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Application of Pressure Management for Leakage Reduction in Water Distribution Networks: Case Study from Antalya-Turkey

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Abstract: Water consumption rates in water distribution networks (WDNs) exhibit wide temporal and spatial changes. Consequently, water pressures show wide changes spatially and temporally. Excess pressure is one of the main factors causing water losses and leakage. Therefore, pressure management is proved to be an efficient and economic method for water losses reduction. The average total water losses (physical and apparent) in WDNs in Turkey are around 50% of the supplied water volumes. Thus, reduction of water losses is among the top priorities of water authorities in Turkey. In this study, hydraulic modelling using the US-EPA EPANET model was applied to a part of Antalya City WDN for a simulation period of one year. Flow rates and water pressures were continuously online measured with 5-minute time intervals by Antalya SCADA (Supervisory Control and Data Acquisition) system. Results of model predictions showed excess water pressure in the simulated WDN all over the year. Therefore, it was decided to reduce the excess water pressure by installing a PRV (Pressure Reducing Valve) that was adjusted according to the optimum pressure head obtained by the hydraulic model simulation. Consequently, physical water losses showed considerable reductions after installing the PRV, as monitored by the SCADA system. However, the novel approach is to use a turbine or a pump as turbine (PAT) to recover the excess energy from WDNs and produce electricity. Accordingly, a detailed study was conducted to examine the application and benefits of such a system to produce energy and reduce water losses at the same time.

Key words: Energy production · Hydraulic modelling · Water distribution network · Water losses reduction

INTRODUCTION

Water distribution networks (WDNs) should be designed to supply adequate quantities of water with enough pressure and acceptable quality for drinking. Low water pressure may cause discomfort in domestic uses for having showers, irrigating the garden, etc. Also, the supplied water with low pressure may not reach the users settled at relatively high elevations. On the other hand, high water pressure causes frequent pipe bursts, reduces the service life of pipes and appurtenances and also causes excess water losses [1]. Therefore, the maximum allowable water pressure in WDNs has been limited to 60 m head according to the recent water losses legislation in Turkey issued in 2014 [2].

Total water losses consist of physical (real) water losses and apparent (commercial) water losses. Physical water losses are described as the water that is lost from the holes and cracks of the pipes and valves and from flooding of reservoirs. Apparent water losses represent the volume of water that is used but not recorded such as illegal water usage, inaccurate water meter readings and data handling errors [3]. Pressure management is an effective and economically feasible method to reduce physical water losses [4, 5, 6, 7]. Therefore, applying pressure management is on the top of agenda of the water authorities in Turkey in order to reduce high water losses that are accounted for 50% of the supplied water volumes [7].

Water consumption rates of the consumers show wide hourly, daily, weekly and monthly variations. Additionally, water consumers are usually settled at different topographical elevations. As a result, water pressures in the WDNs exhibit wide temporal and spatial

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variations. Prediction of water pressures can be achieved only by a well calibrated and verified hydraulic model that uses accurate field observations of flow rates and water pressures [8].

Excess water pressures in WDNs can be reduced by using different types of pressure reducing valves (PRV). However, the reduced pressure is an energy that is dissipated without any use. Therefore, the new approach is to use a micro turbine or a Pump as Turbine (PAT) to reduce the excess water pressure but also to recover the excess pressure to generate electricity [9, 10, 11, 12]. Implementation of micro-hydropower technology in water pipelines has shown potential for energy recovery from excess water pressure [13]. There are many applications for the use of turbines to recover high levels of energy due to breaking pressures on the transmission lines [13, 14]. Su and Karney [15] investigated the influence of water system and turbine characteristics on the economic feasibility of energy recovery by turbines and for the development of general design principles. However, high capital cost of turbine systems is an obstacle for a widespread application in w ater distribution systems. On the other hand, several studies were carried out to investigate the possibility of using pumps in a reverse mode, as hydraulic turbines [16]. Pumps are cheap and simple machines and available in many countries. Derakhshan and Nourbakhsh [17] tested four different PATs and showed that centrifugal pump can operate as turbines at various flow rates and heads. Demarchis *et al*. [16] developed a hydrodynamic model for dynamic analysis of PATs. Puleo *et al*. [18] developed a hydraulic model in order to evaluate the potential energy recovery from the use of centrifugal pumps as turbines in a WDN characterized by the presence of private tanks. The present paper analyses the potential energy recovery by replacing an existing PRV with a PAT system in a real WDN in Antalya City, Turkey. For this purpose, a hydraulic model was applied, excess water pressure was determined and potential power generation was calculated.

MATERIALS AND METHODS

Description of Pilot Study Area (PSA): The methods of this research study were applied to a part of *Konyaalti* Region of Antalya WDN. The region was divided into 18 District Metered Areas (DMAs) in September 2009 for efficient management of water losses. Groundwater wells at *Bogacay* Pumping Station are the water resources for the region. The abstracted raw water quality complies with the drinking water quality standards but chlorine is added to protect the water against possible contamination during distribution. *Hurma* balancing reservoir is the only balancing reservoir in the region. Figure 1 depicts the main elements and the DMAs of the region [1, 19]. DMA No. 2 was chosen as the Pilot Study Area (PSA) for this research study. Most of the PSA is occupied with residential buildings with less than five floors. Total water losses in the PSA were approximately 50% of the supplied water volumes before applying this study. The total length of water pipes in the PSA is 10930 m. Water quantity and quality at *Konyaalti* Region are continuously on-line monitored by Antalya SCADA (Supervisory Control and Data Acquisition) system [8]. Consequently, flow rates and water pressures at the entrance to the PSA are continuously monitored by the SCADA system with 5-minute time intervals.

Hydraulic Modelling: The US-EPA EPANET model was used for the hydraulic modeling of the PSA with a time step of one hour. Figure 2 shows the model input network of the PSA. Patterns of flow rates and water pressures at the entrance to the PSA were extracted from the data sets monitored by the SCADA system. Model calibration resulted in a pipe friction coefficient of Hazen-Williams equal to 100. The model was also verified using different data sets than the ones used for calibration period. Model predictions showed good agreement with field measurements. Details of hydraulic modelling of Konyaaltı region including the PSA is given elsewhere [1].

Recovery of Excess Water Pressure: Excess water pressure could be recovered by using a turbine or a PAT. The produced power can be calculated using the following equation:

$$P = Q\,\rho\,g\,H\,e_0 \qquad (1)$$

where P: power (watt), Q: flow rate (m^3/s), $\tilde{n}$: water density (kg/m^3), g : acceleration due to gravity (m/s^2), H : excess water head (m) and e_o: overall efficiency. In this research study, water density was taken as 1000 kg/m^3 while efficiency was accepted as 0.75.

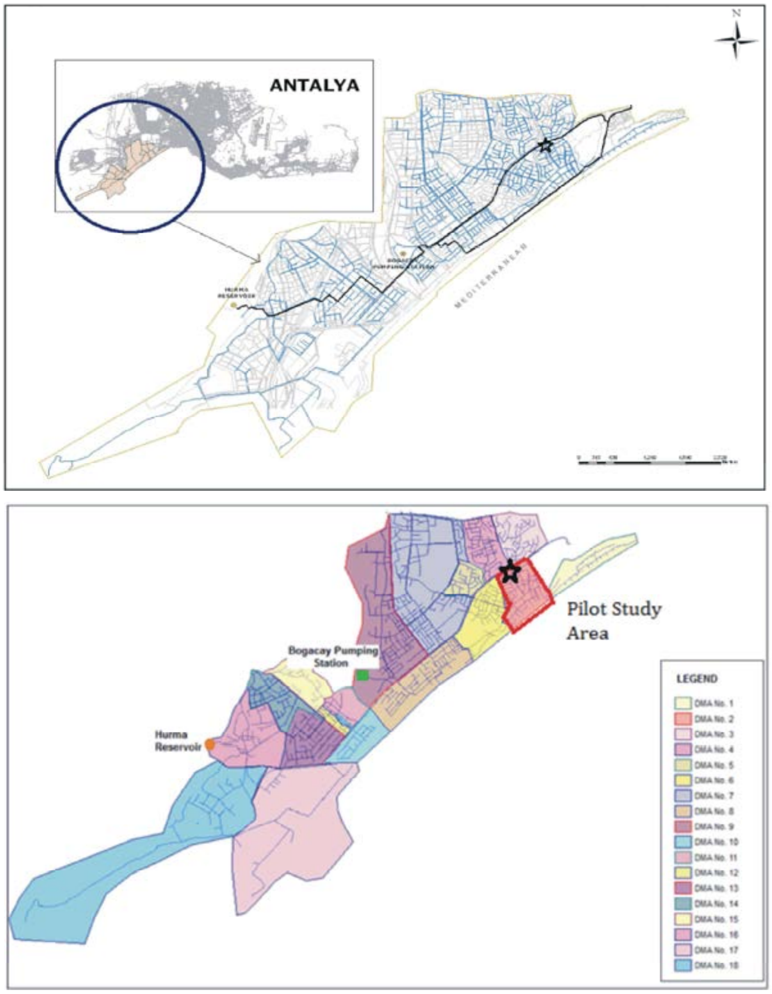

Fig. 1: Konyaalti water distribution network and location of the PSA [updated from Ref. 1 and Ref. 20]

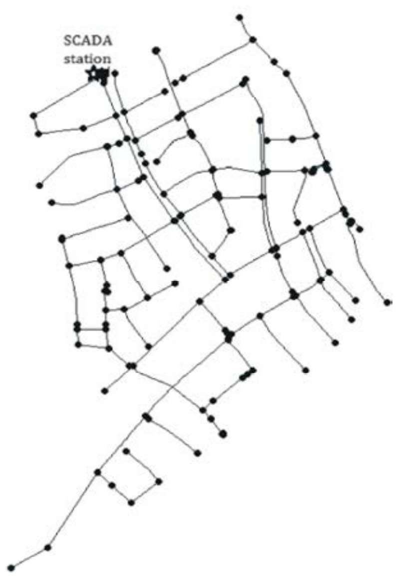

Fig. 2: Water distribution network of the PSA for EPANET model application

RESULTS

Predictions of Water Pressure Variations: Flow rates in WDNs show wide temporal and spatial changes. Accordingly, water pressures also show temporal and spatial changes. It is known that minimum water pressure always occur at the maximum flow rate. Contrarily, maximum water pressure always takes place at the minimum flow rate. Figure 3 shows the monitored flow rates and water pressures in the PSA for one week (between August 2-9, 2009), as an example. The calibrated and verified hydraulic model was used to predict water pressures in the PSA during the maximum and minimum flow rates that were monitored during a whole year. It was found that the predicted minimum pressure head in the PSA was always above 30 m and that the pressure head even exceeded 50 m at some locations. Therefore, the predicted water pressure heads were much higher than the required levels for the PSA that mostly consists of low-rise buildings. The relatively high pressure levels are believed to be an important reason for high physical water losses in the area.

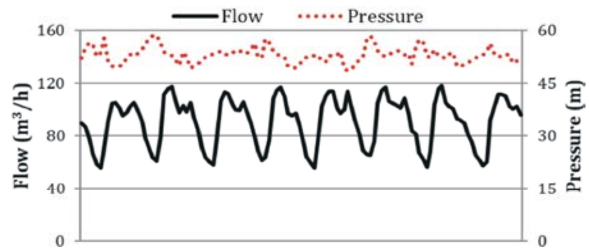

Fig. 3: Monitored flow rates and water pressures at the entrance to the PSA for August 2-9, 2009

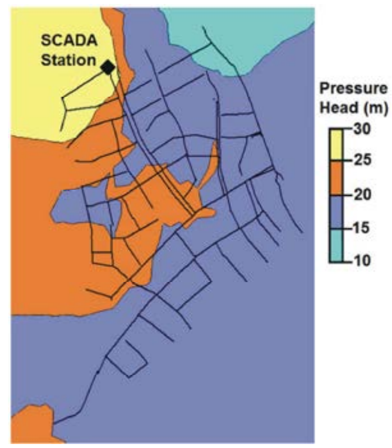

Fig. 4: Predicted water pressures in the PSA at maximum flow rates (120 m^3/h) on August 3, 2010 after installing the PRV

Reduction of Excess Water Pressure: Simulation of water pressures in the PSA showed that the area exhibited excess unnecessary water pressures even during the maximum flow rate. Therefore, it was decided to reduce the pressure to an appropriate level using the capabilities of the calibrated and verified hydraulic model. A pressure head equal to 30 m at the entrance to the PSA was found adequate all around the year and is considered as the "optimum pressure head" in the PSA. Therefore, a PRV, set at 30 meters head, was installed at the entrance to the PSA. Figures 4 & 5 depict the predicted water pressures at the maximum and minimum flow rates respectively after installing the PRV in the year 2010. No complaints were received from the water users due to pressure reduction.

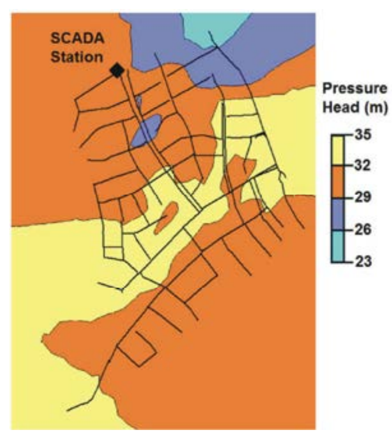

Fig. 5: Predicted water pressures in the PSA at minimum flow rates (26.9 m^3/h) on April 28, 2010 after installing the PRV

Reduction of Water Losses: Maximum and minimum flow rates supplied to the PSA were considerably reduced once the water pressure was reduced at the entrance to the PSA, as shown in Figure 6. As observed from the figure, the initial performance of the installed PRV was not good enough to reduce water pressure to a fixed value of 30 m head. Therefore, it was replaced with a better one that could reduce the water pressure to a value very close to 30 m head, as shown in Figure 6. The average reduction in flow rates in the PSA was estimated at 17 m^3/h or 148920 m^3 of water losses reduction annually [1].

Water consumptions by all users in the PSA were recorded on monthly basis by reading the customer water meters. The water input volume to the PSA was determined through the monitored flow rates by the SCADA system. Consequently, the yearly water balance

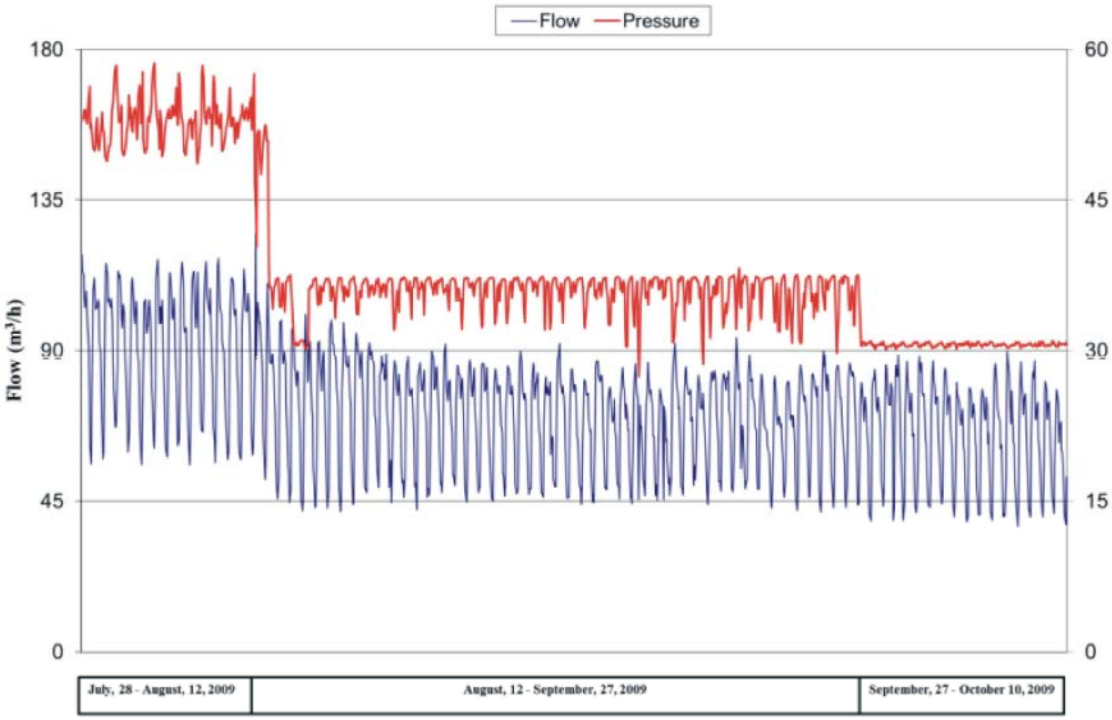

Fig. 6: Flow rate reduction after installing a pressure reducing valve [updated from Ref. 1 and Ref. 20]

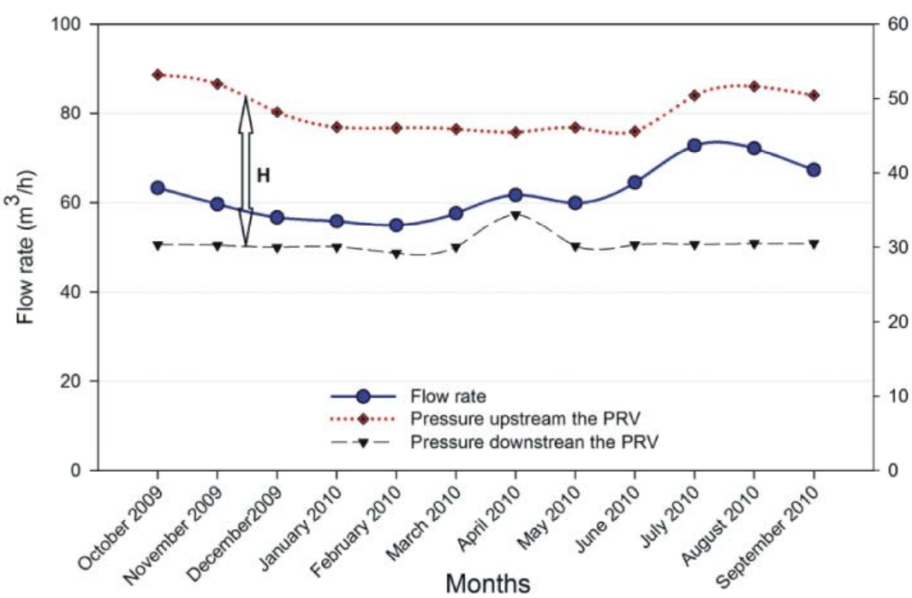

Fig. 7: Excess water pressure (H) after installing the PRV

in 2010 (after installing the PRV) was calculated as given in Table 1 which shows that physical water losses were relatively very low being less than 20%. Thanks to the PRV that reduced the excess pressure levels and hence physical water losses in the PSA.

Potential Energy Production by Excess Pressure Reduction: The water pressures upstream and downstream the PRV besides the flow rates are continuously monitored by the SCADA system. The monthly average water pressures and flow rates after

Table 1: Annual water balance of the PSA in 2010 [21]

System Input Volume	Authorised consumption	Billed authorised	Billed metered	Revenue water
537521 m^3 100%	399844 m^3 74.39%	consumption 398554 m^3 74.15%	consumption 398554 m^3 74.15%	398554 m^3 74.15%
			Billed unmetered consumption 0	
		Unbilled authorised consumption 1290 m^3 0.24%	Unbilled metered consumption 1290m^3 0.24%	Non-revenue water 138967 m^3 25.85%
			Unbilled unmetered consumption 0	
	Water losses 137677 m^3 25.61%	Apparent losses 33111 m^3 6.16%	Unauthorised consumption 0	Customer metering inaccuracies 33111 m^3 6.16%
		Real losses 104566 m^3 19.45%	Leakage on transmission and/or distribution mains	
			Leakage and overflows at utility's storage tanks 0	
			Leakage on service connections up to point of customer metering	

Table 2: Potential energy production at the PSA for the period from October 2009 till September 2010

Date	Flow rate (m^3/h)	Pressure head upstream the PRV (m)	Optimum pressure head (m)	Excess pressure head (m)	Power (kW)
October 2009	63.31	53.14	30.31	22.83	2.944
November 2009	59.66	51.92	30.23	21.69	2.645
December 2009	56.71	48.14	29.97	18.17	2.106
January 2010	55.81	46.10	30.03	16.07	1.833
February 2010	54.94	46.00	29.19	16.81	1.887
March 2010	57.62	45.85	30.02	15.83	1.864
April 2010	61.70	45.42	34.41	11.01	1.388
May 2010	59.90	46.05	30.14	15.91	1.948
June 2010	64.50	45.56	30.33	15.23	2.008
July 2010	72.81	50.39	30.37	20.02	2.979
August 2010	72.16	51.61	30.48	21.13	3.116
September 2010	67.30	50.41	30.50	19.91	2.739
Average		2.288			

installing the PRV is given in Figure 7 for one year period starting from October 2009 till September 2010. Excess water pressure is the difference between water pressure upstream and downstream the PRV. This excess water pressure can be converted into energy to produce electricity if a turbine or a PAT is installed. The potential monthly average energy production is calculated based on Equation 1 and the results are given in Table 2. The flow rates and pressure heads values given in Table 2 were obtained from the SCADA system. The optimum pressure head value was determined by the hydraulic model as 30 m. Therefore, the PRV was adjusted to 30 m. Accordingly, the measured heads by the SCADA system downstream the PRV were very close to 30 m, as given in Table 2. Excess pressure is the difference between the measured pressure head upstream the PRV and the measured optimum pressure head value. The average power to be generated by excess pressure reduction is estimated at 2.288 kW and this makes 20043 kWh annually.

Benefits of Excess Water Pressure Reduction: There are many potential benefits as a result of installing a turbine or a PAT to reduce water pressure and produce green energy. A number of potential benefits have been quantified for one year following the installation of the PAT. Tables 3 and 4 present the calculated potential benefits for water losses reduction and energy production for the period from October 2009 till September 2010. Benefits from water losses reduction is calculated based on the cost of 1 USD/m^3 of water while benefits from energy production is calculated based on the cost of 0.39 USD/kWh, which are the common rates in Turkey.

Carbon dioxide emission is also reduced as a result of installing a PAT or a turbine due to reducing water losses and producing energy. CO_2 emission reduction is calculated based on the reference value of the unit emission equivalence for energy production in Turkey which is 0.53426 kg CO_2/kWh [22]. Antalya Water and Wastewater Administration (ASAT) estimated the energy required to supply one m^3 of water to the consumers as 0.67 kWh [23]. Table 3 shows that annual water losses reduction is calculated as 148920 m^3. Accordingly, yearly potential CO_2 emission reduction due to water losses reduction can be calculated as follows:

Yearly CO_2 emission reduction due to water losses reduction = 148920 × 0.67× 0.53426 ≈ 53307 kg CO_2

Table 3: Annual potential benefits of water losses reduction for the period from October 2009 till September 2010

Average water losses reduction (m^3/h)	Water losses reduction (m^3/year)	Unit Benefit (USD/ m^3)	Total benefit (USD)
17	148920	1.0	148920

Table 4: Annual potential benefits of energy production for the period from October 2009 till September 2010

Average energy production (kWh)	Yearly energy production (kWh/year)	Unit Benefit (USD/kWh)	Total benefit (USD)
2.288	20043	0.39	7817

Total yearly energy production is calculated as 20043 kWh in Table 4. Accordingly, yearly potential CO_2 emission reduction due to energy production can be calculated as follows:

Yearly CO_2 emission reduction due to energy production = 20043 × 0.53426 ≈ 10708 kg CO_2

Consequently, yearly total CO_2 emission reduction due to energy production and water losses reduction is estimated at 64015 kg CO_2.

The above analyses show that there are a lot of benefits for reducing excess water pressure and recovering energy in addition to environmental benefits of conserving water and reducing CO_2 emissions. Therefore, a fund was achieved from The Scientific and Technological Research Council of Turkey (TUBITAK) for the real application of a PAT in the field to produce energy and reduce physical water losses at the same time. The name of the research project is "*Investigation of the Renewable Energy Recovery Potential for Sustainable Water Supply Systems*". With the implementation of this project, operation of the full scale PAT system was initiated in January 2016, as the first one in Turkey, aimed at reducing water losses and producing energy at the same time [24]. The aim was to test the efficiency of such systems to reduce water pressure and recover the lost energy. Consequently, the water authorities were encouraged to apply similar systems because of the environmental benefits of producing green energy and reducing water losses at the same time.

CONCLUSIONS

Improving hydraulic efficiency of WDNs is important to avoid excess water pressure and physical water losses, to reduce the frequency of pipe bursts and to increase the service life of the pipes and appurtenances. Application of pressure management to the PSA showed that reduction in water pressure resulted in an immediate reduction in physical water losses. The total yearly potential benefits of water losses reduction and energy production in the PSA exceeded 156 thousand USD which is much more than the capital and yearly operational costs of the PAT. Moreover, there are additional benefits such as reduction of CO_2 emission that makes the system sustainable. Changes in water demands should be taken into consideration for the hydraulic simulation of the network to estimate the optimum pressure head and to calculate the potential benefits.

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