# Integrated simulation of drinking water treatment

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## ABSTRACT

Major emphasis must be laid on guaranteeing high standards in drinking water quality. This can only be achieved when the drinking water treatment plant operates optimally. In this paper a treatment plant, consisting of ozonation with low dosage of ozone, pellet softening, pH correction and activated carbon filtration, treating lake water with high content of natural organic matter is analysed. Models are developed to describe the processes under changing conditions. For integrated modelling interaction of the treatment steps is considered to take place through the water stream. Water quality parameters are influenced by preceding treatment steps and they determine the performance of the following treatment steps. Assuming that disinfection is sufficient in the treatment plant and suspended and colloidal solids are sufficiently removed in preceding steps, the main controlled parameters for a treatment plant are chemical stability (saturation index SI), biological stability (assimilable organic carbon AOC), disinfection by-products (bromate) and organic micro-pollutants (pesticides). It is concluded that with good use of the by-pass of a pellet softening reactor and with optimised operation of the fluidised bed, the dosage of chemicals can be minimised, resulting in reduction of costs, environmental emissions and maintenance. Ozonation has a key role in the bio-stability and the toxicity of the drinking water. When ozone is only applied for oxidation (low dosages) some organic micro-pollutants are reduced and the run-time of the activated carbon filters is prolonged. However, ozonation decreases the bio-stability of the drinking water and enhances bromate formation. Therefore, the quality benefits related to oxidation of organic micro-pollutants should be weighted against the formation of bromate and AOC. The increase of AOC concentrations should be compensated by longer contact times in the biological filters.

**Key words** | drinking water, integral treatment, operation, simulation

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## NOMENCLATURE

| | |
|---|---|
| $a$ | specific surface area (m$^{-1}$) |
| $A_T$ | total cross-sectional area of reactor (m$^2$) |
| $c$ | concentration of compound in water (g/m$^3$) |
| $c_{g,s}$ | concentration of compound in gas or solid phase (g/m$^3$) |
| $c_{AOC}$ | concentration of AOC in water (mg/m$^3$) |
| $c_{O_3}, c_{g,O_3}$ | ozone concentration in water (g/m$^3$) and gas (g/Nm$^3$), respectively |
| $c_{Ca}$ | concentration of calcium in water (mol/m$^3$) |
| $c_{CO_3}$ | concentration of carbonate in water (mol/m$^3$) |
| $d_b$ | bubble diameter (m) |

| | |
|---|---|
| $d_p$ | particle diameter (m) |
| $D_x$ | dispersion coefficient in water (m$^2$/s) |
| $f$ | activity coefficient |
| $f_1$ | decay function in water |
| $f_2$ | transfer function of compound from water |
| $k_{AOC}$ | decay rate of AOC (s$^{-1}$) |
| $k_L$ | transfer coefficient (m/s) |
| $k_{O_3}$ | slow ozone decay rate (s$^{-1}$) |
| $k_T$ | kinetic constant (m$^4$/mol.s) |
| $k_{UV}$ | decay coefficient of UV absorbance (m$^3$/g.s) |
| $K_D$ | distribution coefficient (−) |
| $K_s$ | solubility constant of CaCO$_3$ (mol$^2$/m$^6$) |

| | |
|---|---|
| $P_0, P_g$ | standard and actual pressure respectively (Pa) |
| $RQ$ | gas to water flow ratio ($Q_g/Q$) (Nm$^3$/m$^3$) |
| $t_r$ | residence time in filter (s) |
| $T_0, T_g$ | standard and actual temperature respectively (K) |
| $Q, Q_g$ | water flow (m$^3$/s) and gas flow (Nm$^3$/s) respectively |
| $Q_s$ | pellet flow (m$^3$/s) |
| $u, u_g$ | water velocity (m/s) and gas velocity (Nm/s) respectively |
| UV | UV absorbance (254 nm) in water (m$^{-1}$) |
| UV$_0$ | stable UV absorbance (254 nm) after completion of the ozonation process (m$^{-1}$) |
| $Y$ | yield factor (m$^4$/g) |
| $\alpha$ | pressure and temperature correction factor $\alpha = (P_g/P_0)(T_0/T_g)$ |
| $\beta_s$ | surface diffusion transfer coefficient (m/s) |
| $\varepsilon$ | porosity of filter bed ($-$) |
| $\varepsilon_e$ | porosity of expanded bed ($-$) |

## ABBREVIATIONS

| | |
|---|---|
| AOC | assimilable organic carbon |
| DOC | dissolved organic carbon |
| NOM | natural organic matter |
| SI | saturation index |

## INTRODUCTION

Surface water treatment plants are designed to accomplish multiple objectives: the removal of particles, including micro-organisms, originally present in the source water; the oxidation of some reduced species; the disinfection of micro-organisms; the removal of natural organic matter (NOM) (Lawler & Nason 2005) and organic micro-pollutants. In addition, the formation of disinfection by-products should be avoided or limited. The main objective of drinking water treatment plants is to produce safe drinking water for consumption (without pathogenic micro-organisms and toxic compounds), to produce attractive drinking water (free from colour, taste and odour) and

to avoid accumulation of solids, corrosion and after-growth of bacteria in the distribution and transport pipelines (van Dijk & van der Kooij 2004). This must be done against the lowest costs with the lowest impact on the environment.

The greatest threat for drinking water companies is the use of bottled water for drinking when tap water quality cannot be guaranteed for that purpose. Recent research suggested that bottled water is about 150 times more expensive than tap water and 30 times less environmentally friendly. Large differences in taste are not detected (Consumentenbond 2005). Therefore, the tap water quality must have an impeccable image and the challenge is to tackle all types of emerging quality problems. In addition, it was found that the environmental impact of the production of drinking water production is negligible compared to other activities such as car driving (Barrios *et al.* 2006). From the Dutch drinking water industry benchmark of 2003 (Vewin 2003), it is concluded that the water companies comply generously with the legal standards for water quality set in the Dutch Water Act. Customers appreciate the water quality: 94% of the customers are happy with the price-quality ratio of the drinking water. Therefore, major emphasis must be laid on guaranteeing the drinking water quality on high standards. This can only be achieved when the drinking water treatment plant operates optimally.

Although drinking water treatment plants have been functioning for more than a century, the operation is not routinely and, in the last decades, has become more and more complex. Because of more stringent regulations and requirements, the plants should produce water of a better quality and therefore different treatment processes are placed in series to meet the guidelines. However, these processes interact with each other; sometimes have contradictionary objectives and operation influences the performance of subsequent processes (Bosklopper *et al.* 2004). In addition, in many cases, the specific purposes of the design of drinking water treatment processes are outdated and the operational goals are changed. Experienced operators, who are able to interact with the processes, are nowadays scarce, because of frequent job rotation and increased automation. Therefore, it is impossible to compensate for the increased complexity of operation. The consequences are that the operation of the drinking water treatment processes is sub-optimal in terms of product quality, costs and environmental emissions.

In this paper the treatment plant of Weesperkarspel, Waternet, consisting of ozonation with low dosage of ozone, pellet softening, pH correction and activated carbon filtration, treating lake water with high content of natural organic matter (NOM) is analysed. Therefore, models are developed to describe the processes under changing conditions. These models are then used to find the optimal operational condition.

## METHODS

### Mathematical description of drinking water treatment processes

Water quality models attempt to simulate changes in the concentration of pollutants as they move through the environment or a reactor. Most reactions of importance in water treatment occur in more than a single phase, i.e. multiphase reactions. The different processes in drinking water treatment have similar mechanisms and can be described with similar partial differential equations, based on the advection-dispersion model. A dissolved or suspended compound in water is subject to transport, transfer and decay, the overall equation for a one-dimensional flow is therefore:

$$\frac{\partial c}{\partial t} = D_x \frac{\partial^2 c}{\partial x^2} - u \frac{\partial c}{\partial x} - f_1(c) - f_2(c, c_{g,s}) \tag{1}$$

The first term on the left side is the change of concentration of a compound in time. When $dc/dt = 0$, there is a stationary situation and the concentration of a compound on a certain location is independent of time. The second term is the turbulent dispersion of the gradient type (following Fick's law). The third term indicates the transport of the compound through the reactor by advection. The fourth term indicates a function for the decay of the compound. The last term indicates a function for the transfer of the compound from the water to the solid or gas phase. The gas or solid phase can be fixed in the reactor, but can also be transported through the reactor. Flow of gas normally occurs in aerators. Flow of the solid phase can be observed in fluidised bed reactors. The equation for this transport is similar to the transport in water. The kinetics can be formulated in different ways for the treatment processes under consideration and, therefore, the overall equations will vary.

### Ozonation

For ozonation of waters with high NOM content and low ozone dosages, the main processes take place in the bubble columns. The processes are advection and dispersion of the water flowing through the bubble column, ozone mass transfer from the gas phase to the water phase, slow decay of ozone and competitive reactivity of constituents in water with dissolved ozone (rapid decay of ozone) (Zhou *et al.* 1994; El-Din & Smith 2001). The differential equations for the calculation of ozone concentration, neglecting dispersion, can be formulated as follows (Rietveld 2005):

$$\frac{\partial c_{O_3}}{\partial t} = -\frac{Q}{A}\frac{\partial c_{O_3}}{\partial x} + k_L RQ \frac{u}{u_g}\frac{6}{d_b}(\alpha K_D c_g - c_{O_3}) - k_{O_3} c_{O_3}$$
$$- \frac{k_{UV}}{Y}(UV - UV_0)c_{O_3} \tag{2}$$

$$\frac{\partial c_{g,O_3}}{\partial t} = -\frac{Q_g}{hA}\frac{\partial c_{g,O_3}}{\partial x} + \frac{k_L}{\alpha}\frac{6}{d_b}(\alpha K_D c_{g,O_3} - c_{O_3}) \tag{3}$$

$$\frac{\partial(UV)}{\partial t} = -\frac{Q}{A}\frac{\partial(UV)}{\partial x} - k_{UV}(UV - UV_0)c_{O_3} \tag{4}$$

The second term on the right side of Equations (2) and (3) indicates the transfer of ozone from the gas phase to the water phase. The third term of Equation (2) represents the slow decay of ozone in water. From practice it is known that direct consumption of ozone is larger when the UV absorbance of humic substances is higher and that during the ozonation process a strong decrease of UV absorbance occurs (Langlais *et al.* 1991). Therefore, it is assumed that the rapid decay of ozone is associated with the decrease of UV absorbance during ozonation (fourth term of Equation (2)) and the extra Equation (4) is introduced.

### Pellet softening

For the removal of calcium ions from the water by pellet softening (Graveland *et al.* 1983; van Dijk & Wilms 1991) and the crystallisation of calcium carbonate on the

pellets, neglecting dispersion and considering the water velocity in the pores of the fluidised pellet bed, the overall equations for transport are (Rietveld 2005):

$$\frac{\partial c_{Ca}}{\partial t} = -\frac{Q}{A_T \varepsilon_e}\frac{\partial c_{Ca}}{\partial x} - k_T a\left\{c_{Ca}c_{CO_3} - \frac{K_s}{f^8}\right\} \tag{5}$$

$$\frac{\partial c_{CaCO_3}}{\partial t} = -\frac{Q_s}{A_T}\frac{\partial c_{CaCO_3}}{\partial x} + \varepsilon_e k_T a\left\{c_{Ca}c_{CO_3} - \frac{K_s}{f^8}\right\} \tag{6}$$

To determine the crystallisation rate over the height, the specific surface area ($a$) of the pellets and consequently the diameter of the pellets ($d_p$) and the porosity ($\varepsilon_e$) over the height of the reactor must be known. The pellet size is dependent on the amount of crystallised calcium carbonate and the velocity of pellet discharge ($Q_s$). The porosity of the expanded bed is dependent on the pellet size, the viscosity of the water and the water velocity through the reactor. With the crystallisation of calcium carbonate on the pellets, a new chemical equilibrium will be installed (Plumer & Busenberg 1982), the concentrations of carbonate, bicarbonate and carbon dioxide will be changed and consequently the pH, the ionic strength and the activity factor will change. Both the concentrations of calcium and carbonate and the activity coefficient have influence on the driving force for crystallisation. To be able to calculate the concentration of carbonate and the activity coefficient over the height of the bed, the conservative parameters m-alkalinity ($m$), p-alkalinity ($p$) and basic ionic strength are introduced (van Dijk & Wilms 1991).

### Biological activated carbon filtration

The content of NOM determines heavily the removal of organic micro-pollutants (such as pesticides) by activated carbon filtration. When NOM is adsorbed adsorption places for the removal of pesticides are occupied and an early pesticide breakthrough will occur. NOM will also block the pores, and as a consequence the internal pores are no longer available for adsorption (Weber 2002). Adsorption capacity of micro-pollutants decreases with preloading time. Preloading by NOM also leads to decreased adsorption kinetics as indicated by the surface diffusion

coefficients (Knappe *et al.* 1994). The adsorption capacity of micro-pollutants, for example atrazin, is strongly hindered for NOM, where the characteristics of NOM also play an important role (Bernazeau *et al.* 1994; Jarvie *et al.* 2005). Therefore, biological removal of NOM can enhance adsorption of organic micro-pollutants (Sontheimer *et al.* 1988). The biological removal of NOM, measured as assimilable organic carbon (AOC), by activated carbon filtration preceded by ozonation is mainly determined by bacteriological growth in the filters. In case the biofilm is totally developed the biological removal process can be described as:

$$\frac{\partial c_{AOC}}{\partial t} = -\frac{Q}{A_T \varepsilon}\frac{\partial c_{AOC}}{\partial x} - k_{AOC}c_{AOC} \tag{7}$$

### Integrated evaluation and simulation of drinking water treatment

For integrated evaluation of drinking water treatment it is important to identify how treatment processes interact and in which way the treatment processes can be influenced. In drinking water treatment interaction takes place through the water stream. Water quality parameters can be influenced by preceding treatment steps and they can determine the performance of the following treatment steps. Finally, the drinking water quality requirements must be met; resulting in water that does not affect the distribution network and is free from toxic compounds and pathogenic micro-organisms. Assuming that disinfection is sufficient in the treatment plant and suspended and colloidal solids are sufficiently removed in preceding steps, the main controlled parameters for a treatment plant consisting of ozonation, softening, pH correction and activated carbon filtration are chemical stability (saturation index, SI), biological stability (AOC), disinfection by-products (bromate) and organic micro-pollutants. The process is disturbed by the change of quality parameters of the water flow into the treatment plant and the compounds that are formed during treatment. For the processes mentioned above the following disturbing water quality parameters are of importance: calcium, bicarbonate, pH, temperature, dissolved organic carbon (DOC), UV

absorbance, organic micro-pollutants, AOC and bromide. The treatment plant is finally controlled by a reduced number of manipulations. The manipulated parameters are division of flow over different parallel units, by-pass ratio, backwash and regeneration frequency and dosing of chemicals (ozone, caustic soda, hydrochloric acid).

For the modelling, the Stimela environment is used where different drinking water treatment processes can dynamically be modelled. The Stimela models are developed in Matlab/Simulink. Partial differential equations are numerically integrated with the consequence that variations in time and space can be followed. The models of individual processes are situated in a model library and can be connected to each other, forming a complete treatment train. In this way, the effect of operational changes in preceding treatment processes can be evaluated (van der Helm & Rietveld 2002).

Optimal, integrated operation of the treatment plant can be determined with an objective function, where a weighted summation of the costs of the manipulated and controlled parameters is made for certain incoming water. The minimum costs represent the optimal operational condition. Because of the importance of the quality of the drinking water in the Netherlands, the weighing factors of the controlled parameters are high in comparison with the manipulated parameters. Therefore, the optimum is mainly determined by the controlled parameters (product water quality). Slight optimisation can be found by comparing the different manipulated parameters.

## Pilot plant installation

To calibrate and validate the models and to use the models for integrated operation of drinking water treatment, the pilot plant of Waternet, location Weesperkarspel, is used. The pilot plant is a copy of the full-scale plant and consists of two parallel lines with 2 ozone bubble columns in series with 2 ozone contact tanks, 1 pellet softening reactor with by-pass possibility and 1 granular activated carbon filter.

In the pilot installation on-line measurement devices are installed. For ozone measurements 6 Wallace & Tiernan MFA Depolox 4 measuring cell U-95650 can be installed on variable locations in the pilot plant. Hardness and alkalinity is measured with an Applikon ADI 2040.

In addition, on line pressure measurements are used to monitor the bed of the fluidised pellet reactor. The data are sent through a Profibus cable to a central computer from where the valves and the dosing devices of the plant can be manipulated. In this way many different set-points can be programmed and variable tests can be executed 24 hours per day.

## RESULTS AND DISCUSSION

### Chemical stability of drinking water

Drinking water is chemically stable when the calcium carbonic acid equilibrium is reached, which is determined by the calcium concentration, alkalinity, pH, ionic strength and temperature. The equilibrium is influenced by the different treatment steps in consideration. Caustic soda is dosed before pellet softening in order to reduce the total hardness from 2.25 mmol/l to 1.5 mmol/l. Softening in a reactor is normally deeper than the required level. Therefore, part of the water can be by-passed and mixed with the effluent of the reactors. The mixture of the effluent of the reactors and the by-pass water must be chemically stable to avoid crystallisation in the filters after the softening step. When super-saturation of calcium carbonate occurs, hydrochloric acid is dosed. In the activated carbon filters NOM is biologically removed resulting in the formation of carbon dioxide, making the drinking water aggressive. Finally, caustic soda is dosed to maintain a SI of about 0.3 in the distribution network.

Actual full-scale operational practice of the pellet softening process is based on fixed masses of pellets and thus a variable bed height with flow and temperature. In addition, by-pass ratio and caustic soda dosing is based on minimisation of super-saturation of the effluent from an individual reactor rather than the quality of the mixed effluent. From modelling exercises based on pilot plant research presented in Figure 1 it can be concluded that with an increasing by-pass ratio, the SI of the mixed effluent of the pellet softening and the by-pass flow decreases. In addition, it can be concluded that actual operation is sub-optimal, with by-pass ratios near to zero and poor acid dosing practice (for neutralisation). The maximum by-pass
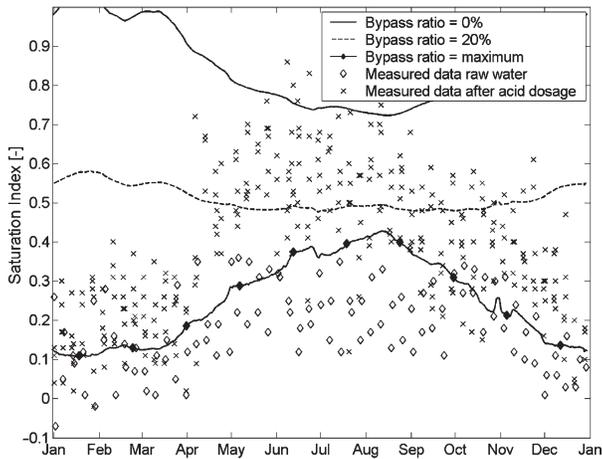
**Figure 1** | Mixed effluent SI of pellet softening with different by-pass ratios. Maximum pellet size is 0.8 mm and fluidised bed height is 4.5 m.

flow is restricted to a minimum flow through the reactor to keep the bed fluidised. Increasing the maximum pellet size in the reactor will result in an increase of SI of the mixed effluent. This is a consequence of the higher flows through the reactor that have to be adopted to keep the bed fluidised and because the specific crystallisation surface decreases. In Figure 2 it can be observed that using an optimal by-pass scheme and considering the hydraulic consequences of pellet size and biological activity in the filters (decrease of pH due to carbon dioxide production), only during the warmer periods acid dosing is required. Actual practice at the full-scale plant of Weesperkarspel is different: low by-pass ratios are adopted (0–20%) and acid dosing is applied
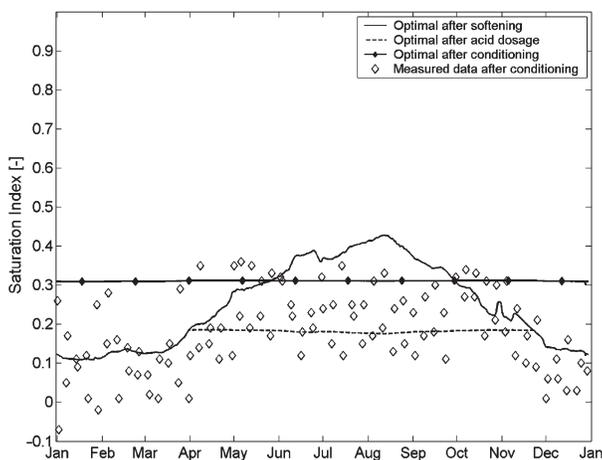
during the entire year. The consequence is that an over-dosage of both caustic soda and hydrochloric acid is applied. By adopting an integrated, model-based and time dependent, softening and conditioning approach, thus, savings can be obtained in the dosing of chemicals, which reduces operational costs and impacts on the environment.

## Biological stability of drinking water

Biological stability of drinking water can, amongst others, be determined by measuring the concentration of AOC. The concentration of AOC is influenced by ozonation and the biological activity in the activated carbon filters. In addition, some AOC will be adsorbed on the activated carbon. The formation of AOC during ozonation depends on one hand on the ozone dosing and on the other hand on the NOM concentrations (measured as UV254 absorbance). It is found that the increase in AOC is a function of the decrease of UV254 absorbance (van der Kooij *et al.* 1989), which was confirmed by measurements at Waternet (see Figure 3). The decrease of UV254 absorbance in its turn depends on the ozone dosage and is independent of temperature.

The removal of AOC by adsorption on activated carbon is limited, also due to the biological activity in the filter bed and the high biodegradability of AOC.

The biological degradation of AOC in the pellet softening process and the activated carbon filters is more or less constant over time. Pellet softening is a continuous process and biological activity will be stabilised after initial start-up. Granular activated carbon filters are, at Waternet,
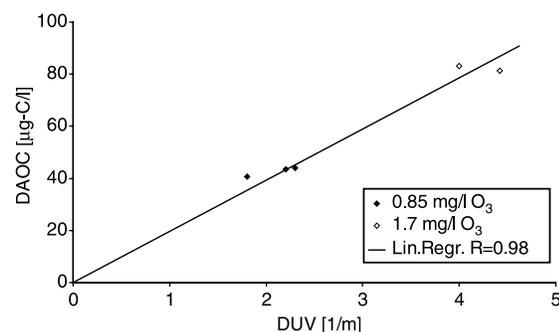


**Figure 2** | Mixed effluent SI-index of pellet softening and after acid and caustic soda dosing. Maximum by-pass ratio and fluidised bed height is 4.5 m.



**Figure 3** | Decrease of UV absorbance as a function of the increase of AOC during ozonation at Weesperkarspel.

regenerated every 18 months and ripening of the filters takes about 2 months. However, because of the large amount of filters present in the full-scale installation, the effects of ripening are levelled off. With an increase in ozone dosage, the AOC formation increases. However, the effluent concentration AOC of the activated carbon filters increases with an increase in influent AOC concentration.

Assuming a steady state situation Equation (7) can be written as:

$$\frac{c_{AOC}}{c_{0,AOC}} = e^{-k_{AOC}*t_r} \tag{8}$$

From data obtained from the pilot plant it can be concluded that the biological removal efficiency of the activated carbon filters (expressed as $k_{AOC}*t_r$) is independent of temperature and influent levels of AOC (see Figure 4).

In Figure 5 the influent and effluent AOC concentrations of pilot filters are presented. Assuming a $k_{AOC}*t_r$-value of 1 (average value), the removal efficiency of the filters is 63%. From the pilot plant experiments it can be concluded that the formation of AOC due to ozonation exceeds the increase of the effect of biodegradation in the granular activated carbon filters. This means that the bio-stability of the drinking water is decreased, with the consequence that after-growth in the distribution network is enhanced. In the Netherlands where chlorine as safety disinfection is not applied, this can have effects on the drinking water quality.
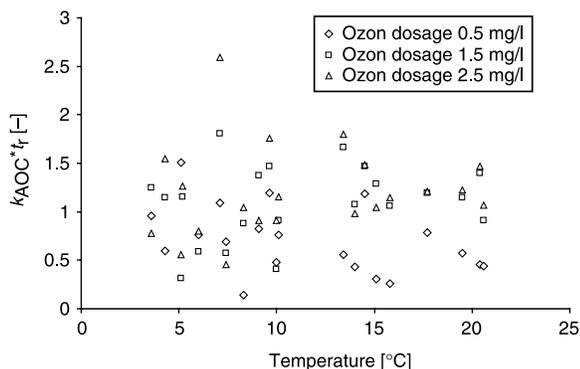


**Figure 5** │ Effluent AOC concentrations at different ozone dosages, measured and predicted.

## Toxicity of drinking water

Toxicity is determined by the amount of organic micro-pollutants and disinfection by-products. At Waternet, location Weesperkarspel, the disinfection by-product bromate is hardly formed (under detection limit), due to the low dosages of ozone applied and the relatively high concentrations of NOM. The formation of bromate is dependent on the CT-value applied. The CT-value is dependent on ozone dosage and decay rate. Rapid decay and slow decay of ozone are dependent on NOM concentration and character, pH and temperature.

From Figure 6 it can be concluded that CT-values lower than $5-10 \, mg/l * min$ should be applied to keep bromate concentrations below $0.5 \, \mu g/l$. Ozonation, however, increases biological activity in the granular activated carbon filters and decreases absorbability of NOM. Both phenomena result in lower NOM loading of the activated carbon filters and thus more adsorption sites for organic micro-pollutants. At Waternet, Weesperkarspel, influent organic



**Figure 4** │ Biological removal efficiency of activated carbon filters as a function of temperature and influent AOC concentration (formed by ozonation).
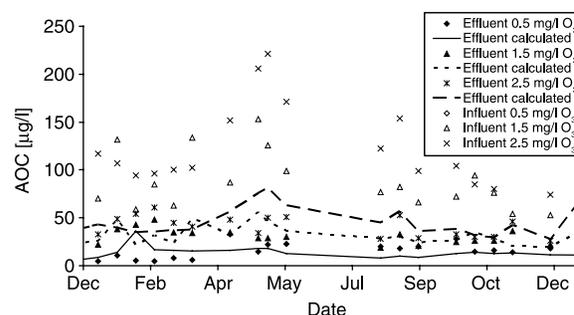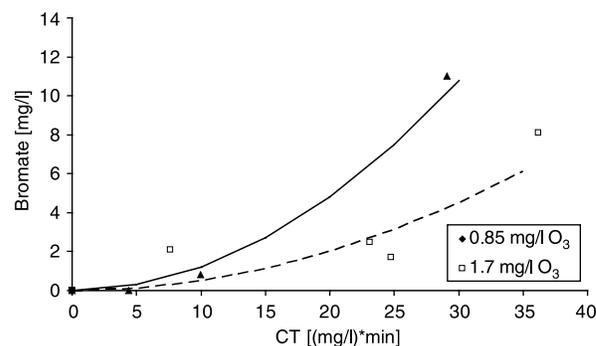


**Figure 6** │ Bromate formation as a function of CT-value for untreated and pre-treated Weesperkarspel water.

micro-pollutant concentration is under detection limit and, therefore, extra adsorption capacity for the removal of organic micro-pollutants is nowadays not required.

Finally, removal of NOM can result in a decrease of copper and lead uptake from the distribution network (Broo *et al.* 1998). At Waternet, Weesperkarspel, the effluent DOC concentration is, therefore, kept at 3 mg C/l ($\pm$ 0.5 mg C/l). The character of NOM is in this respect of importance and ozonation is known to have a positive influence (Korshin *et al.* 2005). For the case of Weesperkarspel these effects are not yet quantified.

## CONCLUSIONS

To be able to optimise the operation of a drinking water treatment plant it is of importance to identify the objectives. Drinking water should be of outstanding quality, chemically and biologically stable and free from pathogenic micro-organisms and toxic compounds. Considering the treatment train of Waternet, location Weesperkarspel, pellet softening has a key role in the conditioning of the water. It can be concluded that with good use of the by-pass and with optimised operation of the fluidised bed, the dosage of chemicals can be minimised, resulting in reduction of costs, environmental emissions and maintenance. In a recent study the environmental impact is calculated for the operation of the treatment plants (Barrios *et al.* 2006). It can be concluded that softening is the main contributor to environmental impact of operation. The use of sodium hydroxide (NaOH) contributes 79.5% of the softening impact. The second largest contributor is biological activated carbon filtration; within BAC filtration the use of steam, as oxidant to activate and regenerate carbon.

Ozonation has a key role in the bio-stability and the toxicity of the drinking water. When ozone is only applied for oxidation (low dosages) some organic micro-pollutants are reduced and the run-time of the activated carbon filters is prolonged. However, ozonation decreases the bio-stability of the drinking water. The increase of AOC concentrations should be compensated by applying longer contact times in biological filters (activated carbon filter, rapid or slow sand filters). This means that reduced operation costs (less regenerations) should be compensated

by increased investment costs. Because biological AOC removal rate is independent of temperature and influent AOC concentration, optimisation of operation is limited. In addition, ozonation is limited by the formation of bromate. Therefore, when ozonation (with low dosages) is not needed for disinfection, the quality benefits related to oxidation of organic micro-pollutants should be weighted against the formation of bromate and AOC. Optimisation of the oxidation/disinfection process should rather be found in an alternative set-up of the treatment train than in improvement of operation.

Hereby NOM plays a crucial role. NOM competes with organic micro-organisms for adsorption sites on the activated carbon and NOM induces AOC formation during ozonation.

For integrated modelling, it is not always possible and necessary to use detailed models of reactor performance. On the one hand, different reactors are placed in parallel, levelling off the differences in individual reactors due to start-up and ripening. On the other hand, detailed, dynamic models will result in long calculation times. The use of simplified models, such as applied for the ozonation and activated carbon processes, gives rapid insight in the interactions in the treatment plant. The disadvantage, however, is that these models require many data to be evaluated at the specific treatment plant.

Modelling and control will not only lead to better water quality and cost reduction, but also to a more stable performance of the plant and a better understanding of the processes.

## ACKNOWLEDGEMENTS

## REFERENCES

Barrios, R., Siebel, M., van der Helm, A., Bosklopper, K. & Gijzen, H. 2006 Environmental and financial life cycle impact

assessment of drinking water production at Waternet. *J. Cleaner Prod.* **16**(4), 471–476.

Bernazeau, F., Mandra, V., Charles, P., Andelme, C. & Bersillon, J.-L. 1994 Pesticides removal on activated carbon: competitive adsorption with natural organic matter. *Water Supply* **14**, 43–48.

Bosklopper, Th. G. J., Rietveld, L. C., Babuska, R., Smaal, B. & Timmer, J. 2004 Integrated operation of drinking water treatment plant at Amsterdam Water Supply. *Water Sci. Technol. Water Supply* **4**(5–6), 263–270.

Broo, A. E., Berghult, B. & Hedberg, T. 1998 Copper corrosion in water distribution systems-the influence of natural organic matter (NOM) on the solubility of copper corrosion products. *Corros. Sci.* **40**(9), 1479–1489.

Consumentenbond 2005 Kraan wint van fles. Consumentengids, The Netherlands.

El-Din, M. G. & Smith, D. W. 2001 Ozone mass transfer in water treatment: hydrodynamics and mass transfer modelling of ozone bubble columns. *Water Sci. Technol. Water Supply* **1**(2), 123–130.

Graveland, A., van Dijk, J. C., de Moel, P. J. & Oomen, J. H. C. M. 1983 Developments in water softening by means of pellet reactors. *J. AWWA* **75**(12), 619–625.

Jarvie, M. E., Hand, D. W., Bhuvendralingam, S., Crittenden, J. C. & Hokanson, D. R. 2005 Simulating the performance of fixed-bed granular activated carbon adsorbers: removal of synthetic organic chemicals in the presence of background organic matter. *Water Res.* **39**(11), 2407–2421.

Knappe, D. R. U., Snoeyink, V. L., Matsui, Y., José Pardos, M. & Bourbigot, M.-M. 1994 Determining the remaining life of a granular activated carbon (GAC) filter for pesticides. *Water Supply* **14**, 1–14.

Korshin, G. V., Ferguson, J. F. & Lancaster, A. C. 2005 Influence of natural organic matter on the morphology of corroding lead surfaces and behaviour of lead-containing particles. *Water Res.* **39**, 811–818.

Langlais, B., Reckhow, D. A. & Brink, D. R. 1991 *Ozone in Water Treatment: Application and Engineering*. Lewis Publishers, MI, USA.

Lawler, D. F. & Nason, J. A. 2005 Integral water treatment plant modelling: improvements for particle processes. *Environ. Sci. Technol.* **39**, 6337–6342.

Plumer, L. N. & Busenberg, E. 1982 The solubilities of calcite, aragonite and vaterite in $CO_2$-$H_2O$ solution between 0 and 90°C. *Geochimica et Cosmochimica Acta* **46**, 1011–1040.

Rietveld, L. C. 2005 *Improving Operation of Drinking Water Treatment through Modelling*. PhD thesis, Delft University of Technology.

Sontheimer, H., Crittenden, J. C. & Summers, R. S. 1988 *Activated Carbon Adsorption for Water Treatment*, 2nd edition. DVGW-Forschungsstelle, Karlsruhe, Germany.

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 Kooij, D., Hijnen, W. A. M. & Kruithof, J. C. 1989 The effects of ozonation, biological filtration and distribution on the concentration of easily assimilable organic carbon (AOC) in drinking water. *Ozone Sci. Eng.* **11**, 297–311.

van Dijk, J. C. & van der Kooij, D. 2004 Water Quality 21 research programme for water supplies in the Netherlands. *Water Sci. Technol. Water Supply* **4**(5–6), 181–188.

van Dijk, J. C. & Wilms, D. A. 1991 Water treatment without waste material-fundamentals and state of the arte of pellet softening. *J. Water SRT-Aqua* **40**(5), 263–280.

Vewin 2003 *Reflections on Performance 2003, Benchmarking in the Dutch Drinking Water Industry*. Vewin, Amsterdam. Available online: http://www.vewin.nl/SiteCollectionDocuments/Publicaties/Overige%20Vewin-uitgaven/2004/Reflections%20on%20performance%202003.pdf

Weber, Jr. W. J. 2002 Natural organic matter preloading of GAC: phenomena, mechanisms, and effects on target compound removal. In: *Proceedings of IWA-Workshop Biological Activated Carbon Filtration*. Delft.

Zhou, H., Smith, D. W. & Stanley, S. J. 1994 Modeling of dissolved ozone concentration profiles in bubble columns. *J. Environ. Eng.* **120**(4), 821–840.