Analysis of different operational control strategies for drinking water pump-tank systems: a case study

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Received: 29 May 2019 / Accepted: 19 November 2019 / Published online: 28 November 2019
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Abstract

The management of drinking water pumping systems is a delicate task that most often requires the use of different pumping strategies ranging from the simplest to the most sophisticated control methods. In order to study the performance of these methods a numerical simulation of three pumping methods was carried out (two real-time control methods and one simple method). The first real-time control method is based on a model of multivolume regulation. It was developed as part of this study. This method is based on the volume of water in the tank and characterized by a cascade operation of the pumps depending on the control volumes. The second real-time control method is based on a progressive regulation model (PR). This model is characterized by a gradual start and stop of the pumps according to two control volumes: a volume of stop and a volume of starting of the pumps (V_{on} and V_{off}). The third method is based on continuous 24-h pumping (H24). The study was validated on two pumping systems supplying the Hotel and Igbaouzene tanks in the city of Sidi Aiche. The results have shown the energy, hydraulic and operational efficiency of the two real-time control methods in the management of water supply systems.

Keywords Regulation model · Pumping system · Distribution tank · Water supply · Performance indicators

1 Introduction

The energy consumed by pumping systems accounts for most of the energy consumed by water companies [29]. In general, pumping systems account for about 20% of the energy consumed by electric motors and 25–50% of the energy required for certain industries [14]. For this reason, a management strategy for pumping systems would be essential to improve the energy efficiency of water supply system (WSS). However, improving energy efficiency must satisfy consumer demand in terms of pressure and flow rate in the distribution network at all times [10]. There are several strategies to improve the energy efficiency of pumping systems, such as design optimization, control optimization, and real-time control [12].

The design optimization involves the search for system features that minimize the total cost of the system without affecting the proper functioning of the hydraulic system and the water supply to consumers, by modifying one or more components of the structure, such as the replacement of a pump, the increase in diameter, the reduction of singularity, etc. This makes the system more economical and reliable. However, an increase in reliability can involve high costs [10].

The efficiency of pumping systems can also be done on the operational part, and there are practically two types: (1) control optimization method that act on the pumping schedule, and (2) real-time control method based on the instantaneous transmission of one of the pumping parameters such as flow rate, pressure and water level in

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the tank. There are also mixed methods that combine the two approaches at the same time.

The control optimization method consist in finding the best strategies for control elements that minimize total costs with consumer demand in terms of flow-rate and pressure [7]. The method mainly concern two types of problems. The first type concerns pumps with constant speed, where only two variables are taken into consideration. This is the value 1 if the pump is activated. Or 0 if the pump is off. The second type concerns pumps equipped with a variable speed drive characterized by a set of optimization variables defining the speed of the pump. Other works consider some network components, such as control valves. Among the work that has been done in this direction. There is mixed integer programming, linear programming (LP) [27], dynamic programming (DP) [31], and stochastic (SP) [13], and also the use of heuristic optimization algorithms such as: genetic algorithm, simulated annealing, optimization of particle swarms, ant colonies, fuzzy logic [5, 25, 32].

The real-time control method is very important in the management of pumping stations [21, 24], where it allows to reduce the volume of water pumped by adapting the pumping flow rate to the water demand while ensuring a quality service to users. In fact, the pumps can be controlled according to suction pressure. However, in most cases, pumps are controlled by the water level in tanks. In these cases, the pumps are only activated when the distribution tanks are empty (or at the minimum level) and deactivated when the same tanks reach the maximum permitted level [10, 12]. A Supervisory Control and Acquisition (SCADA) is a system also used in water supply systems for the real-time control and monitoring of several elements such as pumps, valves, tanks, etc. [24, 30]. The real-time control method helps also to improve WSS efficiency allowing energy gains of about 20% in some cases [10]. Several authors have published works dealing with the real-time control methods such as the work of [18] where they treated software to control and computerize water resource systems to improve their performance. In [15], the author described the operating principle of real-time control methods as well as the possible techniques for its improvement. Jamieson et al. [16] presented the POW-ADIMA project whose objective is to determine the feasibility and efficiency of introducing a real-time and near-optimal control of WSS. In the same year, Slay and Michael presented a study to secure a SCADA control system to avoid any incident in the management of water supply systems [28]. In Dobriceanu et al. [11], the authors presented a paper describing a SCADA system for the control of technological parameters in WSS, which will allow the optimum functioning of the pumping system, safety and endurance growth in the equipments. Kiselychnyk et al.

[17] presented an overview of energy saving solutions for WSS, based on the implementation of automatic control systems and modern electric drives. Boulos et al. [6] presented a Smart Water Network Decision Support System (SWNDSS) for real-time control of WSS for more efficient operations, including water management, quality of water and energy. Cheng et al. [9] presented a real-time hydraulic model combining field measurements provided by SCADA systems. The system is composed of three parts, namely SCADA, state estimation server and client terminal.

Some works have dealt with the automatic aspect of real-time control methods, such as: the classic control system PI (Proportional Integral) that provides better control because its output operate linearly anywhere between fully on and fully off. The PID technique (Proportional Integral Derivative) which was invented in 1910 and which is used in 90% of the control systems, and which adapts well to the control of several non-linear processes [23]. The sliding mode control which showed its robustness in the control of the systems [1]. The Adaptive Fuzzy Control (AFC) that was used in the [3] study to control the water level in two coupled tanks, it treats model uncertainties and external disturbances in an implicit way. Thus there is no need to specify uncertainty and disturbances for this controller design in advance [3]. The fuzzy logic control used in the control of complex systems, and it has better performance than conventional control methods with a simpler algorithm that can be easily implemented on a microcontroller [8]. The Non-linear Model Predictive Control (NMPC) that is well suited to non-linear dynamic multi-variable problems difficult to handled via conventional controllers [26].

Most of research works have been focused on the automation technique or the pumping schedule to minimize the cost of pumping [19, 24], without taking into account the control volumes, where they most often take the limit thresholds ($H_{\max}$ and $H_{\min}$) as ordering instructions, with the exception of the hybrid expert system called EXPLOR presented by Leon et al. [20], which has presented the principle of control volumes, but without giving exact formulas for calculating them.

Despite the many advantages of pumping strategies, many pumping stations, particularly in underdeveloped countries, are not equipped with a control device, where they often resort to outdated pumping methods such as continuous pumping or night pumping. Even existing regulation methods have been designed by automation specialists, who are much more interested in the automatic aspect of the process, regardless of the water demand or pumping characteristics to determine the ordering instructions. This usually leads to frequent violations of the limit thresholds, thus reducing the performance of the regulation system. For this reason, we have developed a real-time control model based on several control volumes.

The model is called MVR (Multi-Volume Regulation), its operating principle is to define the number of operational pumps using an bijective relationship between the number of operational pumps and the control volumes. The control volumes were calculated using a formula that we developed as part of this study. This formula takes into account the intrinsic characteristics of the pumps and the water demand.

The study of pumping strategies can be done via a numerical simulation. These simulations are programs that allow the implementation of water transport and distribution models [10]. The first simulation models were established with the arrival of the computer and Fortran programming language from the 1960s [30]. From the 70's models became powerful allowing long-term simulations. Later in the 1980s these models began to take into account the quality of water in the network [30]. In general, there are four types of simulators: mass balance, regression, simplified hydraulic, and full hydraulic simulation [24].

The mass balance model is the simplest computational method. This model considers only the variation in flow in the tank, while assuming that the pumps generate a variation in level in the tank while neglecting the pump head and the minimum pressure in the network nodes. The main advantage of mass balance models is their speed of computation compared to other models. This favors the choice of simulator type in the treatment of regional supply systems in which the flow is mainly channeled through major pipelines, rather than through distribution networks. The regression models are more accurate than mass balance models. They are based on a non-linear equation set of demand in WSS. However, these models are sensitive to model construction data that can generate invalid results. The simplified hydraulic models integrate the effect of the network connection into a single equation. In some cases the linear equations are sufficient to represent the hydraulic system. The full hydraulic models are robust in terms of system modification and demand variation. These models solve the conservation equations of mass and energy. However, this type of model requires more data to be formulated. They also require a significant amount of work to be properly calibrated [10, 22, 24].

Among the most well-known hydraulic simulators, there is the EPANET simulator developed by EPA (US Environmental Protection Agency) it allows to perform a prolonged simulation of hydraulic behavior and water quality in networks. There are also other simulators for simple modeling such as AquaNet, Cross, HYDROFLO. As well as other more complex simulators such as: Aquadapt, Eracito, MISER, Pipe2012 [10].

In this study three pumping models were simulated for 24 h via a mass balance simulator. These three models

are: the developed model MVR, the Progressive Regulation model (PR) developed by [5] and the H24 continuous model used by the water services. The results obtained were analyzed in terms of energy, hydraulics and operations using a set of performance indicators that we have developed.

2 Pump-tank regulation models

2.1 Multi-volume regulation model MVR

The MVR model is based on the control volumes to manage the number of operating pumps (Fig. 1). In fact, it defines the number of operational pumps in time step (t) according to the volume of water in the reservoir in the previous time step ($t - 1$).

If the water reserve in the tank $V(t - 1)$ is greater than the control volume $V_c(1)$ The MVR model stops the operation of all pumps $N(t) = 0$, if the water reserve $V(t - 1)$ is between $V_c(1)$ and $V_c(2)$, the model transmits the start order of 1 pump $N(t) = 1$, and so on. The formulation (1) explains the basic principle of the MVR model.>

$$n(t) = \begin{cases} 0, & \text{if } V(t-1) \geq V_c(1) \\ n-1, & \text{if } V_c(n) \leq V(t-1) < V_c(n-1) \\ n_p, & \text{if } V(t-1) < V_c(n_p) \end{cases} \quad (1)$$

2.1.1 MVR control volumes

Control volumes are reference values that determine the number of operating pumps. The number of control volumes is equal to the number of pumps in the pumping station.

To calculate these different control volumes, we are based on the principle that the start of a pump at each

Fig. 1 Operating principle of the MVR model

control volume ensures the no violation of the minimum volume of the tank ($V_{\min}$).

For this, we have developed the formula 2 to define the control volumes.

$$V_c(n) = V_{\min} - (Q_p(n-1) - Q_{ch,max}) \cdot \Delta t \quad (2)$$

where $V_c(n)$: control volume (m^3), $V_{\min}$ minimum volume in the tank (m^3), $Q_{ch,max}$ maximum hourly consumption of the normalized pattern (m^3/h), $Q_p(n-1)$ pumping rate of ($n-1$) operating pumps (m^3/h), Δt : time step (h).

2.1.2 Demonstration of the control volume formula

To demonstrate the formula of the control volumes that we developed, we based ourselves on the continuity equation in the reservoir which is written as follows:

$$V(t) = V(t-1) + (Q_p(t) - Q_c(t)) \cdot \Delta t \quad (3)$$

Suppose that at time step ($t-1$), the water level in the reservoir is in the interval $[V_c(n-1), V_c(n)]$. In this case, at time step (t), we have ($n-1$) pumps running, which gives the following pumping rate:

$$Q_p(t) = Q(n-1) \quad (4)$$

We take the worst case at ($t-1$) in order to respect the minimum limit in the tank, i.e. the volume of water is equal to the lower limit of the range:

$$V(t-1) = V_c(n) \quad (5)$$

By replacing Eqs. (4) and (5) in (3), the continuity equation becomes:

$$V(t) = V_c(n) + (Q_p(n-1) - Q_{c,hmax}) \cdot \Delta t \quad (6)$$

The respect of the minimum threshold in the tank requires that the volume $V(t)$ is greater than $V_{\min}$:

$$V(t) \geq V_{\min} \quad (7)$$

By replacing $V(t)$ by its expression, we have:

$$V_c(n) + (Q_p(n-1) - Q_{c,hmax}) \cdot \Delta t \geq V_{\min} \quad (8)$$

This gives:

$$V_c(n) \geq V_{\min} - (Q_p(n-1) - Q_{c,hmax}) \cdot \Delta t \quad (9)$$

So we take the minimum value of V_c not to exceed to define the control volume:

$$V_c(n) = V_{\min} - (Q_p(n-1) - Q_{c,hmax}) \cdot \Delta t \quad (10)$$

2.2 Progressive regulation model (PR)

The PR model was developed by [5]. Its operating principle (Fig. 2) takes into account the water reserve in the tank at the previous step $V(t-1)$ to define the operation control at the time step following $n(t)$.

However, the PR model is characterized by taking into consideration the number of pumps operating at the time of the previous time $n(t-1)$, besides the application of the principle of progressive start/stop of the pumps in order to reduce the transient phenomena [5].

The PR model is based on two control volumes: a start volume V_{on} and a stop volume V_{off} , whose objective is to maintain the water reserve in the limited range ($V_{\min}, V_{\max}$).

If the water reserve $V(t-1)$ is greater than the stop volume V_{off} the model orders the shutdown of one pump, and if the reserve $V(t-1)$ is less than the start volume V_{on} , the model starts one pump.

While, if the reserve $V(t-1)$ is between the two control volumes, the model keeps the same number of operational pumps of the previous time step $n(t-1)$. The following wording summarizes the principle of the PR model [5]:

$$n(t) = \begin{cases} \min[n(t-1) - 1, 0], & \text{if } V(t-1) \geq V_{off} \\ n(t), & \text{if } V_{off} < V(t-1) < V_{on} \\ \max[n(t-1) + 1, n_p], & \text{if } V(t-1) \leq V_{on} \end{cases} \quad (11)$$

2.3 PR control volumes

The formulas of the two control volumes of the PR model were established according to the statistical data of the water demand, and the characteristics of the pumps in order to maintain the water reserve within the control interval limited by the two limit thresholds ($V_{\min}$ and $V_{\max}$).

Fig. 2 Perating principle of the progressive regulation model PR

The expression of the V_{off} is given by the following equation [5]:

$$V_{\text{off}} = \min \left[V_{\text{max}} - (Q_p(n) - Q_{\text{ch.min}}) \cdot \Delta t; V_{\text{max}} - \left(\sum_{n=1}^{n_p} Q_p(n) - n_p \cdot Q_{\text{ch.min}} \right) \cdot \Delta t \right] \quad (12)$$

While the start volume is given by the following formula:

$$V_{\text{on}} = \max \left[V_{\text{min}} - \left(\sum_{n=1}^{n_p} Q_p(n) - (n_p + 1) \cdot Q_{\text{ch.max}} \right) \cdot \Delta t; V_{\text{min}} + Q_{\text{ch.max}} \cdot \Delta t \right] \quad (13)$$

with $Q_{\text{ch.min}}$ minimum hourly consumption of the normalized pattern (m^3/h).

consumed using compliance with the limit thresholds (min and max). The indicator is given by the following relation:

$$\text{OTV} = \frac{\text{Number of violations [h]}}{\text{Period of operation [h]}} \cdot 100[\%] \quad (16)$$

3 Performance indicators

As part of this study, and in order to evaluate the performance of the different models, a set of performance indicators was used to analyze the results obtained. We have developed all the indicators presented below with the exception of the pumping volume indicator. Below the presentation of the different indicators.

3.1 Pumping volume indicator (PVI)

This indicator has been presented for the first time in the works [5], and which allows to evaluate the energy performance of a pumping system compared to the minimization of the pumping volume. This indicator is given by the following relation:

$$\text{PVI} = \frac{V_{\text{opt}}}{V} \quad (14)$$

With,

$$V_{\text{opt}} = V_d - V_i + V_{\text{min}} \quad (15)$$

where V_d : demand water volume [m^3], V_i : initial volume of water in the reservoir [m^3], i.e. $V_i = V(0)$, and V_{min} : minimum water volume [m^3].

The closer the indicator is to 1, the better the energy performance of the pumping volume.

3.2 Overall threshold violation rate (OTV)

This indicator makes it possible to evaluate the overall performance of the system in terms of service and energy

3.3 Minimum threshold violation rate (ITV)

The indicator makes it possible to evaluate the quality of the service of the system and precisely the continuity of water supply, which is directly linked to the respect of the minimum threshold in order to avoid any situation of lack of water. The indicator is given by the following relation:

$$\text{ITV} = \frac{\text{Number of violations of the minimum threshold [h]}}{\text{Period of operations [h]}} \cdot 100[\%] \quad (17)$$

3.4 Maximum threshold violation rate (ATV)

The indicator is used to assess some of the system's energy performance. Indeed, any violation of the maximum threshold will systematically result in a loss of energy corresponding to an excess of pumped water. The following relationship shows how to calculate the indicator:

$$\text{ATV} = \frac{\text{Number of violations of the maximum threshold [h]}}{\text{Period of operations [h]}} \cdot 100[\%] \quad (18)$$

3.5 Water reserve variation indicator (RVI)

The indicator assesses the stability of the system in terms of stability of the reserve, where it shows if the level of water in the tank is stable or not. It is given by the following relation:

$$RVI = \frac{\sigma}{\bar{V}_t} \quad (19)$$

with σ : standard deviation of the water reserve [m^3]; $\bar{V}_t$: average value of the water reserve [m^3].

The standard deviation is calculated by the following formula:

$$\sigma = \sqrt{\sum_{t=1}^{24} (Q_p(t) - \overline{Q_p(t)})^2 / 24} \quad (20)$$

The closer the indicator is to 0, the more the water reserve is stable.

3.6 Distribution pressure indicator (DPI)

This indicator evaluates the quality of service of the system in terms of the level of water in the tank. Where the higher the water level, the higher the distribution pressure, which facilitates the distribution of drinking water. It is given by the following relationship:

$$DPI = \sum_{t=1}^{24} \frac{V_t}{C} \quad (21)$$

With V_t : water reserve in the tank at time t , C : capacity of the tank.

The closer the indicator is to 1, the higher the distribution pressure.

4 Case study

To reinforce the developed models we have applied them to the pumping system of the left shore of the city of Sidi Aiche in the state of Bejaia. The distribution network has approximately 3717 subscribers and is spread over a linear length of approximately 58.6 km.

The system has two pumping units, where each pumping unit has 2 centrifugal pumps (Fig. 3). Indeed, the two pumping units suck water from the Imadalou reservoir $2 \times 300 \text{ m}^3$ fed by the Tichy Haft dam and the Aghrnouz wellfield [2].

The first unit guarantees the supply of drinking water to the Ighaouzene tank. It has 2 pumps, whose nominal flow rate is $22.1 \text{ m}^3/\text{h}$ and a pressure of 83 m. The diameter of the installation is 80–90 mm galvanized steel. According to the normalized pattern the maximum hourly consumption is $45.08 \text{ m}^3/\text{h}$ and the minimum hourly consumption is $3.98 \text{ m}^3/\text{h}$. This tank provides drinking water supply in District 01 and part of District 03 which includes approximately 2000 inhabitants with a consumption of $530.319 \text{ m}^3/\text{day}$.

The second pumping unit discharges to the Hotel tank, which supplies the hospital tank, whose water demand is characterized by a maximum hourly consumption equal to $31.17 \text{ m}^3/\text{h}$ and a minimum hourly consumption equal to $2.75 \text{ m}^3/\text{h}$ depending on standardized model provided by water services. The station has 2 pumps with a flow of

Fig. 3 Characteristics of the Sidi Aiche pumping system

15.2 m³/h and a pressure of 163 m, the diameter of the installation is 80–90 mm of galvanized steel.

4.1 Continuous pumping model (H24)

The management of the two pumping systems by the water services is based on a 24-h continuous pumping that we designate by pumping H24. This type of pumping is very simple in its operating principle where it consists of activating one or more pumps over the entire pumping period. This model does not take into account the water level in the tank. Indeed, if the water level exceeds the maximum threshold, the excess water is discharged via the overflow, and if the water level reaches the minimum level there will be a cutoff of drinking water distribution. For this reason, it is widely used in regions that do not have enough financial resources.

In our study, the water services operated one pump permanently and keep the second for rescue.

The performance of the model depends mainly on the initial choice of pumps in terms of flow and pressure. Where the pumping rate must correspond to the requested flow divided by 24 h of operation.

If the pumps are well chosen this could give good results. However, if the pumps are poorly chosen or the demand for water changes, the performance of the model would be significantly affected.

5 Results and discussion

To study the three pumping models, a numerical simulation of the evolution of the water reserve in the Ighaouzene and Hotel tanks was carried out during 24 h of pumping, where in general, this period with 1-h intervals is the most used [4].

The simulation is based on the water reserve continuity equation (mass balance), and on the regulation algorithm for each model. The choice this model was made for its speed and stability of calculation in the treatment of simple pumping systems. The results were evaluated on three planes: energetically, through a study of energy consumption for each pumping scenario. Hydraulically, using the pumping volume indicator (PVI). And operationally: through the different thresholds violation rates (OTV, ITV and MTV), the water reserve variation indicator (RVI), and the distribution pressure indicator (DPI).

5.1 Control volumes calculation

Both regulation models are based on control volumes. Table 1 shows the control volumes for the RMV and RP models for the Ighaouzene and Hotel reservoirs. For the

Table 1 Control volumes of the control models

	Ighaouzene tank	Hotel tank
$Q_{ch,min}$ [m ³ /h]	3.98	2.75
$Q_{ch,max}$ [m ³ /h]	45.08	31.17
V_{min} [m ³]	0.00	0.00
V_{max} [m ³]	100.00	100.00
$V_c(1)$ [m ³]	45.08	31.17
$V_c(2)$ [m ³]	22.98	15.97
V_{on} [m ³]	73.54	53.11
V_{off} [m ³]	46.26	65.10

With, V_c (i): control volume of the MVR model, and V_{on} and V_{off} : control volume of the PR model

MVR model, control volumes were calculated using formula (2). For the PR model, the calculation of the control volumes for the Ighaouzene tank has shown the inadequacy between the PR model and the tank. Indeed, the calculation gave a stop volume ($V_{off} = 46.26$ m³) lower than the start volume ($V_{on} = 73.54$ m³), which is not physically feasible. To overcome this problem, a stop volume of 1 m³ greater than the start volume was taken in order to guarantee a certain stability of the operation of the pumps.

5.2 Energetic analysis

The results of energy consumption (Fig. 4) have shown the performance of the MVR model compared to the other models (PR and H24). In fact, for the Ighaouzene pumping system, the MVR model has recorded an energy consumption of approximately 179.51 kWh, while the H24 and PR models have consumed 184.56 kWh and 194.09 kWh respectively. This corresponds to an energy gain of 2.7% and 7.5% compared to the model H24 and PR and respectively.

For the Hotel's pumping system, the energy consumption of the MVR model is 229.62 kWh compared to 249.28 kWh for the H24 model and 260.09 kWh for the PR model. This shows that the MVR model has saved 7.9% and 11.7% of energy compared to the model H24 and PR respectively.

Through these results, it can be seen that the regulation models, and particularly the multivolume regulation model (MVR) despite being based on a single variable of energy consumption, in this case the pumping volume, it was effective in reducing energy consumption.

For the progressive regulation model (PR), the level of energy consumption that is relatively high is caused by the principle of operation of the model, which is to stop the pumps gradually. Which generates part of the energy losses.

Analysis of energy results via the volume energy indicator (energy/volume) showed for the Ighaouzene

Fig. 4 Cumulative energy consumption of pumping models

system, the PR model is the most efficient with an indicator of 0.339 kWh/m^3 compared to 0.342 kWh/m^3 for the MVR model and 0.348 kWh/m^3 for the model H24. Same thing for the Hotel system, the PR model was the most efficient with an indicator 0.661 kWh/m^3 compared to 0.668 kWh/m^3 for the MVR model and 0.668 kWh/m^3 for the H24 model.

These results appear paradoxical. On the one hand, the MVR model is the best in terms of energy consumed. On the other hand, the comparison via the volume energy indicator gives the PR model as the most energy efficient. This is explained as follows:

The energy consumed depends on three variables: volume, pressure and pumping efficiency:

$$E = 0.2725 \cdot \frac{V \cdot H}{\eta} \quad (22)$$

E: energy consumed [kWh]; V: volume [m^3]; H: pressure [m]; η : pumping efficiency [%].

While the volume energy indicator is written:

$$\text{Energy/volume indicator} = \frac{E}{V} \quad (23)$$

By replacing the expression (22) in (23), we have:

This shows that the volume energy indicator depends solely on the pressure and the pumping efficiency. Therefore, the indicator can only assess energy in terms of pressure and pumping efficiency.

This explains why the PR model was the best in energy terms in terms of pressure and efficiency. But overall, the MVR model was the most efficient.

The differences in volume energy indicators are caused by the variation in pressure and efficiency. This variation is accentuated by the number of pumps. Indeed, the larger the pump number, the greater the variation in pressure and efficiency. In our case, the system only has 2 pumps, and for this reason the differences between the indicators of the 3 models are marginal.

5.3 Hydraulic analysis

An analysis of the volume of water pumped makes it possible to evaluate the overall performance of the regulation models and also to confirm their energy efficiency, because the pumping volume is the only variable on which these models are based.

The results of the pumped water volume (Table 2) show that they are aligned with the results of energy consumption, where the MVR model is the best model in terms

of reducing the volume of water pumped with about 524.9 m³ of water pumped for Ighaouzene system and 343.6 m³ for the Hotel system. Follow-up of the H24 model with about 530.4 m³ of water pumped for the Ighaouzene system and 364.8 m³ for the Hotel system. Finally, the PR model with approximately 572.8 m³ and 393.6 m³ for the Ighaouzene system and the Hotel respectively.

This reduction in the volume of water pumped for the MVR model represents a volume gain of about 8.4% and 12.7% for the Ighaouzene system and the Hotel respectively, which represents a very good result in terms of reducing the pumping volume.

To study the energy impact of the volume of water pumped, we used the pumping volume indicator (PVI). The calculation of this indicator (Table 2) shows the RVM model achieved the best result with PVI=0.92 for both pumping systems. Followed by the H24 model with PVI=0.91 for the Ighaouzene system and PVI=0.87 for the Hotel system. In last position, the PR model, achieved the poor results with a PVI=84 for the Ighaouzene system and PVI=0.80 for the hotel system. These results show the effectiveness of the MVR model in reducing the volume of water pumped, and also show the energy malfunction of the PR model caused by the poor control of the pumping volume.

5.4 Operational analysis

All management models of drinking water supply systems must guarantee a quality service to the different consumers, and this through the respect of the thresholds in the distribution tank, which allows continuity of service and energy saving at a time, besides providing a sufficiently high distribution pressure to meet the needs of consumers. In addition, it is necessary that this distribution pressure is stable for the proper operation of the various equipments downstream of the distribution tank. All these criteria are studied and evaluated using the indicators that we have developed.

Table 2 Pumping volume parameters

	Ighaouzene system	Hotel system
V_d [m ³]	530.34	366.73
V_i [m ³]	50.00	50.00
V_{min} [m ³]	0.00	0.00
V_{opt} [m ³]	480.34	316.73
$V(H24)$ [m ³]	530.40	364.80
$V(MVR)$ [m ³]	524.90	343.60
$V(PR)$ [m ³]	572.80	393.60
PVI (H24)	0.91	0.87
PVI (MVR)	0.92	0.92
PVI (PR)	0.84	0.80

5.4.1 Threshold violation

The analysis of the respect of the thresholds makes it possible to partially evaluate: (a) the overall performance of the pumping systems; (b) the quality of service of the system; (c) the energy efficiency of the system.

In fact, for the overall performance, the respect of the thresholds (min and max) allows a general assessment of the operation of the pumping system. This criterion is taken into account using the Overall Threshold Violation rate (OTV). On this point, the MVR and PR models have shown their efficacy, where the RMV model has recorded a single violation of the thresholds (OTV=4.17%) in the Hotel's tank, and also for the PR model which has recorded a single violation of thresholds (OTV=4.17%) at the Ighaouzene tank (Fig. 5).

To assess the quality of service, the Minimum Threshold Violation rate (ITV) was used. The results have shown the superiority of the PR model which has recorded no violation of the minimum threshold. It is followed by the MVR model with 1 violation of the minimum threshold (ITV=4.17%) for the Hotel's tank. And lastly, it is the H24 model which has recorded 2 violation of the minimal threshold (ITV=8.33%).

For energy performance, this aspect is partially represented by the respect of the maximum threshold. Indeed, any violation of the maximum threshold corresponds to an energy loss caused by an excess volume of water pumped. The Maximum Threshold Violation rate (ATV) is therefore able to assess this aspect. The MVR model has shown its performance on this point while fully respecting the maximum threshold. The PR model has recorded one violation of the maximum threshold at the Ighaouzene tank with a maximum threshold violation rate of 4.17%. However, the H24 model has obtained the worst result with an ATV rate of 12.5% on the Aghaouzene tank, which partly explains the poor energy performance of this pumping model.

5.4.2 System stability

The evaluation of the quality of service should also be done in relation to the stability of the water reserve in the tank, because this stability will generate a stable distribution pressure. The calculation results (Table 3) have shown that in terms of the stability of the water reserve, the PR model is the best with RVI=0.26 and RVI=0.18 for the pumping system of Ighouzene and the Hotel successively. For the other models, the results were mixed, where it was found that the H24 model was the best for the Ighaouzene system, while the MVR model was the best for the Hotel system.

Fig. 5 Evolution of the water reserve in the distribution tanks

Table 3 Performance parameters of water reserve stability

Parameter	Igbaouzene tank	Hôtel tank
σ (H24) [m ³]	38.07	25.57
σ (RMV) [m ³]	14.62	12.36
σ (RP) [m ³]	19.13	11.76
RVI (H24)	0.77	0.42
RVI (RMV)	0.45	0.57
RVI (RP)	0.26	0.18

Table 4 Distribution pressure parameters

	Igbaouzene tank	Hôtel tank
V_{moy} (H24) [m ³ /h]	49.54	61.29
V_{moy} (MVR) [m ³ /h]	32.21	21.67
V_{moy} (PR) [m ³ /h]	73.34	64.00
C [m ³]	100.00	100.00
DPI (H24)	0.50	0.61
DPI (MVR)	0.32	0.22
DPI (PR)	0.73	0.64

5.4.3 Pressure distribution

Another important criterion in the study of the quality of service is the level of the water reserve in the tank. For this, the pressure DPI indicator was calculated for the 3 models as shown in Table 4. The PR model has presented the best result with a distribution pressure indicator equal to 0.73 for the Igbaouzene tank and 0.64 for the Hotel tank. In second position, it is H24 the model, with a DPI indicator equal to 0.50 for the Igbaouzene tank and

0.61 for the Hotel tank. Whereas in the last position, the MVR model has obtained a DPI indicator equal to 0.32 for the Igbaouzene tank and 0.22 for the Hotel tank. The fact that the MVR model had the wrong result in terms of the level of water in the tank. This is explained by the fact that the control volumes have been shifted down. Where in the formulas of the model this has not been taken into consideration.

6 Conclusion

The real-time control models of drinking water pumping systems have shown their energy, hydraulic and operational performance. Indeed, energetically the multivolume regulation model (MVR) has shown its efficiency by reducing energy consumption by about 2.4% for the Igbaouzene pumping system and 7.9% for the Hotel system. This performance is also added to its simplicity of installation which requires a simple control cabinet equipped with level detectors and some electrical components unlike the progressive regulation model which requires a programmable controller for start-up. The energy performance of the regulation models is strengthened by a hydraulic efficiency through the reduction of the volume of water pumping.

At the operational plane, in terms of compliance with the thresholds, the 2 real-time control models were effective in meeting the thresholds by achieving a threshold violation rate of 4.17%. In terms of water reserve stability and distribution pressure level the RP model has shown its performance on this point by achieving the best result. This operational efficiency is the result of a very good control of the volume of water in the reservoir using well-defined control volumes based on water demand and the characteristics of the pumping system (pumping flow rate).

In terms of the level of water in the reservoir, the MVR model does not take this point into account when calculating the volume of orders, which has a negative impact on the distribution pressure. This constitutes an important axis in which it is necessary to develop in future works, in addition to working to combine these real-time control models with optimization models, which further improves their energy performance.

The use of performance indicators has made the results analysis process much easier, while diagnosing the performance of the system and detecting the source of the anomaly.

However, the pumping volume indicator showed the inferiority of the real-time control models compared to optimization models in terms of energy efficiency. This is explained by the fact that optimization models take into account more parameters in the management of pumping systems. Also, these control methods are best suited to regions that do not have a variable energy tariff or use autonomous energy sources.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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