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AVALIAÇÃO DOS TRANSIENTES HIDRÁULICOS EM BOMBEAMENTO COLETIVO E BOMBEAMENTO INDIVIDUAL EM PERÍMETRO DE IRRIGAÇÃO

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1 RESUMO

Objetivou-se neste trabalho comparar os transientes hidráulicos em projeto de irrigação sob pressurização coletiva e individual, incluindo-se os custos dos investimentos somados aos de energia elétrica. Foram utilizados os softwares IRRICAD, para a extração das curvas de nível, o EPANET para o cálculo da rede em regime permanente e o Sistema UFC, que utiliza o Método das Características (MOC), para calcular a intensidade dos transientes hidráulicos nos dois modelos de projetos, pressurização coletiva e individual. A adoção dos dispositivos antitransientes corretos, neste caso os tanques de ação unidirecional (TAUs) proporcionou um investimento adicional de apenas 2,17% na pressurização individual e 7,60% na pressurização coletiva, consequência da maior quantidade e tamanho dos dispositivos antitransientes, bem como necessidade de tubos de maior classe de pressão. Contudo, considerando-se os investimentos em reservatórios e estações de bombeamento em cada lote, a pressurização individual se tornou mais onerosa que a coletiva, sendo o efeito ainda mais intenso quando foram acrescidos os custos com energia elétrica devido a menor eficiência energética dos conjuntos motobombas das estações individuais.

Palavras-chave: Custos do dispositivo antitransiente, tanque de alimentação unilateral (TAU), sistema UFC7.

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2 ABSTRACT

This work compared the effects of hydraulic transients in irrigation projects under collective and individual pressurization, including the costs of investments added to those of electrical energy. The IRRICAD software was used to extract the contour lines, and the EPANET software was used to calculate the steady-state network and the UFC system, which uses the characteristics method (MOC), to calculate the intensity of the hydraulic transients in the two project models, i.e., collective and individual pressurization. The adoption of the correct antitransient devices, in this case, the one-way surge tanks (TAUs), provided an additional

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investment of only 2.17% in individual pressurization and 7.60% in collective pressurization, a consequence of the greater quantity and size of antitransient devices, as well as the need for tubes with a higher pressure class. However, considering the investments in reservoirs and pumping stations in each batch, individual pressurization became more expensive than collective pressurization, and the effect was even more intense when electricity costs were added due to the lower energy efficiency of the motor pump sets of the individual stations.

Keywords: Antitransient device costs, one-way surge tank, UFC7 system.

3 INTRODUCTION

Public irrigation projects total approximately 200 thousand hectares, distributed across 79 projects and 88 municipalities, notably the majority in the semiarid region of Brazil, and are responsible for 116 direct jobs and 172 indirect jobs for every 100 productive hectares (ANA , 2021), which means that there are currently approximately 580 thousand jobs that depend on irrigated agriculture under the control of public perimeters.

There are two flow regimes in hydraulic projects, the steady state (SR) regime and the transient (TR) regime, which have been neglected in irrigated agriculture in Brazil. In the steady state, the fluid density, velocity, and pressure properties do not change at a given point in the network over a given time interval (Chaudhry, 2014). However, they can vary between different points and remain constant over time for any given point (Wylie; Streeter, 1978). The change in flow conditions that leads to variations in velocity and flow is called hydraulic transient (or water hammer) (Wylie; Streeter, 1979 apud Schimidt, 2016, p. 11).

The hydraulic head values in the steady state can be calculated via the continuity and Bernoulli equations (which refer to the conservation of energy in a given system), whereas under transient conditions, specific equations are used (Vianna, 2021). The analysis of hydraulic transients is not common in the daily routine of irrigation professionals and is a complex topic. However, this topic can be presented in a more intuitive, accessible, and easy-to-understand manner (Veiga, 2014).

Several methods have been applied over the past several decades to determine hydraulic transients (Wylie; Streeter, 1978; Veiga, 2014), and in this work, the method of characteristics (MOC) was used, which is considered the most appropriate and accurate and converts partial differential equations of continuity and motion into ordinary differential equations solved numerically through finite difference techniques (Gray, 1953; Streeter; Lai, 1962; Chaudhry, 2014). Hydraulic transients are very complex and cannot be solved through manual calculations (Veiga, 2014).

The initial equations of hydraulic transients are those of momentum (Equation 1) and the equation of continuity or conservation of mass (Equation 2), according to Carvalho (2011). These are presented as follows (Castro, 2022):

$$\frac{\partial H}{\partial x} + \frac{Q}{S^2}\frac{\partial Q}{\partial x} + \frac{1}{S}\frac{\partial Q}{\partial t} + \frac{f\,Q\,|Q|}{2\,g\,D\,S^2} = 0 \qquad (1)$$

The modulus term in Eq. (1) indicates that flow can occur in both directions.

$$\frac{\partial H}{\partial t} + \frac{Q}{S}\frac{\partial Q}{\partial x} + \frac{a^2}{g\,S}\frac{\partial Q}{\partial x} = 0 \qquad (2)$$

where H is the manometric head (mca), Q is the flow rate ($m^3\,s^{-1}$), t is the time (s), x is the distance in a longitudinal section of the pipe , g is the acceleration of gravity (ms $^{-2}$), D is the pipe diameter (m), S is the cross-sectional area of the pipe (m ^{2}), f is the coefficient of friction (Colebrook) and a is the celerity (ms $^{-1}$).

On the basis of Equations 1 and 2, the method of characteristics allows its algebraic solution (Wyllie; Streeter, 1993 apud Silva, 2006), becoming a standard method for the analysis of transients in closed conduits (Chaudhry, 1993 apud Schimidt, 2016, p. 27).

Using Equations 3 and 4, in a given control volume, two nonlinear differential equations are obtained in the unknowns piezometric load (H) and velocity (V) as a function of space (x) and time (t), which results in the determination of pressures and velocities over time, relating the cause (maneuver) to the effect (hydraulic transient) (Veiga, 2014).

Streeter and Wylie (1982) named them positive characteristic (C^{+}) and negative characteristic (C^{-}) equations 3 and 4, respectively), which can be expressed as follows (Magalhães, 2018):

Equation 3 – Positive characteristic (amount)

$$C^{+}: H_P - H_A + \frac{a}{g\,S}(Q_P - Q_A) + I^{+} = 0 \quad (3)$$

Equation (4) – Negative characteristic (downstream)

$$C^{-}: H_P - H_B - \frac{a}{g\,S}(Q_P - Q_B) + I^{-} = 0 \quad (4)$$

where H_P is the transient load P (in mca) at time t + Δt; H_A is the permanent load A upstream (in mca) at time t; HB is the permanent load B downstream (in mca) at time t (m); Q_P is the transient flow rate (in m ^{3} s $^{-1}$) in P at time t + Δt; Q_A is the flow rate (in m ^{3} s $^{-1}$) in A at time t; Q_B is the flow rate (in m ^{3} s $^{-1}$) in B at time t; a is the celerity (ms $^{-1}$); g is the acceleration of gravity = 9.81 (ms $^{-2}$); S is the cross-sectional area of the pipe (m ^{2}); and I^{+} and I^{-} are the integrations between the head loss and the slope of the section (pipe) (m).

The practical effects of the C^{+} and C^{-} equations on the boundary conditions define the behavior of the boundaries of each pipe at its ends (Tomaz, 2010), which define and give magnitude to the transient effects (Magalhães, 2018).

There are several resources and equipment used to solve (or mitigate) the intensity of a water hammer or hydraulic transient, including subpressures (TAU, double-effect suction cup, bypass, TAEB, and TAEB-EV), overpressures (relief valves and wave anticipators) or even, for both cases (flywheel, TAB, hydropneumatic tank, balance chimney, and “nonslam” suction cups) (Vieira, 2021b).

That said, this work had the specific objective of comparing the effects of hydraulic transients in irrigation projects with collective pressurization and irrigation projects with individual pressurization, with the analysis of the costs of investments added to those of electrical energy over 20 years in an irrigated perimeter.

4 MATERIALS AND METHODS

4.1 Conditions analyzed and software used:

The following conditions were analyzed in this study:

i) Considering only the permanent regime with collective pressurization (RPPC);
ii) Consider only the permanent regime with individual pressurization (RPPI);
iii) Consider the permanent regime and the transient regime with collective pressurization (RPTPC);
iv) Consider the steady-state and transient regimes with individual pressurization (RPTPI). In both conditions in which the transient regime was considered (RPTPC and RPTPI), the intensity of the hydraulic transients was estimated by the MOC via the

UFC software, which was developed by the Federal University of Ceará, and the best alternatives for their attenuation were also evaluated.

The effects of hydraulic transients were compared in the case of collective and individual batch pressurization, determining the lowest value (added to the investment and electricity costs over 20 years). The assumptions adopted in the analysis for both regimes (permanent and transient) were as follows:

- The networks have the same diameter and material (only the pressure classes change when necessary);
- The lots have an area of 6 ha, a unit flow of 0.8 L s $^{-1}$ ha, and a total flow of 4.8 L s $^{-1}$;
- The maximum irrigation operating time was 21 hours per day $^{-1}$ and 30 days per month $^{-1}$ during the period of highest demand (October);

mca was adopted; in those with individual pressurization, 5 mca was adopted;

- All batches will operate at the same time;
- All other perimeter conditions were the same for both alternatives, and only the devices for water hammer mitigation were specified;
- The irrigation sectors for both alternatives studied are the same;
- Standard (or catalog) pumps were used for all the scenarios evaluated.

4.2 Study scenarios:

The following scenarios were analyzed to quantify the effects of hydraulic transients on irrigation perimeters:

- RPPC - permanent regime with collective pressurization;
- RPTPC - Permanent and transient regime with collective pressurization;
- RPPI - permanent regime with individual pressurization;
- RPTPI - Permanent and transient regime with individual pressurization;

The following software was used to develop the work:

- CLIMWAT (FAO), combined with CROPWAT, to obtain data on potential evapotranspiration (ETo) and effective precipitation (PE) incidents in the area;
- IRRICAD, for extracting contour lines of the study area from Google Earth:
- EPANET, for calculating the permanent regime, whose data (network diameter and permanent pressures) were generated from the network drawn via UFC software in the AUTOCAD database;
- UFC system software for calculating hydraulic transients and obtaining the results of the protection used (unidirectional action tank (TAU)) in the 12 subducts analyzed in the RPTPC and RPTPI options.

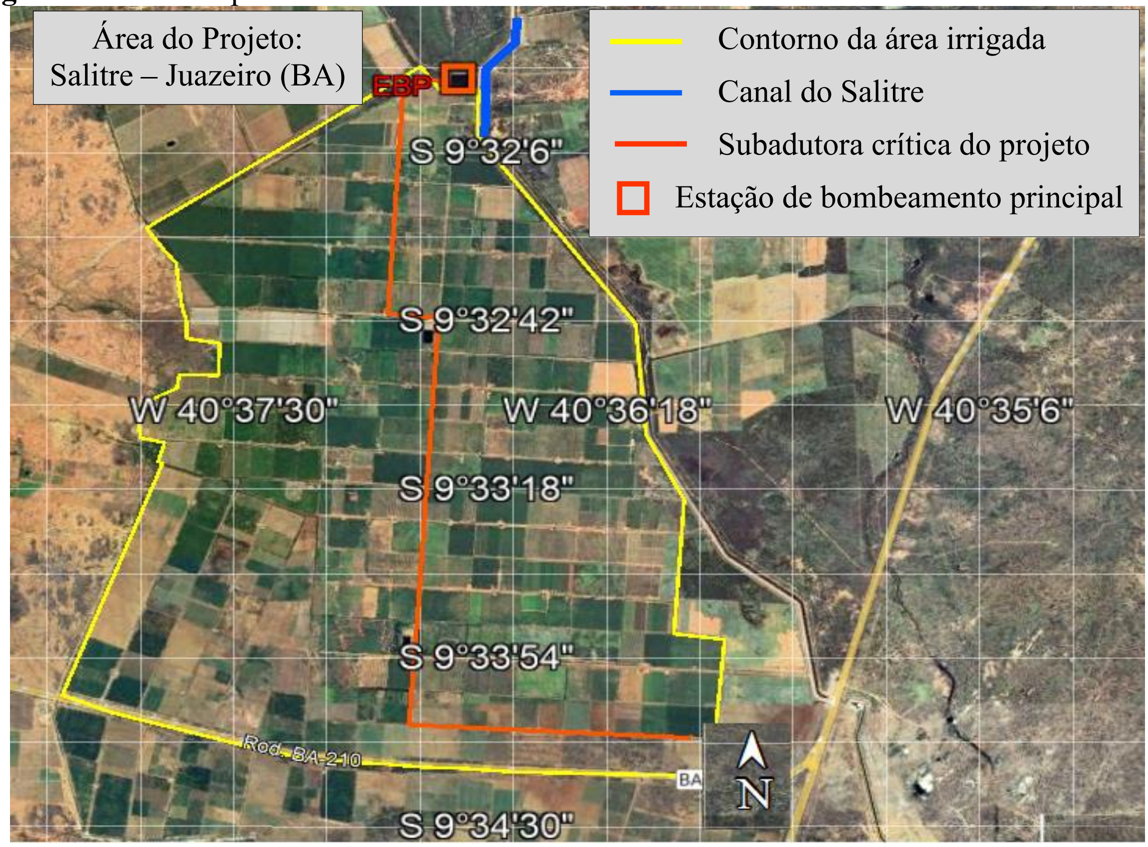
4.3 Identification of the irrigated perimeter area and topography

The irrigation perimeter of the Salitre Project (Codevasf, 2018) in Juazeiro, Bahia, was chosen as the cartographic base. However, the subdivision, flow rate, pumping station, networks, and land tenure were altered in this study. This area is located in the semiarid region of Northeast Brazil and accounts for more than 90% of the country's mango and grape exports. The area in question has a flat topography, and there were subaccretions in which the final lots were at elevations below the collective pumping station, in both the collective pressurization (CP) and individual pressurization (IP) versions.

To extract the contour lines, the IRRICAD software was used from a Google Earth image covering a total area of 1,164.00 ha, including the canal and the main pumping station (EBP) (Figure 1), and 156 lots were launched, with a useful agricultural area of 936 ha.

This area is real and is located between coordinates 8,946,078.79 and 8,941,581.68 South and 320,534.46 and 324,668 East; however, the study hydraulic system has a different configuration.

Figure 1 Evaluated perimeter.



Source: Authors, adapted from Google Earth (2023).

4.4 Determination of the maximum design flow rate and system operating time

The banana crop was considered—merely as a reference for determining the perimeter's operating time, not the actual situation—with Kc (crop coefficient) equal to 1.0 and KL (location coefficient) equal to 0.98, with a maximum daily irrigation time of 21 hours over 30 days per month and an irrigation efficiency of 90%, using a microsprinkler system. Another permanent crop could have been used, or a single flow rate could have been used, since the focus is on analyzing the effect of transients on an irrigation perimeter, not the crop itself.

The maximum design flow was calculated by applying the climatological data (ETo) obtained through CLIMWAT 2.0 software and treated with CROPWAT version 8.0 from the Food and Agriculture Organization (FAO). The first dataset was developed in 2006 and uses data from the agrometeorological group of the FAO/SDRN (Enviromental and Natural Resources Service), and these data can be used to determine the water balance with due reliability. The CROPWAT, also from the FAO, was developed by the Water Development and Management Unit and allows the preparation of the water balance through the input of climate, soil, and plant data.

Notably, CROPWAT does not generate a water balance for permanent crops; it was used only to obtain reference evapotranspiration and effective precipitation data, for which the "precipitation not considered" option was adopted for all months. The station chosen in CLIMWAT was Petrolina, Pernambuco, station number 181, longitude -40.48 and latitude -9.38, with an altitude of 370 m, as it is the closest to the area used as the baseline. A series of historical data are available there, including the EMBRAPA-CPATSA meteorological station.

After the water balance was prepared, operating times of 2,865 and 3,043 hours per year were obtained for the off-peak and reserved periods, respectively. The maximum flow rate was 4.8 $L^{/s}$, and the design flow rate was 748.80 L/s, a value applied to the dimensioning of the pipes, antiblow devices and motor pumps.

4.5 Hydraulic calculations of the perimeter

Once the contour lines (meter-by-meter) are extracted and established, the file is exported from IRRICAD (ten) to the "dxf" format and then converted to " dwg" in AUTOCAD version 2022. This resulted in the plan for use with UFC/EPANET. EPANET is free software developed in Cincinnati, Ohio, USA, and is a valuable tool for the design and simulation of the steady state (SSR) and final costs of the options analyzed.

EPANET was implemented after the networks were launched via UFC via the AUTOCAD database. Once the diameters and pressure classes relative to the steady state were dimensioned (EPANET via UFC), transient analyses were performed via UFC software.

To this end, the network was subdivided into 12 distinct subadductors, analyzed individually for the RPTPC and RPTPI options, and finally, the final quantities and antitransient protections were obtained.

The pressure required at the batch inlet was calculated for the RPPC (31.66 mca) and RPPI (5 mca) options.

4.6 Quantities of alternatives (RPPC, RPPI, RPTPC and RPTPI)

Items common to the alternatives in both regimes (permanent and transitional) were not accounted for, only those that differentiated the solutions. Table 1 below details the items evaluated and rated for all the scenarios considered.

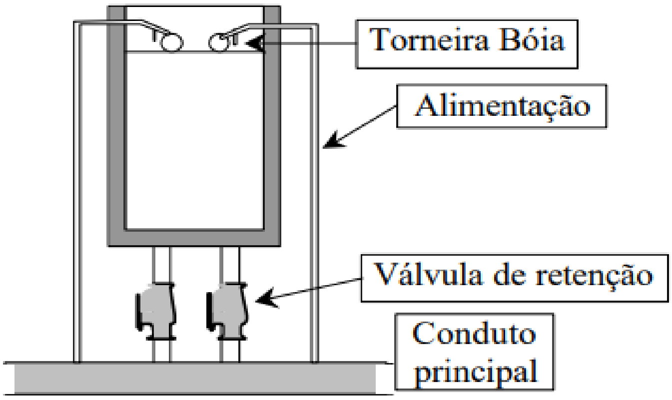
Table 1 Items evaluated and rated for the alternatives considered. Being**:** RPPC – Permanent Regime with Collective Pressurization, RPPI – Permanent Regime with Individual Pressurization, RTPC – Permanent and Transient Regime with Collective Pressurization and RTPI: Permanent and Transient Regime with Individual Pressurization.

ITEM	RPPC	RPPI	RPTPC	RPTPI
Pipes and networks	YES	YES	YES	YES
Collective motor pump sets	YES	YES	YES	YES
Soft starters collective motor pumps	YES	YES	YES	YES
Motor pump sets complete lots	NO	YES	NO	YES
Motor pump starter keys lots	NO	YES	NO	YES
PR/FR valves	YES	NO	YES	NO
High flow buoys	NO	YES	NO	YES
Reservoir lots	NO	YES	NO	YES
Electricity costs EBP	YES	YES	YES	YES
Electricity costs for batch pumps	NO	YES	NO	YES
TH protection devices	NO	NO	YES	YES
Main lines lots	YES	YES	YES	YES
Civil works	NO	NO	NO	NO

Source: Authors (2023).

A one-way action tank (UAT) was chosen to cool hydraulic transients in all subconduits and options, as the number, magnitude, and size of such devices would allow a comparison between collective and individual pressurization options. These devices are manufactured on the basis of simulations of incident transients (underpressure), and there are no standard measurements, such as valves and suction cups. They can have bodies made of steel, concrete, or fiberglass (used in the study), as long as they can withstand the static load resulting from their filling through the supply. They have a float or control valve to prevent overflow and a check valve at the outlet, which opens when underpressure occurs (Figure 2).

Figure 2 One-way action tank (TAU).



Source: Massiero Junior (2008).

4.7 Steps for preparing the research

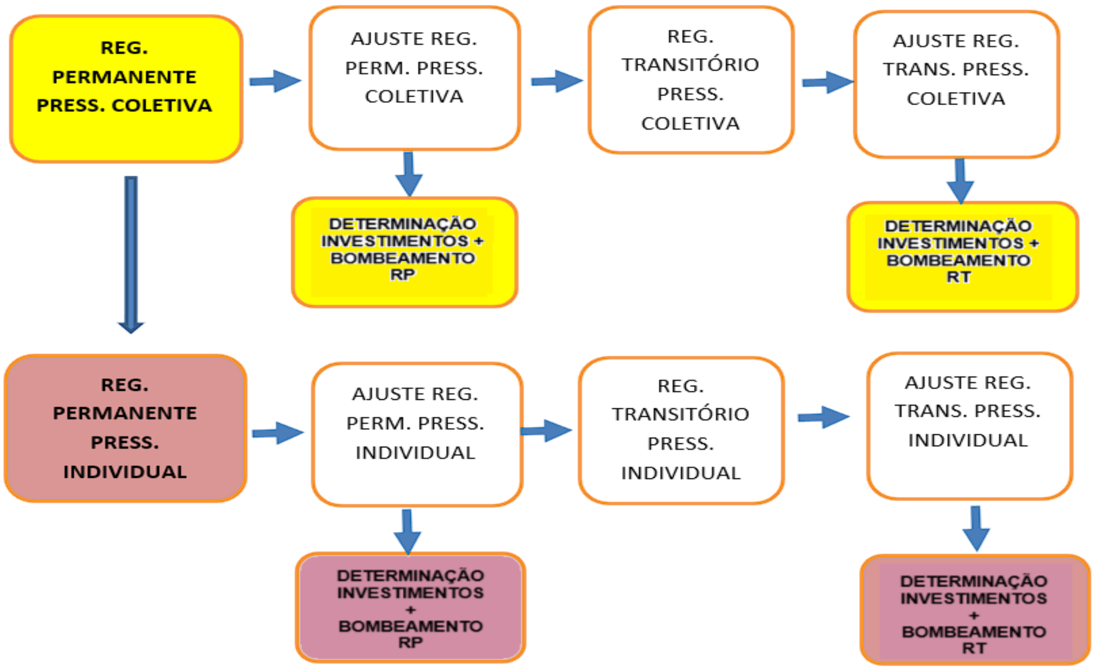
The study began by calculating the permanent regime with collective pressurization (RPPC), which has a higher total manometric height (AMT), followed by individual pressurization by applying EPANET until the minimum inlet pressure value in the batch was reached, which was set at 5.0 mca.

The electricity expenditures (costs) over 20 years were calculated by applying Group A4 seasonal green tariffs to the main pumping station (EBP) and Group B2 Rural Irrigation tariffs to the individual pumping stations (EBI). Both tariffs were from the Neoenergia Concessionaire COELBA (Companhia de Energia Elétrica da Bahia).

After the investments and pumping costs in the steady state with collective pressurization were calculated, the effect of transients (RPTPC) was simulated, and after this step, values for the necessary investments with the antitransient devices were obtained. The same procedure was applied in the steady state with individual pressurization, in which there was a reduction in the AMT of 26.66 mca. Figure

Figure 3summarizes the steps employed in the research.

Figure 3 Steps for preparing the study**.**



Source: Authors (2023).

5 RESULTS AND DISCUSSION

Compared with individual pressurization systems, hydraulic systems with collective pressurization are subjected to more intense transient effects due to the greater magnitude of pumping pressure (H), in which each batch has its own individual reservoir (RES) and individual pumping station (EBI). Compared with the steady-state and transient regimes with individual pressurization (RPTPI), the steady-state and transient regimes with collective pressurization (RPTPC) required more and larger devices to obtain acceptable underpressure values, which was the most potentially dangerous transient effect on the pipelines selected in the study, as shown in Table 2.

The RPTPC option presented 35 collapse points, which required medium and large one-way action tanks (TAUs) (29 and 6 units, respectively), whereas the RPTPI option, in addition to requiring fewer devices, was mostly small (22 units), medium (9 units) and large (only 1 unit) in size.

Table 2. Dimensions and total quantity of one-way action tanks (TAUs) in the collective pressurization (RPTPC) and individual pressurization (RPTPI) alternatives.

TAU Dimension		**Amount**	
Height (m)	**Diameter (mm)**	**RPTPC**	**RPTPI**
1.5	1000	0	22
3.0	2000	29	9
6.0	3000	6	1
Total		35	32

Source: Authors (2023).

Considering only the investments in antitransient devices (Table 3), that is, the adoption of the correct antitransient devices, in this case, the one-way action tanks (TAUs), the additional investment was 7.60% in collective pressurization (alternative 5 in relation to alternative 1) and only 2.17% in individual pressurization (alternative 6 in relation to alternative 2).

Anti-transient devices (alternatives 1 and 5, respectively), which included investments in RES and EBI of the lots (alternatives 3, 4, 7, and 8, respectively), were less costly than the individual pressurization alternatives were. In other words, even though they required greater investment in the main pumping station and in the pressure class of the main pipes (due to the higher AMT), such investments did not exceed those corresponding to EBI and RES.

Table 2 Regimes and alternatives considered.

Regime	Pressurization (alternatives)	Investment (R$)
Permanent	1. Collective (RPPC)	8,065,470.83
	2. Individual (RPPI) <u>without</u> considering the investment in the individual pumping station (EBI [1]) and in the reservoir (RES) of the lots	7,880,218.28
	3. Individual (RPPI) considering the investment in EBI and RES [2] with a volume of 18 m3 of the lots	9,497,994.95
	4. Individual (RPPI) considering the investment in EBI and RES [3] with a volume of 147 m^3 of the lots	9,842,295.95
Permanent and Transient	5. Collective (RPTPC)	8,678,057.31
	6. Individual (RPTPI) <u>without</u> considering the investment in the EBI and RES of the lots	8,093,841.36
	7. Individual (RPTPI) considering the investment in the EBI and RES of volume 18 m3 of the lots	9,711,618.03
	8. Individual (RPTPI) considering the investment in the EBI and RES of volume 147 m3 of the lots	10,055,919.03

[1] EBI – Monobloc electric pump set, three-phase, power = 4.0 hp, AMT = 26.4 mca, Q = 4.8 L s^{-1}, Efficiency = 63.6%, rotation = 3500 rpm

[2] RES – semiexcavated reservoir in the 1st category of material, with a 1.0 mm thick HDPE blanket and 18 m3 volume (preserved volume for 1 hour of pumping)

[3] RES – semiexcavated reservoir in the 1st category material, with a 1.0 mm thick HDPE blanket and a volume of 147 m3 (a reserve volume for 8.5 hours of pumping, corresponding to nighttime with a special discount on the electricity consumption tariff – reserved nighttime).

Source: Authors (2023).

The electricity costs for pumping over 20 years (Table 4) showed that collective pressurization is more expensive than individual pressurization if only main station pumping is considered because of the higher energy consumption and contracted demand. However, if the pumping costs within the batches are added, the situation reverses: individual pressurization becomes significantly more expensive than collective pressurization because of the lower energy efficiency of individual pumping stations (IPSs), which are lower-powered and generally less efficient sets. Considering only the electricity costs at the main pumping stations (EBP1 for collective pressurization and EBP2 for individual pressurization – elevation to the batches), the AMT for collective pressurization was 37% higher than that for individual pressurization. However, if the cost of individual pressurization carried out at the 156 pumping stations on the lots is increased, the total individual pressurization (EBP2 + EBI) becomes 51.6% greater than the collective pressurization.

Table 4. Breakdown of electricity costs in alternatives (20 years)

Item	RPTPC	RPTPI
Energy consumption cost (R$) – main pumping station (EBP [1] and EBP [2])	14,033,539.72	10,127,660.66
Cost of contracted energy demand (R$) – main pumping station (R$)	6,007,235.30	4,505,426.47
Total – main pumping station (R$)	20,040,775.02	14,633,087.13
Energy consumption cost (R$) – sum of 156 individual pumping stations (EBI [3])	0.00	15,750,062.68
Total sum (R$)	20,040,775.02	30,383,709.81

[1] EBP of collective pressurization – Bearing pump, AMT = 77 mca, Q = 151 L/s, Ef = 85%, 1775 rpm, coupled to a three-phase motor, 440 V, 200 hp, mounted on an iron base, 5 units connected in parallel
[2] EBP of individual pressurization – Bearing pump, AMT = 54 mca, Q = 151 L/s, Ef = 82.6%, 1775 rpm, coupled to a three-phase motor, 440 V, 150 hp, mounted on an iron base, 5 units connected in parallel
[3] EBI for individual pressurization (each batch) – monobloc electric pump set, three-phase, power = 4.0 hp, AMT = 26.4 mca, Q = 4.8 L s^{-1}, Efficiency = 63.6%, 3500 rpm, 156 units (batches).
Source: Authors (2023).

Considering the investments added to the expenditures on electricity over 20 years (Table 5), collective pressurization with and without antitransient devices (alternatives 1 and 5) proved to be less costly than individual pressurization, which includes investments in RES and EBI of the lots (alternatives 3, 4, 7, and 8). Consequently, under these conditions, the total value per irrigated hectare was also greater with individual pressurization.

However, it should be noted that irrigation perimeters are managed by nonprofit entities called irrigation districts and that common costs are shared among producers. Therefore, individualizing pressurization—transferring water management to the individual farmer—involves automatic energy savings by the farmer, which automatically results in a reduced main pumping station (EBP) operating time.

Table 5. Comparison of investments added to expenditures on electricity in 20 years in the alternatives considered.

Regime	Pressurization (alternatives)	Invest. + Bomb. (R$)	Unit cost (R$ ha $^{-1}$)
Permanent	1. Collective (RPPC)	28,106,245.85	30,028.04
	2. Individual (RPPI) without EBI and RES	22,513,305.41	24,052.68
	3. Individual (RPPI) with EBI and RES 18 m ^{3}	39,881,704.14	42,608.66
	4. Individual (RPPI) with EBI and RES 147 m ^{3}	40,226,005.14	42,976.50
Permanent and Transient	5. Collective (RPTPC)	28,718,832.33	30,682.51
	6. Individual (RPTPI) without EBI and RES	22,726,928.49	24,280.91
	7. Individual (RPTPI) with EBI and RES 18 m ^{3}	40,095,327.22	42,836.89
	8. Individual (RPTPI) with EBI and RES 147 m ^{3}	40,439,628.22	43,204.73

Source: Authors (2023).

When considering the investment values added to the pumping costs over 20 years in Table 5, the water hammer protection devices presented relative increases of 2.18% (alternative 5 in relation to alternative 1), 0.9% (alternative 6 in relation to alternative 2), 0.54% (alternative 7 in relation to alternative 3), and 0.53% (alternative 8 in relation to alternative 4).

Failure to consider protective devices would result in higher maintenance costs, since the chance of ruptures and collapses is significantly reduced, depending on their recurrence. Furthermore, it could lead to more serious consequences, such as the suspension of irrigation projects for a period of time, generating legal proceedings, including lost profits, and, in the worst-case scenario, physical injuries (even fatal) to system operators and bystanders.

6 CONCLUSIONS

Transient effects were more severe in collective pressurization than in individual pressurization; therefore, the additional burden between the two alternatives (RPPC and RPTPC) was due to the inclusion of protective devices, especially one-way action tanks (TAUs), which require a greater number of devices and larger dimensions. The additional investment in antitransient devices was 7.60% for collective pressurization and only 2.17% for individual pressurization.

In terms of investments, collective pressurization proved to be more advantageous than individual pressurization in the alternatives in which investments in reservoirs and individual pumping stations for the 156 lots were added to the investments in the main pumping stations.

The pumping costs in collective pressurization were less expensive than those in individual pressurization, in which the costs of raising water to the inlet of the lots by the main pumping station were considered, as were the costs of pressurization carried out within the lots by individual pumping stations.

When considering the investment values added to the pumping costs over 20 years, the water hammer protection devices showed relative increases of between 0.53 and 2.18%.

7 REFERENCES

ANA (Brazil). **Irrigation Atlas 2021** : Water use in irrigated agriculture. 2nd ed. Brasília, DF: Ministry of Regional Development, 2021.

CARVALHO, ALB **Fluid-structure interaction under hydraulic transient action** . 2011. Dissertation (Master in Civil Engineering) – Fluminense Federal University, Niterói, 2011.

CARVALHO, HF **Cost–benefit analysis of the implementation of water hammer attenuation devices in water pipelines** . Final Course Work (Undergraduate Degree in Civil Engineering) – Christus University Center , Fortaleza, 2020.

CASTRO, MAH Computational simulation of hydraulic transients in irrigation projects. *In* : RODRIGUES, LN; ZACCARIA, D. **Irrigated Agriculture** : a brief look. Fortaleza: INOVAGRI, 2020. chap. 8, p. 83-88.

CHAUDHRY, M. **Applied Hydraulic Transients** . 3rd ed. New York: Springer, 2014.

CODEVASF. **Salitre Public Irrigation Project** . Brasília: Codevasf, 2018. Available at: https://www.codevasf.gov.br/linhas-de-negocio/irrigacao/projetos-publicos-de-irrigacao/elenco-de-projetos/em-producao/salitre-etapa-i-ba . Accessed on: February 22, 2023.

GOOGLE EARTH. [Image]. **Location map of the Salitre Project** . Available at: https://earth.google.com/web/ . Access on : 11/15/2023.

GRAY, CAM Analysis of the dissipation of energy in water hammer. **Proceedings of ASCE** , Amsterdam , v. 119, no. 274, p. 1176-1194, 1953.

IRRICAD. **Irrigation design software** . Brisbane, 2021. Available at: https://www.irricad.com/?gclid=Cj0KCQiA6rCgBhDVARIsAK1kGPI_MrT3isC6I8fRhxhTs-ozTp-Z_e4oi2r0e0NlKXcwXRBxa5UJHVUaAi07EALw_wcB . Accessed on: May 10, 2022.

MAGALHÃES, CHM **Pipes and safety devices used to minimize the effects of hydraulic transients in adductors** . 2018. Dissertation (Master in Civil Engineering) – Universidade Federal de Pernambuco, Recife, 2018.

MASSIERO JUNIOR, P. **Analysis of transients in a pipeline using the method of characteristics** . 2008. TCC (Degree in Hydraulic and Environmental Engineering) – Federal University of Santa Catarina, Florianópolis, 2008.

SCHIMIDT, MJA **Hydraulic transient simulation and economic combination of the adductor for public supply of the municipality of Torrinha** . 2016. Dissertation (Master in Agronomy/Irrigation and Drainage) – Faculty of Agronomic Sciences, São Paulo State University, Botucatu, 2016.

SILVA, PA **Wave celerity damping in penstocks** . 2006. Dissertation (Master's in Hydraulic Engineering) – Polytechnic School of USP, University of São Paulo, São Paulo, 2006.

STREETER, VL; LAI, C. Waterhammer Analysis Including Fluid Friction. **Journal of Hydraulics Division** , New York, vol. 88, no. 79, p. 79-112, 1962.

STREETER, V.L.; WYLIE, E.B. **Fluid Mechanics** . 7th ed. São Paulo: McGraw **-** Hill do Brasil, 1982.

TOMAZ, P. **Water hammer in pump houses** . 1st ed. São Paulo: Navegar, 2010.

VEIGA, PFE **Course of Hydraulic Transients** - an innovative and practical approach. Barra Mansa: Academia PAM Saint Gobain, 2014. Available at: https://inovagri.org.br/wp-content/uploads/2023/08/VEIGA-FEP-Curso-de-Transientes-Hidraulicos-Uma-abordagem-inovadora-e-pratica-2014.pdf . Accessed on: May 10, 2023.

VIANNA, MR **Water hammer in adductors** . 1st ed. Nova Lima: Bloom, 2021.

VIEIRA, RRF Hydraulic transients and irrigated agriculture. *In* : PAOLINELLI, A.; NETO, DD; MANTOVANI, EC **Different approaches to irrigated agriculture in Brazil: technique and culture** . Piracicaba: ESALQ/USP, 2021b.

WYLIE, E.B.; STREETER, VL **Fluid Transients** . 2nd ed. New York: McGraw-Hill International Book Company, 1978.