Better water quality and higher energy efficiency by using model predictive flow control at water supply systems


ABSTRACT

Fifty-seven per cent of all water supply systems in the Netherlands are controlled by model predictive flow control; the other 43% are controlled by conventional level-based flow control. The differences between conventional level-based flow control and model predictive control were investigated in experiments at five full-scale water supply systems in the first half of 2011. Quality parameters of the drinking water and energy consumption of the treatment and distribution processes were measured and analysed. The experiments showed that the turbidity values are 12–28% lower, and particle volume values 12–42% lower for the systems which are controlled by model predictive flow control. The overall energy consumption of water supply systems controlled by predictive flow control is 1.0–5.3% lower than conventional level-based flow controlled systems, and the overall energy costs are 1.7–7.4% lower.

Key words | demand prediction, drinking water, energy reduction, optimal control, water quality

INTRODUCTION

Automation of water supply systems

Water utilities around the developed world started automating their water supply systems around the mid-1970s by installing and operating telemetry and Supervisory Control And Data Acquisition (SCADA) systems (Bunn 2007; Bunn & Reynolds 2009). Prior to this period, the treatment plants and pumping facilities were mainly operated manually. In the Netherlands, most small-scale water treatment plants (typically groundwater treatment plants serving on average 50,000 people, producing and distributing 6,000 m³ per day) were automated extensively at that time, enabling unmanned operation. Unmanned operation in this perspective means that under normal operational conditions no manual actions of operators are needed for pressure and flow control. Therefore, both pressure control of the pumping stations and flow control of the water treatment plants were fully automated. At night and during the weekends, no personnel is present at the small-scale facilities since the automation systems were implemented. Small-scale water supply systems were automated extensively at an early stage due to two reasons. The first is that manually operating small-scale systems is labour intensive and therefore rather expensive. The second reason is that small-scale systems are rather simple systems: the treatment plants consist mainly of robust aeration and filtration steps,

and also the distribution systems are rather straightforward. Initially, the small-scale water supply systems were automated with relatively simple control loops: the set-point for the production flow was derived directly from the level in the reservoir. This level-based production flow control is simple and robust. However, this way of control results in variations in the production flow, which causes variations in the water quality. In the 1990s, the desire for more advanced control loops grew in order to achieve a more constant production flow.

**Level-based versus model predictive flow control**

Principally there are two options for the automatic production flow control: level-based control and model predictive control. In level-based control loops (see Figure 1), 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 switch levels), or a continuous value for variable speed pumps. In general, the production flow set-point more or less follows the outgoing flow, with a time lag of 2–4 h. The reservoir is merely used as a switching buffer, rather than a buffer to balance the variation in the distribution flow. The production flow varies and the maximum and minimum flow values of the production flow are comparable with the maximum and minimum flow values of the distribution flow (Bakker et al. 2003).

A model predictive flow control algorithm (see Figure 2) consists of a short-term water demand prediction algorithm and a control algorithm. For production flow control, the prediction horizon is typically 24–48 h (Bakker et al. 2003). An extensive review of concepts, methods and organizing principles of water demand prediction is presented by House-Peters & Chang (2011). The control algorithm calculates production flow set-points matching the predicted demand, under the condition that the level in the reservoir stays between a chosen upper and lower limit. The control algorithm can be configured to optimize various optimization goals, such as minimal changes in production flow, minimal energy use, minimal energy costs or a combination of them. In most cases, mathematical optimization techniques are applied in the control algorithm in order to find an optimum. However, if the optimization goal is formulated strictly (e.g., constant production flow), the optimum can be calculated directly by a deterministic model (Bakker et al. 2003). Like level-based flow control, the set-point can be either discrete switching commands for wells, filters or pumps, or a continuous value. In general, predictive flow control results in a constant production flow, where the reservoir is used to balance the fluctuations in the outgoing distribution flow (see Figure 2).

**Application of predictive flow control in the Netherlands**

In this research all 10 Dutch drinking water utilities were interviewed to determine the penetration of predictive flow

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**Figure 1** | Principles of level-based flow control and trends of production flow, distribution flow and level in the clear water reservoir on a day with level-based flow control.
control in the Netherlands. The result of the interviews is that, at present, 57% of the total production flow is controlled by predictive flow control. The production flow of the other 43% of the systems is controlled by level-based flow control (see Table 1).

### Objectives for predictive flow control

There are two main reasons to apply predictive flow control rather than level-based flow control. The first reason is that drinking water treatment plants perform better at a constant production flow rate. Keuning et al. (1998) reported 20% lower values for turbidity and total hardness at a drinking water treatment plant, after the production flow control was changed from level-based control to predictive control. In studies by Gauthier et al. (2001) and Vreeburg et al. (2004, 2008), it was observed that the major part of the particle load in drinking water occurs as a result of peak flow and start-up procedures at the treatment plant. The occurrence of particles in the distribution network leads to discolouration events, which in England and Wales account for 80% of all customer complaints about drinking water quality (Husband & Boxall 2014). Particles in drinking water are therefore a dominant factor in customer satisfaction regarding water supply.

The second reason to apply predictive flow control is the reduction of energy consumption and energy costs. Since the late 1980s, the near optimal control of water supply systems (pump scheduling of distribution pumps) to reduce energy consumption and costs, has been a topic studied by many researchers. Ormsbee & Lansey (1994) and Brdys & Ulanicki (1994) give good overviews of developed algorithms until 1994 and report several successful implementations in Europe and Israel. More recent publications present newly developed optimization algorithms with new mathematical optimizing techniques (e.g., Jamieson et al. (2007); Martínez et al. (2007); Rao et al. (2007); Salomons et al. (2007); Ulanicki et al. (2007); Shamir & Salomons (2008); Cembrano et al. (2011); Savić et al. (2011)).

The dominant reason for most utilities in the Netherlands to implement predictive control, was the wish for a more constant operation of water treatment plants in order to get lower

### Table 1

<table>
<thead>
<tr>
<th>Utility</th>
<th>Total production (million m$^3$ in 2009)</th>
<th>MPC controlled production (million m$^3$ per year)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brabant</td>
<td>167</td>
<td>27</td>
<td>16</td>
</tr>
<tr>
<td>Water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dunea</td>
<td>69</td>
<td>69</td>
<td>100</td>
</tr>
<tr>
<td>Evides</td>
<td>176</td>
<td>176</td>
<td>100</td>
</tr>
<tr>
<td>Oasen</td>
<td>46</td>
<td>43</td>
<td>93</td>
</tr>
<tr>
<td>PWN</td>
<td>100</td>
<td>95</td>
<td>95</td>
</tr>
<tr>
<td>Vitens</td>
<td>329</td>
<td>68</td>
<td>21</td>
</tr>
<tr>
<td>Waternet</td>
<td>65</td>
<td>65</td>
<td>100</td>
</tr>
<tr>
<td>WBG</td>
<td>42</td>
<td>20</td>
<td>48</td>
</tr>
<tr>
<td>WMD</td>
<td>28</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>WML</td>
<td>72</td>
<td>62</td>
<td>86</td>
</tr>
<tr>
<td>Total</td>
<td>1,094</td>
<td>625</td>
<td>57</td>
</tr>
</tbody>
</table>

Figure 2 | Principles of model predictive flow control and trends of production flow, distribution flow and level in the clear water reservoir on a day with model predictive flow control.
turbidity values. The implemented predictive control algorithms in the Netherlands therefore focus mainly on constant production flow set-points. Energy savings and energy cost savings are an important, though less dominant, second reason for the implementation of predictive control. Although predictive flow control is widely applied in the Netherlands, the effectiveness of this method of control has never been studied in detail. This paper describes the results of research that was carried out to quantify the differences between level-based flow control and predictive flow control at five full-scale water supply systems in the Netherlands. This research considers both water quality aspects, as well as energy consumption and costs.

MATERIALS AND METHODS

Experiments at five full-scale water supply systems

Five full-scale water supply systems were examined in the first half of 2011. Under normal operating circumstances, the selected systems are controlled with the predictive flow software OPIR (Bakker et al. 2005). In the experiments the predictive flow control was switched off for 1 week, during which the systems were controlled with level-based flow control loops. The OPIR algorithm optimizes constant production set-points, and controls both the production flow of the treatment plants, as well as the intake and distribution flows of the service reservoirs of the water supply system. The characteristics and the configurations of the systems are shown in Figure 3.

The research comprised examining the behaviour of the systems, during:
1. one week with predictive flow control;
2. one week with level-based flow control.

Water quality and production flow variation

The following water quality parameters were measured (sensors in the clear water main at the treatment plants):
- Turbidity (all systems), measured by Hach Lange 1720 turbidimeter/Endress + Hauser CUR22 turbidimeter.

![Figure 3](https://iwaponline.com/aqua/article-pdf/62/1/4/400420/1.pdf)
Particles (systems #1 and #4), measured by Pamas Waterviewer system.

At all five systems, turbidity measuring devices were installed. The turbidity rate gives a good indication of the load of suspended solids in the water (Low Hui Xiang et al. 2011). At systems #1 and #4, particle measuring devices were installed. Measurements of particle numbers and sizes provide insight into the particle load of the clear water. The measured numbers and sizes of the particles are transformed in a ‘particle volume concentration’ in the units parts per billion (10^{-9} m^3/m^3) as described by Vreeburg et al. (2008).

To assess the variability of the production flow, the production variation per day (PVd) is defined as the sum of the (absolute values of) the difference between subsequent hourly average production flow values (P_{d,h}) divided by the total daily production:

\[ PV_d = \frac{\sum_{h=1}^{24} |P_{d,h} - P_{d,h-1}|}{\sum_{h=1}^{24} P_{d,h}} \cdot 100\% \]

A value of 10\% indicates that, on average, the production flow changes on each hour with 10\% of the average production flow of that day (d).

**Energy consumption and costs**

The specific energy consumption (kWh/m^3) as well as the percentage of the energy consumption during high tariff hours was analysed. 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 at the weekends. At all the researched systems, one continuously measuring electricity meter was available at each water treatment plant and each service reservoir. Using measurements of flow, pressure and reservoir level, the measured energy consumption was divided into three main components: (1) abstraction/treatment, (2) transportation/distribution (clear water pumped in a transport main or towards a high reservoir) and (3) direct boosting (clear water pumped to customers in an area without a high reservoir):

\[ E_{abst} = \frac{1}{\eta_{abst}} \cdot F_{abst} \cdot \frac{dH_{stat,abst} + C_{dyn,abst} \cdot F_{abst}^2}{g} + E_{base} \ [kW] \]

\[ E_{pump} = \frac{1}{\eta_{pump}} \cdot F_{pump} \cdot \left( \frac{P_{pump} - L_{res}}{g} \right) \ [kW] \]

\[ E_{boost} = \frac{1}{\eta_{boost}} \cdot F_{boost} \cdot \left( \frac{P_{boost} - L_{res}}{g} \right) \ [kW] \]

\[ E_{abst}, E_{pump} \text{ and } E_{boost} \text{ are the calculated values of the energy consumption (kW) for abstraction/treatment, transportation/distribution and direct boosting, respectively. The flows } (F_{abst}, F_{pump}, F_{boost} [\text{m}^3/\text{h}]), \text{ pressures } (P_{pump}, P_{boost} [\text{kPa}]) \text{ and the reservoir level } (L_{res} [\text{m}]) \text{ are measured at the treatment plants and service reservoirs. The values for efficiency } (\eta_{abst}, \eta_{pump}, \eta_{boost} [-]), \text{ the static and dynamic head loss parameters } (dH_{stat,abst} [\text{m}] \text{ and } C_{dyn,abst} [\text{m}/(\text{m}^3/\text{h})^2]) \text{ respectively), \text{ and the constant base energy consumption } (E_{base} [\text{kW}]) \text{ were estimated. The values were estimated in a way that that the calculated energy consumption best fitted the measured energy consumption. By doing this, the total measured energy consumption was assigned to the individual 'components' of energy consumption, making it possible to evaluate the effect of the control on these components. Figure 4 gives an example of a trend with both the measured energy consumption and the calculated energy consumption. The figure shows that measured and calculated values resemble each other well } (R^2 = 0.92), \text{ which indicates that the parameters were chosen well.} \]

Figure 5 shows how the total energy consumption of each of the five examined water supply systems is divided over the components.

Energy costs were calculated by multiplying the calculated energy consumption with the average energy costs per kWh. The tariffs are 0.08229 €/kWh during high tariff hours, and 0.04849 €/kWh during low tariff hours.

**RESULTS**

**Comparison**

The differences between level-based control and predictive control were quantified by comparing average values of...
the measured parameters of both researched periods. The results for all water supply systems are summarized in Table 2. Examples of the differences at system #4 are shown in Figures 1 and 2, and for the other systems in Figure 6. The graphs show that predictive flow leads to a lower variation in the production flow and a higher production flow rate at night (during low energy tariff) compared to level-based control. The observed differences in flow patterns and the use of reservoirs during level-based control and predictive control were distinct and comparable for each of the five water supply systems.

**Water quality**

Table 2 shows that the production variation with predictive control (1.2–7.6%) was lower than with level-based control (11.7–37.7%). This resulted in lower turbidity values of on average 17% at all five systems. Figure 7 shows the relation between production flow changes and turbidity at all locations. At all systems a relation was found between flow changes and turbidity, though the correlation was weak ($R^2$ values between 0.25 and 0.6). Especially at systems #1, #2 and #5 lower turbidity rates are valuable, because those systems have rather high turbidity rates.

The experiments at the systems with particle counters installed (systems #1 and #4), showed that, on average, the values of particle volumes were 12–42% lower with predictive control compared to level-based control. This indicates that less variations in the production flow also results in lower particle volumes. The graphs of systems #1 and #4 in Figure 7 show a strong response of particle volume to production flow variations (high increase of particle volume after flow increase). However, the correlation of average values per day between production flow variation and particle volume is weak ($R^2$ values 0.13 and 0.37).

**Energy consumption**

Table 2 shows that the average specific energy consumption is 1.0–5.5% lower for predictive control compared to
Table 2 | Differences between level-based control and predictive control

<table>
<thead>
<tr>
<th>System #1</th>
<th>Level-based control</th>
<th>Predictive control</th>
<th>Difference %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production variation [%]</td>
<td>11.7%</td>
<td>4.1%</td>
<td>-65</td>
</tr>
<tr>
<td>Min/max production flow [m³/h]</td>
<td>0/840</td>
<td>408/808</td>
<td>-52</td>
</tr>
<tr>
<td>Turbidity [NTU]</td>
<td>0.398</td>
<td>0.345</td>
<td>-13</td>
</tr>
<tr>
<td>Particle load [ppb]</td>
<td>30.8</td>
<td>17.9</td>
<td>-42</td>
</tr>
<tr>
<td>Specific energy consumption [kWh/m³]</td>
<td>0.340</td>
<td>0.336</td>
<td>-1.0</td>
</tr>
<tr>
<td>Energy use at high tariff [%]</td>
<td>51.7%</td>
<td>51.0%</td>
<td>-1.4</td>
</tr>
<tr>
<td>Energy costs [€ per 1,000 m³]</td>
<td>€ 22.47</td>
<td>€ 22.09</td>
<td>-1.7</td>
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<table>
<thead>
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<th>Level-based control</th>
<th>Predictive control</th>
<th>Difference %</th>
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<td>Production variation [%]</td>
<td>14.2%</td>
<td>2.9%</td>
<td>-80</td>
</tr>
<tr>
<td>Min/max production flow [m³/h]</td>
<td>186/921</td>
<td>356/681</td>
<td>-56</td>
</tr>
<tr>
<td>Turbidity [NTU]</td>
<td>0.809</td>
<td>0.654</td>
<td>-19</td>
</tr>
<tr>
<td>Specific energy consumption [kWh/m³]</td>
<td>0.733</td>
<td>0.694</td>
<td>-5.3</td>
</tr>
<tr>
<td>Energy use at high tariff [%]</td>
<td>55.5%</td>
<td>51.2%</td>
<td>-7.7</td>
</tr>
<tr>
<td>Energy costs [€ per 1,000 m³]</td>
<td>€ 49.30</td>
<td>€ 45.65</td>
<td>-7.4</td>
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<table>
<thead>
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<th>Level-based control</th>
<th>Predictive control</th>
<th>Difference %</th>
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<tbody>
<tr>
<td>Production variation [%]</td>
<td>12.5%</td>
<td>1.2%</td>
<td>-90</td>
</tr>
<tr>
<td>Min/max production flow [m³/h]</td>
<td>250/1,260</td>
<td>430/933</td>
<td>-50</td>
</tr>
<tr>
<td>Turbidity [NTU]</td>
<td>0.078</td>
<td>0.056</td>
<td>-28</td>
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<td>Specific energy consumption [kWh/m³]</td>
<td>0.605</td>
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<tr>
<td>Energy use at high tariff [%]</td>
<td>51.0%</td>
<td>48.6%</td>
<td>-4.8</td>
</tr>
<tr>
<td>Energy costs [€ per 1,000 m³]</td>
<td>€ 39.77</td>
<td>€ 38.10</td>
<td>-4.2</td>
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<thead>
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<td>Production variation [%]</td>
<td>11.7%</td>
<td>2.8%</td>
<td>-76</td>
</tr>
<tr>
<td>Min/max production flow [m³/h]</td>
<td>208/1,729</td>
<td>755/1,560</td>
<td>-47</td>
</tr>
<tr>
<td>Turbidity [NTU]</td>
<td>0.044</td>
<td>0.039</td>
<td>-12</td>
</tr>
<tr>
<td>Particle load [ppb]</td>
<td>5.4</td>
<td>4.78</td>
<td>-12</td>
</tr>
<tr>
<td>Specific energy consumption [kWh/m³]</td>
<td>0.329</td>
<td>0.324</td>
<td>-1.4</td>
</tr>
<tr>
<td>Energy use at high tariff [%]</td>
<td>58.3%</td>
<td>54.5%</td>
<td>-6.5</td>
</tr>
<tr>
<td>Energy costs [€ per 1,000 m³]</td>
<td>€ 22.38</td>
<td>€ 21.67</td>
<td>-3.2</td>
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<table>
<thead>
<tr>
<th>System #5</th>
<th>Level-based control</th>
<th>Predictive control</th>
<th>Difference %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production variation [%]</td>
<td>37.7%</td>
<td>7.6%</td>
<td>-80</td>
</tr>
<tr>
<td>Min/max production flow [m³/h]</td>
<td>0/473</td>
<td>53/264</td>
<td>-55</td>
</tr>
<tr>
<td>Turbidity [NTU]</td>
<td>0.313</td>
<td>0.273</td>
<td>-13</td>
</tr>
<tr>
<td>Specific energy consumption [kWh/m³]</td>
<td>0.399</td>
<td>0.389</td>
<td>-2.5</td>
</tr>
<tr>
<td>Energy use at high tariff [%]</td>
<td>57.3%</td>
<td>48.2%</td>
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<tr>
<td>Energy costs [€ per 1,000 m³]</td>
<td>€ 27.19</td>
<td>€ 25.29</td>
<td>-7.0</td>
</tr>
</tbody>
</table>
level-based control. This is the result of the fact that with level-based control the difference between minimum and maximum production flows is larger (see Table 2). The specific energy consumption (kWh/m³) at high flows is relatively higher, because of the dynamic head loss components in the abstraction and treatment process, as well as in the transportation and distribution process. As a result, the average specific energy consumption is higher at varying flow rates. The hydraulic head loss occurs predominantly if the water is pumped over longer distances between abstraction and treatment plant, or for transportation. The distances in the examined water supply systems are indicated in Figure 3. Figure 8 shows the differences in specific energy consumption for the discerned components of energy consumption.

A second aspect is a shift of energy consumption from high tariff to low tariff hours at predictive control.
Figure 7  | Relation between production flow variations and turbidity/particle volume in clear water, at systems controlled with predictive control. The graphs on the left show the turbidity and the flow variations in time. The graphs on the right show the relation between average daily values of flow variations and average daily values of turbidity (middle graphs) or particle volume (right graphs).
compared to level-based control (shift varying from 1.4 to 15.9%). This is caused by the fact that with level-based control the reservoirs are filled with too high flow rates during the evening and night. As a result, the reservoir level becomes high early in the night, and the level-based control decreases the production flow. As a consequence, less water is produced or transported and therefore less energy is consumed during the period with low energy tariff (see also Figures 1 and 6). Figure 9 shows the shift in energy consumption for the different components of energy consumption for all five examined systems. The figure shows that the shift occurs especially in the Transportation and Distribution component, and to a lesser extent in Abstraction and Treatment. No shift is observed in the Direct Boosting component, which is the consequence of the fact that this component is pressure controlled and not influenced by the researched flow control.

The combination of the lower specific energy consumption and the shift from high tariff to low tariff results in lower energy costs of 1.7–7.4% for predictive control compared to level-based control. The results show a relatively large variation between the five examined water supply systems. This variation was caused by the fact that the five systems have quite different configurations, as can be seen in Figure 3. As observed in Figure 5, there are also large differences in the way the total energy consumption is divided over the components. The presented differences in

![Figure 8](https://iwaponline.com/aqua/article-pdf/62/1/1/400420/1.pdf)

**Figure 8** | Specific energy consumption per component of energy consumption for each system.

![Figure 9](https://iwaponline.com/aqua/article-pdf/62/1/1/400420/1.pdf)

**Figure 9** | Percentage of energy consumption during high tariff per component of energy consumption for each system.
Table 2 are related to the energy consumption of all three components, including the energy consumed for (pressure controlled) direct boosting. Direct boosting is not influenced by the control, and therefore the numbers in Table 2 (of specific energy consumption, energy use during high tariff and energy costs) are not fully representative for the real difference between the control of the systems. Table 3 shows for each of the water supply systems which part of the energy consumption is influenced by the method of control, and how the differences in energy costs are related to the influenced energy consumption. The table shows that the observed differences between predictive control and level-based control are relatively larger when the differences are related to the influenced energy consumption.

### DISCUSSION

#### Relation production variation–turbidity

In comparison to the period with level-based control, in the period with predictive control at all five systems lower turbidity values (and particle volumes) and lower production variation values were observed. However, the relation between production variation and turbidity is weak (see Figure 7, $R^2$ values between 0.25 and 0.6). This indicates that the production variation is not the only factor which influences the turbidity. Other disturbances in the treatment process (like filter backwashing, Vreeburg et al. (2004), Bakker et al. (1998)) might also be responsible for variations in the turbidity. However, backwashing and other disturbing events were not monitored in this study.

#### Limited energy savings

The observed energy cost savings in this study (5.2% on average) were smaller than reported energy cost savings in other studies, such as Bunn & Reynolds (2009): 12% measured savings; or Martínez et al. (2007): 17% simulated savings. This difference can be explained by a number of reasons. The effectiveness of changing the control of a water supply system depends on three main factors: (1) the effectiveness of the optimal control in relation to the existing control; (2) flexibility in the system to change the control; (3) influence of control on operational costs. In the first factor the existing control particularly plays a dominant role: if the existing control is rather bad, then the potential savings can be quite large. However, if the existing control is already rather good, the potential savings are limited.

The second factor relates to the flexibility of the system. If there are large buffers in the network and pump and treatment capacity largely exceeds the average demands, a large range of operational control strategies is possible without violating the boundary conditions. Among the very different control strategies, the most efficient can be selected by the optimal control algorithm. In systems with less flexibility, the range of possible control strategies is smaller, and therefore the potential savings are smaller.

The third aspect relates to how much the energy consumption and costs are influenced by the control. If pump efficiencies or pump heads change dramatically depending on the control of the system, or if there are large differences in energy tariffs, potential savings can be very high. In systems where the control hardly influences energy consumption, Limited energy savings

<table>
<thead>
<tr>
<th>Energy consumption influenced by control (%)</th>
<th>Difference in energy costs between predictive control compared to level-based control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Related to total energy consumption (%)</td>
<td>Related to influenced energy consumption (%)</td>
</tr>
<tr>
<td>System #1</td>
<td>26.3</td>
</tr>
<tr>
<td>System #2</td>
<td>80.4</td>
</tr>
<tr>
<td>System #3</td>
<td>98.0</td>
</tr>
<tr>
<td>System #4</td>
<td>57.9</td>
</tr>
<tr>
<td>System #5</td>
<td>100.0</td>
</tr>
</tbody>
</table>
consumption and where tariff differences are small, the
potential savings are much smaller.

In this study, there was quite a large difference between
the examined controls (factor 1). However, in the investi-
gated predictive control algorithm, a constant production
flow was the main goal, and not the energy and cost
reduction. This limited the energy and cost savings of the
investigated predictive control systems. The flexibility of
the systems was limited due to relatively small buffers in
the system (factor 2), which also limited the energy savings.
The dominant factor that the energy savings in this study
were limited, is that the control did not influence the
energy to a large extent (factor 3). This is quite different
from other studies, where the water supply systems have
large high reservoirs (which can be filled during low
energy tariff) and where pump efficiencies are highly influ-
enced by the control strategy. Bunn & Reynolds (2009)
show examples where the pump efficiencies vary up to 20%.

Other aspects

The experiments were carried out in a relatively short time
and a limited number of parameters was studied. Therefore
this study describes not all differences between the level-
based control and the predictive control of a water supply
system. Some differences can only be measured over a
longer period of time. Two factors which were not high-
lighted in this study are wear of pumps and valves, and the
occurrence of process alarms and alerts. Both of these are
reported by Keuning et al. (1998), who studied the effects
of the implementation of predictive control at one location
in less detail, but over a longer period of time. Keuning
reported that predictive control resulted in less wear,
because of less variation in the operation, and therefore
less starts and stops of pumps occurred. The value of the
production variation in Table 2 is a measure for the
number of starts/stops of pumps. As can be observed in
the table, the values for level-based control were some
three to eight times higher than for predictive control. Keun-
ing also reported that failures and alarms occurred less
frequently when using predictive control, because processes
switched on and off less often. At each switch there is a
small risk of a failure in the installation, resulting in a
process alert or alarm.

Another factor is the ease of operation. The process
operators of system #1 and system #3 stated that the most
valuable aspect for predictive control for them was the
ease of operation. With level-based control, the operation
demanded much more attention, especially during high
demand periods. The predictive control was better able to
cope with changing demand situations and to adjust the con-
trol accordingly.

CONCLUSIONS

Experiments at five full-scale water supply systems prove
that predictive control will lead to a better water quality
and a more energy-efficient water supply compared to
level-based control:

- The production variation was three to eight times lower.
- Turbidity values were 12–28% lower.
- Particle volume values were 12–42% lower.
- The overall energy consumption was 1.0–5.3% lower.
- The overall energy costs were 1.7–7.4% lower.

The quality improvements were the result of the fact
that the variations in the production flow were on average
some three to eight times lower for predictive control com-
pared to level-based control. Variations in production flow
resulted in peaks in the turbidity values of the clear water.
The observed higher energy efficiency was the result of
more constant production flows which lead to a lower aver-
age energy consumption. Moreover, relatively less energy
was consumed during high tariff, resulting in a lower
energy bill. Both quality improvements and higher energy
efficiency make predictive control a valuable asset for
water supply companies.

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