Evaluation of control strategies for drinking water treatment plants using a process model

G. I. M. Worm, J. J. G. Wuister, K. M. van Schagen and L. C. Rietveld

ABSTRACT

This research adds a method to evaluate control strategies to the design methodology for drinking water treatment plants. A process model dealing with parameters related to the calcium carbon dioxide equilibrium was set up. Using the process model, the existing control strategy was compared with a new control strategy and the effects of two different sets of input data were studied. It was demonstrated that the efficiency of the pellet softening process and the plant's capacity were increased, and that chemicals and energy usage were reduced. At the same time, the deviation of the total hardness of the produced water to the desired value was decreased.

Key words | control, control-design methodology, control strategy evaluation, drinking water treatment, process model

G. I. M. Worm (corresponding author)
PWN, PO Box 2113, 1990 AC Velserbroek,
The Netherlands
E-mail: *ignaz.worm@pwn.nl*

G. I. M. Worm
L. C. Rietveld
Faculty of Civil Engineering and Geosciences,
Department of Water Management,
Delft University of Technology,
PO Box 5048, 2600 GA, Delft,
The Netherlands

J. J. G. Wuister
K. M. van Schagen
Royal HaskoningDHV, PO Box 1132, 3800 BC,
Amersfoort,
The Netherlands

INTRODUCTION

In the Netherlands, the operation of drinking water treatment plants has changed over the last 7 years. Permanent 24/7 watches have been abandoned and were replaced by a centralized and fully automated operation. The level of automation in water supply companies has increased from human control up to the level of remote multi-task supervisory control (Sheridan 2002). Although the operation supervisor is still responsible for the drinking water treatment and distribution, process automation software plays an increasing important role. As a consequence, more attention should be (and is) paid to the design and testing of new process automation software.

For control-design of a single step of a drinking water treatment plant a methodology has been set up (Van Schagen *et al.* 2010). The methodology takes the specific properties of a drinking water treatment plant into account compared to a classical chemical plant, like the direct dependency of the customers' consumption and the production setpoint, the impossibility to discharge off-spec material and laboratory measurements of water quality which have a delay of several days to weeks. Often, multiple control strategies will be able to meet the objectives within the operational constraints. The methodology by Van Schagen, however, lacks a way to determine the optimal control strategy. The definition of optimal depends on the company, plant and treatment plant's objectives and constraints. The hypothesis in this study is that a process model is a valuable tool to evaluate alternative control strategy designs with predetermined criteria and to determine their ability to meet operational objectives and constraints dynamically in the same way as has been reported for waste water treatment plants (Vrecko *et al.* 2006; Stare *et al.* 2007).

This approach has been applied full-scale to the drinking water treatment plant Wim Mensink of PWN. To have a more efficient operation, in terms of chemical use, energy and production capacity, a new, more flexible control strategy for the pellet softening was designed with the control-design methodology for drinking water treatment processes. In this research the evaluation of the current and a new control strategy is described, using the process model Stimela (Van der Helm & Rietveld 2002). An objective and realistic evaluation of a control-design and its expected effects on the produced drinking water is of interest for operation supervisors, control engineers, process engineers and managers.

doi: 10.2166/aqua.2013.031

MATERIAL AND METHODS

Wim Mensink

The Wim Mensink plant (production capacity 7,200 m^3/h) forms an integrated system with the conventional drinking water treatment plant Bergen and the ultrafiltration/reverse osmosis (RO) plant Heemskerk, see Figure 1. For reasons of process stability, the RO plant produces a fixed flow of 2,100 m^3/h. At Bergen (production capacity 4,200 m^3/h), conventionally treated water is softened by mixing with RO water in a fixed ratio. The water treated at Wim Mensink is softened by mixing with RO water and by applying pellet softening. Because of the fixed production of RO water at Heemskerk and varying flow needed in Bergen, a varying flow of RO water is available for Wim Mensink. Since RO water was supplied to Wim Mensink in a fixed ratio of the produced water as well, sometimes not all of the produced RO water can be supplied to the plants Bergen and Wim Mensink. In that case, this surplus of RO water is discharged to the dune area which is the source for the plants Bergen and Wim Mensink. In 2007 and 2008, as a consequence, approximately 10% of the produced RO water (1.7 Mm^3/year in 2007 and 2008) was discharged.

The Wim Mensink drinking water treatment plant has two lanes. Since the pellet softening is exclusively part of Lane 1, Lane 2 is a by-pass for the pellet softening treatment step. In the current control strategy Lane 1 treats a fixed ratio of two-thirds of the raw water and Lane 2 treats one-third. Within Lane 1 a second by-pass is available, see Figure 2. If the raw water supply to Lane 1 exceeds the water extracted by the softening reactors, the remaining untreated water flows through this by-pass to the cascades directly. If less water is supplied to Lane 1 than extracted by the reactors, water flows from the cascades to the reactors, so in the reverse direction, causing recirculation.

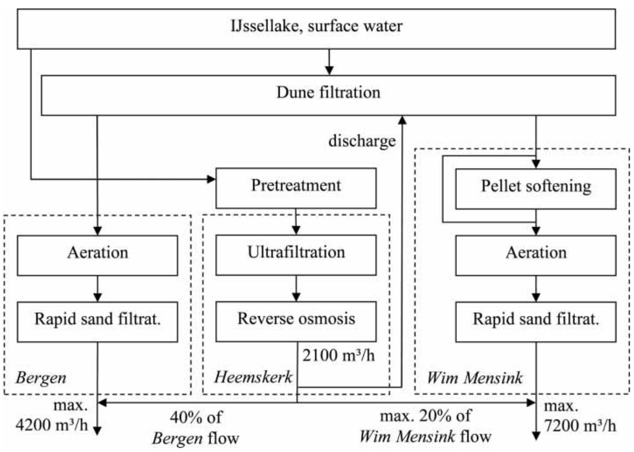

Figure 1 | The Bergen, Wim Mensink, Heemskerk drinking water treatment system.

Control strategies

The control-design methodology for drinking water treatment processes consists of five steps: (i) determine plant-wide control objectives; (ii) determine operational constraints; (iii) identify important disturbances; (iv) determine controlled variables; and (v) determine the control configuration.

Table 1 shows the control objectives (step 1) using the six controlled variables (step 4) of the Wim Mensink case. The most relevant operational constraints (step 2) are listed in Table 2. The most relevant disturbances (step 3) have been derived from historic data in 2007 and 2008 and are listed in Table 3. In the control configuration (step

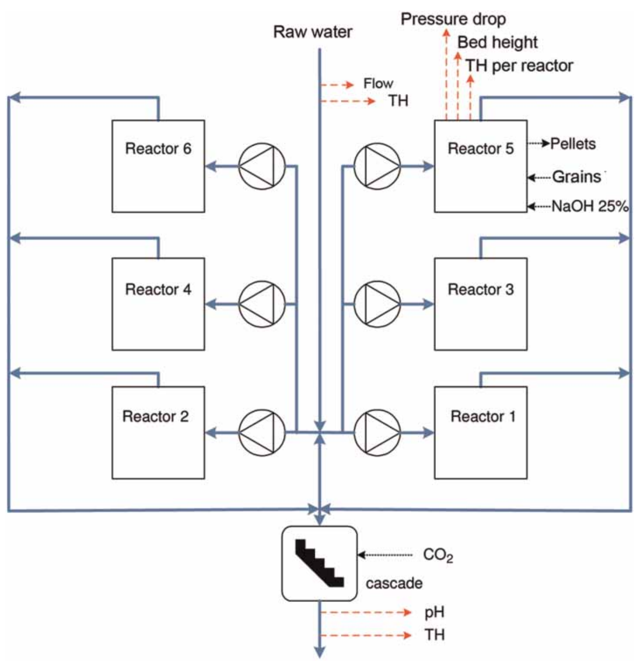

Figure 2 | Detail of the layout of the pellet softening treatment step. 'TH' (total hardness), 'Pressure drop', 'Bed height', 'TH per reactor', and 'pH' refer to online measurements; 'Pellets', 'Grains', 'NaOH 25%', and 'CO_2' are control actions.

Table 1 | Controlled variables and control objectives for the Wim Mensink case

Controlled variable	Objective	Level
Discharge of RO water	Minimal	Company
$TH_{clear\ water\ reservoir}$	Average 1.5 mmol/L, between 1.4 and 1.6 mmol/L in 95% of time	Plant
$SI_{clear\ water\ reservoir}$	Between –0.1 and 0.3	Plant
CO_2 dosage	Minimal	Treatment step
NaOH dosage	Minimal	Treatment step
Number of switching of reactors	Minimal	Treatment step

SI: saturation index.

Table 2 | Operational constraints for the Wim Mensink case

Parameter	Constraint	Level
Available RO water flow for Wim Mensink	Between 0 and 1,300 m^3/h	Company
Production flow	As calculated by daily-demand-prediction software Plenty® Control	Plant
Flow per lane	Maximum 3,600 m^3/h	Plant
$SI_{effluent\ cascade\ Lane\ 1}$	Between –0.1 and 0.3, to prevent crystallization in the sand filters	Plant
Flow through pellet softening reactors	$n \times 500\ m^3/h$, with $n =$ number of active reactors	Treatment step
Recirculation within Lane 1	Prevented	Treatment step
Minimal NaOH dosage	50 L/h to prevent dripping nozzles	Reactor

5), not more than three control actions are available which can be used to realize the objectives: (i) the RO flow; (ii) the number of active reactors; and (iii) the positions of the valves at the Lanes' inlets, see Figure 3.

Current control strategy

In the current control strategy (CS0) the number of active reactors depends on the flow over Lane 1, see Table 4.

Table 3 | Relevant disturbances from historic data (2007 and 2008)

Disturbance	Range	Level
Daily decrease or increase of RO water flow	0–300 m^3/h	Company
Daily decrease or increase of production flow	0–900 m^3/h	Plant
Variation in $pH_{raw\ water}$	7.5–8.1	Plant
Variation in $TH_{raw\ water}$	2.2–2.7 mmol/L	Plant

The NaOH 25% (caustic soda) dosage is calculated with:

$$Q_{NaOH25\%} = Q_{Lane1} \cdot ((TH_{raw} - TH_{setp\,Lane1}) + (TH_{casc} - TH_{setp\,Lane1})) \cdot \alpha$$

where $Q_{NaOH25\%}$ is the total caustic soda 25% flow (m^3/h), Q_{Lane1} is the flow over Lane 1 (m^3/h), TH_{raw} is the TH of the raw water (mol/m^3), $TH_{setp\ Lane1}$ is the setpoint for TH in the cascades of Lane 1 (mol/m^3), and TH_{casc} is the TH in the cascades of Lane 1 (mol/m^3). $TH_{setp\ Lane1}$ is calculated from the desired TH in the drinking water reservoirs, the flow and TH of the RO water, the flow over Lane 1 and Lane 2 and TH_{raw}, using a mass balance. Constant α (m^3/mol) is calculated with:

$$\alpha = \frac{MW_{NaOH} \cdot \beta_{dilution}}{\rho_{NaOH\,diluted}}$$

with the molecular weight of caustic soda MW_{NaOH} being 0.040 kg/mol, dilution factor $\beta_{dilution}$ is 4 and the density of the diluted caustic soda $\rho_{NaOH\ diluted}$ is 1,279 kg/m^3, α is $0{,}125 \times 10^{-3}\ m^3/mol$. The pellet discharge is based on the pressure difference over the fluidized bed: when the pressure difference is exceeded the three discharge valves in the bottom of the reactor open one by one during a fixed period. A fixed amount of grains is dosed batch wise, when a predetermined weight of calcium, representing a number of pellets, has been removed. A fixed weight of grains is dosed, representing the same number as pellets discharged. CO_2 is dosed in the upper cascade in a fixed ratio with the NaOH flow (master control) and fine-tuned on the online measured pH in the cascade effluent (slave control) using one Siemens DR 24 and two Siemens DR21 hardware proportional-integral (PI)-controllers. The flow ratio over Lane 1 and Lane 2 is 2:1 to maximize the bypass and minimize recirculation. However, this ratio leads to

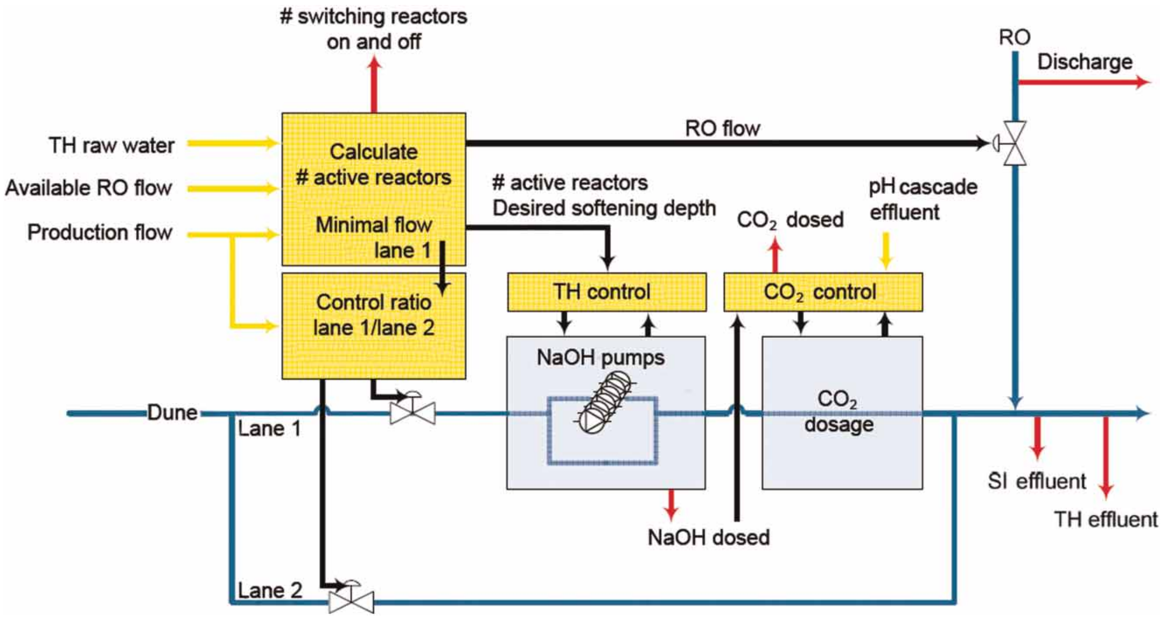

Figure 3 | Control configuration for the Wim Mensink case. 'Dune', 'Lane 1', 'Lane 2', and 'RO' refer to water flows; 'TH raw water', 'Available RO flow', 'Production flow', and 'pH cascade effluent' refer to online measured parameters; '# switching reactors on and off', 'discharge', 'CO_2 dosed', 'SI effluent', 'TH effluent', and 'NaOH' dosed are the controlled variables; the remaining arrows are the control actions.

Table 4 | Switching on and off reactors as a function of the flow over Lane 1

Reactor	Setpoint switching on reactor [m^3/h]	Setpoint switching off reactor [m^3/h]
1st	450	400
2nd	666	500
3rd	1,700	1,100
4th	2,000	1,750
5th	2,666	2,300
6th	3,100	2,500

unequal loads of the cascades and rapid sand filters. The value of the ratio is stored as a constant in the Manufacturing Execution System (MES) application Plenty Control. Control strategy CS0+ differs from CS0 in the control of the bed height (higher, thus in time yielding an increase of the crystallization surface) and discharge of pellets (smaller) to increase the available crystallization surface in the reactor.

New control strategy

Based on the objectives, operational constraints, possible disturbances and the controlled variables, a new control strategy (CS1) was set up, which calculates the lowest possible number of active reactors based on the maximum removal of TH per reactor. A minimal number of active reactors yields a maximum by-pass and maximum softening depth per reactor which leads to maximum efficiency in the crystallization kinetics and thus maximum saving of NaOH (Van Schagen *et al.* 2006). The total NaOH dosage is calculated from the desired removal of TH (master, P-controller) and fine tuned on the measured TH of the mixed water of Lane 1, Lane 2 and RO water (slave, PI-controller) using a Siemens S7 PLC. The total NaOH dosage is independent of the number of active reactors. The pellet discharge aims to discharge pellets of a constant size. To be able to do so, pellets are discharged when the pressure difference over the lowest half meter of the reactor exceeds a threshold. Grains are dosed based on the online measured bed height. The control of the CO_2 dosage is equal with the CO_2 dosage of CS0 and CS0+. Because flow through a treatment step is one of the most important parameters in terms of its effectiveness (Worm *et al.* 2009), equal flows over the cascades and rapid sand filters are preferred over the unequal division of flows in the current control strategy. Therefore, for CS1, the flow ratio over Lane 1 and Lane 2 will be equal as long as enough water is supplied to Lane 1 to prevent recirculation within Lane 1.

Stimela process model

Applying the 10 steps of good modeling practice (Rietveld *et al.* 2010), a Stimela process model was set up. The model calculates the water quality through a drinking water treatment plant dynamically and is used to calculate to what extent the control objectives are met. In this research, for each control strategy the control rules were grouped in a separate file. Linking points were added for setpoints (input) and measurements (output) (Van der Helm *et al.* 2009). The calibrated pels25_s_c module describes the fluidized bed behavior and the crystallization of a pellet softening reactor (Van Schagen *et al.* 2008a, b; HaskoningDHV 2011). To limit calculation time, a single pellet reactor was modelled. The effluent quality of this reactor was assumed to represent the quality of the other five reactors as well. Like pellet softening, aeration and mixing of different water qualities affect the Ca-CO_2 equilibrium. To model the water quality the aeration module cascad_s_c (HaskoningDHV 2011) was used.

Model runs

Table 5 shows the specifications of the model runs. Model run 1 was carried out to validate the model. In run 1, run 2 and run 3 the input data were equal, but the control strategy differed. Run 4 equals run 3, except for the fact that all available RO water was supplied to the treatment plant, so including the surplus that otherwise would have been discharged to the dunes. Thus, the adaptation of the model and the new control strategy CS1 to perturbations is determined. Since the desired production level did not change, in run 4 less raw water was taken in. The input parameters for the model are specified in Table 6.

Table 5 | Summary of model runs

Run	Control strategy	Input data	Initial state
1 (validation)	CS0 (actual control)	Historic	Bed height 3.2 m
2	CS0+ (actual control, higher bed)	Historic	Bed height 4 m
3	CS1 (new control)	Historic	Bed height 4 m
4	CS1 (new control)	Historic, but more RO water and less raw water	Bed height 4 m

Model calibration and validation

The validation of the model, run 1, was carried out with field data from the full scale plant. For validation, bed height measurements were taken weekly by lowering a disk in the reactor until it reaches the fluidized bed (accuracy ±0.05 m), covering a period of 50 days. In the same period, pellet size distributions were determined weekly by sieving samples that were taken each half meter over the height of the bed. The data were acquired in the period

Table 6 | Model input data for the Wim Mensink case

Parameter	Unit	Location	Measurement	Frequency
Flow	m^3/h	Raw water lane 1 and 2	Online	1/2 h
Flow	m^3/h	Supplied RO water	Online	1/2 h
Temperature	°C	Influent RO water	Laboratory	1/week
		Influent raw water	Laboratory	1/week
Conductivity	mS/m	Influent RO water	Laboratory	1/week
		Influent raw water	Laboratory	1/week
$[Ca^{2+}]$	mg/L	Influent RO water	Online	1/2 h
		Influent raw water	Laboratory	1/week
$[Mg^{2+}]$	mg/L	Influent RO water	Laboratory	1/week
		Influent raw water	Laboratory	1/week
$[HCO_3^-]$	mg/L	Influent RO water	Laboratory	1/week
		Influent raw water	Laboratory	1/week
pH	–	Influent RO water	Laboratory	1/week
		Influent raw water	Laboratory	1/week

January 20, 2009, until March 10, 2009. A stable initial state was made by running the model for 90 days prior to January 20, 2009, with historic input data. First the control of the fluidized bed of a single reactor was validated for the parameters listed in Table 7. Then the controls of the waterquality of Lane 1 and the complete treatment plant were validated for the parameters listed in Table 8.

For the calibration and validation results based on online measurements, the root mean square (RMS) error is calculated, with

$$\varepsilon(t) = y(t) - y_m(t)$$

where $y(t)$ is the measured value at time t and $y_m(t)$ is the model output at time t, and

$$\mathrm{RMS} = \sqrt{\frac{1}{n}\sum_{t=1}^{n}\varepsilon^2(t)} \quad (1)$$

Table 7 | Validation parameters for single reactor

Parameter	Unit	Location	Measurement	Frequency
Bed height	m	Reactor 4	Manual by lowering disc	1/week
Pellet diameter	mm	In each of seven layers in reactor 4	Manual by sieving samples	1/week
TH	mmol/L	Reactor 4	Online	1/h
NaOH dosage	l/h	Reactor 4	Online	1/2 h

Table 8 | Validation parameters for Lane 1 and clear water reservoir

Parameter	Unit	Location	Measurement	Frequency
SI	–	Effluent cascade aerator	Calculated by laboratory	1/week
		Clear water reservoir	Calculated by laboratory	1/week
TH	mmol/L	Effluent cascade aerator	Online	1/15 min
		Clear water reservoir	Online and calculated by laboratory	1/week, resp. 1/15 min

To calculate the normalized RMS error, the RMS error is divided by the historical data mean.

Evaluation criteria

The controlled variables and objectives (steps 1 and 4, shown in Table 1) and operational constraints (step 2, shown in Table 2) define an optimization problem with the optimal control strategy as a result. Three out of the six controlled have been selected as evaluation criteria: (i) the average TH in the clear water reservoir; (ii) the RO discharge; and (iii) the average total NaOH dosage. The desired TH in the clear water reservoir should be 1.5 mmol/L. The discharge of RO water into the dune area (m^3/h) should be minimal to save costs, chemicals and energy. The discharge was calculated by extracting the RO flows transported to Bergen and Wim Mensink from the production flow of Heemskerk. A minimal NaOH dosage (L/h) leads to reduction of costs and reduction of emission of greenhouse gases during production (being aware that NaOH is a by-product of the chlorine production) and transport. A fourth criterion is the NaOH efficiency (mmol × h/L^2) which is calculated by dividing the average amount of removed calcium through the average NaOH dosage.

Software availability

Stimela version 10.6 was used, running on the Matlab (version 7.9.0.529, R2009b) and Simulink (version 7.2, R2009b) platform. Stimela is owned by DHV water and Delft University of Technology. The latest version can be downloaded from www.stimela.com when logged in. The used data come from the production Aspentech IP21 database owned by PWN. The model was run on a HP/Compaq laptop, type 8510w (Intel core2 Duo CPU, 2.4GHz) with operating system Windows XP 2002, servicepack3.

RESULTS AND DISCUSSION

Model calibration and validation

Diffusion coefficient D_f is used to model the crystallization kinetics, more specific the transportation of supersaturated water to the pellet surface. The original value of D_f in the pellet softening model, 2.67×10^{-11} m²/s, was derived from data from the Weesperkarspel pilot plant (Van Schagen 2008a). To calibrate the TH of the effluent of reactor 4, D_f of the pellet softening model was increased to 9×10^{-10} m²/s. As a consequence, the normalized RMS error of the TH in reactor 4 decreased from 15.5 to 10.6%. Figure 4 shows the results of the validation of the modeled control of the fluidized bed, of the NaOH dosage, and of the validation of the removal of calcium in reactor 4. The difference between the measured specific diameters of the pellets and the modeled pellet diameters is caused by the fact that the samples are taken at the lowest part of each layer, while the model calculates a single value for each layer. The extreme peak in online measured data of the TH of reactor 4 between day 23 and 29 and on day 43 is explained by a failing measuring device (the data of the other active reactors showed the same extremes). The average number of pellet discharges in the full scale plant is five times per day, which approximates the average of six times per day of pellet discharges in the model.

Figure 5 shows the results of the validation of the modeled water quality in the effluent of the cascade of Lane 1. The SI was calculated by the laboratory from samples. The

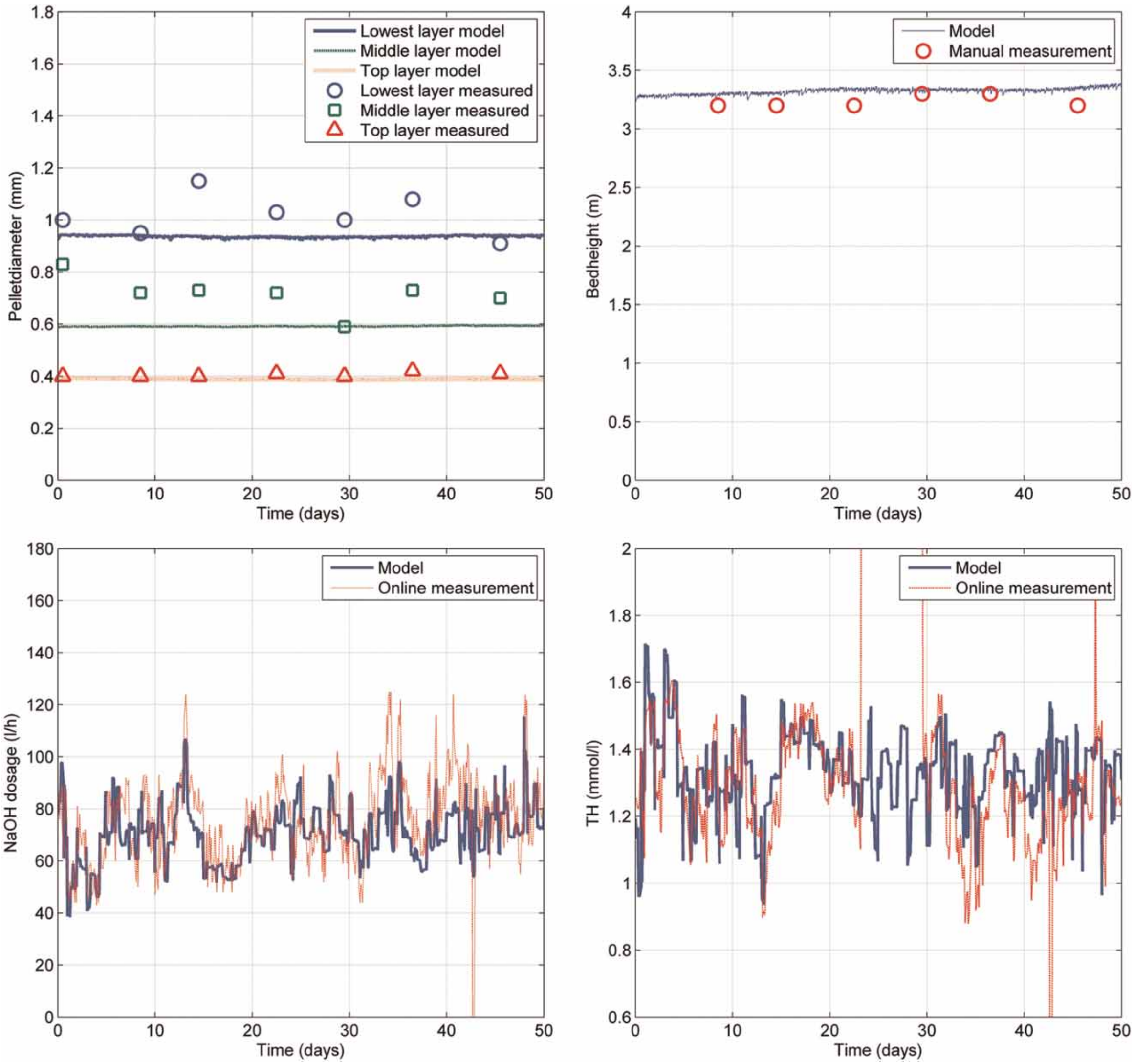

Figure 4 | Validation results for reactor 4. Pellet size distribution (top left), bed height (top right), NaOH dosage (bottom left) and TH (bottom right).

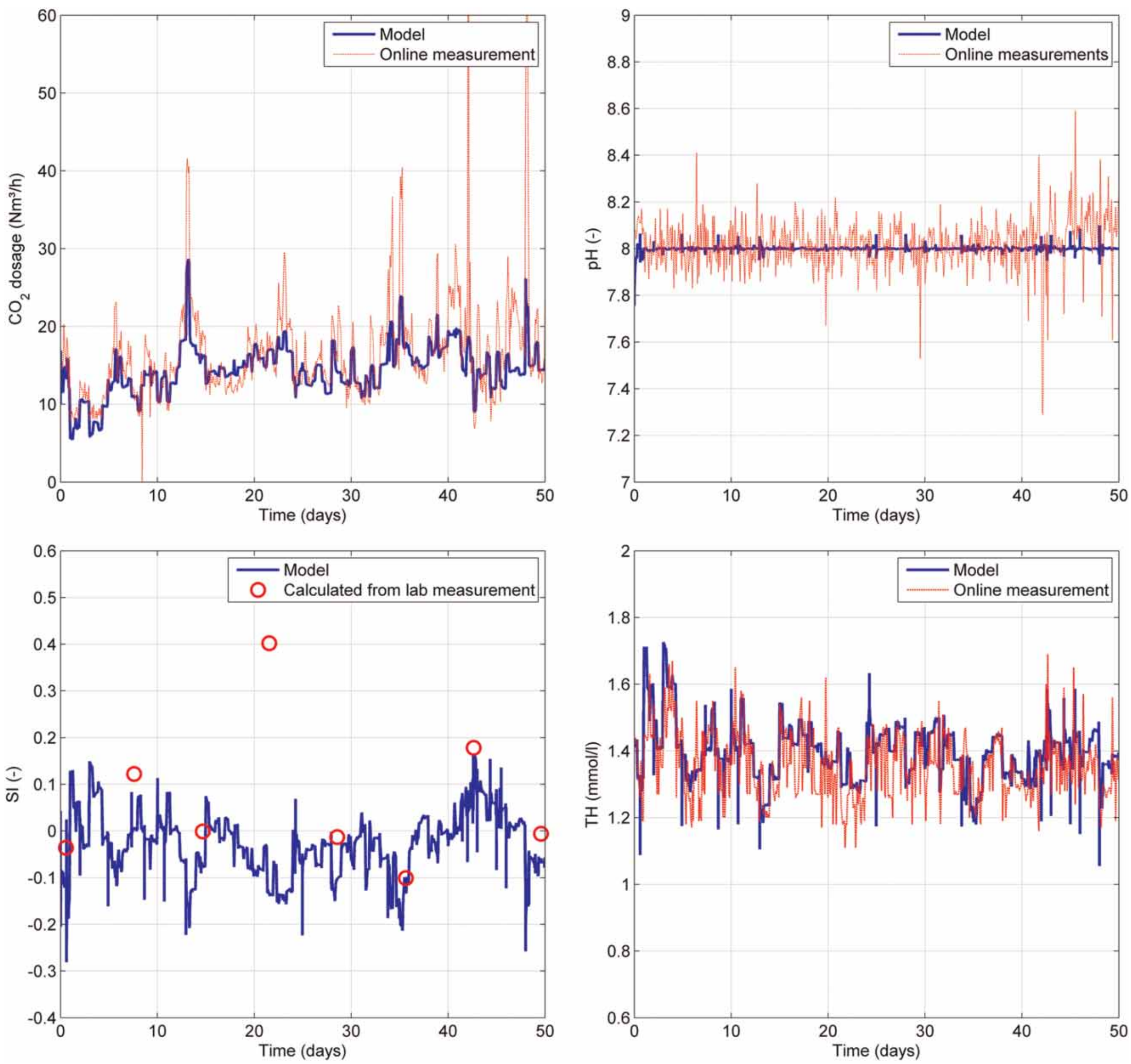

Figure 5 | Validation results for water quality Lane 1. CO_2 dosage (top left), pH (top right), SI (bottom left) and TH (bottom right).

dissolution of CO_2 in the upper cascade is incomplete as a consequence of degassing and turbulence in the cascade. To compensate for this ineffectiveness, a factor for CO_2 dissolving efficiency of 0.35 was introduced.

Figure 6 shows the results of the validation of the modeled TH and SI after mixing in the clear water reservoir.

Table 9 shows the RMS error according to Equation (1) and normalized RMS error for the online measured parameters shown in Figures 4–6. As shown in Table 10, the average total NaOH dosage in run 1 is 310 L/h. At Wim Mensink in the period January 20 2009 until March 10 2009, according to waybills, 268 ton NaOH 50% was delivered (nine truckloads), equaling an average flow of 357 L/h. Operators mention a small chance that a load was unloaded at a different site than mentioned on the waybill, which might explain the difference. Concluding, the results in Figures 4–6 and Table 9 show the model can be used for the purpose of this research, evaluating control strategies, especially when considering that field data were used to calibrate and validate.

Evaluation of the new control strategy

Figure 7 and Table 10 show the results of the four model runs.

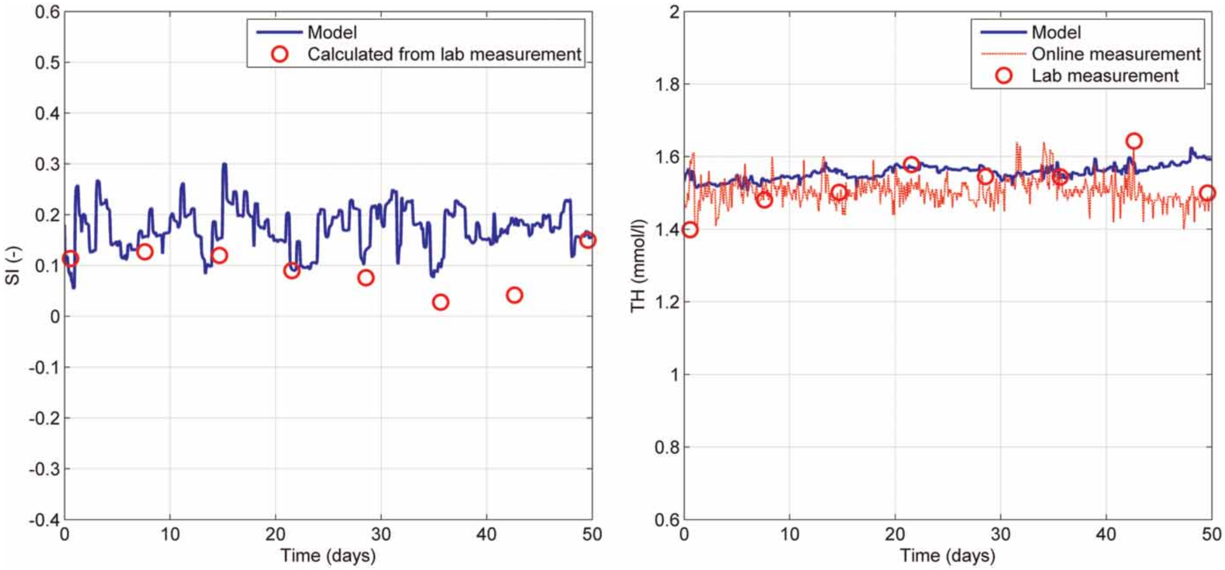

Figure 6 | Validation results for clear water reservoir. SI (left) and TH (right).

Table 9 | Root mean square (RMS) error for a selection of validation parameters

Location	Parameter	RMS error	Normalized RMS error (%)	Remark
Reactor 4	NaOH dosage	13 L/h	17	Extreme day 42 excluded
Reactor 4	TH	0.14 mmol/L	11	Extremes days 23–29 and 42 excluded
Lane 1	CO_2 dosage	4.0 Nm^3/h	24	Extremes days 8, 42 and 48 excluded
Lane 1	pH	0.11	1.4	
Lane 1	TH	0.09 mmol/L	6.8	
Clear water reservoir	TH	0.07 mmol/L	4.5	

Table 10 | Summary results for the Wim Mensink case

Run (control strategy)	Average number of active reactors (–)	Average total NaOH dosage (L/h)	Average TH clear water reservoir (mmol/L)	Efficiency (mmol × h/L^2)	Reduction of RO discharge (10^3 m^3/h)
1 (CS0)	4.38	310	1.56	0.0144	0
2 (CS0+)	4.38	308	1.55	0.0146	0
3 (CS1)	3.94	332	1.50	0.0146	0
4 (CS1)	3.81	322	1.50	0.0145	33

The comparison of runs 1 and 2 demonstrates that the increase of the bed height (and the crystallization surface as a consequence) in the reactor leads to a decrease of the NaOH dosage, and to an increase of the efficiency. As a consequence of the latter, the TH in the clear water reservoir decreases and approaches the desired TH of 1.5 mmol/L more closely. The main yield of the new control (run 3 and run 4) is a more constant TH, approaching the desired value of 1.5 mmol/L closely. Since the efficiency of run 3 is equal with run 2, the higher NaOH dosage in run 3 is caused exclusively by deeper softening leading to the desired TH of 1.5 mmol/L in the clear water reservoir. When compared with runs 1, 2 and 3, in run 4, all available RO water was used in the treatment plant. Thus, compared to the field situation in the studied period, an RO water discharge of 33×10^3 m^3 was prevented. As a consequence of the extra RO water supplied, the average number of active reactors was reduced from 4.4 to 3.8, thus increasing the softening capacity. The capacity of the plant as a whole

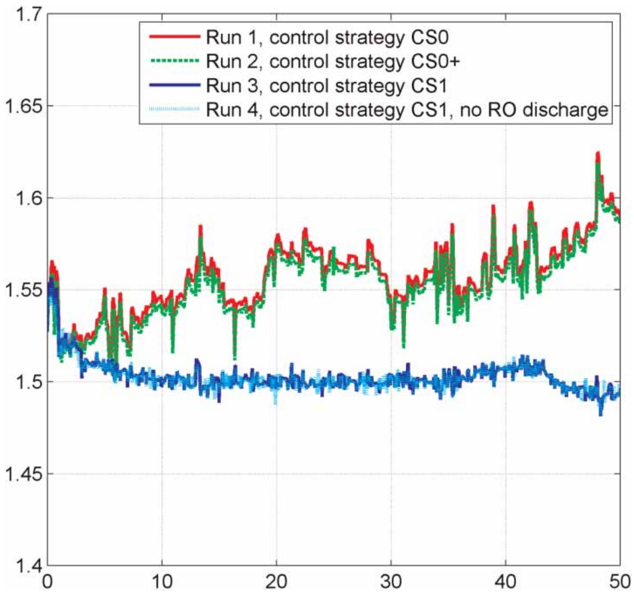

Figure 7 | TH in the clear water reservoir for runs 1 and 2 (upper lines) and for runs 3 and 4 (lower lines).

was increased by dividing the flow over Lane 1 and Lane 2 equally. In the present situation, the plant's capacity is limited by the flow over Lane 1, being two-thirds of the total flow. Run 4 shows a decrease of the NaOH dosage as a consequence of the extra RO water supplied, despite a decrease of the efficiency of the pellet softening compared to run 3, as a consequence of the less deep softening per reactor.

So, using the process model it was demonstrated that compared with the present control strategy, the new control strategy leads to a better water quality in the clear water reservoir, prevents RO water discharge, limits the NaOH dosage and limits the number of active reactors. The reduction of RO water discharge with 33×10^3 m^3 over the 50 days studied saves at least 3 k€ (circa 20 k€/year) on energy and chemicals. The field data were taken in a period when the production of RO water was limited with circa 20% due to maintenance. More RO-discharge would have been prevented and, as a consequence, more NaOH would have been saved if the plant would have operated on design capacity.

CONCLUSIONS

This research focused on the evaluation of control strategies, set up in the last step of control-design methodology for drinking water treatment plants. The objective was to prove that a dynamic process model is a valuable tool to evaluate alternative control strategies for drinking water treatment plants and to determine their expected effectiveness in a short time. The process model Stimela was extended with a separate file with the control rules and points to link to in the model. It was applied to the pellet softening of the Wim Mensink drinking water treatment plant. With the new control strategy the softening and treatment capacity of Wim Mensink has been increased, the TH of the water in the clear water reservoir has been controlled exactly on the desired value of 1.5 mmol/L and the efficiency of the NaOH dosage has been improved. The discharge of RO water has been reduced with 33×10^3 m^3 over the 50 days studied, saving at least 3 k€ (circa 20 k€/year) on energy and chemicals.

ACKNOWLEDGEMENTS

The authors wish to thank Alex van der Helm and Xiaoyu Yuan for their contribution to this research. This research is part of the Waterspot project which was co-funded by Agentschap NL, agency of the Dutch Ministry of Economic Affairs with an Innowator subsidy.

REFERENCES

HaskoningDHV 2011 Stimela. Retrieved 8 February, 2013, from www.stimela.com.

Rietveld, L. C., van der Helm, A. W. C., van Schagen, K. M. & van der Aa, L. T. J. 2010 Good modelling practice in drinking water treatment, applied to Weesperkarspel plant of Waternet. *Environ. Model. Softw.* **25** (5), 661–669.

Sheridan, T. B. 2002 *Humans and Automation*. John Wiley & sons, Inc., Santa Monica.

Stare, A., Vrecko, D., Hvala, N. & Strmcnik, S. 2007 Comparison of control strategies for nitrogen removal in an activated sludge process in terms of operating costs: a simulation study. *Water Res.* **41** (9), 2004–2014.

Van der Helm, A. W. C. & Rietveld, L. C. 2002 Modelling of drinking water treatment processes within the Stimela environment. *Water Sci. Technol. Water Supply* **2** (1), 87–93.

Van der Helm, A. W. C., Van der Aa, L. T. J., van Schagen, K. M. & Rietveld, L. C. 2009 Modelling of full-scale drinking water treatment plants with embedded plant control. *Water Sci. Technol. Water. Supply* **9** (3), 253–261.

Van Schagen, K. M., Babuska, R., Rietveld, L. C. & Baars, E. T. 2006 Optimal flow distribution over multiple parallel pellet reactors: a model-based approach. *Water Sci. Technol.* **53** (4–5), 493–501.

Van Schagen, K. M., Rietveld, L. C. & Babuska, R. 2008a Dynamic modelling for optimisation of pellet softening. *J. Water Supply Res. Technol. AQUA* **57** (1), 45–56.

Van Schagen, K. M., Rietveld, L. C., Babuska, R. & Baars, E. T. 2008b Control of the fluidised bed in the pellet softening process. *Chem. Eng. Sci.* **63** (5), 1390–1400.

Van Schagen, K. M., Rietveld, L. C., Veersma, A. & Babuska, R. 2010 Control-design methodology for drinking-water treatment processes. *Water Sci. Technol. Water Supply* **10** (2), 121–127.

Vrecko, D., Gernaey, K. V., Rosen, C. & Jeppsson, U. 2006 Benchmark Simulation Model No 2 in Matlab-Simulink: towards plant-wide WWTP control strategy evaluation. *Water Sci. Technol.* **54** (8), 65–72.

Worm, G. I. M., Mesman, G. A. M., van Schagen, K. M., Borger, K. J. & Rietveld, L. C. 2009 Hydraulic modelling of drinking water treatment plant operations. *Drink. Water Eng. Sci.* **2** (1), 15–20.

First received 20 March 2012; accepted in revised form 14 March 2013