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ORIGINAL ARTICLE

Optimization model for water allocation for agricultural activities in alluvial aquifer in the Brazilian semi-arid region[1]

Modelo de otimização para alocação de água para atividades agrícolas em aquífero aluvial no semiárido brasileiro

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HIGHLIGHTS:

Shrimp farming raises the annual net income for the Morada Nova Irrigation Project, which highlights its economic importance.
Water resource scarcity limits land use, especially in February and March.
Dependence on groundwater is a financial risk in water-scarce years, requiring strategies that reduce shrimp farming cycles.

ABSTRACT: The semi-arid region is marked by uncertainties and variability in the water volume available for multiple uses. The objective of the study was to construct a linear programming model that promotes maximization of the net income of the producer and optimization of the use of water resources in alluvial aquifer in the Brazilian semi-arid region, with a view to economic and water sustainability, establishing an optimal plan for agricultural exploitation. The proposed model used technical coefficients from primary data obtained in the various production units, as well as secondary data from technical-scientific studies conducted in the region, and considered constraints. Simulations were performed for three levels of water availability and two annual cycles of shrimp farming, considering the volume exploited per cycle and the continuous expansion of the activity in the region. The model proved to be efficient in the proposal of an optimal plan of occupation and optimization of groundwater resources, which, in its potential condition, has a relevant importance in the shrimp farming activity from the economic dimension perspective. Sensitivity analysis of the model parameters allowed understanding the stability of the optimal solution in the face of variations in the technical coefficients. The water resource had slack equal to zero, indicating that it is a limiting resource. Drastic reduction in net income due to reduction in water availability points to risks associated with years of water scarcity. Reduction of one cycle in shrimp farming in years of moderate water scarcity is a feasible alternative from a financial perspective.

Key words: net income, groundwater, shrimp farming, agricultural production, water use

RESUMO: O semiárido é marcado por incertezas e variabilidade do volume hídrico disponível para usos múltiplos. O objetivo com o estudo foi construir um modelo de programação linear que proporcione a maximização da receita líquida do produtor e a otimização do uso dos recursos hídricos em aquífero aluvial no semiárido brasileiro, com vistas à sustentabilidade econômica e hídrica, estabelecendo um plano ótimo de exploração agropecuária. O modelo proposto utilizou coeficientes técnicos oriundos de dados primários obtidos nas diversas unidades de produção, bem como de dados secundários de trabalhos técnico-científicos realizados na região e considerou restrições. Foram realizadas simulações de três níveis de disponibilidade de água e de apenas dois ciclos anuais da produção de camarão, tendo em vista o volume explotado por ciclo e a contínua expansão da atividade na região. O modelo se mostrou eficiente na proposta de um plano ótimo de ocupação e na otimização dos recursos hídricos subterrâneos, que, em sua condição potencial, tem na atividade da carcinicultura uma importância relevante sob a ótica da dimensão econômica. A análise de sensibilidade dos parâmetros do modelo permitiu compreender a estabilidade da solução ótima frente às variações nos coeficientes técnicos. O recurso água apresentou folga igual a zero, indicando se tratar de um recurso limitante. A drástica redução na receita líquida face à redução na disponibilidade de água sinaliza para os riscos associados aos anos de escassez hídrica. A redução em um ciclo no cultivo do camarão em anos de escassez hídrica moderada é uma alternativa factível sob a ótica financeira.

Palavras-chave: receita líquida, águas subterrâneas, cultivo de camarão, produção agropecuária, uso da água

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Introduction

Variability in the water volume available for multiple uses and the recurrent periods of water scarcity in the semi-arid region cause pressure on the consumption of groundwater, which plays a fundamental role in the continuity of agricultural activities (Ingrao et al., 2023). Overexploitation of groundwater interferes with sustainability, raising the risks of scarcity in the rate of circulation and stress of this resource. Thus, water consumption needs to be optimized in all human activities, in view of the increasing scarcity of fresh water (Zhang et al., 2021; Akbar et al., 2022).

In the agricultural sector, efficient decision-making is essential to maximize yield, minimize costs, and mitigate environmental impacts (Ridoutt & Pfister, 2010). In this context, there has been an increasing use of optimization techniques based on processes that involve multiple objectives in various areas, particularly decision-making in this sector (Galán-Martín et al., 2017).

When seeking optimization, producers must select the production alternative that is most efficient in the use of available production resources and that meets certain objectives. In situations where decision-making is related to the allocation of limited resources, such allocation depends both on the producers' decision and on their rationality, which requires the use of efficient methods to assist them in optimizing this decision (Robert et al., 2016).

Sustainable management of water resources is a growing concern around the world and, if the set of demands is greater than water availability in a given region, there will be a risk of shortages (Cordão et al., 2020). In the context of the Morada Nova Irrigation Project (MNIP), located in a region characterized by prolonged periods of drought, groundwater availability plays a key role in the maintenance of agricultural activities throughout the year, but it is necessary to monitor the volume exploited, in order to avoid overexploitation (Nunes et al., 2022).

Given the nature of this problem, it is necessary to adopt measures that enable the planning of water use, assisting the producer in decision making, project managers and regulatory bodies, aiming at maximizing net income, given the existing constraints. By adopting a multidisciplinary approach, this study provides information on the amount of exploitable groundwater, taking into account climatic, hydrological and agricultural demand factors and the environmental impacts of shrimp farming. The hypothesis is that an optimization model for water allocation can guarantee the continuity of agricultural activities in an alluvial aquifer in the semi-arid region of Brazil.

In this context, the study aimed to construct a linear programming model that promotes maximization of the net income of the producer and optimization of the use of water resources in alluvial aquifer in the Brazilian semi-arid region, with a view to economic and water sustainability, establishing an optimal plan for agricultural exploitation. In addition, the study contributes to identifying management strategies and adaptation measures that allow obtaining an optimal plan for groundwater allocation, considering environmental sustainability and economic efficiency.

Material and Methods

The study was carried out over the years 2021 and 2022 in the Morada Nova Irrigation Project, located in the Baixo Jaguaribe microregion, Banabuiú Valley, Ceará state, Brazil, with geographic coordinates of 5° 06' 07" S and 38° 08' 02" W, and orthometric height of approximately 44 m (Figure 1).

Table 1 contains the climatic characteristics of the region according to the Köppen classification (1991-2021).

The irrigating farmers of MNIP are characterized as family farmers, whose mean areas for exploitation of the lots are 4.5 ha, with predominance of annual crops and use of surface irrigation systems, such as furrow and flood systems. Among the crops, there is a strong emphasis on forage production, due to the practice of dairy cattle farming in the region. In addition, there are some pressurized irrigation projects, due to the current situation of the reservoirs and the availability of electricity. At the same time, there is a significant increase in the interest of investors in the shrimp farming activity, which is in full expansion.

The model proposed in this study is based on the use of technical coefficients obtained from primary information collected in several production units, as well as secondary data from technical-scientific studies conducted in the region and from the Association of Water Users of the Morada Nova Irrigated Perimeter (Audipimn), which provided information on the characteristics of the production units, such as crops grown along the year and profile of producers.

Based on this information, the technical coefficients of the proposed model, which are described in more detail in the following section, were calculated (Hillier & Lieberman,

Table 1. Climatic characteristics of the region

Climate characteristics	Data
Climate classification (Köppen)	BSW'h' (very hot and semi-arid)
Annual rainfall in 2021	593 mm
Rainfall distribution	Irregular
Average annual rainfall	718 mm
Potential evapotranspiration	2,159 mm
Average air temperature	28.4 °C
Relative air humidity	73%
Average wind speed	2.75 m s^{-1}

Adapted from Alvares et al. (2013)

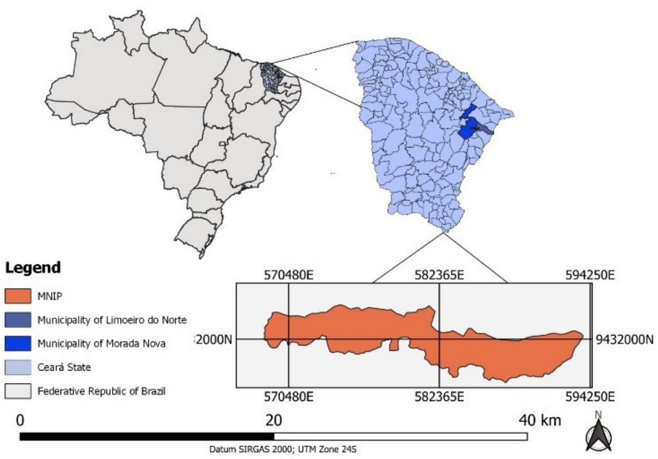

Figure 1. Location of the Morada Nova Irrigation Project, Baixo Jaguaribe microregion, Banabuiú Valley, Ceará state, Brazil, 2021

1988). It is important to emphasize that the use of primary and secondary data contributed to obtaining more precise and representative coefficients of the agricultural reality of the region.

The mathematical model of linear programming used consisted of an objective function, subject to constraints: land availability, market, exploitable reserve of groundwater, need for bulky feed for the cattle herd and areas with high percentages of exchangeable sodium.

The model is represented by the following Eqs. 1, 2, 3 and 4:

$$\text{MAX NI} = \sum_{i=1}^{n} P_i Y_i X_i - \sum_{i=1}^{n}\sum_{j=1}^{m} A_{ij} C_{ij} X_i - \sum_{i=1}^{n}\sum_{h=1}^{12} CT\left(\frac{W_{ih}}{E}\right) X_i \qquad (1)$$

With the following constraints:

$$\sum_{h=1}^{12}\sum_{i=1}^{n}\left(\frac{W_{ih}}{E}\right) X_i \le VT \; (i = 1 \cdots, n) \qquad (2)$$

$$\sum_{i=1}^{n}\sum_{j=1}^{m} A_{ij} X_i \le AVL_j \; (i = 1 \cdots, n;\ j = 1 \cdots, m) \qquad (3)$$

$$X_i \ge 0 \qquad (4)$$

where:

NI - total net income of the Project (R$);

i - whole number representing the crop (i = 1..., n);

j - whole number representing other inputs (j = 1..., m);

h - whole number representing the month of the year (h = 1..., 12);

P_i - unit price of the product of the i-th crop (R$ kg^{-1});

Y_i - yield obtained with the i-th crop (kg ha^{-1});

X_i - area cultivated with the i-th crop (ha);

A_{ij} - amount required of input j by crop i (kg ha^{-1});

C_{ij} - unit cost of input j for crop i (R$ kg^{-1});

CT - unit cost of the water tariff (R$ ha^{-1});

W_{ih}/E - monthly gross water depth to irrigate the i-th crop (mm);

E - irrigation efficiency (decimal form);

VT - annual volume of water available; and,

AVL_j - maximum availability of input j.

The Eq. 1 corresponds to the objective function, which aims to maximize the net income of the producer. The variables or activities (X_i) used in the formulation of the model were: Rice 2, sown in February (i=1), Rice 8, sown in August (i=2), Maize (i=3), Native pasture (i=4), Paulistinha grass (i=5), Forage sorghum (i=6), Banana (i=7), Coconut (i=8) and Shrimp (i=9).

It is worth pointing out that fixed costs related to the purchase of lots, interest rates on financing and rents, or differentiation of fertility and technology level of the areas were not considered in the formulation of the proposed model.

Table 2 shows the monthly plan for occupation of the area, containing the most exploited activities in the MNIP in 2021, which supported the formulation of the model.

Rice (*Oryza sativa* L.) is grown in both halves of the year. Maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L.) are grown in the first half. Forage, composed of Paulistinha grass (*Cynodon dactylon*) and native pasture, is produced throughout the year. Paulistinha grass is cut every 44 days, while the native pasture is destined for animal trampling. Shrimp production is carried out intensively, allowing up to three production cycles to occur annually.

In the model studied, the water depths applied refer to the entire cycle of crops or activities. Monthly water requirements of crops were calculated as follows:

a) Reference evapotranspiration (ETo) – reference evapotranspiration data were calculated by the Penman-Monteith method (FAO), using the Cropwat for Windows program, Version 8.0. Input data for ETo calculation were obtained from a historical series for the municipality of Morada Nova, Ceará state, for the period of 1991-2020.

b) Crop coefficients (Kc) – established for each stage of development of annual crops and the Kc in full development for perennial crops (Table 3). The Kc values used were obtained from the FAO-56 manual (Allen et al., 1998).

c) Mean crop evapotranspiration (ETm) – obtained by the expression (Eq. 5):

$$ETm = ETo \times Kc \qquad (5)$$

d) Irrigation requirement (IR) – calculated using the expression (Eq. 6):

$$IR = ETm - \text{effective precipitation} \qquad (6)$$

Irrigation requirement, which corresponds to the difference between maximum crop evapotranspiration and effective precipitation, was calculated based on monthly data of the climatological variables required (maximum and minimum average temperature, relative air humidity, wind speed and insolation).

Table 2. Monthly occupation plan of the activities in the Morada Nova Irrigation Project, Baixo Jaguaribe microregion, Banabuiú Valley, Ceará state, Brazil, 2021

Crops	Months (2021 base year)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rice 2		xx	xx	xx	xx							
Rice 8								xx	xx	xx	xx	
Maize		xx	xx	xx								
Native pasture	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
Paulistinha grass	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
Forage sorghum		xx	xx	xx								
Banana	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
Coconut	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
Shrimp	xx	xx	xx		xx	xx	xx		xx	xx	xx	

e) Water requirement or gross depth (GD) – calculated using the expression (Eq. 7):

$$GD = \frac{IR}{Ea} \quad (7)$$

where:

Ea - water application efficiency.

Regarding the shrimp farming activity, data were collected "in loco" to calculate the water requirement. The water depth used per cycle is 2,129 mm, but it is estimated that 40% of this water depth comes from reuse. Thus, when considering three annual cycles, a total of 3,832 mm is obtained. Annual water requirement (mm) coefficients of the activities are presented in Table 4.

The objective was to obtain an optimal standard of agricultural exploitation, compatible with the characteristics of exploitation of the MNIP, in order to maximize the annual net income resulting from the production. Thus, fixed mean values were considered in the model. Therefore, the model studied is represented by the following objective function (Eq. 8):

$$\begin{aligned} MAX\ NI &= 2400R2 + 2400R8 + 1700MZ + 500NP + \\ &+ 1600PG + 8000S + 2000B + 2500C + 38100SHR \end{aligned} \quad (8)$$

where:

MAX NI - maximization of net income;
R2 - area cultivated with rice in February (ha);
R8 - area cultivated with rice in August (ha);
MZ - area cultivated with maize (ha);
NP - area cultivated with native pasture (ha);
PG - area cultivated with Paulistinha grass (ha);
S - area cultivated with sorghum (ha);
B - area cultivated with banana (ha);
C - area cultivated with coconut (ha); and,
SHR - area with shrimp (ha).

Area constraints (Eqs. 9 to 20) resulting from the combination of activities in the 12 months of the year determine that the occupation of the area must be less than or equal to the available area. For the study, the area considered was 4,436 ha, which corresponds to the irrigable area of the MNIP.

A) AREA

$$TJAN)\ NP + PG + B + C + SHR \leq 4,436 \quad (9)$$

$$TFEB)\ R2 + MZ + NP + PG + S + B + C + SHR \leq 4,436 \quad (10)$$

$$TMAR)\ R2 + MZ + NP + PG + S + B + C + SHR \leq 4,436 \quad (11)$$

$$TAPR)\ R2 + MZ + NP + PG + S + B + C \leq 4,436 \quad (12)$$

$$TMAY)\ R2 + NP + PG + B + C + SHR \leq 4,436 \quad (13)$$

$$TJUN)\ NP + PG + B + C + SHR \leq 4,436 \quad (14)$$

$$TJUL)\ NP + PG + B + C + SHR \leq 4,436 \quad (15)$$

$$TAUG)\ R8 + NP + PG + B + C + \leq 4,436 \quad (16)$$

$$TSEP)\ R8 + PN + PG + B + C + SHR \leq 4,436 \quad (17)$$

$$TOCT)\ R8 + PN + PG + B + C + SHR \leq 4,436 \quad (18)$$

$$TNOV)\ R8 + PN + PG + B + C + SHR \leq 4,436 \quad (19)$$

$$TDEC)\ PN + PG + B + C + \leq 4,436 \quad (20)$$

where:

TJAN - cultivated area in January,
T - JAN, FEB, ... DEC months.

The water constraint presented in Eq. 21 ensures that the water demand of the activities will not be greater than available water. Nunes et al. (2022) conducted a study in an area of 1,087.8 ha in the MNIP and found that the exploitable resources, considering the total volume of water that can be safely exploited in the area, corresponded to 8.8 × 10^6 m^3 per year. As an area of 4,436 ha was used in the model, this value was corrected to 35.886 × 10^6 m^3 per year.

B) WATER

$$\begin{aligned} &TOTW)\ 1030R2 + 8690R8 + 440MZ + 8920NP + \\ &9940PG + 70S + 16650B + 14580C + 38320SHR \leq 35886000 \end{aligned} \quad (21)$$

For the production of the crops, absence of constraints for labor and capital for implementation was assumed, and it was necessary to incorporate minimum and maximum areas to guarantee the working capital of the producer, in

Table 3. Crop coefficients (Kc) by growth stage for different crops in the Morada Nova Irrigation Project, Baixo Jaguaribe microregion, Banabuiú Valley, Ceará state, Brazil, 2021

Crops	Kc			
	I	II	III	IV
Rice	1.05	1.10	1.20	0.8
Maize	1.0	–	1.15	1.05
Native pasture	0.6	–	0.75	0.75
Paulistinha grass	0.4	–	–	1.05
Forage sorghum	0.5	–	1.2	0.5
Banana	1.1	1.1	1.1	1.1
Coconut	1.0	1.0	1.0	1.0

I - Germination and emergence stage; II - Vegetative growth stage; III - Flowering and fruit development stage; IV - Maturation and senescence stage

Table 4. Annual water requirement (AWR) coefficients of the activities in the Morada Nova Irrigation Project, Baixo Jaguaribe microregion, Banabuiú Valley, Ceará state, Brazil, 2021

Crops	Rice 2	Rice 8	Maize	Native pasture	Paulistinha grass	Forage sorghum	Banana	Coconut	Shrimp
AWR (mm)	103	869	44	892	994	7	1,665	1,458	3,832

order to conciliate the cycle of the activities and the financial return. The area destined for shrimp farming was composed of unreclaimable halomorphic soils, according to a study conducted by Bezerra (2006).

The Eqs. 22 to 30 represent the constraints on the production of the various activities, resulting from several factors, such as internal demand, demand for bulky feed for the cattle herd and the crops already stabilized. This data was obtained from the summary of information on public irrigation projects for the 2020 agricultural year, based on data from the Departamento Nacional de Obras Contra as Secas (DNOCS).

C) CROP PRODUCTION AND SALT-DEGRADED AREAS (ha)

$$\text{R2) } R2 = 150 \quad (22)$$

$$\text{R8) } R8 = 100 \quad (23)$$

$$\text{MZ) } MZ \leq 20 \quad (24)$$

$$\text{NP) } NP \geq 420 \quad (25)$$

$$\text{PG) } PG \geq 96 \quad (26)$$

$$\text{SORG) } S \leq 73 \quad (27)$$

$$\text{BAN) } B = 10 \quad (28)$$

$$\text{COCO) } C = 10 \quad (29)$$

$$\text{SHR) } SHR \leq 1016 \quad (30)$$

where:

R2 - area to be cultivated with rice in February;

R8 - area to be cultivated with rice in August;

MZ - maximum area to be cultivated with maize;

NP - minimum area to be cultivated with native pasture;

PG - minimum area to be cultivated with Paulistinha grass;

SORG - maximum area to be cultivated with sorghum;

BAN - area to be cultivated with banana;

COCO - area to be cultivated with coconut; and,

SHR - maximum area with shrimp – associated with areas with high percentages of sodium.

A comparative analysis of the results obtained by the linear programming model studied was performed for a volume of water of 35,886,000 m^3 per year. In addition, a sensitivity analysis of the model was performed with three levels of available water: 28,708,800; 21,531,600; and 14,354,400 m^3 per year, corresponding to reductions of 20, 40 and 60% in the exploitable reserve of the aquifer. Finally, a sensitivity analysis was performed considering only two annual cycles of shrimp farming activity, given the volume exploited per cycle and the continuous expansion of the activity in the region.

The linear programming model was solved using the program developed by Lindo Systems Inc., named Linear Interactive and Discrete Optimizer (LINDO), which aims to solve systems of linear equations, using the iterative algorithm "revised simplex method".

Results and Discussion

The linear programming model generated the optimal cultivation plan shown in Table 5, which meets all the constraints proposed in the model and maximizes net income.

The optimal plan contemplates the highest level of net income with all activities being part of the base. Native pasture and Paulistinha grass activities participated in the base at its lowest level, in view of the respective constraints of greater than or equal to. The model suggests the use of 76.57% of the total area available for shrimp production, which has a significant demand for water and, in contrast, a high net income per unit area, compared to the other activities.

There is no shadow price associated with these activities, as they were all recommended in the model in question. According to Kuosmanem et al. (2021), the shadow price represents the resulting change in the value of the objective function, given an increment of one unit in the constant of the constraint, assuming that all other coefficients and constants remain unchanged.

The area constraint is a static limitation, which cannot be modified. As shown in Table 6, the occupation of the area ranged from 12.1% (December) to 35.1% (February and March).

It should be noted that the monthly occupation plan receives a significant influence from the shrimp farming activity and that, in the present study, the intervals between cycles were fixed in the months of April, August and December, for all producers. However, the existing variation is not static because shrimp cultivation is not carried out in fixed months.

Table 5. Optimal solution of the linear programming model

Activities	Water depth (mm)	Objective function coefficient (R$ ha^{-1})	Area (ha)	Optimized net revenue (R$ ha^{-1})
Rice 2	133	2,400.00	150	360,000.00
Rice 8	869	2,400.00	100	240,000.00
Maize	44	1,700.00	20	34,000.00
Native pasture	892	500.00	420	210,000.00
Paulistinha grass	994	1,600.00	96	153,600.00
Forage sorghum	7	8,000.00	73	584,000.00
Banana	1,665	2,000.00	10	20,000.00
Coconut	1,458	2,500.00	10	25,000.00
Shrimp	3,832	38,100.00	778	29,664.279.00
Total				31,213,100.00

Table 6. Area of occupation (ha) in the Morada Nova Irrigation Project (MNIP)

Activity	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rice 2		150	150	150	150							
Rice 8								100	100	100	100	
Maize		20	20	20								
Native pasture	420	420	420	420	420	420	420	420	420	420	420	420
Paulistinha grass	96	96	96	96	96	96	96	96	96	96	96	96
Forage sorghum		73	73	73								
Banana	10	10	10	10	10	10	10	10	10	10	10	10
Coconut	10	10	10	10	10	10	10	10	10	10	10	10
Shrimp	778	778	778		778	778	778		778	778	778	
Monthly occupancy (%)	29.6	35.1	35.1	17.6	33.0	29.6	29.6	14.3	31.9	31.9	31.9	12.1
Total	1,314	1,557	1,557	779	1,464	1,314	1,314	636	1,414	1,414	1,414	536

When considering the 90-day cycle, it is possible to observe that shrimp cultivation is carried out three times throughout the year, with intervals of approximately one month between cycles. This fluctuation in shrimp farming can be influenced by several factors, including resource availability, market demand, and management techniques used by producers (Valderrama & Engle, 2002; Tahim et al., 2019; Paiva et al., 2022).

Table 7 shows the current values of the objective function coefficients used in the model and the respective decreases and increases allowed in the net income of each activity, without causing changes in the levels of the optimal solution.

For maize, for example, it can be observed that the financial return per unit produced by this crop can be reduced by up to R$ 1,262.52 ha^{-1} or increased to "Infinity", without changing the level of the optimal solution. Therefore, sensitivity analysis of the parameters of the linear programming model is critical for understanding the behavior of the model and for making strategic decisions. The rice, banana and coconut crops, regardless of the values of the objective function, will always be given their respective areas, as the area restriction is equal.

Table 7. Sensitivity analysis of the net income of the basic variables for the linear programming model

Variable	Area of the variable (ha)	Net income R$ ha^{-1}		
		Decrease	Current	Increase
Rice 2	150	Infinity	2,400.00	Infinity
Rice 8	100	Infinity	2,400.00	Infinity
Maize	20	1,262.52	1,700.00	Infinity
Native pasture	420	Infinity	500.00	8,368.78
Paulistinha grass	96	Infinity	1,600.00	8,282.93
Sorghum	73	7,930.40	8,000.00	Infinity
Banana	10	Infinity	2,000.00	Infinity
Coconut	10	Infinity	2,500.00	Infinity
Shrimp	778	31,931.79	38,100.00	109,954.54

Linear programming is a useful tool for optimizing the allocation of limited resources, such as land use and water use. The technical coefficients used in linear programming models, however, are often estimated and are consequently subject to variations (Dantas Neto, 1994). Thus, it is of great interest not only to obtain an optimal basic solution, but also to know the intervals of these coefficients for which the solution remains optimal, in order to perform a sensitivity analysis of the model.

For the sensitivity analysis of the land resource, as shown in Table 8, it was found that the occupied areas did not reach the maximum available value of 4,436 ha. This indicates that the land resource was not a limiting resource, showing slack and, consequently, shadow price equal to zero. It was also observed that the model shows, associated with each monthly land constraint, the respective value of area decrease that can be used by the constraint, without changing the basic variables of the optimal solution of the linear programming model.

Similar results were obtained by Santos et al. (2009) in the Baixo Acaraú Irrigation Project, in the state of Ceará, Brazil. The authors used a linear programming model for optimization, which consisted of proposing alternative crops and areas for 8-ha lots that provide the maximization of the producer's net income, incorporating the restrictions of land, water, and market availability. When conducting sensitivity analyses in linear programming models, Santos Júnior et al. (2015) obtained a shadow price equal to zero for the land resource and concluded that this resource showed no constraint to obtain a higher financial return in the Formoso Irrigated Perimeter, in the state of Bahia, Brazil.

According to Table 9, the total water volume can increase by 9,097,470 m^3 or decrease by 29,835,690 m^3, without changing the optimal solution and the shadow price.

Table 8. Sensitivity analysis of the land resource for the linear programming model

Month	Area occupied (ha)	Amount of slack (ha)	Shadow price (R$ ha^{-1})	Area decrease (ha)	Area increase (ha)
January	1,314	3,121	0.0	3,121	Infinity
February	1,630	2,805	0.0	2,805	Infinity
March	1,630	2,805	0.0	2,805	Infinity
April	852	3,584	0.0	3,584	Infinity
May	1,464	2,971	0.0	2,971	Infinity
June	1,314	3,121	0.0	3,121	Infinity
July	1,314	3,121	0.0	3,121	Infinity
August	636	3,800	0.0	3,800	Infinity
September	1,414	3,021	0.0	3,021	Infinity
October	1,414	3,021	0.0	3,021	Infinity
November	1,414	3,021	0.0	3,021	Infinity
December	536	3,900	0.0	3,900	Infinity

Table 9. Sensitivity analysis of the total volume of water available

Water	Volume available (m^3)	Amount of slack (m^3)	Shadow price (R$ 10 m^{-3})	Volume decrease (m^3)	Volume increase (m^3)
Total water	35,886,000	0	0.99	29,835,650	9,097,470

Water is a scarce resource and the total annual volume available did not allow room for slack, so a shadow price is assigned, which corresponds to a reduction in the value of the objective function if this volume becomes more restrictive in one unit. In this context, the shadow price for each 10 m^3 of water is R$ 0.99, that is, for each increment of 10 m^3 of this resource, the value of net income would increase by R$ 0.99, without causing changes in the basic variables of the optimal solution. Similarly, each reduction of 10 m^3 in water use would reduce net income by R$ 0.99.

The variability of the water volume available requires constant qualitative and quantitative analysis of water resources, in order to avoid overexploitation, risk of scarcity in the circulation rate and stress of this resource, with a view to water sustainability. Water consumption, regardless of the activity performed, needs to be optimized, given the growing scarcity of fresh water. In this context, optimization techniques based on processes that involve multiple objectives are often used in several areas, and in the agricultural sector, decision-making aims, for example, to maximize yield, minimize costs, and mitigate environmental impacts (Galán-Martín et al., 2017; Zhang et al., 2021; Akbar et al., 2022; Ingrao et al., 2023).

Table 10 shows the recommendation of the activities or basic variables obtained in the optimal solution for four levels of water availability. It can be observed that the variation in water availability affects only the area destined for shrimp cultivation, causing a reduction in the total area occupied.

The reduction in area indicates that not all activities can be maintained at full capacity when there is scarcity of water. Therefore, to optimize the use of available water, it is necessary to adjust activities and allocate resources efficiently, as well as monitoring water resources continually.

Maximum water restriction (60%) results in a reduction of approximately 70% in net income. This behavior highlights the importance of implementing optimization models, with a view to ensuring water availability and allowing an efficient planning of the activities carried out in the MNIP.

It is worth pointing out that the reduction in water availability is not a standard trend, considering that the sequence of years used to calculate the exploitable reserve results from a prolonged period of drought. This demonstrates that this may not represent the best current condition of an optimal plan for the MNIP, requiring continuous monitoring of water reserves so that, annually, it is possible to determine with greater certainty the water availability and, consequently, the optimal plan.

The reduction in the annual cycles of shrimp farming, from three to two, led to the occupation of the entire area available for shrimp cultivation and a significant increase (more than 500%) in the area destined for the cultivation of Paulistinha grass (Table 11). This strategy causes a reduction of only 10.3% in the annual net income of the MNIP, compared to the condition with three annual cycles of shrimp farming.

Despite a one-third reduction in the objective function coefficient for shrimp due to the reduction of one cycle, this activity was included in the maximum limit of its restriction (1,016 ha) as it still had the highest value of all the variables.

On the other hand, forage sorghum, despite having the second highest value of the objective function coefficient (R$ 8,000 ha^{-1}), did not increase in area due to its restriction being lower or equal, as opposed to Paulistinha grass, which has no area restriction.

According to Bernzen et al. (2023), the main environmental issues related to shrimp production include decreased biodiversity, water pollution and scarcity of potable water, and the risk of soil salinization. In this context, when considering the reality of the MNIP, there may be an expansion of the areas

Table 11. Reduction of one cycle in shrimp farming

Variable	Area of the variable (ha)	Net income R$ ha^{-1}		
		Decrease	Current	Increase
Rice 2	150	Infinity	2,200.00	Infinity
Rice 8	100	Infinity	2,200.00	Infinity
Maize	20	1,629.17	1,700.00	Infinity
Native pasture	420	Infinity	500.00	935.81
Paulistinha grass	487	1,042.82	1,600.00	8,126.02
Sorghum	73	7,988.73	8,000.00	Infinity
Banana	10	Infinity	2,000.00	Infinity
Coconut	10	Infinity	2,500.00	Infinity
Shrimp	1,016	20,887.32	25,400.00	Infinity

Table 10. Optimal solution obtained by the model for four levels of water availability

Activities	Water availability (m^3 per year)			
	35,886,000	28,708,800	21,531,600	14,354,400
Rice 2	150	150	150	150
Rice 8	100	100	100	100
Maize	20	20	20	20
Native pasture	420	420	420	420
Paulistinha grass	96	96	96	96
Forage sorghum	73	73	73	73
Banana	10	10	10	10
Coconut	10	10	10	10
Shrimp	778	591	404	216
Total area (ha)	1,657	1,470	1,283	1,095
Reduction in area (%)		11.29	22.57	33.92
Net income (R$)	31,213,100.00	24,095,840.00	16,978,570.00	9,861,305.00
Reduction in net income (%)		22.80	45.60	68.41

restricted to agricultural cultivation, which may affect small farmers, who will be forced to migrate to shrimp farming and often cannot afford the investment. However, despite the ecological problems related to shrimp farming, the activity remains attractive, due to the potential for higher income (Ray et al., 2022; Bernzen et al., 2023).

Conclusions

1. The high occupation of the Irrigation Project with rice cultivation before the 2012-2017 water crisis, despite being a low-risk activity, practically no longer contributes to the occupation plan due to the average 90% reduction in cultivation during the period of full irrigation.

2. Sensitivity analysis of the water resource showed a slack equal to zero, indicating that it is a limiting resource, and the consequence lies in the monthly occupation of area at its most favorable level in February and March, with only 35% of the total area of the Project.

3. Drastic reduction in net income due to reduction in water availability points to risks associated with years of water scarcity and dependence on groundwater, the only source of water currently available in the Project.

4. Reduction of one cycle in shrimp farming in years of moderate water scarcity is a feasible alternative from a financial perspective, given the level of reduction in the annual net income of the Project.

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