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Pressure regulation and energy recovery in water distribution networks using pumps as turbines

Regulação da pressão e recuperação de energia em redes de distribuição de água utilizando bombas que funcionam como turbina

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ABSTRACT

Water distribution networks (WDNs) are considered a potential renewable energy source, as they have more than enough pressure energy to deliver water to users. To control excessive pressure, WDNs are commonly divided into district metered areas (DMAs) with pressure-reducing valves (PRVs). The energy wasted by PRVs can be recovered using pumps as turbines (PATs). However, selecting the appropriate pump remains a challenge, as it must account for daily pressure and flow variations from consumers (off-design conditions). In this article, a combination of models was validated and applied to select the suitable pump for operating in an actual WDN. The replacement of two PRVs with PATs in a real network, previously divided into two DMAs and operating at constant speed was investigated. Economic and environmental analyses were also conducted. PAT_1 was technically superior to PAT_2, as PAT_2 exhibited negative outlet pressure, affecting the pressure in DMA_2. Optimal efficiencies are achieved at flow rates corresponding to the pump's best efficiency point or near it, mimicking pressure control as if they were the valves themselves. The most efficient pump recovered 4,331 kWh/year, equivalent to a reduction of 1,732,400 gCO2/year, serving two households categorized as low-income. PATs proved to be a viable alternative, with a payback period of 2.1 years, as it can recover renewable energy. However, for effective pressure control in WDNs, other operational strategies, such as variable speed operation, should be explored.

Keywords: WDN sectorization; PAT off-design operation; pressure control; energy recovery; sustainability.

RESUMO

As redes de distribuição de água (WDN) são consideradas fonte renovável potencial, apresentando energia de pressão mais que suficiente para entregar água aos usuários. Para controlar a pressão excessiva, comumente as WDN são divididas em áreas de medição distrital (DMA), com válvulas redutoras de pressão (PRV). A energia desperdiçada pelas PRV pode ser recuperada por bombas como turbinas (PAT). Entretanto, a seleção da bomba adequada ainda é um desafio, pois devem-se considerar as mudanças diárias de pressão e vazão dos consumidores (*off-design*). Neste artigo, uma combinação de modelos foi validada e aplicada para selecionar a bomba adequada para operar em uma WDN real. A substituição de duas PRV por PAT de uma rede real previamente dividida em duas DMA, operando em velocidade constante, foi investigada. As análises econômica e ambiental também foram efetuadas. A PAT_1 foi tecnicamente melhor que PAT_2, que apresentou pressão de saída negativa, prejudicando a pressão na DMA_2. As melhores eficiências só ocorrem nas vazões no melhor ponto de eficiência da bomba ou próximo a ele, reproduzindo o controle da pressão como se fossem as próprias válvulas. A melhor bomba recuperou 4.331 kWh/ano, o equivalente à redução de 1.732.400 gCO_2/ano, atendendo duas casas categorizadas como baixa renda. A utilização de PAT mostrou-se uma alternativa viável, com período de retorno de 2,1 anos, uma vez que é capaz de recuperar a energia renovável. Contudo, para o controle efetivo da pressão em WDN, devem-se buscar outras estratégias de operação, como a operação em velocidade variável.

Palavras-chave: setorização de WDN; operação PAT fora de projeto; controle da pressão; recuperação de energia; sustentabilidade.

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Introduction

In recent years, global discussions on sustainability and new accessible renewable energy sources have intensified (Bhattacharya et al., 2016). In this context, water supply systems (WSS) received special attention for their recoverable energy potential. Water transportation to end-users in water distribution networks (WDNs) requires high pressure embedded in their pipes, which often exceeds the necessary amount (Spedaletti et al., 2021). For this reason, water management authorities often segment WDNs into district metered areas (DMAs) by inserting pressure-reducing valves (PRVs), which reduce variable upstream pressure to a specific constant downstream pressure (Covelli et al., 2016). Indeed, PRVs reduce network pressure and, therefore, leakages (Alves et al., 2022). However, at the same time, they waste potentially recoverable hydraulic energy (Stefanizzi et al., 2020).

In view of this, several studies suggested that PRVs can be replaced by pumps functioning as turbines (PATs) to recover the energy wasted by these valves (Lima et al., 2017; Liu et al., 2019; Ebrahimi et al., 2021). PATs are hydraulic pumps operating in reverse (Carravetta et al., 2018) that can efficiently perform the role of PRVs in pressure control while providing an additional energy generation resource (Renzi and Rossi, 2019). These machines are cheaper than the traditional hydraulic turbines (Renzi et al., 2020) and are more suitable for recovering small energy powers occurring in PRVs (Carravetta et al., 2014). However, their widespread application still depends on pump manufacturers, who rarely provide information about the performance of these machines in turbine mode (Mitrovic et al., 2021).

As a result, many studies were conducted to predict PAT performance. Some approaches utilized methods based on the best efficiency point (BEP) (Alatorre-Frenk, 1994; Yang et al., 2012) and the pump-specific speed number (Singh and Nestmann, 2010; Tan and Engeda, 2016). However, when installed in WDNs, a PAT must function under various conditions due to the dynamic operations of the networks throughout the day, forcing the machine to operate away from its BEP (off-design), and making it impossible to define a single operational point for the PAT (Polák, 2019). Only recently scientific studies were understood and published on PATs off-design performance, and new theoretical collaborations have been proposed (Stefanizzi et al., 2018; Renzi et al., 2020).

Despite the encouraging results of these investigations, few studies paid attention to the pump's pressure control operating in a network for the maximum energy recovery as its primary function. The novelty of this work lies in detailing the PAT's behavior operating at a constant speed, as if the valve itself was replaced, comparing the pump's outlet pressure and the network nodes' pressure with the pre-defined valve control according to specific regulations. As an additional technology, the power and efficiency of the machine are evaluated based on the pressure control or lack thereof.

Furthermore, it is important to analyze the economic viability and quantify the environmental processes inherent to the PAT operation in a network (Rossi et al., 2016), demonstrating the achieved sustainability. Therefore, the objective of this study was to present a methodology that would enable effective pressure control in WDNs using PATs at constant speeds, replacing PRVs strategically positioned in a network previously divided into DMAs. With the off-design selection of PATs presented in this study, it is possible to analyze the machines functioning to regulate the working pressure in the network, as if they were the PRVs themselves. Finally, the payback period (PP) and the environmental advantages of using these machines were estimated.

Methodology

PAT selection

For the selection of PATs, two traditional models that consider the pump's BEP to predict the behavior in turbine mode (Sharma, 1985; Williams, 1994; Yang et al., 2012) were combined with a model whose formulation represents the PATs off-design behavior (Rossi et al., 2019). The combinations were validated using experimental data from PATs in the literature (Derakhshan and Nourbakhsh, 2008). The most effective combination was determined by comparing the relative differences between the experimental and theoretical data of the models, using the calculation of the coefficient of determination (R^2). Table 1 presents the formulations of the methods that utilize the pump's BEP, while Equations 1–5 describe the PATs' operation in off-design condition.

Where:
QBEP: the flow rate of the pump at the best efficiency point;
HBEP: the pump pressure at the best efficiency point; ηmax corresponds to the maximum pump efficiency;
QPAT: the flow rate in turbine mode at the best efficiency point;
ηPAT: the maximum turbine efficiency;
h: the pressure head of the PAT;
q: the discharge rate of the PAT (based on the pump's flow pressure);
ηb: the pump efficiency.

$$\frac{\psi_{PAT}}{\psi_{BEP,PAT}} = 0.2394R^2 + 0.769R \quad (1)$$

$$\frac{\eta_{PAT}}{\eta_{BEP,PAT}} = -1.9788R^6 + 9.0636R^5 - 13.148R^4 + 3.8527R^3 + 4.5614R^2 - 1.3769R \quad (2)$$

$$R = \frac{\phi_{PAT}}{\phi_{BEP,PAT}} \quad (3)$$

Table 1 – Models that consider the pump best efficiency point to predict the PAT performance.

Method	h (m)	q (m³/h)	η
Sharma (1985) e Williams (1994)	$H_{PAT} = H_{BEP}/\eta_{max}^{1.2}$	$Q_{PAT} = Q_{BEP}/\eta_{max}^{0.8}$	$\eta_{PAT} = \eta_{max}$
Yang et al. (2012)	$h = 1.2/\eta_{max}^{1.1}$; $h = H_{PAT}/H_b$	$q = 1.2/\eta_{max}^{0.55}$; $q = Q_{PAT}/Q_b$	$\eta_{PAT} = \eta_b$

$$\phi = \frac{Q}{ND^3} \quad (4)$$

$$\psi = \frac{gH}{(ND)^2} \quad (5)$$

Where:
HPAT: the turbine head at the pump's nominal rotation [m];
H: the pump head at nominal rotation [m];
QPAT: the turbine flow rate at the pump's nominal rotation [m³/s];
Q: the pump flow rate at nominal rotation [m³/s];
ϕ: the flow coefficient;
ψ: the head coefficient;
N: the rotation speed [rps];
D: the machine's diameter [m];
G: the acceleration due to gravity [m/s²].

As previously reported, when installed in a network, the PAT is subject to variations in flow and pressure related to user consumption. In this case, the machine almost always operates off-design. Therefore, its joint operation with models that predict the PAT's off-design behavior is desirable, justifying the proposed association. Additionally, the performance of the turbine mode of a pump begins with the prediction of the BEP, which serves as an initial condition and plays a crucial role in estimating the PAT's behavior (Sales e Souza, 2022). Once the most appropriate association was defined, the selection of a pump considered the flow data (Q_PAT = Q_PRV) and pressure dissipation data (= H_PRV) from the PRVs in a WDN. The flow used to select the pump was the average flow during the pump's operating hours. Figure 1 describes the pump's selection procedures.

Utilization of PATs as a replacement for PRVs

The PRVs in the network were replaced by PATs operating at a constant speed. The machine's operating period was considered from 6 AM to 11 PM. In this analysis, the system includes a bypass arrangement with PRV1 and PRV2 operating in parallel (Figure 2A).

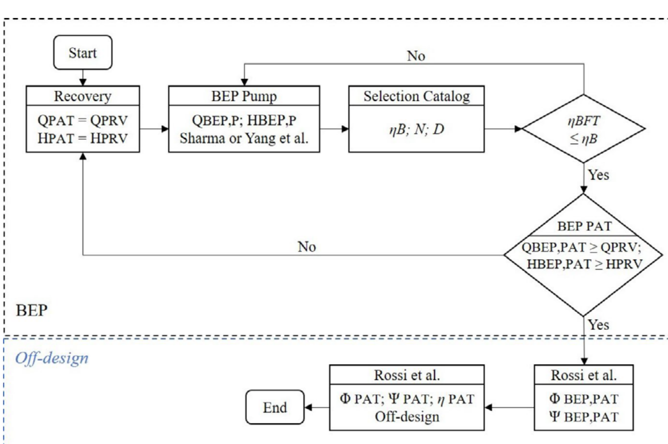


Figure 1 – PAT selection method.

PRV2 only operates when PRV1 is undergoing maintenance and will be replaced, as shown in Figure 2B. In this case, PRV2 is activated by the bypass during periods of reduced water consumption in the distribution network (during the early morning hours), which justifies the PAT's operating time. PRV2 ensures pressure regulation when the pressure head is greater than the head loss provided by the machine. As the working hours begin, an on-off valve (VOF1) allows the flow of the PAT. At the end of working hours, VOF1 closes, and VOF2 opens, directing the flow to PRV2. VOF3 is activated during PAT maintenance.

Pressure control and energy recovery by PATs in WDNs

The pressure control by the PAT was evaluated as if it were the PRV itself. The machine must maintain the operational conditions of the valve, including the pressure difference or head loss (ΔH), control or outlet pressure (Pc), and the regulated pressure downstream of the PRV according to Brazilian regulations (ABNT, 2017). ΔH represents the pressure energy that can be recovered by the PAT, as illustrated in Figure 3. As the pump operates in reverse, instead of consuming energy, it generates an output power based on an efficiency (ηPAT) related to the flow and pressure behavior of a network throughout the day. Thus, it is possible to estimate the energy recovered by the machine by applying Equation 6, which calculates the power. From this, the recovered energy can be estimated by multiplying it by the machine's operating time.

$$P[kW] = \frac{Q_{PAT}\, H_{PAT}\, \rho\, g\, \eta_{PAT}}{1000} \quad (6)$$

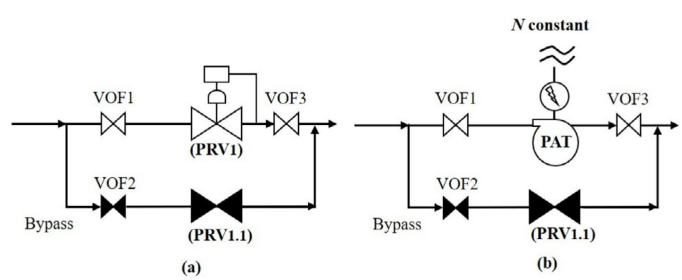


Figure 2 – (A) PRV1 installation and (B) PAT operating at constant speed.

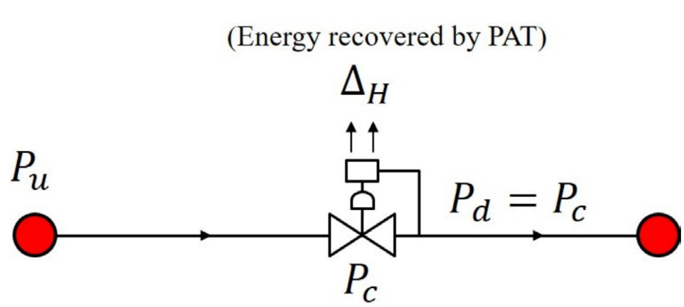


Figure 3 – Energy dissipated by PRV and recovered by PAT.

Where:
Pu: the upstream pressure at the valve;
Pd: the outlet/downstream pressure at the valve;
P: the hydraulic power in [kW];
Pc: the control pressure of the valve;
QPAT: the flow rate of the PAT in [m^3/s];
HPAT: the head recovered by the PAT in [m];
P: the density in [kg/m^3];
ηPAT: the efficiency of the PAT during the operating period;
g: the acceleration due to gravity in [m/s^2].

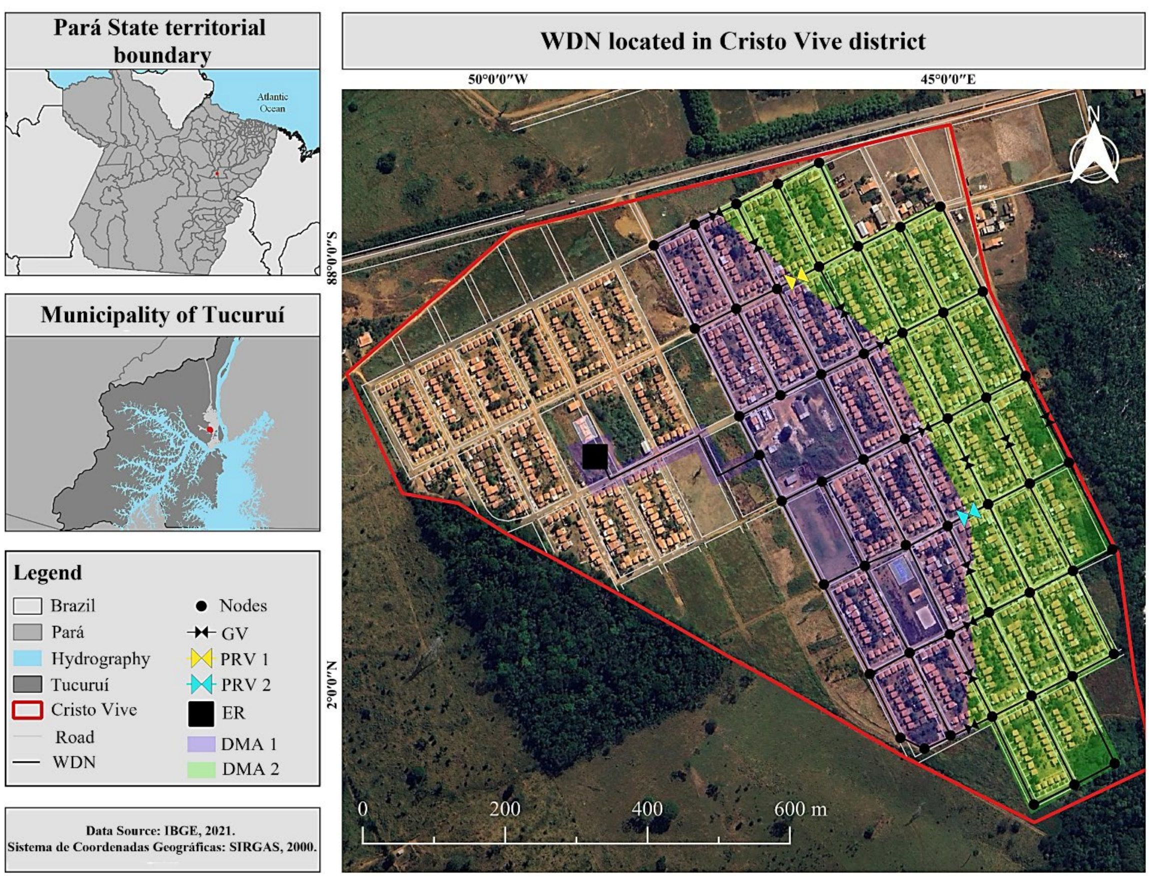
Case study

The methodology described so far was applied to a WDN that serves part of a neighborhood in the municipality of Tucuruí (PA), located in northern Brazil. This network was designed to serve an area of approximately 300 m² with a topographic variation ranging from 64 to 128 m, supplying water to 743 residences. It consists of 87 pipes, 79 nodes, and 12 gate valves (GV). The network operates by gravity in turbulent flow regime, with pressure inadequacies outside the limits of legislation. The information about the WDN was obtained through interviews with the local municipality. The other part of the network was not studied due to the lack of registered project information.

To regulate the pressures in the network, the procedures adopted were those described by Souza et al. (2023). The authors used the hydraulic simulator EPANET 2.0 software to divide the WDN into DMAs, strategically positioning the PRVs in the pipes. As a result, the designed WDN achieved pressure levels in compliance with the legislation, which establishes minimum dynamic pressures of 10 m and maximum static pressures of 50 m (ABNT, 2017). The network was divided into two DMAs, with one PRV in each district, as shown in Figure 4. PRV1 operates with a Pc of 13.14 m and ΔH of 34.64 m, while PRV2 has a Pc of 14.73 m and ΔH of 33.30 m. It should be noted that the replacement of PRVs with PATs was also simulated in the EPANET 2.0, following the procedures described in Souza et al. (2023).

Economic advantages

The use of PATs in WDNs offers an economic advantage, and these machines prove to be a cost-effective energy recovery solution. In order to confirm this, it is necessary to evaluate the costs and expected benefits of implementing these machines, especially in WDNs. In this analysis, we calculated the payback period (PP).



GV: gate valves; ER: elevated reservoir.

Figure 4 – WDN divided into two DMAs using two PRVs.

PAT total implementation cost

The total cost of PAT installation considers the sum of capital costs (CC), operation and maintenance costs (OMC), and civil works costs (CWC). The CC includes all the equipment necessary for PAT installation. The OMC consists of individual device maintenance and operation costs, while the CWC estimates the civil works required to adapt the PAT installation to the network. The assumed service life of a generic mechanical and electrical equipment is 15 years (Stefanizzi et al., 2020). The operation and maintenance costs were assumed to be 0.5% and 2.5% per year, respectively, of the CC (Irena, 2012). The CWC cost was considered to be 30% of the CC (Fontana et al., 2012).

Payback period

The payback period (PP) was calculated to determine the time required to recover the investment made in PATs by replacing PRVs. When the discount rate is applied to the PP, it is referred to as the discounted payback period. The discount rate is expressed as percentage and represents the sum of capital remuneration costs, opportunity costs, risks, and inflation (Padilha and Mesquita, 2022). In Brazil, a discount rate of 11.61% was applied (Damodaran, 2019). In the calculation of the PP, the energy tariff of R$ 0.76597/kWh from the local utility company was used, assuming the self-consumption of the system In addition, a 7.8% growth in energy tariffs was estimated for the local utility company's annual tariff increase from 2017 to 2022. Equation 7 presents the calculation of the discounted PP (Duarte et al., 2010).

$$PP = UPD + \left[\frac{UVD}{PVS + UVD}\right] \quad (7)$$

Where:
UPD: last deficit period;
UVD: last deficit value;
PVS: first surplus value.

Environmental advantages

Another advantage would be the reduction of greenhouse gas (GHG) emissions associated with the recovery of renewable energy in WDNs. However, this comparison becomes unfeasible when the energy used by the WSS is already derived from a renewable source (Tucuruí Hydroelectric Power Plant in PA). Despite that, in an environmental analysis, it is necessary to compare a renewable energy project with possible alternatives (Balacco et al., 2018).

Thus, a comparative analysis of the PAT installation impact was conducted in terms of the equivalent reduction of CO2 emissions produced by car circulation in Brazil. To estimate the CO2 equivalent, an average conversion factor of 400 gCO2/kWh was adopted (Caputo and Sarti, 2015). The Institute of Applied Economic Research (IPEA) (Henrique and Carvalho, 2011) and the Ministry of the Environment (Brasil, 2014) reported the average emission of gCO2/km and the average driving distance of Brazilian cars, as shown in Table 2.

Table 2 – CO_2 emission and average driving distance of Brazilian vehicles.

Vehicle	Emissions per km (gCO_2/km)*	Average driving distance ($km/year$)**
Car	190	12,000
Motorcycle	70	10,500

*Henrique and Carvalho (2011); **Brasil (2014).

Based on these values, the environmental benefit that the installation of PAT could avoid in terms of CO2 emissions and the number of equivalent circulating cars emitting the same quantity of CO2 were estimated.

Results and Discussion

Validation and determination coefficient

Figure 5 illustrates the comparison of the dimensionless curves (a) ψ-ϕ and (b) η-ϕ, which represents the trend of the proposed combinations with the experimental data of PATs presented by Derakhshan and Nourbakhsh (2008).

Table 3 presents the calculation of R^2 for the two associations. It can be observed that the Yang-Rossi method combination exhibits the highest R^2 values, particularly when analyzing machine efficiency. Therefore, it is possible to apply this association and extend it to various machines, as it accurately reproduces the trend lines of the experiments, regardless of the pump's BEP in turbine mode, specific speed, and efficiency of each machine.

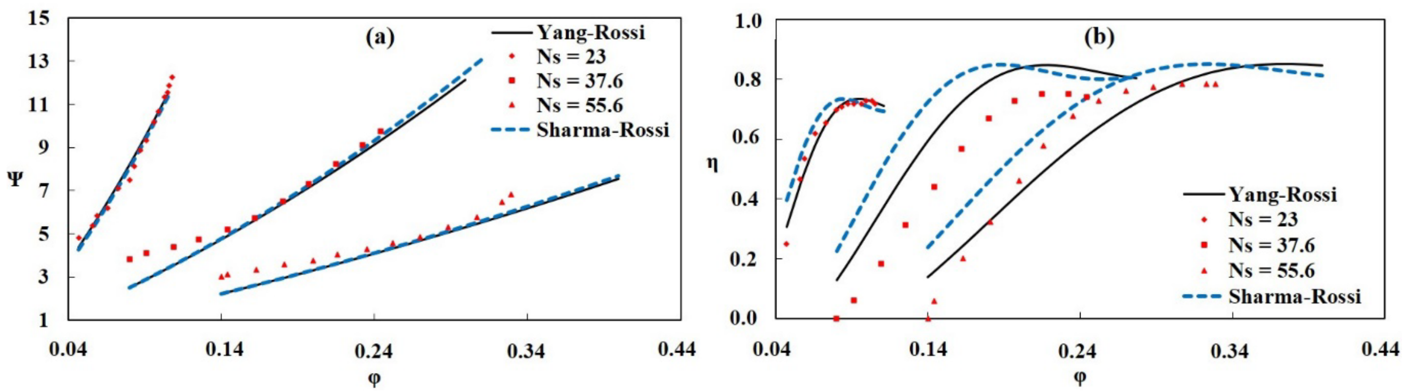
Pump characteristics

The characteristics of the pumps selected to replace the PRV1 and PRV2 valves are presented in Table 4. The flow and head values are higher in turbine mode, as observed in the literature (Rossi and Renzi, 2018).

Table 5 presents the obtained values for PAT1 and PAT2 operating off-design, with a focus on the BEP values. This behavior is significant for analyzing the PAT operation, which is highly dependent on flow rates within a WDN (Coelho and Andrade-Campos, 2018). The Yang-Rossi model accurately predicted the PAT behavior under both design and off-design conditions.

Pressure control using PAT at constant speed

Figure 6 presents the ΔH of PAT1 and PAT2 operating at a constant speed. It can be observed that the ΔH of PAT1 closely resembles PRV1 during the time intervals of 6–9 AM, 3–5 PM, and 7–10 PM (Figure 6A). On the other hand, the ΔH of PAT2 only matches PRV2 at 9 AM and at 9 PM (Figure 6B). As a result, the outlet pressure of the machines is affected, especially in the case of PAT2, as shown in Figure 7, which displays the outlet pressure of PAT1 (a) and PAT2 (b) compared to PRVs and without pressure control. PAT1 (Figure 7A) deviates from the valve during the time interval of 10 AM to 3 PM and at 6 PM. On the other hand, PAT2 (Figure 7B) exhibits negative values of outlet



Ψ: head coefficient; ϕ: flow coefficient; Ns: specific speed.
Figure 5 – Curves (A) ψ-ϕ and (B) η-ϕ.

Table 3 – Determination coefficients for both proposed associations.

PATs (Derakhshan and Nourbakhsh, 2008)	R^2			
	Yang-Rossi		Sharma-Rossi	
	Ψ	H	Ψ	H
Ns = 23	0.983	0.969	0.981	0.709
Ns = 37.6	0.916	0.710	0.926	-0.067
Ns = 55.6	0.800	0.913	0.824	0.718

R^2: determination coefficient; Ψ: head coefficient; η: efficiency; Ns: specific speed; H: pump head at nominal rotation.

Table 4 – Operational characteristics BEP for the selected pump ITAP 50 – 330/2.

Characteristic	PRV_1		PRV_2	
	Pump	Turbine	Pump	Turbine
Q [m³/h]	10.00	16.03	10.62	16.87
H [m]	19.50	41.81	18.74	39.45
Efficiency [-]	0.59	0.57	0.60	0.58
Specific speed [rad/s]	0.12	0.09	0.13	0.09
Impeller diameter [m]	0.24		0.22	
Rotation speed [rpm]	1,130			

Table 5 – PATs 1 and 2 off-design operation.

PAT1					PAT2				
φt	ψt	ηt	Qt (m³/h)	H (m)	φt	Ψt	ηt	Qt (m³/h	H (m)
0.015	17.23	0.55	14.06	35.89	0.021	19.93	0.56	15.16	34.88
0.016	18.64	0.56	15.00	38.83	0.022	21.10	0.58	15.88	36.92
0.017	**20.08**	**0.57**	**16.03**	**41.81**	**0.023**	**22.28**	**0.58**	**16.87**	**39.45**
0.018	21.56	0.58	16.87	44.91	0.024	23.49	0.59	17.32	41.11
0.019	23.07	0.57	17.81	48.06	0.025	24.72	0.59	18.04	43.25

Φt: PAT flow coefficient; ψt: PAT pressure coefficient; ηt: PAT Efficiency; Qt: PAT flow; H: PAT head.

pressure from 11 AM to 2 PM and at 6 PM. The pressure matches PRV2 only at 9 AM and at 10 PM.

These results can be justified by the occurrence of flow rates that are far from the BEP at certain times of the day, which are related to user consumption, and the operation of the machines at a constant speed. Therefore, the best efficiencies are observed only when flow rates are near or at the BEP. For this reason, the PATs are unable to properly exploit the high variations in flow rates, resulting in pressure levels in the network that are below or above the recommended by the legislation. Figure 8 illustrates the behavior of pressures at certain hours of the day during the operation of the PATs. It is noteworthy that there is better pressure control in DMA1 due to the proximity of PAT1 to PRV1 for most of the operating hours.

Despite inadequacies of the pressure limit during certain hours of the scheduled 6 AM to 9 PM operation, PAT1 approached the PRV1 operational conditions and satisfactorily controlled the network pressure. On the other hand, PAT2 deviated significantly from PRV2. With pressures exceeding 50 m, there would be a high volume of leaks, while reduced pressure hours could lead to consumer supply disruptions. This suggests that consideration should be given to replacing only PRV1 and keeping PRV2 in operation to balance the supply pressure.

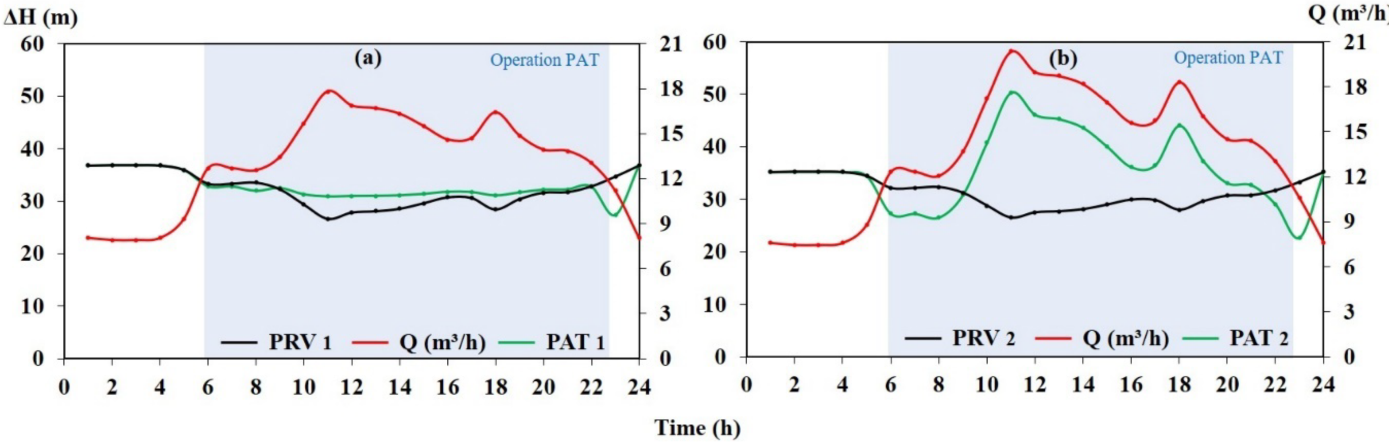


Figure 6 – PAT$_1$ ΔH comparison and (A) PRV$_1$ PAT$_2$ and (B) PRV$_2$ at constant speed.

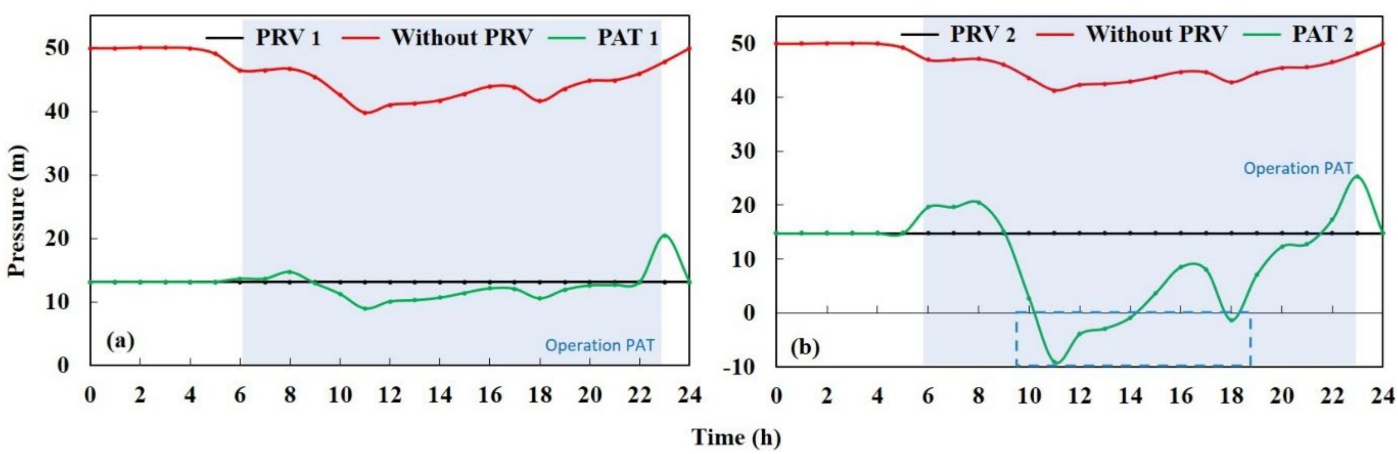


Figure 7 – Outlet pressure of (A) PAT$_1$, PRV$_1$ and without pressure control PAT$_2$, (B) PRV$_2$ e without pressure control.

In fact, it is not always financially advantageous to replace a valve with a pump operating in reverse (Souza et al., 2021), as the low energy dissipation (ΔH) leads to the selection of a smaller-sized machine for pressure control, significantly increasing water losses through leaks and electrical energy waste. In such cases, energy recovery is hindered, resulting in lower hydraulic efficiencies at higher flow rates (Alberizzi et al., 2018).

During the period from 11:01 PM to 5:59 AM, the bypass is activated, and PRV1 and PRV2 adequately control the pressure. The use of PRVs operating in parallel with PATs appears to be an effective solution for maintaining pressure in the districts, especially during the early morning hours when the machines cannot effectively exploit reduced flow rates. This was also suggested in the study by Ebrahimi et al. (2021), who observed an undesired increase in node pressure during the early morning. They concluded that PRVs can work well in conjunction with PATs during the periods of reduced consumption to control the network pressure. This strategy was also employed by Crespo Chacón et al. (2020), who proposed a bypass system for months when peak demand would result in reduced pressures.

Economic analysis

The investment required to replace PRV1 with PAT1 amounted to R$ 12,803. It would take 2.1 years to recover the investment, as shown in Figure 9. This PP was similar to previous studies (Muhammetoglu et al., 2017; Stefanizzi et al., 2020) and very short compared to conventional turbines and, overall, in relation to the lifespan of the investment. For the water sector, this PP is considered economically viable (Corcoran et al., 2013). With such a short PP, it is estimated that the system will have the capital to replace the PAT structure or maintain/expand the existing system starting from the second year of the project, considering the assumed 15-year lifespan of generic mechanical and electrical equipment in this study.

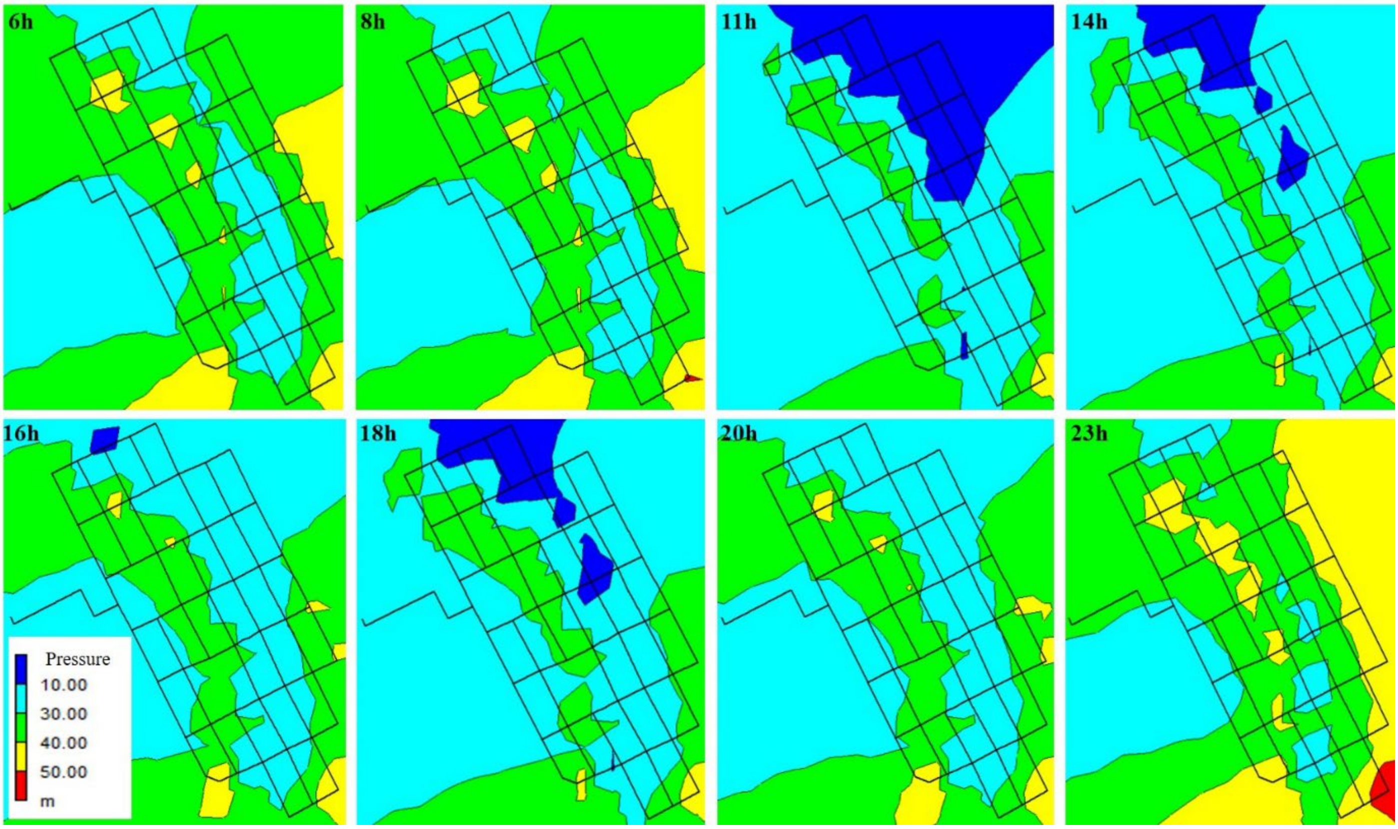


Figure 8 – Network pressure with PAT_1 and PAT_2.

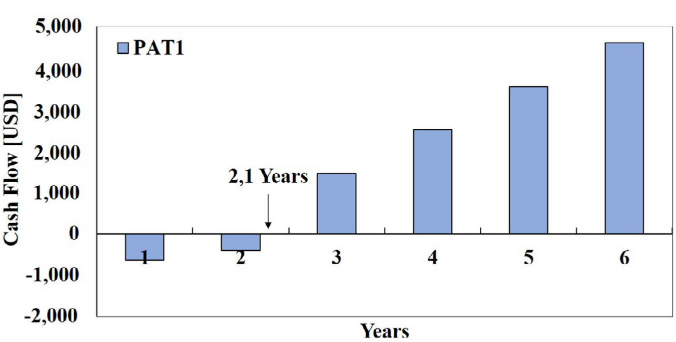


Figure 9 – Payback period of PAT_1 for the first 6 years of project.

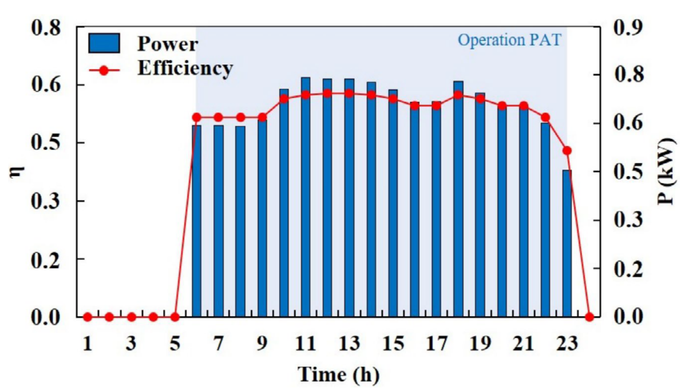


Figure 10 – PAT1 performance and output power.

Energy recovery and environmental analysis

As PAT1 performed better than PAT2, only the energy recovery of the first machine was presented. Figure 10 shows the output power of this pump during the 18-hour operation, ranging from 0.45 kW to 0.74 kW, with an average of 0.66 kW. This results in an energy gain of 4,331 kWh per year for 18 hours of PAT operation per day. This total would be sufficient to supply two low-income households with a consumption of up to 220 kWh/month for approximately one year. As an environmental advantage, the machine's energy gain was equivalent to a reduction of 1,732,400 gCO2 per year, approximately equal to one car or three motorcycles. These data demonstrate that PATs can bring significant environmental benefits when employed in a WDN, considering that it is an emerging technology with great economic and sustainable potential. Table 6 provides a summary of the environmental benefits for PAT1.

Table 6 – Number of Brazilian vehicles equivalent to PAT_1 reduction of gCO_2/year.

Vehicle	gCO_2/year per vehicle	PAT_1 Gain [kWh/year]	Conversion PAT_1 [gCO_2/year]	Equivalence [Vehicles/year]
Car	2,280,000	4,331	1,732,400	≈ 1
Motorcycle	735,000			≈ 3

Conclusion

In this study, a methodology was presented that facilitated the PRVs replacement with PATs, first for pressure control and then as an additional technology for recovering wasted pressure energy from valves. For this purpose, a combination of PAT selection methods was validated based on experimental data available in the literature and proved to be reliable. A WDN was divided into two DMAs, each with two PRVs, to adjust pressures according to regulations. Through simulations conducted in EPANET 2.0 software, the PRVs were replaced with PATs operating at constant speed.

The simulations showed that the machines deviated from the operational conditions of the valves at certain times of the day. However, PAT1 closely followed PRV1 for several operating hours, unlike the second machine, which exhibited negative outlet pressures. As a result, the pressure in DMA1 complied with regulations for most of the hours, while inconsistent pressures were observed in DMA2. When machines operate at a constant speed, they can only achieve better efficiencies with flows near or at BPE. This means that only PAT1 could partially adapt to operational conditions demanded by consumers.

PAT1 recovered the energy of 4,331 kWh per year, resulting from an average power of 0.66 kW over 18 hours of operation. This would meet the needs of approximately two low-income households. Furthermore, the energy gain from just one machine would be equivalent to a reduction of 1,732,400 gCO2 per year, comparable to the emissions of one car or three motorcycles. Considering that it is a pump with low dissipation, PAT1 was able to recover a considerable amount of energy, leading to a payback period of 2.1 years, similar to values mentioned in recent literature. However, with the pump operating at a constant speed, it was impossible to achieve maximum off-design performance. Therefore, the analysis of PATs operating at variable speed is highly recommended for future studies to obtain better efficiency results for flows at and outside the BEP. Additionally, it is important to analyze the regulatory aspect of self-consumption of WSS with energy recovered by PATs. This would encourage water utilities in Brazil to adopt this technology.

Contribution of authors:

VIANA, I. L. B.: Conceptualization; Data curation; Methodology; Software. BATISTA, J. C. M.: Data curation; Investigation; Software; Validation. SÁ, J. H. M.: Investigation; Writing – original draft. RAMALHO, R. V. C.: Formal Analysis; Writing – review & editing. LOPES, R. M.: Project administration; Resources; Visualization; Supervision. SOUZA, D. E. S.: Conceptualization; Formal Analysis; Project administration; Supervision. MESQUITA, A. L. A: Project administration; Resources; Visualization; Supervision.

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