

Integrated Treatment Plant and Distribution Network Models to Predict the Drinking Water Quality from Source to Tap

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ABSTRACT

An accurate and real-time prediction of the water quantity and quality inside drinking water treatment plants is paramount to a more efficient and stable operation and can be utilized to proactively inform customers about changes in the delivered water quality. Although multiple attempts have been done to create real-time simulations of complete treatment plants, up until now the influence of residence time inside the pipes and treatment processes was ignored. In groundwater treatment, however, due to often long transport pipes between the well fields and the plant, the residence time is of significant influence. Therefore, a new modelling approach linking hydraulic simulations using EPANET with chemical calculations using PHREEQC was developed and validated for the small-scale groundwater treatment plant of Hoenderloo. By connecting the model of the treatment plant to a model of its distribution network a real time prediction of the delivered water quality, tracing packages of water all the way from the source wells to the customer tap, can be made.

Keywords: Drinking Water Treatment, Water Quality Modeling, Distribution Networks

1 BACKGROUND

With 96 active groundwater treatment plants supplying water to over 5.6 million customers Vitens is the largest drinking water company in the Netherlands. An aging workforce, coupled with recent technological and societal developments, however, drive Vitens to adapt and transform the operation of its drinking water treatment plants and distribution networks from a craft and experience-driven to a data-driven and automated approach. One of the main focus points of the transition is on customer interaction and an increased focus on the produced and delivered water quality.

Although the quality of the treated and delivered water is the most crucial parameter in water treatment, at this moment little to no real-time information on the water quality is available. The quality of the water is instead monitored by an extensive monitoring program performed by laboratory analysis. The process of taking samples, transporting them to the laboratory and receiving the analysis results often takes well over 24 hours, rendering a quick adjustment to the treatment process based on a change in water quality impossible. In addition, by the time a disparity in water quality is detected, and before we have the change to issue a warning, the water is often already consumed by our customers.

One possible solution would be to install a wide variety of online sensors for specific components inside the treatment plant and distribution network. This would, however be a very costly and labor intensive operation to setup and maintain. With the SLIMM project, short for Self Learning Integrated Modeling and Monitoring, we have developed a different approach. Instead of relying on physical sensors we aggregate all existing real-time sensor data, lab analysis data and asset information and use a combination of data-driven and white box models as ‘soft’ sensors. By following the water from the abstraction wells, through the raw water supply pipes, the treatment processes and the reservoirs a real-time prediction of the water quality at each location in the treatment plant, as well as of the effluent, can be attained. The output of this model can then be coupled to a model of the distribution network to follow the water quality from the plant clear water reservoir to the consumer’s tap. Although multiple attempts have been done to create complete simulation models of ground- and surfacewater treatment plants [1], this approach is the first to include the influence of hydraulic residence time inside the pipes and treatment processes.

A multitude of possibilities rise from this coupled model environment. Knowledge on the exact composition of the incoming raw water mixture allows for finer tuning of the treatment processes and chemical dosing points. The ability to determine the exact impact of maintenance works or process disturbances on the delivered water quality allows for early warning of our ‘vulnerable’ customers, such as hospitals and factories.

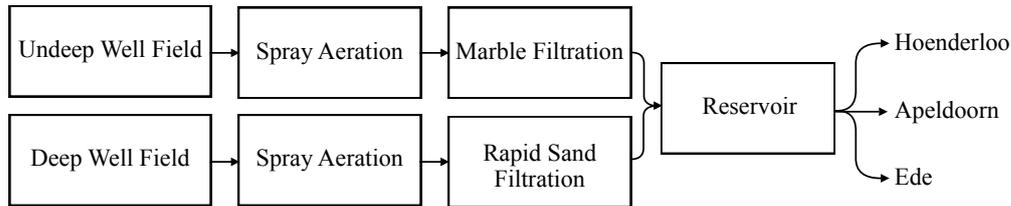


Figure 1. Schematic overview of the Hoenderloo WTP treatment process.

2 METHODS

2.1 The Hoenderloo Water Treatment Plant

To validate the approach a model was developed and validated for the Hoenderloo WTP (Water Treatment Plant). Hoenderloo WTP is a relatively small scale groundwater treatment plant capable of supplying 2.5 million cubic meters of drinking water per year. Hoenderloo is supplied with groundwater from two well fields situated 1.5 kilometers away from the treatment plant. One well field has 4 pumps of differing capacity to pump up shallow groundwater low on calcium and iron. The other well field uses 5 pumps of equal capacity to supply the installation with deep groundwater void of oxygen but high on dissolved iron and manganese. The groundwater from the well fields is treated by two separate lanes. The shallow groundwater is aerated by means of spray aeration and passed through marble filtration to decrease the water aggressiveness. The deep groundwater is aerated through spray aeration followed by rapid sand filtration to remove iron and manganese. The water from the two treatment lanes is then mixed and enters a clear water reservoir from which the water is pumped to the nearby towns of Hoenderloo, Apeldoorn and Ede. A schematic overview of the treatment process is presented in figure 1.

Due to the large distance between the well fields and the treatment plant, as well as the difference in water quality between the pumps as well as the fields, the groundwater mixture entering the installation is of constantly changing quality.

2.2 Distribution Network

From the Hoenderloo reservoir the water quality is traced through a model of the Hoenderloo town distribution network. At two points in the network, situated between 700 and 1500 meter from the treatment plant, virtual samples of the water quality were taken at intervals of once per 5 minutes. An overview of the Hoenderloo town distribution network is presented in figure 2.

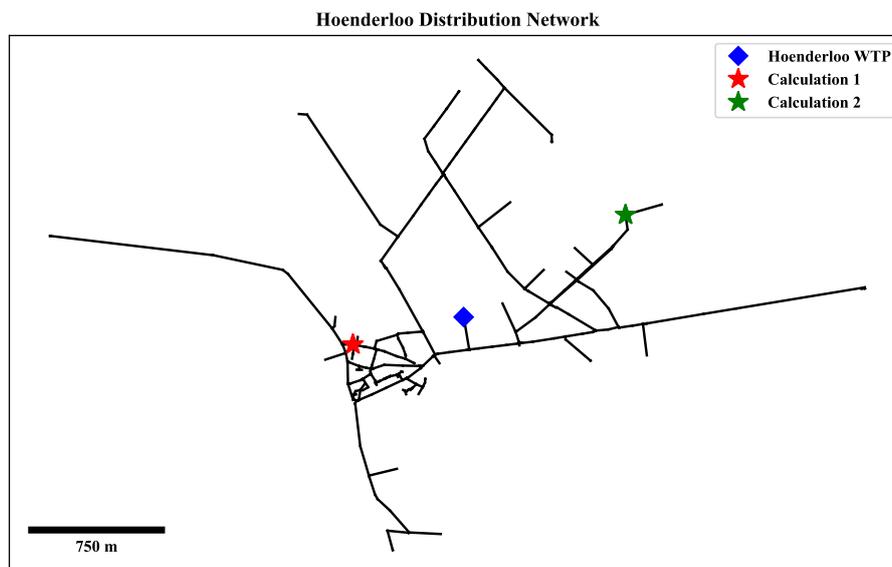


Figure 2. Schematic overview of the Hoenderloo distribution network and two virtual sampling points.

2.3 Modeling Approach

To simulate the water quality inside the treatment plant a hydraulic model of the pipes, pumps, valves and reservoirs was made using network simulation package EPANET [2]. This hydraulic model was then linked with process information from the plants SCADA systems, such as valve position, reservoir level and pump speeds, to attain a real-time prediction of the water flows and pressures inside the treatment plant. Chemical calculation software PHREEQC [3] was used for mixture calculations and for simulating quality changes inside the treatment processes.

Hydraulic Retention Time

To account for the hydraulic retention time the model divides the pipes inside the treatment plant and the distribution network into segments with a dynamic volume. This approach differs from previous attempts to integrate PHREEQC and EPANET [4]. Instead of tracing a predefined set of parameters through the network and assembling PHREEQC solutions at each node, this approach follows discrete volume blocks of solutions through the network using a Lagrangian time-based approach [5]. A schematic representation of the model setup is presented in figure 3.

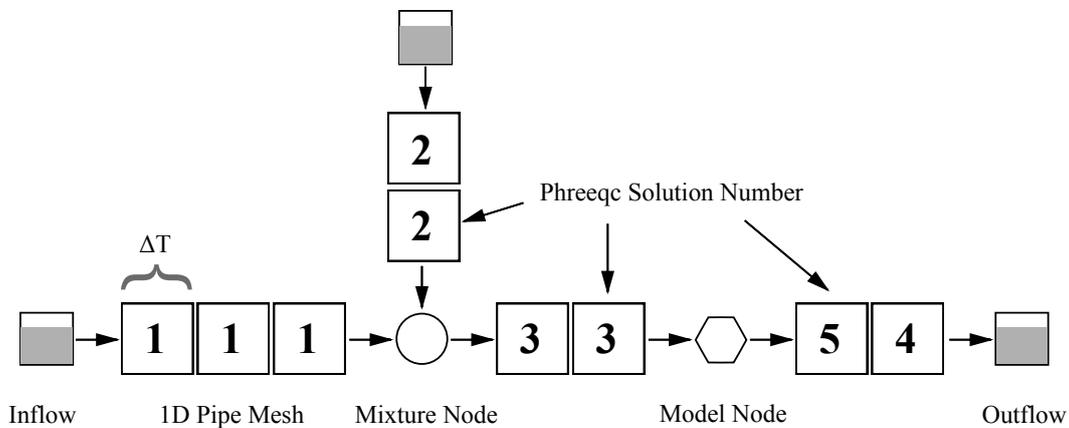


Figure 3. Schematic overview of the model setup

The volume of the segments is chosen to represent the volume of water moved through that segment during a single time step. Each package is linked to a PHREEQC solution number which refers to all the information about the solution such as temperature, ion composition, redox state and activity.

The resulting arrays of integers are pushed with the solution number of the upstream node and subsequently popped from the downstream node. When the flow inside the pipes and treatment processes changes the arrays are resampled to a new length using either nearest neighborhood interpolation for a fast yet relatively imprecise calculation or linearly interpolated and mixed for a more computationally intense but more precise calculation. An overview of the array manipulations is presented in figure 4.

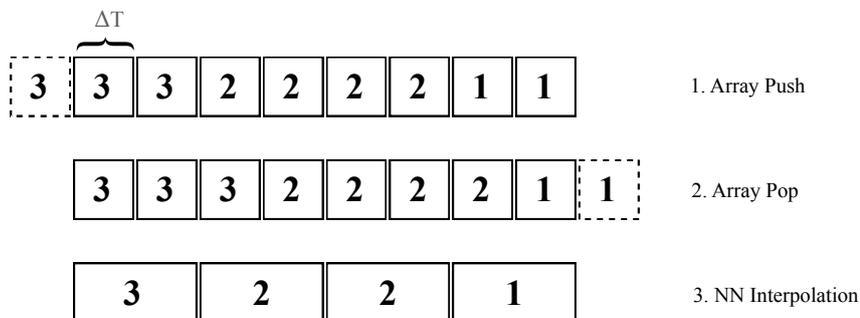


Figure 4. Array manipulations

In mixture nodes the water from multiple segments is mixed and the new water quality entering the downstream segments is calculated from the ratio of water supplied by the upstream segments. To cut down on the number of tracked solutions a new mixture is only calculated if the mixture ratio of upstream solutions differs from the previous time step by a user specified margin.

In model nodes the impact of treatment processes on the water quality is simulated. For the Hoenderloo model the performance of the treatment processes was chosen as a fixed value based on historic lab measurements and thus not time and state dependent. The marble filters, for example, were set to always dissolve the amount of calcite to reach a saturation index (SI) of -0.2, regardless of runtime or bed condition.

Water quality changes inside the pipes due to interaction with the pipe walls, dispersion and decay reactions were not modeled.

Reservoirs and Storage nodes

Storage in reservoirs and other volumes of water is schematized as continuous ideally stirred tank reactors (CISTRs), assuming that all water that enters the reservoir is instantaneously and completely mixed with the water already in the reservoir. Assuming no quality changes inside the CISTR occur the quality of the solution inside the reactor at time step $t + \Delta t$ can be described as a mixture between the solution entering the reactor during Δt and the solution inside the reactor at time t using:

$$F_1 = 1 - e^{-\frac{Q}{V}} \quad F_2 = 1 - F_1$$

With F_1 the fraction of new solution entering the reactor, F_2 the fraction of solution present in the reactor at time t , Q the flow rate into the reactor and V the volume of water inside the reactor.

3 RESULTS

3.1 Model Validation

To validate the model the electrical conductivity of the water at several points inside the treatment plant was measured for the duration of several days and compared with the electrical conductivity calculated from the water composition using PHREEQC. Conductivity is a good indicator for the ion composition of the solution and is simple, robust and continuously measurable, as opposed to manual sampling followed by lab analysis.

3.2 Incoming Water Quality

The conductivity of the incoming water from the deep well field was measured once every minute and compared with the calculated conductivity (figure 4). The conductivity was calculated using PHREEQC from the ion composition of the water abstracted by the different wells, which are sampled yearly. The spikes in conductivity occurring on 12 December between 10:00 and 19:00 were found to be caused by residual water in the piping system between the groundwater wells. For some pump switch scenarios the newly enabled pump first has to push a plug of residual water before its own water arrives at the treatment plant, resulting in the aforementioned short spikes in incoming water quality. The water quality prediction of the undeeper well field (not pictured) gave an equal fit.

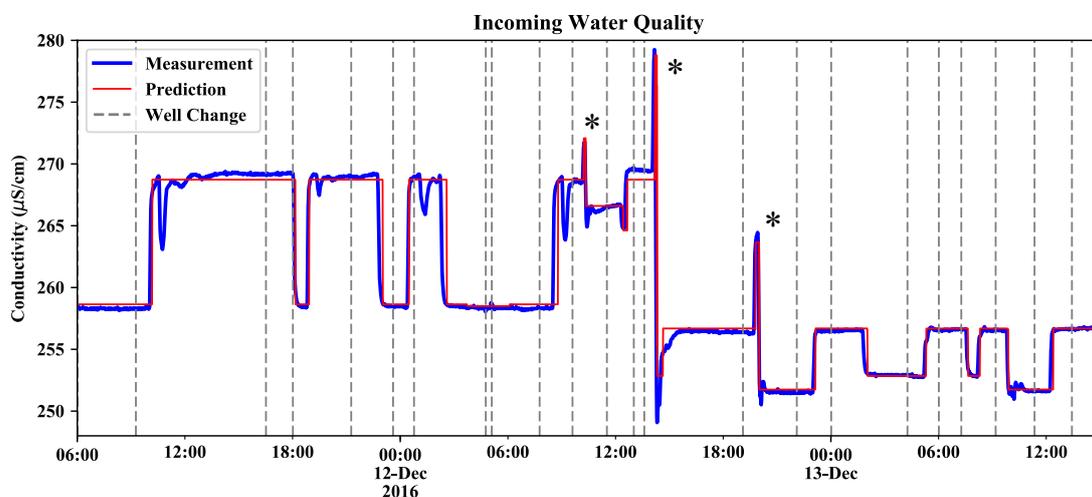


Figure 4. Measured versus modelled electrical conductivity of the incoming water from the deep well field. Spikes in the raw water conductivity are annotated with an asterisk

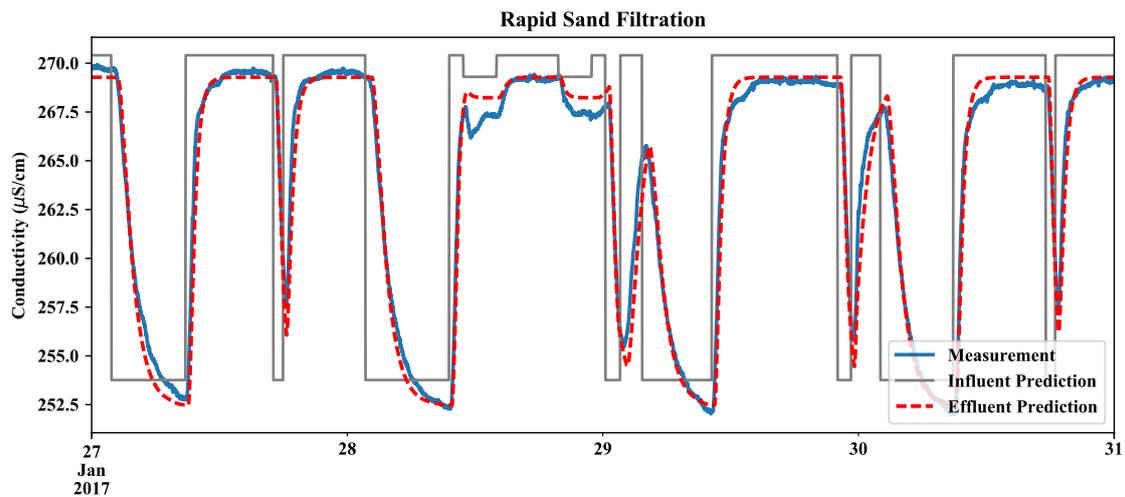


Figure 5. Measured versus modelled conductivity of the effluent of rapid sand filter 4

3.3 Spray Aeration and Rapid Sand Filtration

Inside the rapid sand filters the sharp changes in incoming water quality are dampened due to the residence time and mixing inside the treatment process. By modelling the rapid sand filters as a CISTR (supernatant layer) followed by a plug flow (filter material) and another CISTR (filtrate storage) an accurate prediction of the filter effluent was attained.

The spray aeration process was simulated based on lab measurements as 80% effective for oxygenation and 50% effective for CO₂ removal. Inside the sand bed iron was removed until a saturation index (SI) of 0.0 for Fe(OH)₃ was reached and a manganese removal of 98% was assumed, regardless of filter load and filtration velocity. The removal of ions from the solution results in a slight reduction in conductivity between the influent and effluent of the filter, as can be seen in figure 5. Inside the marble filters (not figured) the SI of calcite was modelled to increase to -0.2.

3.4 Clear Water Storage

The combined water from the sand and marble filters enters the clear water storage reservoir, modelled as a CISTR with a volume ranging between 1000 and 700 m³. The measured versus modelled conductivity of the water entering and leaving the reservoir is presented in figure 6. A discrepancy was found between the predicted and measured conductivity on the 22nd of February. Although presumably caused by an unregistered well change no exact cause has been found and therefore remains under investigation. As the conductivity of the water is calculated by PHREEQC from the ion composition, a prediction of the ion composition of the clear water can be made (figure 7).

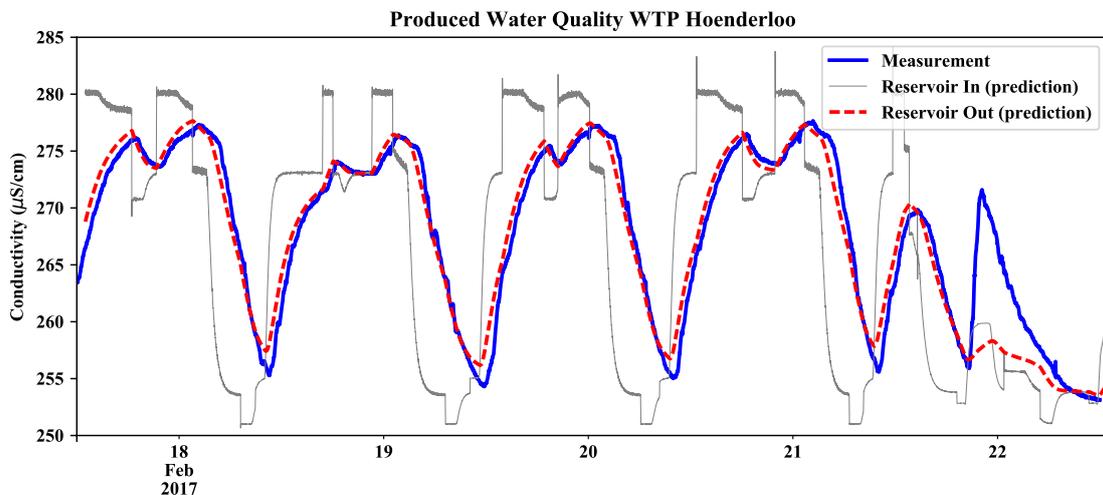


Figure 6. Measured versus modelled conductivity of the clear water produced by the Hoenderloo WTP

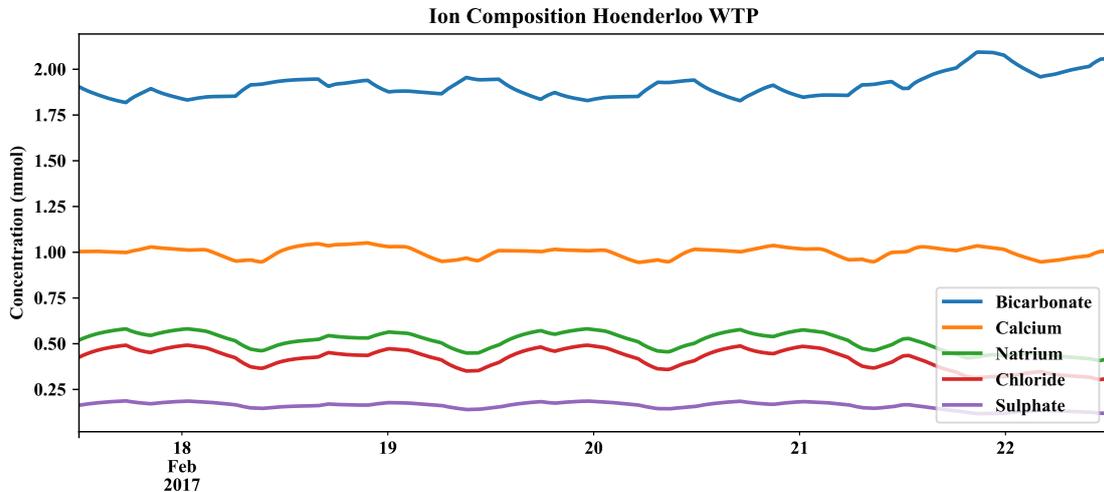


Figure 7. Modeled concentration of the five major ions in the clear water produced by the Hoenderloo WTP.

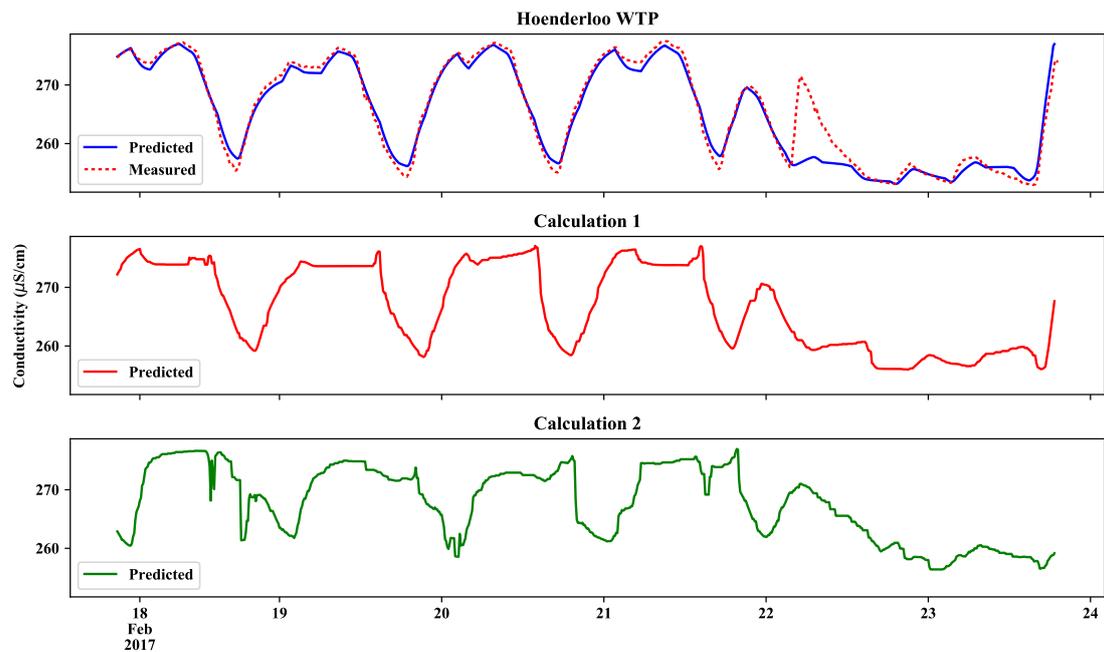


Figure 8. Modeled and measured effluent conductivity of the Hoenderloo WTP (top) and the predicted water quality delivered to customers at two locations (see figure 2) inside the Hoenderloo distribution network (middle and bottom)

3.5 Delivered Water Quality

Applying the same approach of using discrete volume blocks of a specified solution the water leaving the Hoenderloo clear water reservoir was traced through the Hoenderloo town distribution network. The water quality delivered to customers at two points inside the network, one in the town center and one in the outskirts, was calculated, as is presented in figure 8.

Inside the town center the pattern of the water quality produced by the WTP is clearly identifiable, albeit delayed by the travel time and distorted by changes in water consumption during the day. At the outskirts of the town, with lower water consumption and longer residence times of the produced water, the WTP effluent pattern is harder to identify. In addition, stagnant water in pipes that switch flow direction multiple times during the day, further influencing the water quality delivered to the customer. As of yet no conductivity measurements inside the distribution network have been done to validate the functioning of the model.

DISCUSSION AND CONCLUSIONS

By linking hydraulic simulations in EPANET with chemical simulations in PHREEQC a prediction of the real-time water quality delivered by the Hoenderloo WTP could be made. The chosen approach, following discrete packages of solutions through the raw water supply lines and treatment processes proved sufficiently accurate to predict the conductivity of the water at every point inside the treatment plant. Because the model uses the complete ion composition of every abstraction well as input a prediction of, for instance, the amount of sodium, chlorine and hardness can be made. In addition, predictions of the pH and Calcium Carbonate Precipitation Potential (CCPP), the most relevant parameters from a consumer perspective, can be made as well. The accuracy of this prediction, however, remains to be tested.

The influence of travel time in the raw water pipes leading to the treatment plant proved to be significant, with the impact of well changes taking anywhere between 1 and 4 hours, depending on the production rate of the treatment plant, to arrive at the installation. Changing the treatment intensity and chemical dosage immediately after changing wells, an approach currently used at several of Vitens's treatment plants, is therefore not efficient and can even be counter-productive. With well changes following in rapid succession chances are that, by the time the expected water quality arrives at the treatment plant, another set of wells is already running.

Although for this model the use of static aeration and filtration models proved sufficient to predict the effluent quality, future iterations of the model will include more advanced and dynamic treatment models. This will allow for a better prediction under non-standard conditions such as during maintenance works and will allow for a more optimal control of the treatment process. For instance, in several of the other treatment plants Vitens employs a similar treatment train as installed in Hoenderloo is used as a pre-treatment for a pellet softening installation. Being able to precisely predict the water quality entering the softener and the required chemical dosage is not only expected to lead to a significant decrease in chemical use but will also result in water of a more constant quality leaving the WTP.

The same approach to trace the water quality through the treatment plant can be applied to trace the clear water through the distribution network. With further improvements in the near future this technique can and will be applied to proactively inform our customers about the water quality they receive.

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