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Hydraulic modelling of drinking water treatment plant operations

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Abstract

For a drinking water treatment plant simulation, water quality models, a hydraulic model, a process-control model, an object model, data management, training and decision-support features and a graphic user interface have been integrated. The integration of a hydraulic model in the simulator is necessary to correctly determine the division of flows over the plant's lanes and, thus, the flow through the individual treatment units, based on valve positions and pump speeds. The flow through a unit is one of the most important parameters in terms of a unit's effectiveness. In the present paper, a new EPAnet library is presented with the typical hydraulic elements for drinking water treatment processes. Using this library, a hydraulic model was set up and validated for the drinking water treatment plant Harderbroek.

1 Introduction

Water supply companies are gradually changing to a centralized, fully-automated operation. This will bring a more standardized and stable operation and as a consequence, a higher and more stable water quality, but fully-automated operation introduces a risk as well. This risk, the erosion of the skills and knowledge of the operation supervisors, can be dealt with through training, using a drinking water treatment simulator. Within this simulator, a simulator engine must connect water quality models, a hydraulic model, a process-control model, an object model, training and decision-support features and a graphic user interface (Worm et al., 2008). The integration of a hydraulic model within the simulator is necessary because interventions, such as the adjustment of valve positions or pump speeds, will lead to a change in the division of flows through the plant and, thus, in the flow through the individual treatment units. The flow through a unit is one of the most important parameters in terms of the unit's effectiveness. Furthermore, the presentation of actual flows and levels in the simulator is essential for acceptance by its end users. Hydraulic model studies are commonly part of the design of a drinking water treatment plant (Hranisavljevic et al., 1999) but have been generally limited to a single treatment step (Gallard et al., 2003; Van Schagen et al., 2006). The modelling software EPAnet is used worldwide to design water distribution networks and the optimization of its operation, up to a level of full integration with SCADA (supervisory control and data acquisition) systems (Martínez et al., 2007; Fontenot et al., 2003). The current EPAnet library, however, lacks elements that describe the hydraulic properties of drinking water treatment plant units such as wells, aerators and rapid sand filters. In this study the use of EPAnet to build a hydraulic model of a drinking water treatment plant is reported. The model provides an opportunity for online control of the hydraulic behaviour of a drinking water treatment plant. The case of drinking water treatment plant Harderbroek, consisting of cascade aeration, rapid sand filtration and tower aeration is reported.

2 Materials and methods

2.1 Library and model setup

In EPAnet (version 2.00.12) six types of valves are available (Rossman, 2000), of which four were used in the treatment plant library. A pressure sustaining valve (PSV) was used to maintain a fixed pressure at the upstream junction in the model by adding a specific head difference to the elevation of the junction:

$$H = \text{elevation}_{\text{upstream junction}} + \Delta H$$

where ΔH is the setting of the PSV. If the sum of the elevation and the specified head difference exceeds the actual head in the junction, the actual head is the result. A pressure breaker valve (PBV) forces a specified pressure loss to occur across the valve and does not represent a true physical device:

$$\Delta H = H_{\text{upstream junction}} - H_{\text{downstream junction}}$$

where ΔH is the setting of the PBV. A throttle control valve (TCV) simulates the behaviour of a fully-opened or partially-closed valve according to:

$$\Delta H = \xi \cdot \frac{v^2}{2 \cdot g}$$

where the setting for the TCV is ξ, which is constant for a valve with a fixed position. The general purpose valve (GPV) has a specific flow – head loss relationship. This relationship can be linear or quadratic, as well as custom defined. The library with the models for well abstraction, cascade aeration, tower aeration and rapid sand filtration with a controlled, fixed water level is given in Table 1. These models are described in the next sections based on the four elementary blocks of EPAnet. For all pipes in the model, the roughness coefficient k is 0.1 mm.

2.1.1 Wells

The groundwater level in the aquifer is modelled with a reservoir; the drawdown is modelled by a GPV with a linear relationship to the abstracted flow (Moel et al., 2006).

2.1.2 Cascade aeration

The points of interest in a cascade aerator, from a hydraulic perspective, are the level of the upper weir and the water level in the last cascade step, or the collection canal or pipe of the cascade effluent. The setting of the PSV is the level of the crest of the upper cascade. The GPV represents the height of the water surface above the upper weir. The GPV flow – head loss relationship of the upper weir is calculated for a sharp-crested weir corrected for contractions on both ends of it (Daugherty et al., 1985), assuming the value for the discharge coefficient C_D is 0.62:

$$Q = 1.84 \cdot (L - 0.1 \cdot n \cdot H) \cdot H^{3/2} \tag{1}$$

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where Q is flow (m^3/s), L is the width of the weir (m), n is the number of end contractions and H is the difference in level between the crest and the water in an undisturbed zone in front of the weir (m).

2.1.3 Rapid sand filtration

The library contains a representation of a rapid sand filter with a fixed water level during the runtime, using a pump or control valve in the effluent pipe that compensates for the increasing filter bed resistance. The total resistance over the filter is mainly caused by the water inlet, the filter bed, the filter bottom nozzles, the effluent pipe inlet and the control valve or pump. The water inlet can be modelled either with a pipe in the case of a siphon, with a TCV in the case of a valve, or with a GPV and a PSV in the case of a weir. The pressure drop over the filter bed increases in time as a consequence of clogging and is calculated using a separate water quality model. For a static calculation, the pressure drop as a consequence of clogging is considered to be fixed, and therefore is modelled using a PBV. For the interaction between the EPAnet model and a water quality model in a drinking water treatment plant simulator, see (Worm et al., 2008). The resistance of the filter bottom nozzles can often be derived from the specifications of the manufacturer and the number of nozzles. Because of the increasing resistance with increasing flow, the nozzles can be modelled using a TCV. In practice however, the pressure drop over the nozzles during filtration will be negligible. TCV 2 simulates the behaviour of the control valve.

2.1.4 Tower aeration

In a tower aerator, water is distributed over a column with packing, through which air is blown. From a hydraulic perspective, the tower aerator is modelled in the same way as the cascade aerator. The height of the weir, plus the flow on top of the crest of the weir, is modelled using a PSV and a GPV.

2.2 Drinking water treatment plant Harderbroek

The drinking water treatment plant Harderbroek, owned and operated by Vitens, consists of 16 wells, four cascades, eight rapid sand filters and three tower aerators. The model was set up using the hydraulic line scheme of the plant, P&IDs and other technical drawings.

2.2.1 Wells

The wells are grouped in two series of seven. Each well is equipped with a submerged pump, which has been added to the model. In each series, one well is equipped with a speed-controlled pump, the other six are equipped with fixed-speed pumps. The water level inside and outside each well is measured and logged, as is the flow per well. For accuracy in the model, the water level measurement inside the well has been used instead of the groundwater level minus the drawdown estimation. The value of the measurement is the distance between the water level and the sensor at −13.3 m+NAP (Dutch standard level). The pumps' curves are available.

2.2.2 Cascades

The top of the weir of each of the four cascades has a level of 4.71 m+NAP. The relationship between flow and water level is calculated with Eq. (1) above. In a normal operation, three cascades are in operation. After aeration the water from the cascades is collected in the rapid sand filter influent canal.

2.2.3 Rapid sand filters

Each rapid sand filter is fed using an open/close valve and a weir. Each filter has a speed-controlled pump in the effluent pipe that controls the water level in the filter at a fixed level. This pump replaces the control valve in the library's model. The water level is measured, and so are the pressure drop over the filter and the pressure under the bottom of the filter. The value of the water level measurement equals the distance from the sensor at 3.80 m+NAP to the water level. The speed of the pump is shown as a percentage, where 0% equals an electricity frequency of 15 Hz and 100% equals an electricity frequency of 58 Hz. The pump's curves are available. In normal (i.e. average) operation, four rapid sand filters are in operation.

2.2.4 Tower aerators

The countercurrent tower aerators have a weir on 6.08 m+NAP. This is the head that the rapid sand filter pumps face upstream. During normal operation, two aerators are in use, and change according to a fixed scheme. Downstream of the aerators, the head in the pipes is determined by the level of the clear water reservoirs.

2.3 Modelling approach

To enable integration of the EPAnet model with other systems, iteration within the model was minimized. The model calculates the static hydraulic situation in the water treatment plant for the actual settings (in EPAnet by choosing the total duration of a model run to be zero). To calculate the resistance in the pipes, the Darcy-Weisbach equation is used. The scope of calibration and validation covered the part from the well to the clear water reservoir, without the rapid sand filter backwashing. Calibration focused on the minor loss coefficients affecting the distribution of flows over the cascades and the rapid sand filters. Validation focused on the production of the wells at given (inner) well water levels, on the division of flows over the cascades, and on the flows through the rapid sand filters for given pump speeds and water levels. For calibration and validation, nine datasets from the full-scale plant were used within the period 28 June to 23 July.

Calibration. From the randomly picked dataset on 28 June at 10:30 h, the following input for the model was selected: well water level, the operation of the well pumps ("on" if flow exceeds zero), the operation of the cascades ("on" if flow exceeds zero), the operation of the rapid sand filters ("on" if flow exceed zero), the water level in the rapid sand filters, the speed of the rapid sand filters' effluent pumps, the operation of the tower aerators and the estimated levels in the clear water reservoirs. The speeds of the two speed-controlled well pumps were set manually to match the flow of the historic data because the pump speeds were lacking in the dataset. The model results of the following parameters were compared with the historic data: flow per well (not the wells containing the two speed-controlled pumps), flow per cascade, influent per filter and effluent per filter.

Validation. For the validation, the same input and output parameters were used as for the calibration. Four validation experiments were carried out: one for the flows from the wells, one for the flows over the cascade aerators, one for the influent and one for the effluent of the rapid sand filters. The experiment consisted of the comparison of the calculated and historic data. For each experiment two moments were selected with a minimum flow, two with an average flow, two with a maximum flow and two during the backwash of a rapid sand filter. Moments with minimum flow occurred on 7 July at 23:30 h and 21 July at 19:30 h; moments with an average flow were on 8 July, 10:30 h and 17 July, 10:30 h; with a maximum flow were on 30 June, 15:30 h and 1 July, 15:30 h; and with the situation during backwash of a rapid sand filter were on 4 July, 17:30 h and 23 July, 11:30 h.

3 Results and discussion

Figure 1 shows the model layout. The 16 wells can be recognised in the left part of the model, the four cascades, the eight rapid sand filters and the three tower aerators in the center and on the far right are the two clear water reservoirs.

Calibration. Pipe roughness coefficient k was kept constant during calibration. The loss coefficient of the feeding pipe to cascade 4 was decreased from 2 to 0 to meet the measured data. The loss coefficient of the inlet valves of the rapid sand filters was decreased from 2 to 1 to optimise matching the influent and the effluent from the rapid sand filter.

Validation. For the wells, 55 data points were collected. The model shows good results compared to the historic data, Fig. 2. The average of the absolute errors is 3.6%. For the cascade aerators, 22 data points were used. The model results approach historic data as well, see Fig. 3. The average of the absolute errors is 2.4%. For the rapid sand filters' influent, the average of the absolute errors is 4.4%, based on 34 data points, seen in Fig. 4. During validation of the effluent flow of the rapid sand filters, the pressure drop measurements over the filter beds of filters 5, 6 and 8 sometimes appeared to be unrealistically small. In those cases, the pressure drop was estimated by subtracting the pressure measured in the effluent pipe from 26 kPa, that being the average pressure of a non-operating filter. For the rapid sand filters' effluent, the average of the absolute errors is 4.7%, based on 34 data points, see Fig. 5. In four cases, most probably as a consequence of accelerating during start-up, pump speeds were more than 20% below the low value of the normal range. In these cases, the pump speeds were replaced by the average speed of the pump. No historic data were available for the flow over the tower aerators. For all validation results, it should be noted that any possible inaccuracy of the measuring equipment was not taken into account.

3.1 Case: backwashing of a rapid sand filter

During backwashing of a rapid sand filter, either the other filters increase the filtration rates or another filter takes over. For a flow of 1015 m^3/h, five rapid sand filters are in operation, see Fig. 6. During backwashing of a rapid sand filter, the flow of the filter is divided over the four other filters. The speeds of the four effluent pumps increased 20%. The resulting filtration rates are between 250 and 260 m^3/h, high enough for the process-automation system to take a fifth filter in operation.

4 Conclusions

Modelling software EPAnet can be used to model the hydraulic behaviour of drinking water treatment plants by using the library described in this paper, containing models for a well, a cascade aerator, a rapid sand filter and a tower aerator. A model was set up for drinking water treatment Harderbroek. The resistance, or series of resistances, at each treatment step was schematized by a series of the basic EPAnet elements valves, reservoirs, junctions and pipes. The model was calibrated and validated with historic full-scale plant data. A treatment plant library was developed to describe the resistance at each treatment step.

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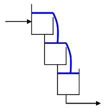
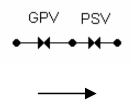
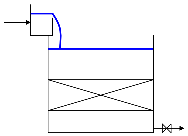
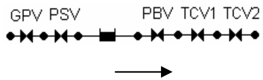
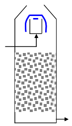
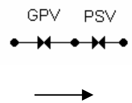
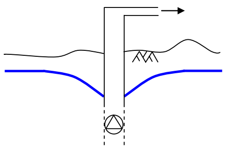
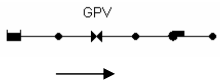
Table 1. Treatment step library.

Treatment unit		EPAnet model
Cascade aeration		
Rapid sand filter (fixed water level)		
Tower aeration		
Well abstraction		

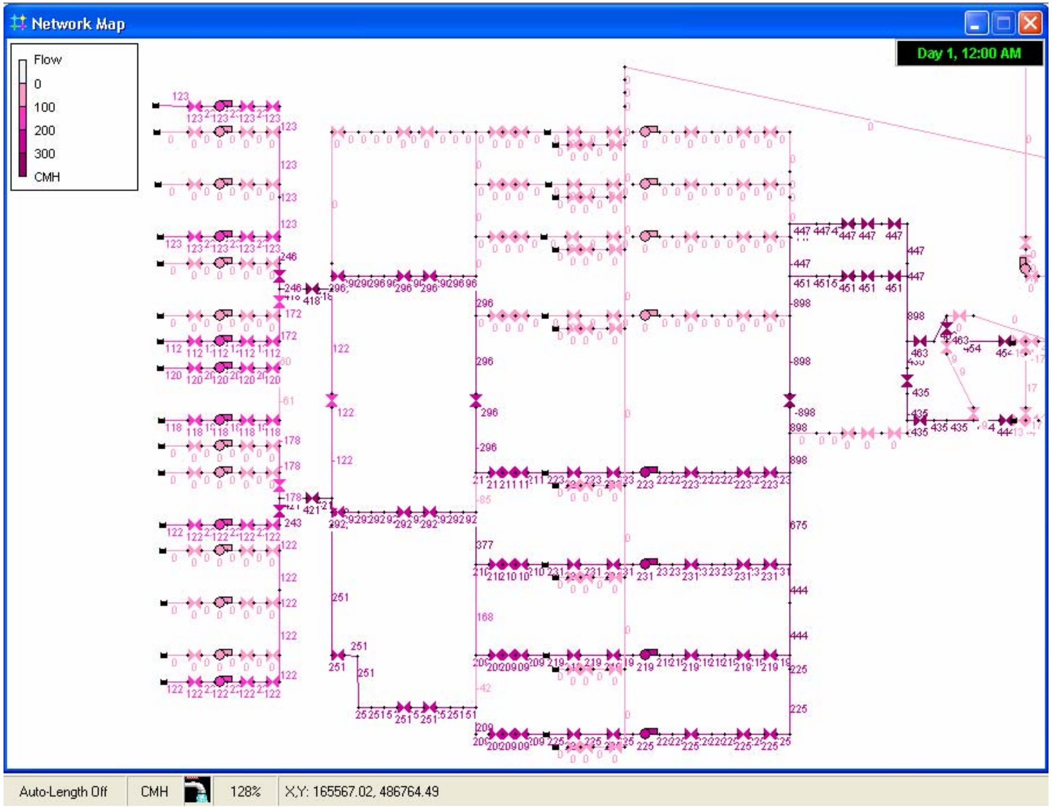


Fig. 1. Layout of the Harderbroek model.

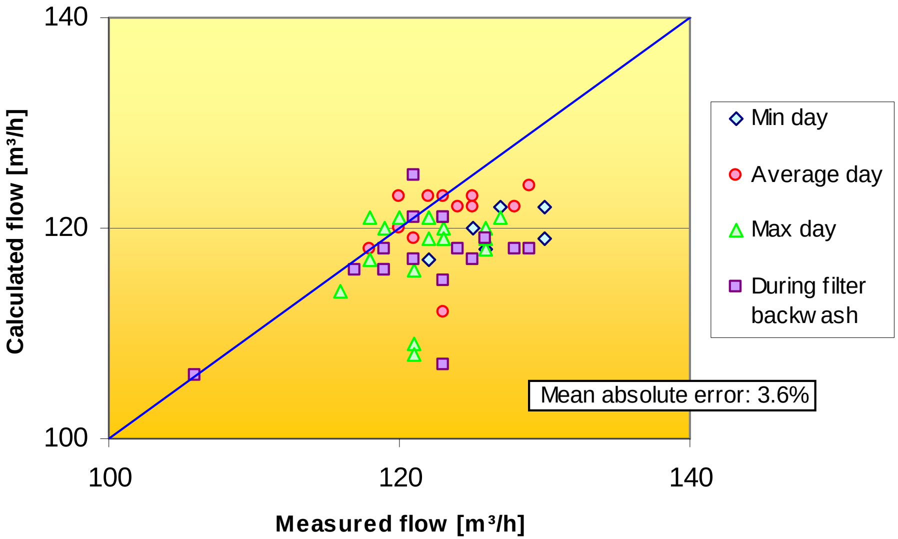


Fig. 2. Validation results of flows from wells. Days with minimum flow (Min day): 7 July, 23:30 h and 21 July, 19:30 h. Days with average flow (Average day): 8 July, 10:30 h and 17 July, 10:30 h. Days with maximum flow (Max day): 30 June, 15:30 h and 1 July, 15:30 h. Days with situation during backwash of a rapid sand filter (During filter backwash): 4 July, 17:30 h and 23 July, 11:30 h.

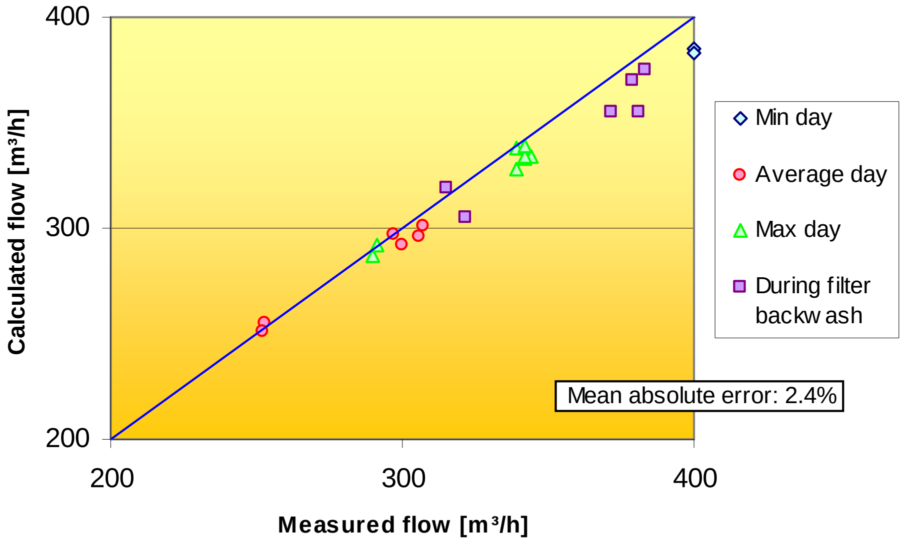


Fig. 3. Validation of flows in cascade aerators. Days with minimum flow (Min day): 7 July, 23:30 h and 21 July, 19:30 h. Days with average flow (Average day): 8 July, 10:30 h and 17 July, 10:30 h. Days with maximum flow (Max day): 30 June, 15:30 h and 1 July, 15:30 h. Days with situation during backwash of a rapid sand filter (During filter backwash): 4 July, 17:30 h and 23 July, 11:30 h.

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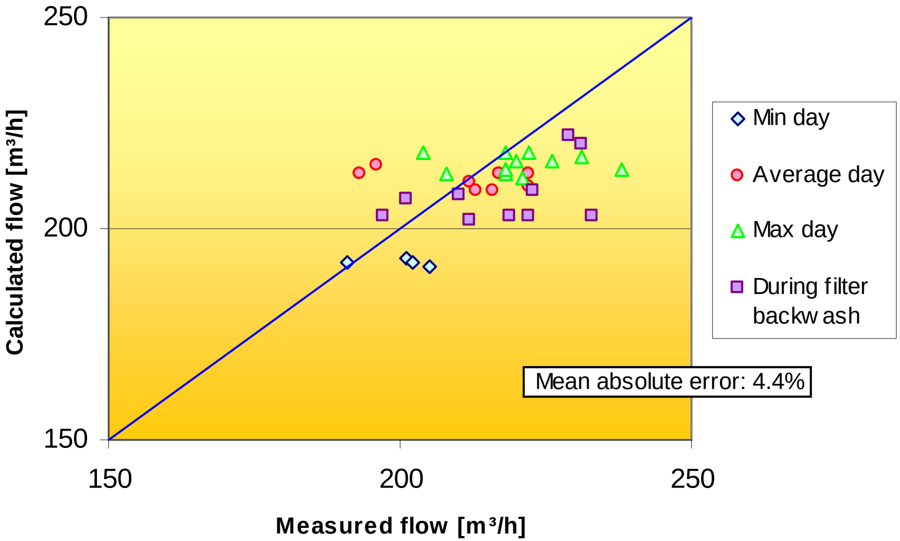

Fig. 4. Validation of influent flows rapid sand filters. Days with minimum flow (Min day): 7 July, 23:30 h and 21 July, 19:30 h. Days with average flow (Average day): 8 July, 10:30 h and 17 July, 10:30 h. Days with maximum flow (Max day): 30 June, 15:30 h and 1 July, 15:30 h. Days with situation during backwash of a rapid sand filter (During filter backwash): 4 July, 17:30 h and 23 July, 11:30 h.

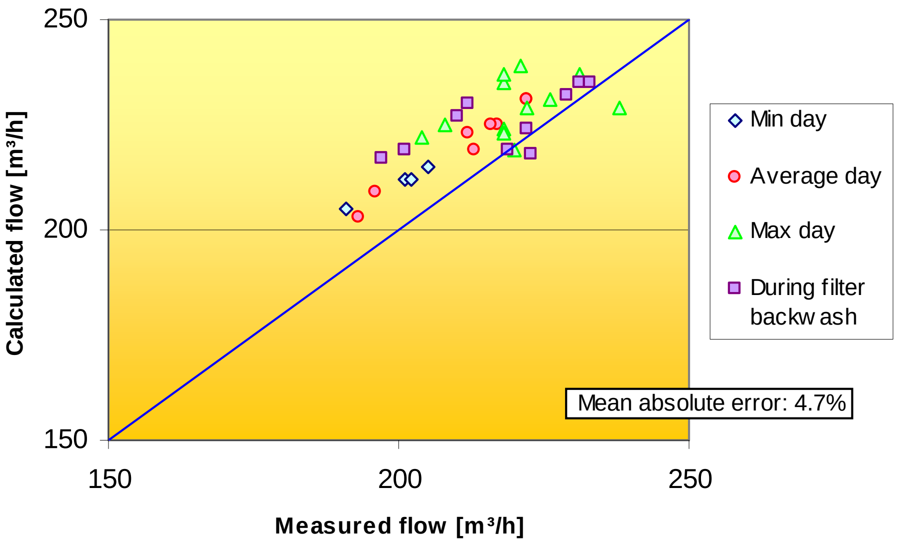

Fig. 5. Validation of effluent flows rapid sand filters. Days with minimum flow (Min day): 7 July, 23:30 h and 21 July, 19:30 h. Days with average flow (Average day): 8 July, 10:30 h and 17 July, 10:30 h. Days with maximum flow (Max day): 30 June, 15:30 h and 1 July, 15:30 h. Days with situation during backwash of a rapid sand filter (During filter backwash): 4 July, 17:30 h and 23 July, 11:30 h.

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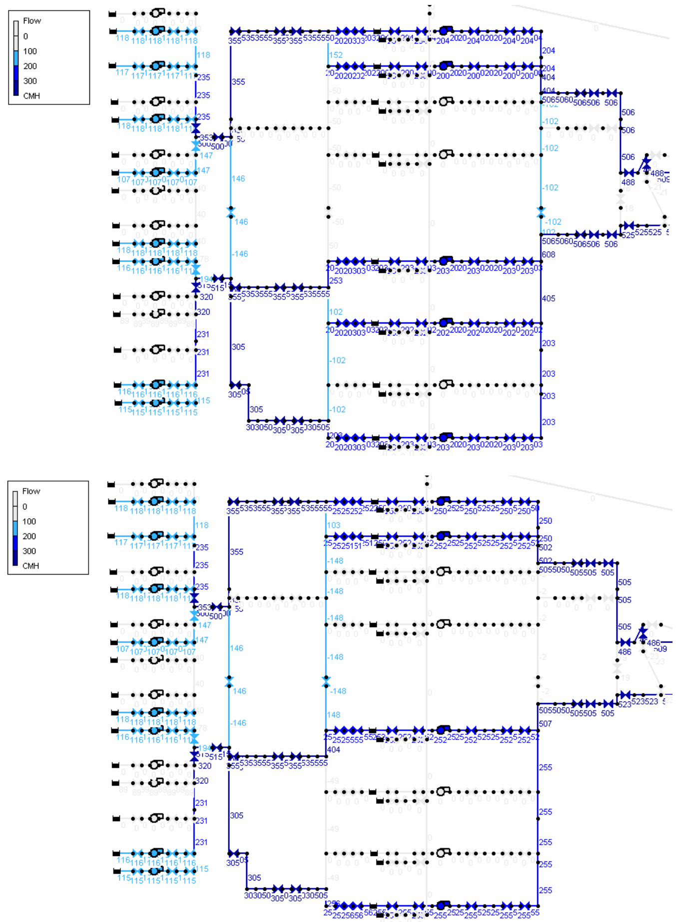

Fig. 6. With a flow of 1015 m^3/h, five rapid sand filters are in operation, see upper figure. During backwashing of one rapid sand filter, the flow of the filter is divided over the four other filters (lower figure). Speeds of the four effluent pumps increase by 20%.

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