Higher energy efficiency and better water quality by using model predictive flow control at water supply systems

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Abstract
Half of all water supply systems in the Netherlands are controlled by model predictive flow control; the other half are controlled by conventional level based control. The differences between conventional level based control and model predictive control were investigated in experiments at five full scale water supply systems in the first half of 2011. Energy consumption of the treatment and distribution process and quality parameters of the drinking water were measured and analyzed. The experiments prove that the overall energy consumption of water supply systems controlled by model predictive flow control is 1,5-5% lower than conventionally controlled systems, and the overall energy costs are 2,5-7% lower. Turbidity and particle numbers are 10-20% lower for the systems which are controlled by model predictive flow control.

Keywords
Prediction; control; water quality; drinking water; energy reduction

INTRODUCTION

The use of reservoirs in water supply systems

Reservoirs in water supply systems have several functions. One of the main functions is to level off fluctuations in the water demand, allowing the Drinking Water Treatment Plant (DWTP) to produce water at a constant flow rate. A constant production flow rate leads to better water quality and lower energy consumption. In practice the reservoirs in many water supply systems are used in an inefficient way, resulting in fluctuations in the production flow rate. The inefficient use of the reservoirs is caused by the application of simple level based flow control algorithms. By applying more advanced model predictive flow control algorithms, efficient use of the reservoirs can be guaranteed.

Expected influence of control on water quality

In general a better water quality is to be expected when a Drinking Water Treatment Plant is operated at a constant flow rate. This is especially true for the chemical/physical processes in the treatment process, since:

- The coagulation / flocculation process can be disturbed by variations in the flow rate;
- Aeration has an optimal efficiency at a given flow rate;
- Sand filtration has an optimal efficiency at a constant flow rate. Significant changes in flow rate may cause the breakthrough of particles;
- In the activated carbon filtering process, production flow variations result in a varying contact time, causing variations in the efficiency of the process;
- Pellet softening is a delicate process, where switching on / off reactors causes variations in the produced water quality;

Automation of water supply systems in the Netherlands

The automation of water supply systems in the Netherlands started in the 1970's. At that time it became technically possible and economically feasible to substitute human operators by automation systems, and to run the water supply systems unmanned. This was particularly true for small scale water supply systems, therefore the automation started at these kind of smaller systems. At present all water supply systems in the Netherlands have been automated and are running unmanned.

The first automated water supply systems were controlled by straightforward PLC based control loops. The flow control (quantitative control) was based on the level in the reservoir. This level based flow control is simple and robust, but results in an inefficient use of the reservoir and leads to unwanted fluctuations in the production flow. In the 2000's the desire for a more efficient control of water supply systems grew, and the first water supply systems were automated with model predictive flow control systems. At present about half of the water supply systems are controlled by level based flow control, and the other half is controlled by model predictive flow control (DHV, 2011).

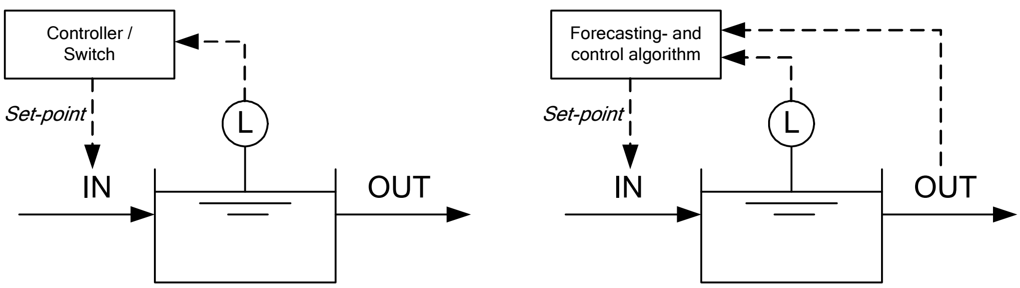

Figure 1. Principles of level based flow control (left) and model predictive flow control (right)

Level based flow control

In level based control loops (see Figure 1, left side), the production flow set-point is directly related to the level in the reservoir. The production flow set-point increases at a decreasing level in the reservoir, the set-point decreases at an increasing level. This set-point can be given as discrete commands to start or stop pumps or filters (based on fixed switching levels), or a continuous value for variable speed pumps (based on a PI(D) control loop).

Level based flow control results in inefficient use of the reservoir. The incoming flow set-point more or less follows the outgoing flow, with a lag of 2-4 hours. The reservoir is merely used as a switching buffer, rather than a buffer to level off fluctuations of water production and supply. The production flow set-point shows many flow changes, and the maximum and minimum flow values of the production flow are comparable with the maximum and minimum flow values of the outgoing flow.

Model predictive flow control

In model predictive flow control (see Figure 1, right side) a demand forecasting algorithm forecasts the outgoing flow, based on the measured outgoing flow and sometimes one or more other parameters (Bakker, et al, 2003). The control algorithm of the model predictive flow calculates production flow set-points to keep the level in reservoir between a chosen upper and lower boundary, under the condition that the forecasted outgoing flow will occur. Typically the forecasting horizon is 48 hours. The control algorithm can be configured to optimize various optimization goals, such as minimal changes in production flow, minimal energy use, minimal energy costs, et cetera. A combination of those is possible as well. Like level based flow control, the set-point can be either discrete commands or a continuous value.

With model predictive flow control the (theoretical) optimal useage of the reservoir can be achieved. Deviations in predicted and real outgoing as well as incoming flows can disturb the production algorithm, causing sub-optimal results. However, in practise those deviations are relatively small, resulting in a nearly optimal control when using model predictive flow control.

METHODS AND MATERIALS

Experiments at five full scale water supply systems

In order to examine the differences between level based flow control and model predictive flow control, five full scale water supply systems with model predictive flow control systems were selected. At each of those water supply systems the model predictive flow control software OPIR® (DHV, 2011) was implemented "on top" of the existing level based flow control. Meaning that, the existing control loops were maintained as a back-up for the eventual failure of the model predictive control algorithm. Therefore that the selected water supply systems had both level based flow control as well as model predictive flow control installed. The process diagrams and the characteristics of the systems are shown in Figure 2 and **Table 1**.

The experiments comprised of examining the behaviour of the systems, during:

1. One week with model predictive flow control.
2. One week with level based flow control.

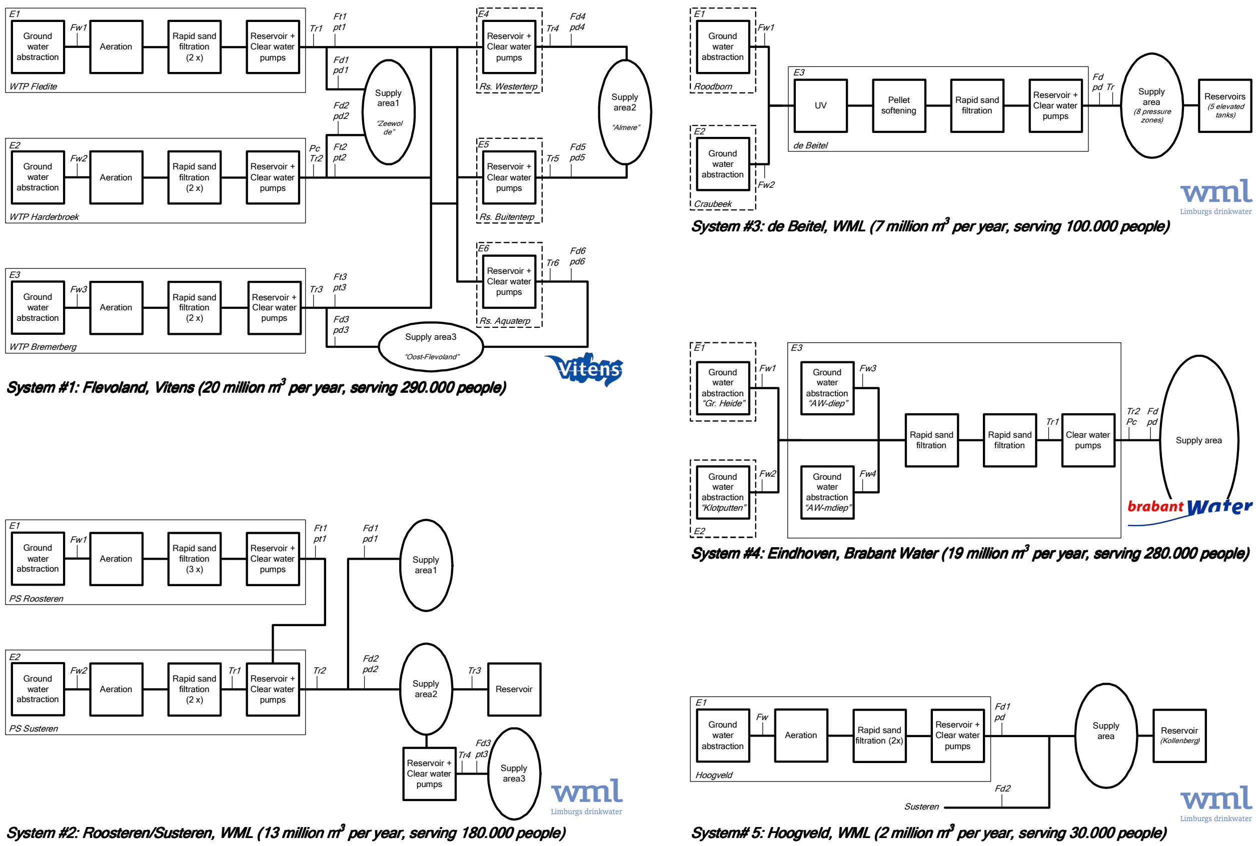

Figure 2. Full scale water supply systems where the experiments were conducted, including all measured items ("Tr" = turbidity, "Pc" = particle count, "Ft"/"pt" = transportation flow/pressure, "Fd"/"pd"=distribution flow/pressure, "Fw"=raw water flow, "E"=energy consumption).

Table 1. Characteristics of the five water supply systems. The demand is the average demand in the period of the experiment. The reservoir volume is also related to the demand in this period.

	# reservoirs	Set-points flow control	Res. volume m^3 per m^3/d	Demand m^3/d	Experiment Period
System #1	6	Discrete / Continuous	87 %	55,000	24/1 – 7/2 2011
System #2	4	Discrete / Continuous	53 %	32,500	15/2 – 1/3 2011
System #3	6	Floating	53 %	19,000	13/4 – 27/4 2011
System #4	1	Discrete	55 %	55,000	12/4 – 26/4 2011
System #5	2	Discrete	116 %	4,650	12/5 – 25/5 2011

Effects of control

Flow, pressure and level measurements
For each pumped flow (transportation and distribution) both flow and pressure were measured. At the abstraction / treatment only the flow was measured. At each reservoir of the water supply system the water level was measured. All the measurements were available at 5-minute time step.

Energy consumption measurements
The energy consumption is measured in order to examine the effect of control on the energy consumption of water supply systems. Both the total energy consumption (kWh/m^3) as well as the percentage of the energy consumption during high tariff / low tariff hours were analyzed. In the Netherlands the high tariff applies for each weekday from 7 AM to 11 PM, the low tariff applies to all the other hours and in the weekends.
In most situations only one measurement of the total energy consumption was available. This measurement consists for a small part of energy consumption in the water supply system which is not directly related to the water production and distribution processes. This is energy consumption for lightning, office and process computers, heating, cooling etcetera.
In order to obtain a better insight, a theoretical calculation of the energy consumption was made. A distinction was made for the energy consumption due to abstraction/treatment (including energy consumption not related to water supply) , transportation and distribution of water.

Abstraction:

$$E_{abst} = \frac{1}{\eta_{abst}} \cdot F_{abst} \cdot \frac{dH_{stat,abst} + C_{dyn,abst} \cdot F_{abst}}{g}$$

Treatment:

$$E_{treat} = \frac{1}{\eta_{treat}} \cdot F_{treat} \cdot \frac{dH_{stat,treat} + C_{dyn,treat} \cdot F_{treat}}{g} + E_{base}$$

Distribution / transport:

$$E_{dist} = \frac{1}{\eta_{dist}} \cdot F_{dist} \cdot (p_{dist} - \frac{L_{res}}{g}) \qquad E_{trans} = \frac{1}{\eta_{trans}} \cdot F_{trans} \cdot (p_{trans} - \frac{L_{res}}{g})$$

Where:

–	E_{abst}, E_{treat}, E_{dist}, E_{trans}	Calculated energy consumption abstraction, treatment, diswtribution and transportation [kW]
–	F_{abst}, F_{treat}, F_{dist}, F_{trans}	Measured Flow [m^3/h]
–	p_{dist}, p_{trans}	Measured pressure [kPa]
–	L_{res}	Measured level in the reservoir from which the water is pumped [m]
–	g	Gravitation acceleration (9,81) [m/s^2]
–	η_{abst}, η_{treat}, η_{dist}, η_{trans}	Estimated total efficiency of pump + motor (+ VSD if applicable) [-]
–	$dH_{stat,abst}$, $dH_{stat,treat}$	Estimated Static head [m] (all energy consumption with a linear relation with the production flow is incorporated in this parameter)
–	$C_{dyn,win}$, $C_{dyn,zuiv}$	Estimated dynamic head loss coefficient [$m / (m^3/h)^2$]
–	E_{base}	Estimated constant (independent of flow) base energy consumption [kW]

The parameters for efficiency, static head, dynamic head loss coefficient and base energy consumption were estimated in a way that that the calculated energy consumption best fitted on the measured energy consumption.

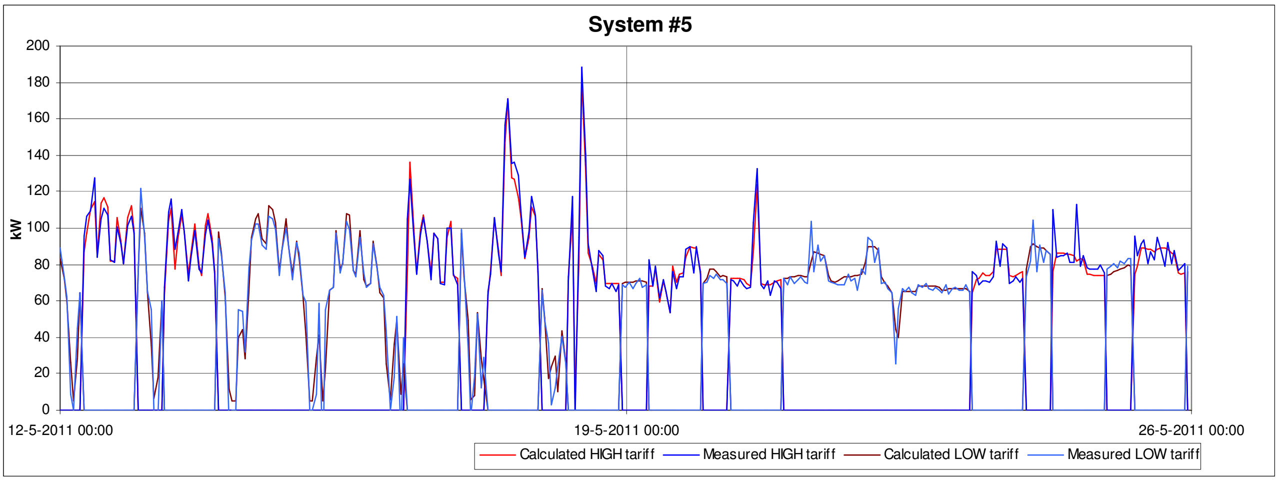

Figure 3. Example of trend with calculated energy consumption and measured energy consumption

Water quality measurements

All examined water supply systems are ground water systems, where only variations in turbidity and particles as a result of production flow changes were to be expected. Therefore not all of the expected differences caused by different operation could be investigated. The following water quality parameters were measured:

- Turbidity (all systems).
- Particles (systems #1 and #4), important for discoloration processes, (Vreeburg et al, 2008).

RESULTS

Observed difference in flow pattern and use of reservoir

The observed differences in flow patterns and the use of the reservoirs between level based flow control and model predictive control were very distinct for each of the five water supply systems. In Figure 4 an example is shown of the trends at system #3. In the week with model predictive flow control (at the right) the production flow is very constant with little variations. The number of production flow changes in the week with level based flow control (at the left) is 10 times higher than in the week with model predictive flow control. Another difference is the moment at which the energy is consumed: with level based flow control, both production and distribution flows are lower during the night (low energy tariff) and higher during the day (high energy tariff). This shift in time causes that the energy consumption with level based flow control is higher during high tariff hours compared to model predictive flow control.

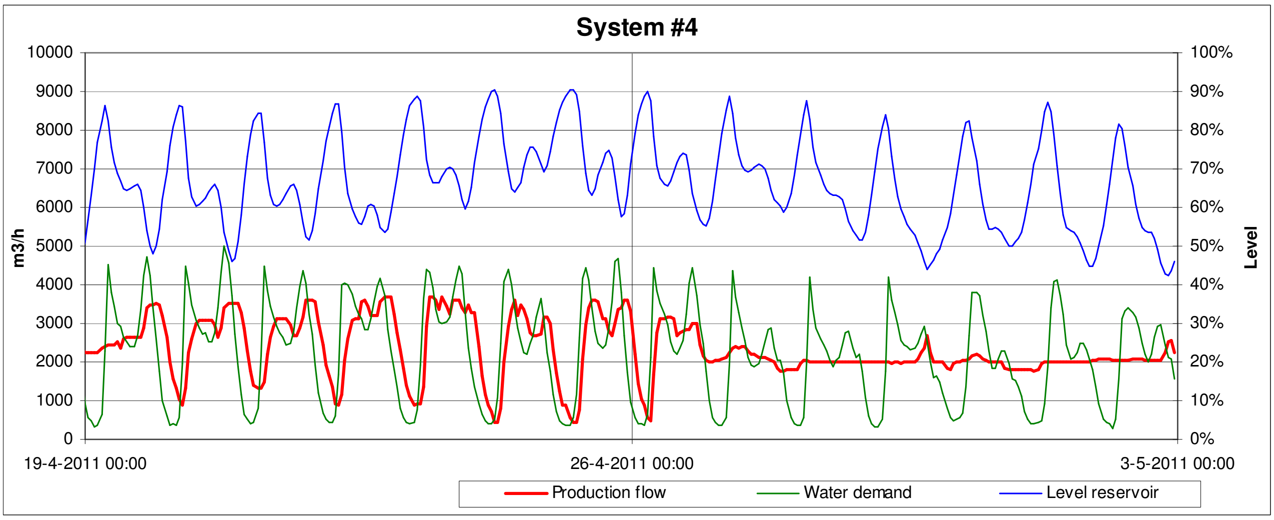

Figure 4. Example of trends of production and distribution flow, and level in the clear water reservoir in a week with level based flow control (19-4 to 26-4, left side) and a week with model predictive flow control (27-4 to 3-5, right side).

Quantitative differences

The differences between level based flow control and model predictive flow control were quantified by comparing average values of the measured parameters. The result for all water supply systems is summerized in Table 2.

Table 2. Quantitative differences between level based flow control and model predictive flow control

	Level based flow control	Model predictive flow control	Difference %
System #1			
Specific energy consumption [kWh/m^3]	0.3395	0.3362	-1.0%
Energy use at high tariff [%]	51.7%	51.0%	-0.7%
Energy costs [€ per 1,000 m^3]	€ 22.47	€ 22.09	-1.7%
Turbidity [NTU]	0.142	0.125	-12%
Particle load [ppb]	30.8	17.9	-41%
System #2			
Specific energy consumption [kWh/m^3]	0.7327	0.6937	-5.3%
Energy use at high tariff [%]	55.5%	51.2%	-4.3%
Energy costs [€ per 1,000 m^3]	€ 49.30	€ 45.65	-7.4%
Turbidity [NTU]	0.526	0.428	-18%
System #3			
Specific energy consumption [kWh/m^3]	0.6048	0.5866	-3.0%
Energy use at high tariff [%]	51.0%	48.6%	-2.4%
Energy costs [€ per 1,000 m^3]	€ 39.77	€ 38.10	-4.2%

Turbidity [NTU]	0.078	0.056	-28%
System #4			
Specific energy consumption [kWh/m^3]	0.3286	0.3240	-1.4%
Energy use at high tariff [%]	58.3%	54.5%	-3.8%
Energy costs [€ per 1,000 m^3]	€ 22.38	€ 21.67	-3.2%
Turbidity [NTU]	0.06	0.06	0%
Particle load [ppb]	0.142	0.125	-11%
System #5			
Specific energy consumption [kWh/m^3]	0.3993	0.3891	-2.5%
Energy use at high tariff [%]	57.3%	48.2%	-9.1%
Energy costs [€ per 1,000 m^3]	€ 27.19	€ 25.29	-7.0%

DISCUSSION

Energy consumption influenced by flow control

The results of the energy consumption and costs in Table 2 show a relatively large variation between the five examined water supply systems. This is caused by the fact that the five systems are quite different from each other, regarding treatment process, topology and elevation. This causes large differences in the way the total energy consumption is divided over the processes, and which part of the energy consumption is influenced by the flow control. Figure 5 shows the division of the energy consumption over the water supply processes of the 5 examined systems.

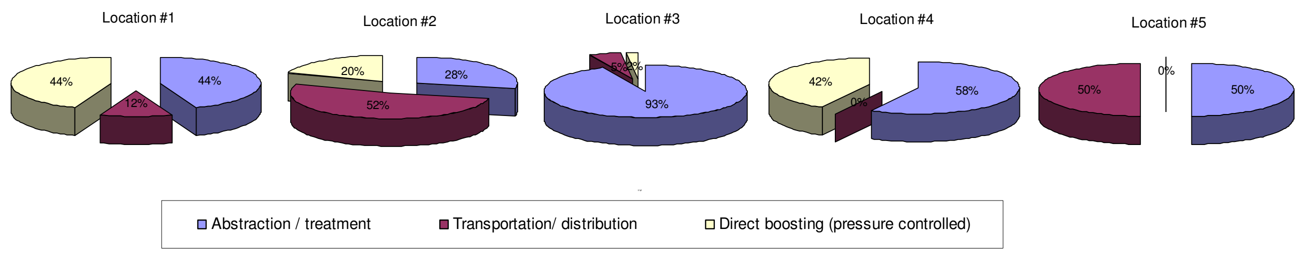

Figure 5. Division of total energy consumption over the water supply processes.

The energy consumption of abstraction / treatment is fully influenced by the type of flow control (except for system #1, where only 1 of the 3 drinking water treatments plants were controlled by model predictive flow control). The energy consumption for transportation / distribution (pumping from 1 reservoir to another reservoir, elevated or on the ground) is also fully influenced by the type of flow control. The energy consumption for direct boosting (pumping from a reservoir directly to consumers) however is pressure controlled, and therefore fully NOT influenced by the type of flow control.

The percentage of the total energy consumption which is actually influenced by the type of flow control is very different for the 5 examined systems: varying from 26% (system #1) to 100% (system #5). The presented savings in Table 2 are related to the total energy consumption. The figures are therefore not fully representative for the real difference between the control of the system. In Table 3 is shown for each of the water supply systems which part of the energy consumption is actually influenced by the type of control, and what the energy savings of model predictive control are related to the influenced energy consumption.

Table 3. Energy consumption related to type of control, and "corrected" savings

	Energy consumption influenced by control	Savings related to All energy cons.	Savings related to Influenced energy cons.
System #1	26.3%	-1.7%	-6.4 %
System #2	80.4%	-7.4%	-9.2 %
System #3	98.0%	-4.2%	-4.3 %
System #4	57.9%	-3.2%	-5.5 %
System #5	100.0%	-7.0%	-7.0 %

Table 3 shows that observed differences between model predictive control and level based control are relatively smaller when the differences are related to the influenced energy consumption.

Variations in water demand during experiments

The effects of the type of control can be examined most precisely in case all other aspects remain constant in the entire period of the experiment. Therefore at first the experiments were planned to take place in January and February, a period in which the demand is relatively low and stable. However, because of maintenance activities the experiments at systems #3, #4 and #5 could not take place earlier than April and May. The weather in the last week of April was particularly good in the Netherlands, resulting in rather high demands in this week. This particular week was the week in which systems #3 and #4 were controlled by level based flow control. The difference in demand in both compared weeks was 7% for system #3 and 14% for system #4 (for comparison: the differences in demand at the other locations were around 1%).

An objective evaluation of the results for systems #3 and #4 is difficult, because the circumstances were not the same in both periods of level based flow control and model predictive flow control. The accuracy of the results is therefore less than the results of the other experiments.

CONCLUSIONS

Based on experiments at five full scale water supply systems, it was shown that advanced model predictive control will lead to a more efficient water supply and a better water quality:

- The overall energy consumption is 1.5-5% lower
- The overall energy costs are 2.5-7% lower.
- Turbidity and particle numbers are 10-20% lower.

The experiments show objective and tangible benefits, which can support the decision making to replace conventional level control by more advanced model predictive flow control. This will lead to a more efficient water supply with better water quality.

REFERENCES

Bakker, M. Van Schagen, K.M. and Timmer, J (2003). Flow control by prediction of water demand. Journal of Water Supply: Research And Technology-AQUA 52(6), 417–424.

DHV (2011). http://aqua-suite.com. Visited 1 September 2011.

J.H.G. Vreeburg, D. Schippers, J.Q.J.C. Verberk, J.C. van Dijk (2008). Impact of particles on sediment accumulation in a drinking water distribution system. Water research 42, 4233–4242.