basin are the EPAGRI 108 (late cycle), BR IRGA 409, BRS 7 "TAIM", BR IRGA 410, EL PASO L 144 and QUALIMAX 1 (medium cycle) and IRGA 417, IRGA 419, IRGA 420 and IRGA 418 (early cycle).

The scenarios in 2016 were established by taking into account the present distribution of rice cultivation systems (Figure 1) and the trends highlighted by the specialists from the Instituto Rio Grandense do Arroz and by local rice producers. Two future configurations were set: a baseline scenario, which examines the consequences of continuing current water usage trends in rice irrigation, and an optimistic scenario, which assumes improvements in water use efficiency in rice irrigation.

The following trends were identified and used to build the baseline scenario:

- Reduction in pre-germinated systems and increase in conventional systems due to the development of *Clearfield* rice varieties (Projeto Clearfield, 2004): *Clearfield* rice varieties have been shown to be an effective way for controlling red rice infestations. This recent technology points towards a shift in rice production systems from the established use of pre-germinated seeds to the use of conventional systems with germination in dry soil. The observed changes, according to representatives of the rice irrigators in the Pardo Basin Committee, have been occurring at a rate of 5% per annum. However, it is important to consider that 20% of the rice producers who have been using the pre-germinated system successfully are unlikely to switch to other available alternatives.
- Increase of levelled and decrease of non-levelled soils: this is a clear trend in the Pardo River Basin as this technology has proved to enhance the effectiveness of rice cultivation, including better weed and pest control, more sowing uniformity, easier harvesting and more efficient irrigation. The rate of increase was indicated to be 2% per annum by the Basin Committee.
- Increase in the use of early and medium-cycle varieties, particularly IRGA 422 CL, which has been launched for the *Clearfield* system, and decrease in the use of long-cycle varieties. According to the specialists from the Instituto Rio Grandense do Arroz, the percentage distribution in the Pardo River Basin in 2016 will be approximately 50, 40 and 10% for early, medium and long cycle varieties respectively.

The optimistic scenario differs from the baseline in two aspects: the rate of increase in the use of levelled soils is 5% instead of 2% per annum, and the use of early rice varieties is 100%. This configuration is very close to what the Instituto Rio Grandense do Arroz is seeking through the development of “Projeto 10” (Project 10), which aims at increasing average rice productivity to 10 tons per hectare (Instituto Rio Grandense do Arroz, 2004; Menezes *et al*., 2004). According to this project, one of the main strategies to achieve this objective is levelling the soils of the rice-growing areas to provide better soil and water management conditions. This may also result in greater economy of water, given that the depth of water ponding can be kept much lower, as compared to non-levelled areas. Additionally, the cultivation of early varieties allows for a reduced use of water as a result of a shorter period of irrigation.

It is important to note that these future scenarios were established with the assistance of professionals from the Instituto Rio Grandense do Arroz, local rice farmers and other local rice entities. After the configuration was set, it was presented to, and approved by the Pardo Basin Committee, which is composed of representatives of water users, including rice producers.

4.3 Future water demands

The water demands for rice irrigation in the Pardo River Basin were calculated using the mathematical model proposed by Fietz *et al*. (1986), Fietz (1987) and Beltrame & Louzada (1991), given by:

$$I = ET_m + S_s + L_s + F_l + P_p \qquad (1)$$

where I is the total water demand, ET_m is the demand to meet crop evapotranspiration, S_s is the demand for soil saturation, L_s is the depth of the water ponding, F_l is the lateral infiltration through paddy bunds and P_p is the deep percolation.

In this study, each term of this equation was represented separately by a 30-meter resolution grid in the GIS software Spring (Camara *et al.*, 1996). The grids were then integrated to calculate the spatial and temporal water demands over the whole Basin using the full equation. The water demands were computed for 10-day intervals over the whole rice season, which goes from October to February in the South of Brazil.

Crop evapotranspiration (ET_m): The ET_m was calculated using the equation of Doorenbos & Pruitt (1976):

$$ET_m = ET_o \times K_c \tag{2}$$

where K_c is the crop coefficient and ET_o is the reference evapotranspiration. The reference evapotranspiration was estimated by the Class A pan method:

$$ET_o = E_{pan} \times K_p \tag{3}$$

where K_p is the pan coefficient and E_{pan} is the pan evaporation. K_p is a coefficient related to wind speed, surrounding vegetation and relative air humidity. In this study, it was assumed as 0.85. Four weather stations across the region were used, and their area of influence was established using the Thiesen-Polygon method. Weather data for those stations were available from 1969 to 1980. The 10-day average pan evaporation was calculated from these data.

Rice varieties have different water requirements mostly because of the length of their cycle. Varying K_c values were used for each crop growing stage in accordance to Fietz (1987), as follows: 1.6 for the vegetative stage, 2.1 for the reproductive and 1.4 for the maturation stage. Rice evapotranspiration throughout the Pardo River Basin was then calculated by multiplying the grid representing the reference evapotranspiration and the grid representing the crop coefficients. The latter was obtained through a land use map, which in turn was obtained from reclassifying a 30-meter resolution LANDSAT image.

Soil saturation (S_s): The equation:

$$S_s = (P_s - \theta_i) \times prof \tag{4}$$

where S_s is the water requirement to saturate the soil at the initial period of irrigation, P_s is the soil porosity, θ_i is the initial soil moisture content and *prof* is the soil depth down to the level of the watertable, was used to estimate the water requirements for soil saturation.

Soil characteristics, including soil-water retention curves, were obtained from field surveys conducted by Ecoplan (1997). Soils were assumed to be initially saturated (i.e., initial moisture content = soil porosity) in the pre-germinated systems. In the conventional systems, the moisture content at 0.06 atm pressure was assumed to be the initial soil moisture content (Associação Brasileira de Normas Técnicas, 2007). Soil porosity, initial soil moisture content and soil depth were represented by three grids in the software Spring, and these were used to calculate the water requirements for soil saturation according to the aforementioned equation.

Water ponding (L_s): The depth of water ponding is mainly a function of the terrain shape, i.e., whether the topography is levelled or non-levelled. In levelled soils, this depth is maintained at an approximate depth of 60 mm, whereas in non-levelled soils, at 120 mm, in most of the rice farms in the Pardo River Basin (Andrade & Rabuski[1]). Also, in pre-

[1] Personal communication. Rio Pardo, Instituto Rio Grandense do Arroz, 2005.

germinated systems, a 50-mm water ponding is required for seed sowing (Sociedade Sul Brasileira de Arroz Irrigado, 2007).

Lateral infiltration (F_l): The lateral infiltration through paddy bunds was estimated using Darcy's equation:

$$F_l = A \times K_{sat} \times i \quad (5)$$

where F_l is the lateral flow, A is the vertical section through which water flows, K_{sat} is the soil-water conductivity and i is the hydraulic gradient. It was assumed that lateral infiltration takes place through a hypothetical section of soil defined as the product of soil depth and the linear extension of the bordering bunds. The average perimeter/area ratio of rice paddies in the South of Brazil was used to replace "A" in Darcy's equation. K_{sat} and soil depth were obtained from studies carried out by Ecoplan (1997). The hydraulic gradient was calculated as L_s/B_t, where L_s is the height of the water ponding (which varies according to the terrain shape) and B_t is the width of the bunds, assumed to be 700 mm. Using the software Spring, an infolayer of soil types was transformed into two grids, each representing the soil depth and the soil conductivity, K_{sat}. The rice cultivation map in turn, was converted into a numerical grid representing the hydraulic gradient.

Deep percolation (P_p): Given the fact that deep percolation (vertical flow) in paddy fields is minor due to the existence of a high watertable level and absence of vertical gradients (Cauduro, 1996; Louzada, 2004), this component of the total rice irrigation requirement was ignored in this study.

Rainfall input is not usually considered in the estimate of water demands for rice cultivation in Rio Grande do Sul. Even though it could be considered by using average historical records, the amount of rainfall which is effectively incorporated as water availability would depend mostly upon management strategies adopted by each rice farmer. Also, omitting rainfall input can be beneficial from the point of view of irrigation management because rain water can be never relied upon as a water source. Considering rainfall input would be more important if the methodology was to be applied to an area over which the rainfall rates varied greatly. In the Pardo River Basin, however, most differences among water demands for rice irrigation result from different rice cultivation systems used, rather than from differences in rainfall distribution.

Sowing dates: As mentioned above, the period of simulation was set from October to February, using a 10-day-time interval. The sowing periods were established as shown in Table 1. The end of the harvest season for all rice cultivation systems was set on the 10th of February.

Table 1. Sowing seasons adopted for each rice cultivation system[a]

Rice Cultivation System	Description	Sowing Season[b] (day/month)
L-PG/E	Levelled soil, pre-germinated, early	20/10 to 31/10
L-PG/M	Levelled soil, pre-germinated, medium	10/10 to 20/10
L-PG/L	Levelled soil, pre-germinated, late	01/10 to 10/10
L-C/E	Levelled soil, conventional, early	01/11 to 10/11
L-C/M	Levelled soil, conventional, medium	20/10 to 31/10
L-C/L	Levelled soil, conventional, late	10/10 to 20/10
NL-C/E	Non-levelled soil, conventional, early	01/11 to 10/11
NL-C/M	Non-levelled soil, conventional, medium	20/10 to 31/10
NL-C/L	Non-levelled soil, conventional, late	10/10 to 20/10

[a]Rice cultivation system: in this study, this term refers to the combination of land topography (i.e., levelled or non-levelled rice paddy), rice varieties (early, medium or late maturation) and sowing conditions (i.e., dry soil – conventional, or wet soil – pre-germinated)
[b]Harvest season for all rice cultivation systems starts on 10/02

5 RESULTS AND DISCUSSION

5.1 Rice-growing area in 2016

The results indicate that an extensive area suitable for the development of irrigated riziculture in the Pardo River Basin is available, particularly in the lower part of the basin, in areas adjacent to the Pardo and Pardinho rivers, where Albaqualf soils prevail. The total area available for the activity was found to be 45,000 hectares, which is 5.5 times the area cultivated today. The mathematical function adjusted to historical data estimates a total rice-growing area of 10,094 hectares in 2016, 19% greater than the current farmed area. This increment is shown in Figure 2.

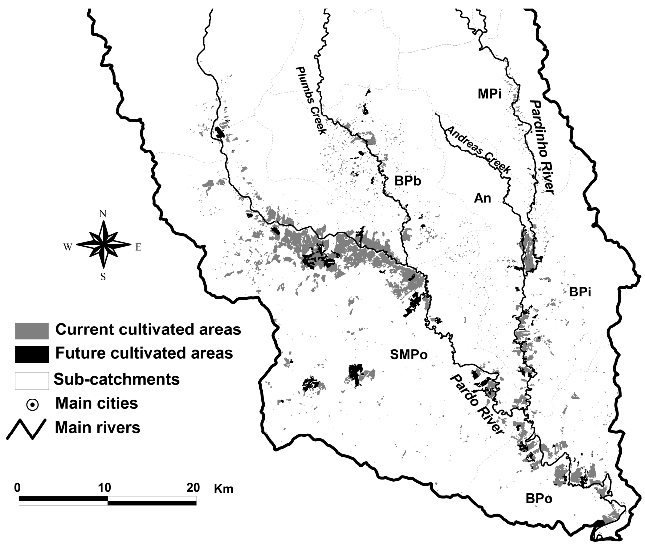


Figure 2. Incremented rice-growing area in 2016 in the Pardo River Basin

5.2 Future scenarios in 2016

The distribution of the rice cultivation systems over the area projected for 2016 for the **baseline** and **optimistic** scenarios is shown in Tables 3 and 4. The **current** scenario is also presented in Table 2.

Table 2. Distribution of the rice cultivation systems across the Pardo River Basin in the **current** scenario (2004/2005)

Region[a]	Total Cultivated Area (ha)	L-PG/E	L-PG/M	L-PG/L	L-C/E	L-C/M	L-C/L	NL-C/E	NL-C/M	NL-C/L
An	185	20.9	31.4	52.3	0	0	0	16.1	24.1	40.2
BPb	643	81.8	122.8	204.6	0.1	0.1	0.2	46.7	70.1	116.8
BPi	880	133.4	200.1	333.5	11.5	17.3	28.9	31.1	46.6	77.7
BPo	1,309	129.4	194.1	323.5	0	0	0	132.5	198.7	331.2
MPi	141	22	33	55	2.7	4	6.7	3.5	5.3	8.9
SMPo	5,273	447.1	670.6	1,117.7	63.2	94.8	157.8	544.3	816.5	1,360.9
Basin	8,432	834.6	1,252	2,086.6	77.5	116.2	193.6	774.2	1,161.3	1,935.7
Basin - %	100	9.9	14.8	24.7	0.9%	1.4	2.3	9.2	13.8	23.0
			49.4			4.6			46.0	

[a]An = Andreas Creek / BPb = lower Plumbs Creek / BPi = lower Pardinho River / BPo = lower Pardo River / MPi = middle Pardinho River / SMPo = middle Pardo River

Table 3. Estimated distribution of the rice cultivation systems across the Pardo River Basin in 2016 – **baseline** scenario

Region	Total Cultivated Area (ha)	L-PG/E	L-PG/M	L-PG/L	L-C/E	L-C/M	L-C/L	NL-C/E	NL-C/M	NL-C/L
An	221	35.4	28.3	7.1	43.1	34.5	8.6	32.0	25.6	6.4
BPb	770	131.0	104.7	26.2	142.5	114.1	28.5	111.5	89.2	22.3
BPi	1,054	216.1	172.9	43.2	237.2	189.7	47.4	73.8	59.0	14.8
BPo	1,568	203.8	163.1	40.8	266.6	213.2	53.3	313.6	250.9	62.7
MPi	168	34.4	27.6	6.9	37.8	30.2	7.6	11.8	9.4	2.4
SMPo	6,313	726.5	581.3	145.3	1,136.3	909.0	224.3	1,293.6	1,034.9	258.7
Basin	10,094	1,347.2	1,077.7	269.4	1,863.5	1,490.8	372.7	1,836.3	1,469.0	367.3
Basin - %	100	13.3	10.6	2.7	18.5	14.8	3.7	18.2	14.6	3.6
			26.6			37.0			36.4	

Table 4. Estimated distribution of the rice cultivation systems across the Pardo River Basin in 2016 – **optimistic** scenario

Region	Total Cultivated Area (ha)	L-PG/E	L-PG/M	L-PG/L	L-C/E	L-C/M	L-C/L	NL-C/E	NL-C/M	NL-C/L
An	221	77.3	0	0	101.7	0	0	42	0	0
BPb	770	269.5	0	0	354.3	0	0	146.16	0	0
BPi	1,054	432.1	0	0	516.5	0	0	105.4	0	0
BPo	1,568	407.7	0	0	737	0	0	423.4	0	0
MPi	168	68.9	0	0	84	0	0	15.1	0	0
SMPo	6,313	1,452	0	0	3,217.4	0	0	1,643.6	0	0
Basin	10,094	2,707.5	0	0	5,010.9	0	0	2,375.7	0	0
Basin - %	100	26.8	0.0	0.0	49.6	0.0	0.0	23.6	0.0	0.0
			26.8			49.6			23.6	

5.3 Future water demands

The results for each component of the total water requirement for rice irrigation are presented below.

5.4 Crop evapotranspiration (ET_m)

The volumes required to supply the evapotranspirative demand for each scenario and time interval are presented in Table 5.

Table 5. Evapotranspirative demands in the Pardo River Basin – current and future scenarios

Scenario/ Projection	Time interval (10 days)[a]												Entire rice season
	oct/02	oct/03	nov/01	nov/02	nov/03	dec/01	dec/02	dec/03	jan/01	jan/02	jan/03	feb/01	
	Volume (10^6 m^3)												
Current	0.95	2.49	3.94	4.70	4.61	4.50	7.67	7.88	4.16	4.42	4.77	4.54	54.63
Future – baseline	0.12	0.94	3.31	5.64	5.52	5.33	9.29	9.50	4.97	5.31	5.74	5.47	61.14
Future - optimistic	0.00	0.00	1.41	5.64	5.52	5.33	9.29	9.50	4.97	5.31	5.74	5.47	58.15

[a] oct/02 = from October 11th to October 20th / oct/03 = from October 21st to October 31st
nov/01 = from November 1st to November 10th / nov/02 = from November 11th to November 20th / nov/03 = from November 21st to November 30th
dec/01 = from December 1st to December 10th / dec/02 = from December 11th to December 20th / dec/03 = from December 21st to December 31st
jan/01 = from January 1st to January 10th / jan/02 = from January 11th to January 20th / jan/03 = from January 21st to January 31st
feb/01 = from February 1st to February 10th

The total evapotranspirative demand is 54.6 hm^3, 61.1 hm^3 and 58.1 hm^3 in the current, future baseline and future optimistic scenarios, respectively. The current total cultivation area in the basin is 8,430 hectares and the area for the future scenarios is 10,094 hectares. Although the future area is 20% greater in size, the future water demand is only 12% higher compared to the present water demand. For the optimistic scenario, the water demand is only 6.4% higher than the demand in the current scenario.

The demand at the beginning of October is nil in the optimistic scenario due to the sole cultivation of early maturation varieties. The highest demands occur in December for all scenarios.

Soil saturation (S_s): The demands for soil saturation are shown in Table 6. It is important to point out that these demands appear only at the beginning of the rice season.

Table 6. Soil saturation demands in the Pardo River Basin – current and future scenarios

Scenario / Projection	Time interval (10 days)[a]			Entire rice season
	oct/02	oct/03	nov/01	
	Volume (10^6 m^3)			
Current	0.95	0.90	0.45	2.30
Future – baseline	0.38	2.02	1.67	4.07
Future – optimistic	0.00	0.00	3.92	3.92

[a] oct/02 = from October 11th to October 20th / oct/03 = from October 21st to October 31st / nov/01 = from November 1st to November 10th

The demands for soil saturation are 2.3 hm^3, 4.1 hm^3 and 3.9 hm^3 for the current, future baseline and future optimistic scenarios, respectively. The demands for soil saturation are higher in the future scenarios due to an increase in areas occupied by the conventional farming systems. The water demand for soil saturation is greater in these systems because the soils contain little moisture, or are even dry at the beginning of the irrigation season. In pre-germinated systems, on the other hand, the soils are initially saturated by rain water prior to ploughing before spring. This avoids using water from the water storages, reducing the water demand.

Note that water demands for soil saturation in the future optimistic scenario do not exist in October because the optimistic scenario only utilizes early maturation varieties, which are sown later than other varieties.

Water ponding (L_s): The water demands for water ponding are presented in Table 7.

Table 7. Demands for water ponding in the Pardo River Basin – current and future scenarios

Scenario / Projection	Time interval (10 days)[a]					Entire rice season
	oct/01	oct/02	oct/03	nov/01	nov/02	
	Volume (10^6 m^3)					
Current	1.04	1.88	3.60	1.97	0.97	9.46
Future – baseline	0.13	0.69	1.97	3.45	3.35	9.59
Future – optimistic	0.00	0.00	1.35	1.62	5.86	8.83

[a] oct/01 = from October 1st to October 10th / oct/02 = from October 11th to October 20th / oct/03 = from October 21st to October 31st / nov/01 = from November 1st to November 10th / nov/02 = from November 11th to November 20th

The same explanation given for the soil saturation demand is also valid for the water ponding demand in regard to the distribution of these demands in each time interval. In the future optimistic scenario the water ponding is established later than in the current and future baseline scenarios. The total demands for water ponding are 9.46 hm^3 in the current scenario, 9.56 hm^3 in the baseline future scenario and 8.83 hm^3 in the future optimistic scenario.

Lateral infiltration (F_l): Table 8 shows the volumes of water necessary to restore the water losses through lateral infiltration in the paddy bunds in the Pardo River Basin for the three scenarios of this study.

Table 8. Water demands for lateral infiltration in the Pardo River Basin – current and future scenarios

Scenario/ Projection	Time interval (10 days)												Entire rice season
	oct/02	oct/03	nov/01	nov/02	nov/03	dec/01	dec/02	dec/03	jan/01	jan/02	jan/03	feb/01	
	Volume (10^6 m^3)												
Current	0.01	0.06	0.47	0.72	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	8.22
Future – baseline	0.00	0.02	0.13	0.47	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	7.50
Future - optimistic	0.00	0.00	0.02	0.08	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59	4.82

[a] oct/02 = from October 11th to October 20th / oct/03 = from October 21st to October 31st
nov/01 = from November 1st to November 10th / nov/02 = from November 11th to November 20th / nov/03 = from November 21st to November 30th
dec/01 = from December 1st to December 10th / dec/02 = from December 11th to December 20th / dec/03 = from December 21st to December 31st
jan/01 = from January 1st to January 10th / jan/02 = from January 11th to January 20th / jan/03 = from January 21st to January 31st
feb/01 = from February 1st to February 10th

The water demands to supply the water losses due to lateral infiltration through paddy bunds initiates earlier in the current and future baseline scenarios because these scenarios utilize early, medium and late cycle varieties. For the optimistic scenario, on the other hand, the varieties are all of early maturation, meaning that they are sown later than the other varieties, which results in zero water demand in October. The total water demand for lateral infiltration is 4.82 hm^3 in the optimistic scenario, compared to 8.22 and 7.50 hm^3 in the current and future baseline scenarios, respectively. Compared to the current scenario, this demand is less in the future scenarios because of soil levelling, a technique that allows the maintenance of a lower water pond and consequently, a lower hydraulic gradient and less infiltration.

Integrated analysis of the water demands: the different proportions of rice cultivation systems (i.e., combination of topographic conditions, rice varieties and sowing conditions) in the three scenarios considered in this study (current, future baseline and future optimistic), associated with different edaphoclimatic conditions, determine different water demands in the Pardo River Basin both in time and space. Table 9 shows the total water demands for rice cultivation in the Pardo River Basin for the three scenarios. Table 10, in turn, presents the participation, in percentage terms, of each component of the total water demand for rice irrigation in all scenarios. Table 11 shows the specific volumes demanded by each component. The specific volumes, or specific demands, are defined as the demand divided by the cultivated area.

Table 9. Total water demands for flooded rice irrigation in the Pardo River Basin – current and future scenarios

Scenario/ Projection	oct/01	oct/02	oct/03	nov/01	nov/02	nov/03	dec/01	dec/02	dec/03	jan/01	jan/02	jan/03	feb/01	Entire rice season
	Volume (10^6 m^3)													
Current	1.04	3.78	7.05	6.82	6.39	5.49	5.38	8.55	8.75	5.03	5.29	5.65	5.41	74.63
Future – baseline	0.13	1.20	4.95	8.56	9.46	6.38	6.18	10.15	10.36	5.83	6.16	6.60	6.33	82.30
Future - optimistic	0.00	0.00	1.35	6.97	11.58	6.11	5.92	9.87	10.09	5.56	5.90	6.33	6.06	75.73

Time interval (10 days)

[a] oct/01 = from October 1st to October 10th / oct/02 = from October 11th to October 20th / oct/03 = from October 21st to October 31st
nov/01 = from November 1st to November 10th / nov/02 = from November 11th to November 20th / nov/03 = from November 21st to November 30th
dec/01 = from December 1st to December 10th / dec/02 = from December 11th to December 20th / dec/03 = from December 21st to December 31st
jan/01 = from January 1st to January 10th / jan/02 = from January 11th to January 20th / jan/03 = from January 21st to January 31st
feb/01 = from February 1st to February 10th

Table 10. Proportion of each component in the total water demand for rice irrigation in the Pardo River Basin – current and future scenarios

Scenario/ Projection	Evapo-transpiration (10^6 m^3)	Soil Saturation (10^6 m^3)	Water Ponding (10^6 m^3)	Lateral Infiltration (10^6 m^3)	Evapo-transpiration (%)	Soil Saturation (%)	Water Ponding (%)	Lateral Infiltration (%)
Current	54.63	2.30	9.46	8.24	73.20%	3.08%	12.68%	11.05%
Future – baseline	61.14	4.07	9.60	7.48	74.29%	4.95%	11.67%	9.09%
Future - optimistic	58.15	3.92	8.83	4.83	76.78%	5.18%	11.66%	6.37%

Table 11. Specific volumes demanded by each component of rice irrigation in the Pardo River Basin – current and future scenarios

Scenario/ Projection	Evapo-transpiration	Soil Saturation	Water Ponding	Lateral Infiltration	Total
	Specific volumes (m^3 ha^{-1})				
Current	6,479.7	272.8	1,122.0	977.3	8,851.9
Future – baseline	6,057.1	403.2	951.1	741.0	8,152.4
Future - optimistic	5,760.8	388.3	874.8	478.5	7,502.5

The main contributor for the rice irrigation demand in all scenarios is evapotranspiration, which accounts for around 73.0% to 77.0% of the total water requirements. The specific demand (demand per cultivated area) is less in the future optimistic scenario due to the use of early maturation varieties of rice. The proportion of this component increases in the optimistic scenario, at 76.78% compared to 73.20% and 74.29% for the current and future baseline scenarios, respectively. This indicates that the irrigation efficiency in the optimistic scenario is greater than in the other scenarios because the other components have reduced water demands. Ideally, the most efficient method of irrigation would be the one in which the water used is equal to the evapotranspiration. That is, the higher the proportion of water used for the evapotranspirative demand - as compared to that for the other components - the more efficient the water utilization.

The water volumes to meet the demand for soil saturation vary from 273 m^3 ha^{-1} $season^{-1}$ in the current scenario to 403 m^3 ha^{-1} $season^{-1}$ in the future baseline scenario. The demand for this component increases in the future scenarios in comparison with the current scenario due to the gradual decrease in the utilization of pre-germinated systems. Nevertheless, water demands for soil saturation, as compared to other components, are the least significant in all scenarios, at 3.08% in the current, 4.95% in the future baseline and 5.18% in the future optimistic scenarios.

The specific demands for water ponding decrease from the current to the future scenarios. The total demand in the current scenario is 1,122 m^3 ha^{-1} $season^{-1}$, whereas in the future baseline and optimistic scenarios, it is 951 m^3 ha^{-1} $season^{-1}$ and 875 m^3 ha^{-1} $season^{-1}$, respectively. This reflects the benefits of the land-levelling technology, as this technology allows for less use of water. In percentage terms, the total demand for water ponding accounts for approximately 12% of the total water demand for rice irrigation in the Pardo River Basin for all scenarios.

The water demand to restore the losses of water through paddy bunds is 11.05% of the total water requirement of the current scenario, and its specific demand is 977 m^3ha^{-1} $season^{-1}$. In the future baseline scenario this demand is 741 m^3 ha^{-1} $season^{-1}$, representing 9.09% of the total water requirement. For the optimistic scenario, the total demand for lateral infiltration reduces to 478 m^3 ha^{-1} $season^{-1}$, which is approximately 6.5% of the total water demand for rice irrigation. This demand is reduced in the future scenarios due to land-levelling, which allows for a reduced hydraulic gradient and consequently, a reduced flow through the bunds. Also, the shorter cycle of the rice varieties in the future optimistic scenario helps minimize the total amount of water that is lost through lateral infiltration in the whole season.

The total water demand for rice irrigation in the Pardo River Basin is about 74.6 hm^3 in the current scenario. The prediction for 2016 is that this demand will increase to 82.3 hm^3, if the current riziculture trends in the Pardo River Basin continue (represented by the future baseline scenario). However, the results also show that the observed pace of increase in the rice-growing area could continue without necessarily increasing water demands, if some changes were made to the rice cultivation systems, particularly towards technologies that allow a more efficient water use in the paddies. This was demonstrated through the results obtained for the future optimistic scenario. The specific consumption of water (i.e., the total demanded volume divided by the cultivated area) is currently 8,852 m^3 ha^{-1} $season^{-1}$ (for a total area of 8,430 ha) and it is estimated to be 7,502 m^3 ha^{-1} $season^{-1}$ (for a total area of 10,094 ha) in the future optimistic scenario. This represents an increase of 19.7% in the rice-growing area and an increase of only 1.465% in total water demands. The main contributors to this reduction in the specific water demand are land-levelling and the use of early maturation rice varieties. Table 12 presents the rates of increase in both rice-growing areas and water demands for the scenarios set for this study.

Table 12. Rate of growth of rice cultivation areas and water demands from 2008 to 2016 in the Pardo River Basin

Scenario/ Projection	Total Cultivated Area (ha)	Total Water Demand (10^6 m^3)	Rate of Growth of Rice Area (per annum)	Rate of Growth of Water Demand (per annum)
Current	8,431	74.6	-	-
Future – baseline	10,094	82.3	1.51%	0.82%
Future - optimistic	10,094	75.7	1.51%	0.12%

It is important to note that the specific volumes calculated with the current methodology vary from 7,502 to 8,852 m³ ha^{-1} $season^{-1}$ which are much lower volumes than those usually claimed by the rice farmers, according to the Department of Water that provides licenses for water use in the State of Rio Grande do Sul, Brazil (Muller & Dewes, 2005). This is in part due to losses of water that occur along the water distribution systems, which were unaccounted for in the present study. Other studies carried out in controlled parcels of land cultivated with rice in the South of Brazil have found volumes very similar to the ones found in this study (e.g., Weber, 2000; Marcolin & Macedo, 2001; Machado *et al*., 2006). However, it is a common practice amongst the irrigators to request licenses for use of higher amounts of water, in order to account for water losses along the distribution system and mostly, to guarantee the water supply during the rice season.

Figure 3 shows the variation in the water demands for rice irrigation during the rice-growing season in the Pardo River Basin for the future scenarios set for this study. It can be observed that there are significant differences in water demand between the two scenarios at the beginning of the rice-growing season due to variations in rice cultivation practices. However, from the end of November onwards, the demand in each scenario becomes virtually identical as this is determined mostly by the rate of evapotranspiration, which is a function of climate. The minor differences in water demand that occur from mid-November are due to the different demands for water to restore the losses that occur through paddy bunds (lateral infiltration). This demand is lower in the future optimistic scenario, due to a higher proportion of land-levelled farms. The higher water requirements in the beginning of the rice season for the future baseline scenario are due to the existence of rice varieties of late maturation that have to be sown in anticipation of the early maturation varieties. Also, the initial demands, such as water ponding and soil saturation, begin earlier in this scenario for the same reason. The low water demands in both scenarios at the end of November are due to the lower evapotranspirative demand attributable to the plants being just at the beginning of the growing season. Evapotranspiration begins to increase from the beginning of December and it decreases again in January. Although the climatic conditions that drive evapotranspiration remain strong in January, the demand for water for the rice crop during this month is not as high, because water requirements decrease after the reproductive stage.

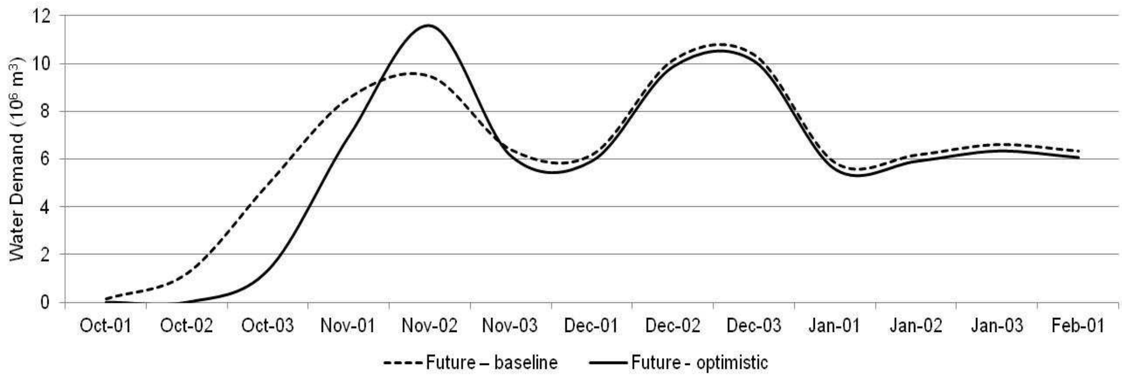


Figure 3. Temporal variation in water demand for rice irrigation for current and future scenarios in the Pardo River Basin

6 CONCLUSIONS

This study considered two future scenarios: a baseline scenario that follows the historical tendencies in the rice cultivation systems in the Pardo River Basin and an optimistic scenario that incorporates changes to the rice cultivation systems, thereby reducing the use of water in the paddy fields. When comparing the water requirements for these scenarios with the water requirements for the current scenario, the results indicate that the use of water per hectare (specific demand) will be reduced, although the rice-growing area tends to increase. However, when looking at the future optimistic scenario, which contains a rice-growing area 20% larger than the current area, the increase in the total water demand is only 1.5%, indicating that the rice-growing area can expand without a large increase in the demand of water for rice irrigation. In order to achieve this however, rice farmers will have to invest in technology such as soil-levelling and also consider the use of early maturation rice varieties. Fortunately, these are changes that are being implemented already, although not as fast as it would be necessary to achieve the configuration set for the optimistic future scenario.

Nevertheless, the most important outcome of this study was to show mathematically that the specific water demand for rice irrigation can be effectively reduced when these technologies are applied, and this may encourage both rice farmers and the Government to disseminate the benefits of these technologies. These techniques have also been proven to increase rice productivity, as other components of rice cultivation, such as control of pests, weeds and diseases and application of fertilizers, can be benefited from them as well.

In an area such as the Pardo River Basin, which has been experiencing critical issues in terms of water availability, the results of this study also suggest that even with improved rice cultivation practices and subsequent reductions in water usage, it is probable that future expansions in the rice-growing area will need to be limited. This will depend upon how fast water requirements grow in alternative uses, such as household usage created by a growing population, or industry usage boosted by a growing economy.

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