ADVANCED CONTROL OF A WATER SUPPLY SYSTEM: A CASE STUDY

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ABSTRACT

WTP Gruszczyn supplies drinking water to a part of the city of Poznań, in the Midwest of Poland. The conventional production flow control and pressure control of the facility was replaced by the advanced control software called OPIR. To assess the differences between conventional and advanced control, production flows and pressures of two operational periods were compared. The comparison showed that advanced control led to 83% less variation in the production flow and 29% lower pressure of the clear water pumps. The lower pressure resulted in 20% less background leakage and the overall energy costs of the system were reduced by 11.5% (337,000 kWh per year).

INTRODUCTION

A water supply system is designed to produce drinking water of good quality, and to supply this water to the customers under sufficient pressure. The goal in the operation of the system is to produce and supply the drinking water with a high reliability at the lowest operational costs. Initially, the water supply systems were operated manually by operators, but since the mid 1970's water utilities started automating the systems (Bunn, 2007). At first, the control loops in the automation systems were rather straightforward, because of the limited computational force of these systems. This simple and robust automation is sub-optimal with respect to the performance of the treatment plant and to energy efficiency (Bakker et al., 2003).

To improve the performance of water supply systems, advanced control software has been developed and implemented. This type of software is used for pump scheduling of clear water pumping stations and for production flow control of water treatment plants. Bakker et al. (2013, in press) showed that this type of software leads to 5% lower energy costs and 19% lower turbidity values at water supply systems in the Netherlands; Bunn and Reynolds (2009) showed reductions of energy cost of 12% at water supply systems in the United States.

A second possibility to improve the performance of water supply systems is the implementation of pressure management. In most cases, implementing pressure management includes both creating smaller pressure zones, called district metered areas (DMA's), and installing reducing elements like pressure reducing valves (PRV) in the distribution network. Pressure management can lead to a reduction of the water losses: for example, Girard and Stewart (2007) show in their case study a reduction of the water loss of 21% as a result of reducing the pressure. The reduction of the water losses also leads to a reduction in the system's energy consumption (Colombo and Karney, 2005).

In this paper, a case study of the implementation of advanced control software is presented, to control both the production flow, using an adaptive demand forecasting model, and the pump pressure by applying dynamic pressure control.

CASE STUDY

Water company Aquanet S.A. is responsible for the water supply in the city of Poznań (550,000 inhabitants), in the Midwest of Poland. Like most water supply companies in Poland, Aquanet manually operated the water treatment and pumping facilities by operators. In 2011 Aquanet decided to fully automate the control of one of their water supply systems (WTP Gruszczyn) and to run the system unmanned. The lay-out of the system is shown in Figure 1 and Figure 2.

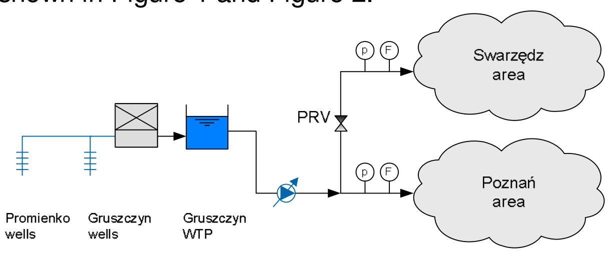

Figure 1: Schematic drawing of the water supply system of Gruszczyn

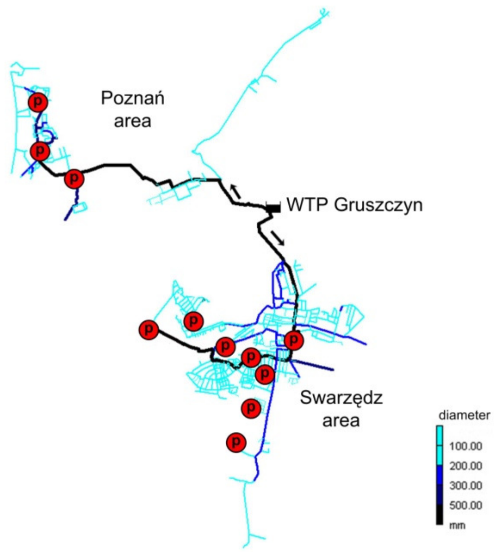

Figure 2: Distribution system of Gruszczyn, including nine new and two existing pressure measuring points

The goal of the automation project was to run the water supply system unmanned, and to optimize the control of the system. Optimized control should result in a reduction of operational costs by minimizing the energy consumption.

MATERIALS AND METHODS

Production flow control

In the first stage of the automation and optimization project, a relative simple production flow control loop was programmed in the programmable logic controller (PLC). In this control loop the production flow set-point was directly derived from the level in the clear water reservoir (increasing level resulted in decreasing set-point, and vice versa). This level based production flow control was capable of controlling the production unmanned. However, this control was not optimal, because many production flow changes occurred, resulting in a sub optimal water quality, and water production was not at the lowest possible energy costs.

In the second stage of the project, the computer-based predictive production flow control software (OPIR) was installed. This predictive flow control model forecasts the water demand for the next 48 hours with 15-minutes time steps. The self learning forecasting algorithm automatically builds up a database with specific water demand curves and factors of the supply area, and uses these curves and factors to predict future demand. The functional details and the performance of this forecasting model is described by Bakker et al. (2013, submitted). Based on the forecast of the water demand, the flow control algorithm calculates set-points for the production flow. The boundary condition in this calculation is that the level in the clear water reservoir must stay between a chosen upper and lower level; the optimization is to produce the water with a minimum of production flow changes at the lowest possible energy costs. Figure 5 shows trends of the production flow of both level based control as well as model predictive flow control.

Influence of production flow control

The production flow control influences the variability of the production flow, which can be expressed in the production variation per day (PV_d). The production variation is defined as the sum of the (absolute values of) the difference between subsequent hourly average production flow values ($F_{prod,d,h}$) divided by the total daily production:

$$PV_d = \frac{\sum_{h=1}^{h=24} \left| F_{prod,d,h} - F_{prod,d,h-1} \right|}{\sum_{h=1}^{h=24} \left| F_{prod,d,h} \right|} \cdot 100\% \qquad (1)$$

Production flow control also influences the energy consumption for the production of the drinking water. Because real-time energy measurements were not available, the energy consumption for abstraction and treatment P_{prod} was estimated with:

$$P_{prod} = P_{base} + C_1 \cdot F_{prod} + C_2 \cdot F_{prod}^3 \; [kW] \qquad (2)$$

Where P_{base} [kW] is the constant, flow independent, energy consumption, F_{prod} [m^3/h] is the production flow, C_1 is a value representing energy consumption for static head loss and C_2 for dynamic head loss. The values for P_{base}, C_1 and C_2 were chosen, such that the average estimated energy consumption matched the specific energy consumption based on the energy invoice of 2011 (0.456 kWh/m^3 for abstraction and treatment).

Pressure control

The distribution pumping station of WTP Gruszczyn consists of five identical pumps all equipped with variable speed drives (VSD). The pumps are operated as one group at a fixed pump pressure. The clear water is pumped in two directions towards individual supply areas. Initially the two areas were separated from each other by a PRV in order to reduce the pressure in one zone while keeping a higher pressure in the other zone. The operators chose a relative high pressure set-point for the clear water pumping station, because of a lack of information about the pressure in the entire network during flow variations.

In the automation and optimization project, nine new pressure measuring points were installed in the distribution network (see Figure 2). The measured pressures showed that there was no need to separate the two pressure zones, and that the existing PRV could be removed. After removing the PRV, the pressures in both zones were equalized.

For the control of the clear water pumping station, the dynamic pressure control module (DPCM) of the OPIR software was installed. Figure 3 shows the user interface of the DPCM.

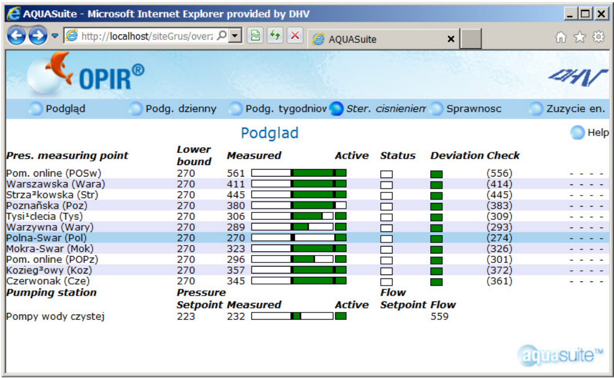

Figure 3: Interface of the dynamic pressure control module (DPCM), showing all measured pressures and their lower bound values, and highlighting which measuring point is the master in the control loop

In the conventional control, the pressure set-point was a static value chosen by the operator. The DPCM is a feedback control model, which dynamically calculates a set-point for the pumping station by comparing the measured pressures at the measuring points with their individual lower bound values. The measuring point with the lowest pressure in relation to its lower bound value is the master in the control loop. The DPCM uses a proportional integral derivative (PID) control mechanism to derive a pressure set-point for the pumping station, based on the desired (lower bound) and measured pressure value of this master pressure measuring point.

Using off-line pressure measuring points

The nine installed pressure measuring points are equipped with a local logger and GSM modem. The measured pressures were buffered locally and sent to the SCADA system of WTP Gruszczyn once per day. This implies that the measured values were not in real-time available. However, the DPCM estimates the real-time pressure p_i for each pressure measuring point i as a function of the real-time measured pressure at the pumping station p_{ps} and distribution flow to the area F_{dist}:

$$p_i = p_{ps} + a + b \cdot F_{dist}^2 \quad [kPa] \tag{3}$$

The values for a and b in equation (3) were derived by the DPCM using data of the previous 72 hours (see Figure 4).

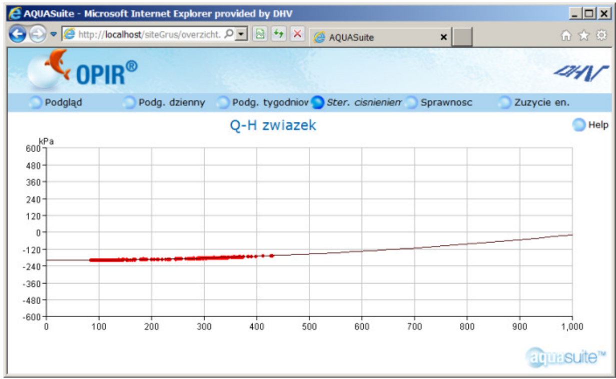

Figure 4: Least squares fit of measured pressure drop between pumping station and pressure measuring point as a relation of the flow to the area

By this functionality, the DPCM is a feedback control model using a predicted value as input, and can therefore be considered to be a hybrid form of a predictive controller and a feedback controller as described by Ulanicki et al. (2000).

Influence of pressure control

Pressure control influences the average pressure in the water distribution network and as a results also the leakage in the distribution network. The background leakage q_{leak} can be described with (Gomes et al., 2011; Araujo et al., 2006; Vairavamoorthy and Lumbers, 1998):

$$q_{leak} = K_f \cdot p^{\beta} \tag{4}$$

Where K_f is a leakage coefficient for the area, p is the average pressure in the area, and β is pressure exponent. According to Gomes et al. (2011), the pressure component β varies between 0.5 (for leaks with a fixed leaking area, which is the case with steel pipes or other rigid pipes) and 2.5 (for leaks with a leaking area which is highly sensitive pressure fluctuation, which is the case with HDPE pipes or other flexible pipes). Gomes et al. (2011) use a value of 1.0, where Ulanicki et al. (2000) use a value of 1.5 for background leakages. As proposed by May (1994) and adapted by Araujo et al. (2006) we will use 1.18 for β in this paper.

If the pressure in the area changes, the background leakage in the area will change according to:

$$\frac{q_{leak,1}}{q_{leak,0}} = \left(\frac{p_1}{p_0}\right)^{\beta} \tag{5}$$

A reduction of the leakage will lead to a reduction of the amount of water to be pumped. Therefore, also the energy consumption will be reduced. This reduction dE_{loss} can be estimated with:

$$dE_{loss} = dV_{loss} \cdot E_{spec,tot} \quad [kWh] \tag{6}$$

Where dV_{loss} is the difference in water loss in the water distribution system and $E_{spec,tot}$ is the total specific energy consumption for abstraction, treatment and distribution (0.600 kWh/m^3).

Changing the pressure will also affect the energy consumption by the clear water pumps. The difference in energy consumption dE_{pump} is calculated with:

$$dE_{pump} = \frac{\rho \cdot V \cdot dp}{1000 \cdot 3600 \cdot \eta} \; [kWh] \qquad (7)$$

Where ρ is the specific mass of water (1,000 kg/m^3), V is the pumped volume of water, dp is the difference in pump pressure, and η is the total efficiency of pump + motor of the clear water pumps (estimated to be constant at 0.60).

RESULTS AND DISCUSSION

Comparison of operational periods

To evaluate the results of the project, the operational data (flows, pressures, water levels) of a period with conventional control were compared with a period of optimized automatic control. The implementation of the advanced control software was done in several phases, and after initial implementation a period of tuning followed. Therefore, a contiguous period with a sharp transition from conventional control to advanced control was not available. Therefore, we compared, for both control strategies, a three weeks period in November: conventional control in November 2011, and advanced control in November 2012.

Production flow control

Figure 5 shows trends of the total water demand, production flow and reservoir level of both examined periods.

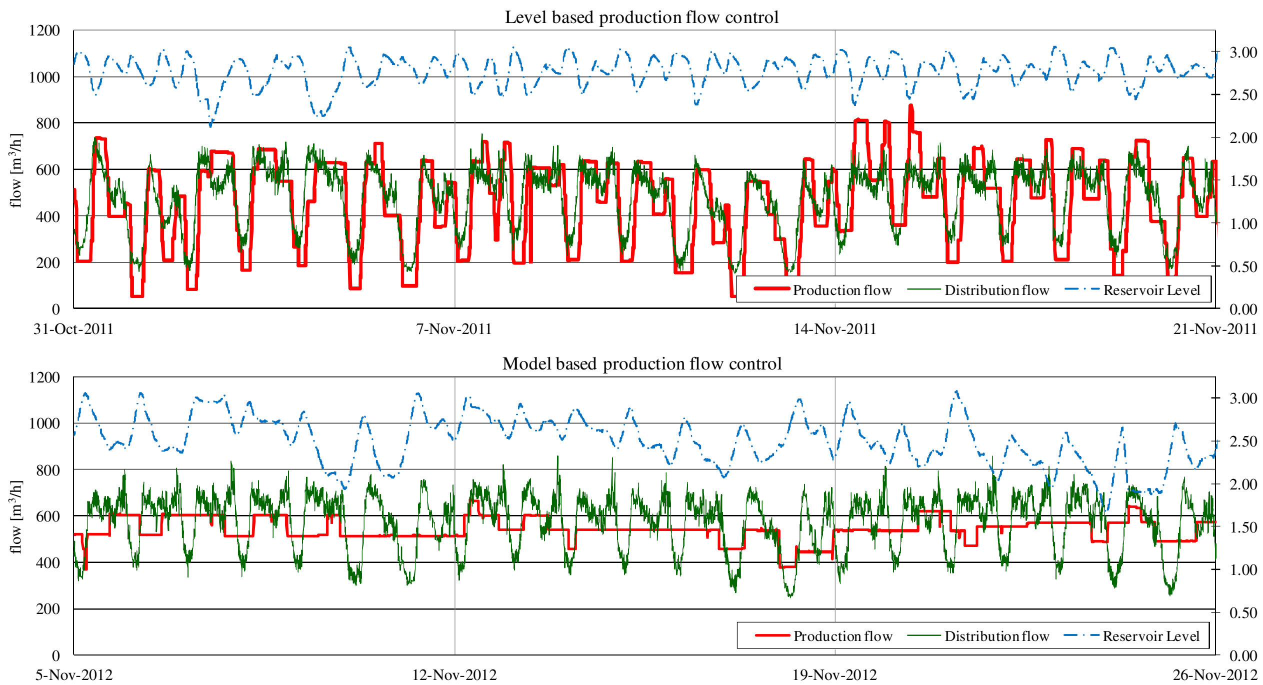

Figure 5: Difference between level based (upper graph) and model based (lower graph) production flow control

The trend with level based control shows that the production flow was switched up and down every day, and that the minimum and maximum flow values were almost equal to the minimum and maximum distribution flow values. The trend with model based control shows a more stable production flow, with a smaller difference between maximum and minimum flows.

Table 1 shows that model based control leads to a 83% lower value for the production variation, calculated with equation (1). Bakker et al. (2013, in press) showed that treatment performance was better at lower values of production variation, resulting in lower values of the turbidity of the clear water.

Table 1 also shows the minimum and maximum observed production flows in both periods, and the difference between the maximum and minimum values. The table shows that the difference between the maximum and minimum production flows was 67% lower with model based control.

Table 1: Difference between level based and model based production flow control

	Level based	Model based	Difference
PV [%]	9.3	1.6	-83%
Production flow			
Min. flow [m^3/h]	52	367	+600%
Max. flow [m^3/h]	875	636	-27%
Max.-Min. [m^3/h]	823	269	-67%
Energy (est.)			
Cons. [kWh/m^3]	0.456	0.447	-1.9%
Cost [€/1,000 m^3]	27.43	26.68	-2.7%

A third aspect shown in Table 1 is the energy consumption and energy cost, which are calculated with equation (2) for both periods. The energy consumption [kWh/m^3] is 1.9%, and relatively more energy is consumed during low tariff hours resulting in a reduction of the costs of 2.7%. With a total annual production of WTP Gruszczyn of 5 million m^3 per year, the implementation of model based production flow control led to a reduction in energy consumption of 43,500 kWh per year (€ 3,750 per year).

Pressure control

Figure 7 and Figure 8 show trends of the water demand, the outlet pressure at the pumping station and the average pressure in the area of both examined periods.

In the initial setup of the water supply system, a PRV was reducing the pressure to one of the two supply areas (Swarzędz area, see Figure 1). The pumps were operated at a fixed pressure (330 kPa), and the fixed outlet PRV was set to reduce the pressure to the Swarzędz area to 280 kPa. The installed PRV was a medium driven automatic control valve Cla-val NGE9001 (DN250). Prescott and Ulanicki (2003) used this type of valve to develop their dynamic model of PRVs. According to this model, the PRV shows a limited flow dependence: during low flows the outlet pressure is somewhat higher than during high flows. This characteristic was also observed in the trends of flow and pressure to the Swarzędz area (Figure 6).

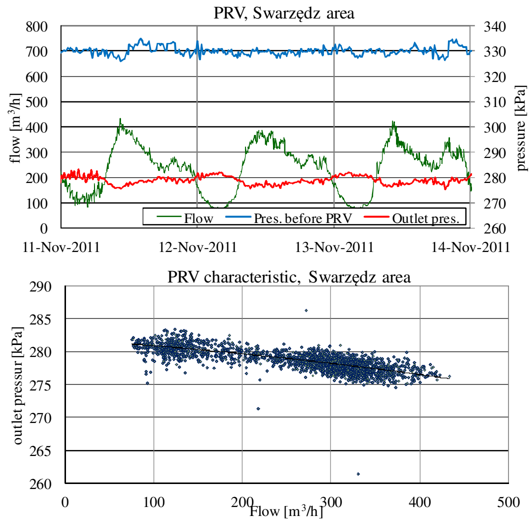

Figure 6: Outlet pressure in the water main to Swarzędz area with conventional pressure control including PRV

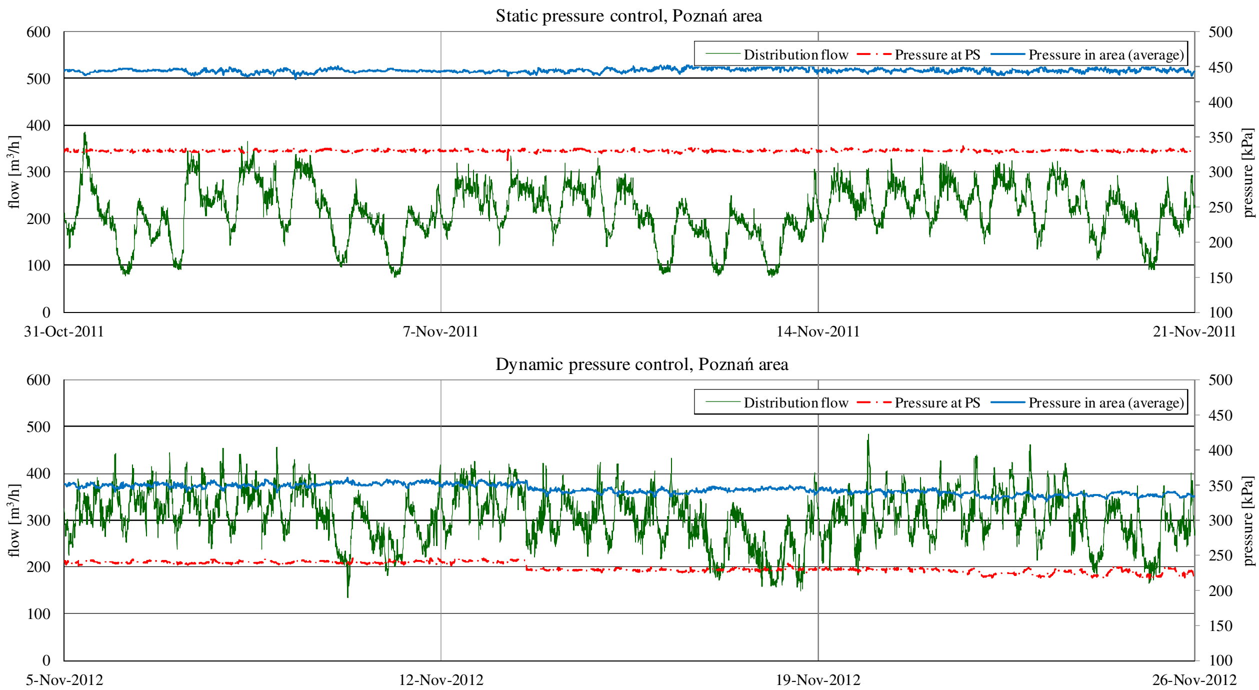

Figure 7: Difference between static (upper graph) and dynamic (lower graph) pressure control, Poznań area

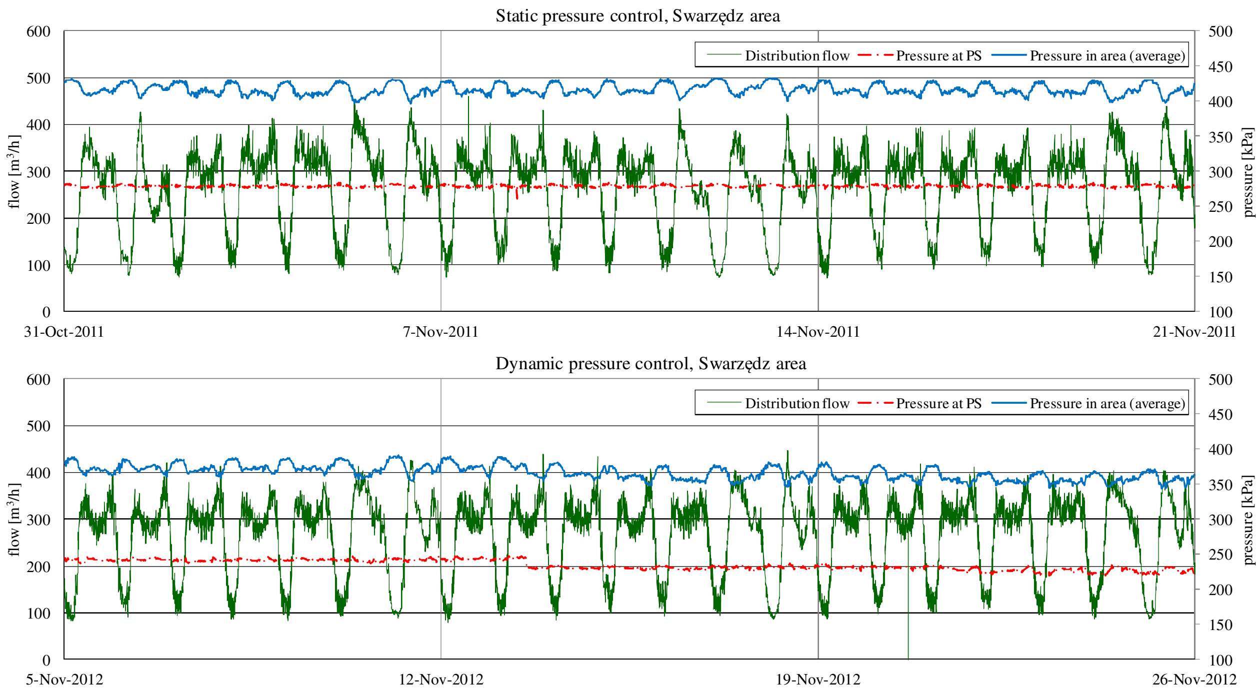

Figure 8: Difference between static (upper graph) and dynamic (lower graph) pressure control, Swarzędz area

The flow dependence of the PRV, however, was unwanted. During low flows the dynamic head loss between the pumping station and the distribution area was lower, and therefore, a lower, instead of a higher, outlet pressure was desired.

The result of the DPCM at the clear water pumping station is shown in Figure 9.

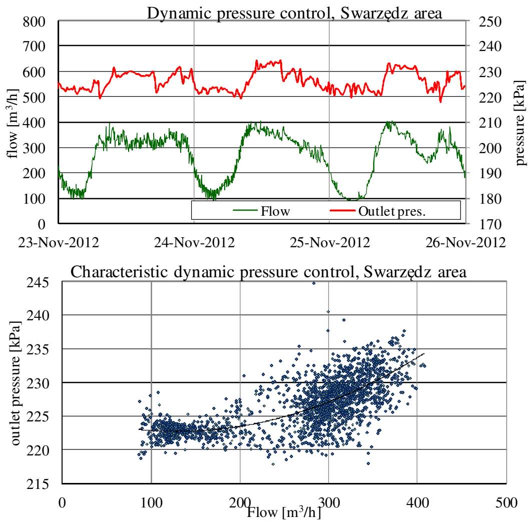

Figure 9: Outlet pressure in the water main to Swarzędz area with dynamic pressure control

The trend shows that the outlet pressure was lower during low flows and higher during high flows. This was caused by the fact that head loss between the pumping station and the area is a quadratic function of the flow. Using the DPCM therefore also resulted in a quadratic relation between the pressure and the flow, as can be seen in the lower graph of Figure 9. The scatter in the graph is rather high, because of differences between the set points of the local controller and DPCM.

The DPCM worked as a flow modulated PRV, which is also available as integrated medium controlled device, like the AQUAI-MOD® hydraulic controller (Abdel Meguid et al., 2011). The advantage of the DPCM over a flow modulated PRV, is that the DPCM can be tuned easier, and that the DPCM adapts automatically to changing hydraulic or demand characteristics. A potential drawback of the DPCM is that it needs power and functioning communication infrastructure, which is not necessary for a medium controlled device. In the considered case study, this was not an issue because the pressure was controlled at the treatment facility which has a permanent and failsafe power supply and communication infrastructure.

The measured pump pressure of the clear water pumping station ("PS") was reduced by 97 kPa (29%) after implementation of the DPCM, see Table 2. The average pressure in the distribution network was decreased by 100 kPa (23%) in the Poznań area and 50 kPa (12%) in the Swarzędz area. The reduction of the pressure in the Swarzędz area was lower, because in the initial setup of the system the pressure was already reduced in this area with a PRV (reduction by 50 kPa on average). The water flow to the Poznań area was in the period with dynamic pressure control 92 m^3/h (43%) higher than in the period with static control. This increase is caused by a large industrial customer in the area, who increased its water demand. The water flow to the Swarzędz area shows little difference (2%) in the two periods.

Table 2: Difference between static and dynamic pressure control

	Static control	Dynamic control	Diffe-rence
Poznań area			
Flow [m^3/h]	214	306	+43%
PS [kPa]	330	233	-29%
MP1 [kPa]	395	298	-25%
MP2 [kPa]	475	373	-22%
MP3 [kPa]	462	361	-22%
Area avg. [kPa]	*444*	*344*	*-23%*
Swarzędz area			
Flow [m^3/h]	261	267	+2%
Outlet [kPa]	279	233	-16%
MP1 [kPa]	470	422	-10%
MP2 [kPa]	516	452	-12%
MP3 [kPa]	439	390	-11%
MP4 [kPa]	365	318	-13%
MP5 [kPa]	329	281	-14%
MP6 [kPa]	381	337	-12%
Area avg. [kPa]	*417*	*367*	*-12%*

A reduction of the pressure in the area resulted in a reduction of the water losses in the distribution network. By applying equation (5), a reduction in background leakage was calculated of 26% for the Poznań area, and 14% for the Swarzędz area (which corresponded to a 20% reduction for the entire Gruszczyn system). The total water losses of the water utility Aquanet amounted 5.30 million m^3 or 11.3% (Aquanet, 2012). We assumed that the water losses were equally distributed over all supply areas, because no detailed information about water losses in different areas was available. With the above, we estimated the water losses in the Gruszczyn system in 2011 at 565,000 m^3 per year and in 2012 at 450,000 m^3 per year (water loss reduced from 11.3% in 2011 to 9.0% in 2012, difference 113,500 m^3).

Girard and Stewart (2007) and Gomes et al. (2011) showed that a reduction in the pressure in a water supply area also leads to a reduction in the number of main breaks and service breaks. Based on the reduced pressure in the area, a reduction in the number of breaks may be expected in this case study as well. However, the number of breaks in the concerning areas were not registered separately, making it impossible to confirm the expected reduction in breaks.

Reduction of energy consumption

The reduction of energy consumption due to the implementation of advanced control software consists of three elements:

1. Savings due to production flow control;
2. Savings due to lower pump pressure of clear water pumps
3. Saving due to reduced water losses.

The energy reduction by production flow control was estimated at 43,500 kWh per year (€ 3,750 per year) earlier in this paper. The energy reduction due to lower pump pressure was calculated with equation (7). With a pumped volume (V) of 5 million m^3 per year, and a pump head (dp) of 97 kPa, this results in a dE_{pump} of 225,000 kWh per year (€ 13,550). The energy reduction due to reduced water losses was calculated with equation (6). Based on a reduced water loss of 113,500 m^3 per year (see above), the reduction in energy consumption was calculated at 68,500 kWh per year (€ 4,100).

The reductions in energy consumption are listed in Table 3. The table shows that the lower pump pressure is the main contributor to the reduction of the overall energy consumption of 337,000 kWh per year (€ 21,500 per year). The observed reduction corresponded to a reduction of 11.5% of the overall energy consumption of the Gruszczyn water supply system.

Table 3: Energy savings due to the implementation of advanced control

	Energy kWh/year	**Costs** €/year
1. production flow control	43,500	3,750
2. lower pump pressure	225,000	13,550
3. reduced water loss	68,500	4,200
Total	337,000	21,500

CONCLUSION

The implementation of the production flow control and the dynamic pressure control modules of the OPIR software at WTP Gruszczyn, resulted in a more constant production flow and a reduction of the pump pressure of the clear water pumps. The project has led to considerable savings in the operational costs by the reduced energy consumption (337,000 kWh per year, or € 21,500 per year). The project has shown that extra information from the distribution network (from nine new pressure measuring points) in combination with advanced control software led to a more efficient water supply system.

ACKNOWLEDGMENTS

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