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Drinking Water Engineering and Science Discussions

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A bottom-up approach of stochastic demand allocation in water quality modelling

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Abstract

An "all pipes" hydraulic model of a DMA-sized drinking water distribution system was constructed with two types of demand allocations. One is constructed with the conventional top-down approach, i.e. a demand multiplier pattern from the booster station is allocated to all demand nodes with a correction factor to account for the average water demand on that node. The other is constructed with a bottom-up approach of demand allocation, i.e., each individual home is represented by one demand node with its own stochastic water demand pattern.

The stochastic water demand patterns are constructed with an end-use model on a per second basis and per individual home. The flow entering the test area was measured and a tracer test with sodium chloride was performed to measure travel times. The two models were evaluated on the predicted sum of demands and travel times, compared with what was measured in the test area.

The new bottom-up approach performs at least as well as the conventional top-down approach with respect to total demand and travel times, without the need for any flow measurements or calibration measurements. The bottom-up approach leads to a stochastic method of hydraulic modelling and gives insight into the variability of travel times as an added feature beyond the conventional way of modelling.

1 Introduction

The goal of drinking water companies is to supply their customers with good quality drinking water 24 h per day. With respect to water quality, the focus has for many years been on drinking water treatment. Recently, interest in the water quality of a drinking water distribution system (DWDS) has been growing. Water age is an important aspect of water quality in a DWDS as it influences disinfectant residual, disinfection by-products, bacterial regrowth, coagulation, flocculation, sedimentation, corrosion and contaminant propagation. The key element of a water quality model for a DWDS is a detailed hydraulic model (Slaats et al., 2003; Vreeburg, 2007), which not only takes

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into account the maximum flows but also the flows at all other time steps (Powell et al., 2004; Slaats et al., 2003; Vreeburg and Boxall, 2007). A hydraulic model with an accurate simulation of the occurrence of turbulent and laminar flow and stagnant water is needed. Therefore, knowledge of the water demand on a detailed level is essential.

This requires a different approach in demand allocation, where the demands show less (auto)-correlation and are determined on smaller temporal and spatial scales (Blokker et al., 2008) than the conventional "top-down" approach of demand allocation (Blokker et al., 2008). Here, top-down demand allocation means that a demand multiplier pattern (DMP; e.g. measured at the pumping station) is allocated to the demand nodes with a correction factor to account for the average water demand on that node, thereby applying strongly correlated water demand patterns on all nodes. A different way is to use a "bottom-up" approach of demand allocation. This means that stochastic water demand patterns are modelled for each individual home and a unique water demand pattern is constructed for each demand node by summation of the individual household water demand patterns.

In this paper the top-down and bottom-up demand allocations in an "all pipes" hydraulic model are compared with respect to the resulting flow patterns and water age as measured in a tracer study. The bottom-up demand allocation was done with the use of the end-use model SIMDEUM (Blokker et al., 2009).

2 Methodes and materials

A distribution network of about 10 km of mains and 1000 homes was selected as a test area. In this network, the total flow was measured and a tracer study was performed to determine the water age at four locations in the network. An "all pipes" hydraulic model was constructed with two methods of demand allocation: one with a top-down approach of demand allocation with one unique DMP, and another with a bottom-up approach of demand allocation of individual stochastic demand patterns. The model results were compared to the measured flow and water age.

2.1 The network

The selected network is situated in the Dutch town Zandvoort, along the sea. The network was built in the 1950–1960's and consists of 3.5 km of PVC pipes, and 5.7 km of lined cast iron pipes (Table 1); it supplies about 1000 homes, 2 hotels and 30 beach clubs (Fig. 1). The area is supplied from one point with a fixed head through a booster pump.

The water use in the network was determined from the historic flow patterns at the booster station as measured by the Provincial Water Company Noord-Holland (PWN) and is, on average, 24 m^3/h. Domestic water demand is 70% of the total demand. As leakage in the Netherlands is generally very low (2–4%), no leakage is assumed in this network.

The drinking water is distributed without any disinfectant, as is common in the Netherlands. A tracer study with NaCl was done between 2 September and 20 October 2008.

2.2 Measurement setup for the tracer study

The tracer was added at the booster station; in the network, four measurement locations were selected (Fig. 1). Location 1 and location 2 are located near apartment buildings on a ⌀ 100 mm PVC and ⌀ 100 mm CI pipe. Location 3 is situated in the basement of the hotel. Location 4 is situated in the basement of a small apartment building of 15 residences.

Sodium chloride (NaCl) was used as a tracer and the electrical conductivity was measured. From these measurements, the travel time was determined. NaCl has several advantages for use as a tracer, viz. at a measurable dosage, it causes no disruption or health risk to customers; it yields results of good accuracy and is low-cost (Skipworth et al., 2002). At the booster location, NaCl was dosed to a fixed concentration in order to raise the electrical conductivity (EC, in mS/m) by a measurable amount: EC ≈57 mS/m without dosage, and EC ≈68 mS/m with dosage. The tracer was dosed in pulses of

3 h on and 20 h off. This means that, per day, one positive and one negative step input were induced.

In order to reach a fixed concentration, the incoming flow was measured (Tokimec UFP-10) and the dosage was controlled (Fig. 2). The booster pumps ensured a constant concentration of the tracer in the water over the pipe and a fixed head.

The (average) flow was logged every minute for 16 full days of flow measurements at the booster station and 11 full days of flow measurements at location 3. The measured flows are denoted $DMP_{booster}$ and DMP_{hotel}. The flow measurements at location 3 showed that the daily demand varied between 2.21 and 4.32 m^3/h and can be fitted on a Weibull distribution. Based on 11 days, the parameters of the Weibull distribution are estimated at $a = 3.247 \pm 0.4$ and $b = 4.741 \pm 1.7$.

At all four locations, the EC was measured (LIQUISYS M CLM223). At these locations, the pressure was also measured (3 Endress+Hauser Cerabar VU 130; 1 Endress+Hauser Cerabar M). The measurements required a continuous 40 l/h extraction. The EC measurement at the booster station was not logged; instead the dosage regime was recorded.

The water age between the booster station and locations 1, 2, 3 and 4 was determined by the time between the centres of the ascending and descending tails of the EC pulses and by the time between the weighted mean of the pulses (Fig. 3). The weighted mean is determined between the centres of the ascending and descending tails.

2.3 Hydraulic model and demand allocation

EPANET 2.0 (Rossman, 2000) was used as a hydraulic network model solver. Basically, two models were constructed that are distinguished by demand allocation. $Model_{TD}$ is the model with the top-down approach of demand allocation; $Model_{BU}$ is the model with the bottom-up approach of demand allocation.

The measurement locations 1, 2, 3 and 4 were assigned a continuous extraction of 40 l/h. No pressure dependent demands or leaks were introduced in the model.

The remaining demand allocation was conducted as follows:

1. In $Model_{TD}$ an identical DMP ($DMP_{booster}$, Fig. 4) was allocated to all demand nodes with a correction factor to account for the average demand. The base demand was assigned according to the demand category (Table 2). N.B. a demand node may serve multiple homes or beach clubs.

2. In $Model_{BU}$ different demand patterns were assigned to different demand category nodes (Table 2).

- To the beach club demand nodes, the same $DMP_{booster}$ and base demand as in the $Model_{TD}$ were assigned.

- To the hotel demand nodes, the measured DMP_{hotel} (Fig. 4) and base demand as in the $Model_{TD}$ were assigned. The NH hotel (measurement location 3) had a variable base demand randomly drawn from a Weibull distribution.

- To each residential demand node (small and large homes), a unique stochastic water demand pattern was assigned. The stochastic water demand patterns were obtained from the end-use model SIMDEUM (Blokker et al., 2009). Specific data about Zandvoort was used for household composition and water-using appliances (Table 3) as input into SIMDEUM. The residences type A (often apartments, mainly in the north) do not have a garden and no outdoor water use. In the south, residences type B (villas) are found. The census data were not used, because in the measurement period (late summer) it was expected that more people would be occupying the homes than only the inhabitants. For the $Model_{BU}$ 10, weekday patterns and 4 weekend day patterns were simulated.

The hydraulic and pattern time step was set to 15 min in the $Model_{TD}$ and to 5 min in the $Model_{BU}$; the quality time step was set to 1 min in both models.

2.4 Model validation

The $Model_{TD}$ was run once and the system flow and water age at four locations were determined. The $Model_{BU}$ was run 10 times with 10 different sets of stochastic water demand patterns and 10 different base demands at the NH hotel (location 3). The resulting system flow (Q_{SIM}) is the averaged pattern from the 10 resulting patterns; the resulting water age at the three locations was determined by the average and the 95% confidence interval of the 10 simulations. This 95% confidence interval is due to variation, not to uncertainty.

The resulting system flow Q_{SIM} was compared against the average measured flows $Q_{booster}$ on a time scale of 5 min. The measured water age at four locations and different times of day was compared to the modelled water age in the network. The difference between model and measurement is expressed by the Mean Error (ME), Root Mean Square Error (RMSE), and declaring variance R^2. The absolute values of ME and RMSE are expressed in hours; the relative values are percentages of the measured travel times. For the $Model_{TD}$ all average modelled values were compared with the measured data. For the $Model_{BU}$ all modelled values between $\mu - 2\sigma$ and $\mu + 2\sigma$ were compared with the measured data; the modelled value closest to the measured value was used to determine the statistical measurements.

3 Results

3.1 Demand multiplier pattern

The modelled and measured flow patterns at the booster station were compared. By looking at the diurnal pattern we can get a feel for how well the model resembles reality. To quantify the resemblance, the auto- and cross-correlation of the flow patterns were considered. The cross-correlation between the flow patterns shows how well the modelled flow patterns fit the measured flow patterns; cross-correlation can be established for different time lags, which shows if the modelled flow patterns exhibit a delay with respect to the measured flow patterns. The auto-correlation of the flow patterns shows how variable the flow patterns are.

Figure 5 shows the diurnal pattern. The modelled flow pattern has a more distinct morning peak than the measured pattern. The simulated pattern shows a later decline to low night use than the measured flow. The small peaks around 04:00 a.m. are due only to the hotel's demands. The modelled flow shows these peaks because the beach clubs have them in the applied $DMP_{booster}$ and the hotels have them in the applied DMP_{hotel}. These two peaks were most likely related to cleaning.

Figure 6 shows that the modelled flow pattern has a smaller auto-correlation than the measured flow pattern. The cross-correlation between $Q_{booster}$ and Q_{SIM} is at a maximum of 0.9 at a time lag of 0, i.e. there is no delay. The morning peak of Q_{SIM} coincides with the morning peak of $Q_{booster}$ (Fig. 5).

3.2 Water age

At locations 1, 2 and 4 the measured EC resembles the rectangular pulse at the booster station and the centres of the ascending and descending tails and the weighted means between those centres can easily be determined (Fig. 7). Each pulse at the booster station led to 3 measured travel times at those locations, 138 measurement points in total at each location. At location 3, the pulse changed shape due to mixing and dispersion, and often more than one pulse can be seen (Fig. 7). The travel time can only be determined at the ascending tail of the pulse. Each pulse at the booster station led to 1 measured travel time at location 3, 46 measurement points in total.

Figure 8 shows the measured and modelled water age over the day at the four measurement locations; Table 4 summarises the statistics. Depending on the network layout and the measurement location, the maximum water age is reached around 07:00 a.m., which is related to low night use. The fast decrease in water age after the maximum is related to the peak in demand in the morning. The 95% confidence interval of the water age in the $Model_{BU}$ is the largest for location 4 in the looped network layout because there are only 15 homes present behind the measurement location. The individual behaviour of the people in those homes has a large effect on demand and thus on travel time.

The average and 95% confidence interval of the water age from the $\mathrm{Model_{BU}}$ and the water age from the $\mathrm{Model_{TD}}$ with $\mathrm{DMP_{booster}}$ were compared with the measured water ages. Most of the measured water ages are confined by the 95% confidence interval of the Model_{BU} results. For all locations the $\mathrm{Model_{BU}}$ predicts the water age better than $\mathrm{Model_{TD}}$. Both models predict the water age with a ME and RMSE of less than 30%, except for location 1 where the $\mathrm{Model_{TD}}$ significantly underestimates the measured water age. The R^2 of the $\mathrm{Model_{BU}}$ is >67%, for the $\mathrm{Model_{TD}}$ R^2 is not a meaningful value, and therefore it is not shown in the table.

4 Discussion

It is possible to construct accurate water demand patterns with the end-use model SIMDEUM. In this paper the flow pattern as measured in an area of 1000 homes ($\mathrm{Q_{booster}}$) was compared with the flow pattern from the simulated water demand patterns of the model ($\mathrm{Q_{SIM}}$). The $\mathrm{Q_{SIM}}$ fit the $\mathrm{Q_{booster}}$ well with a cross-correlation of almost 90%.

The night use of the simulated flows closely matched the measured flows. This indicates a very low leakage in this network. The hotels and beach clubs did not have a residential demand pattern assigned to them; instead, measured DMP were used. The beach clubs had an average demand of 9% of the total DMA demand; the average demand of the hotels is 23% of the DMA demand. It would be an asset if SIMDEUM could be extended to not only simulate residential water demand, but also the demand by hotels, for example.

It is possible to construct a water age model with accurate water demand patterns using the bottom-up approach without the need for calibration on demands; i.e. an ME and RMSE of less than 25% and an R^2 of more than 70% are obtainable. The water age is predicted better with the stochastic bottom-up approach of demand allocation than with the commonly used top-down approach of demand allocation. This is the result of the stochastic nature of the bottom-up approach which provides information on the variability of water demand and thus the variability of water age. With the top-down approach it is also possible to introduce variability; based on two weeks of flow measurements 14 different DMP and 14 corresponding day factors (with values between 0.9 and 1.3) were imposed (Blokker and Beverloo, 2009). This resulted in a narrow 95% confidence interval around the mean, as shown in Fig. 8. This improved ME, RMSE and R^2 slightly, but the Model_{BU} still performed better (data not shown).

Both models resulted in similar flow patterns at the booster station and similar water ages at the demand nodes. The models had more distinct results with respect to flow direction reversals during the day and maximum instantaneous flow velocities (Blokker and Beverloo, 2009). The Model_{BU} showed a flow direction reversal in 30% of the pipes; the Model_{TD} showed it for only 15% of the pipes. The Model_{BU} resulted in 75% of the pipes in a greater flow velocity, which is on average 25% higher than with the Model_{TD}. In 12% if the pipes, the Model_{BU} resulted in a higher flow regime (turbulent or transitional flow, rather than laminar flow). These differences between the two models will affect water quality modelling where dispersion is significant, such as in the case of dissolved substances.

The bottom-up modelling approach is probabilistic in nature and offers a new perspective for assessing water quality in the drinking water distribution system. In the case presented, it shows that, especially at location 4, the variability is very high.

5 Conclusions

A bottom-up approach of demand allocation (i.e., water demand patterns are modelled stochastically per individual home and subsequently the individual water demand patterns are summed to obtain the water demand patterns at demand nodes) leads to a flow pattern that resembles the measured flow patterns of a DMA well (correlation of 90%). The individual demand patterns were obtained from the end-use model SIMDEUM without the need for any flow measurements.

A bottom-up approach leads to good results in predicting water age in a DMA-sized distribution network, i.e. an ME and RMSE of less than 25% and an R^2 of more than 70%. There is no need for measuring water demand patterns, nor for calibrating demand based on water quality parameters.

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Table 1. Pipe diameters and materials in network.

Diameter (mm)	Length (km)	
	CI	PVC
< 100		1.4
100	1.3	0.6
150	3.4	1.1
180		0.4
225	1.0	
total	5.7	3.5

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Table 2. Demands in $Model_{TD}$ and $Model_{BU}$, # units with given base demand are reported; these are not all connected to an individual demand node.

Demand category	$Model_{TD}$			$Model_{BU}$		
	#	base demand (m^3/h)	pattern	#	base demand (m3/h)	pattern
small beach club	21	0.05	$DMP_{booster}$	21	0.05	$DMP_{booster}$
large beach club	11	0.10	$DMP_{booster}$	11	0.10	$DMP_{booster}$
residence type A	100	0.015	$DMP_{booster}$	869	N.A.	SIMDEUM res. type A
residence type B	210	0.02	$DMP_{booster}$	210	N.A.	SIMDEUM res. type B
apartment building	25	≥ 0.30	$DMP_{booster}$	N.A. (moved to residence type A)		
apartment building, measurement loc. 4	1	0.20	$DMP_{booster}$			
NH Hotel	1	3.247	$DMP_{booster}$	1	Weibull distributed (a DPM_{hotel}=3.247, b=4.741)	
beach hotel	1	1.783	$DMP_{booster}$	1	1.783	DPM_{hotel}
Palacehotel	1	0.50	$DMP_{booster}$	1	0.50	DPM_{hotel}
measurement location	4	0.04	constant demand	4	0.04	constant demand
Total		24.0			22.9–26.5	

Table 3. Specific input data into SIMDEUM; data of Zandvoort Boulevard (1040 homes) in 2003–2007 (CBS).

		Zandvoort Boulevard	SIMDEUM residence type A	SIMDEUM residence type B
Households	One person households	56%	34%	20%
	Household without children	34%	30%	34%
	Household with children	10%	36%	46%
	Average household size	1.6	2.3	2.7
Age distribution	0 to 12 years old	4.8%	15%	4.8%
	12 to 21 years old	3.7%	10%	3.7%
	21 to 65 years old	62.5%	63%	62.5%
	65 years and older	29%	12%	29%
Water using appliances	WC		No 6L cisterns	
	Outside tap		No	Yes, 0.7/day (summer season)
Average water use (L per person per day)			129.3	149.2

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Table 4. Average absolute and relative differences between measured and modelled water age. Good comparisons between models and measurements (ME and RMSE ≤30% and $R^2 > 0.7$) are highlighted.

	Model$_{TD}$				Model$_{BU}$			
	Loc 1	Loc 2	Loc 3	Loc 4	Loc 1	Loc 2	Loc 3	Loc 4
ME	−0.27	−0.48	−1.45	−4.41	−0.01	0.06	0.01	0.48
ME (%)	−5.89	−8.23	−14.73	−12.63	−0.32	0.95	0.10	1.36
RMSE	1.85	1.77	2.47	5.68	0.73	0.47	0.07	1.25
RMSE (%)	40.50	30.18	25.17	16.28	16.02	8.01	0.66	3.58
R^2	N.A.	N.A.	N.A.	N.A.	0.77	0.93	1.00	0.87

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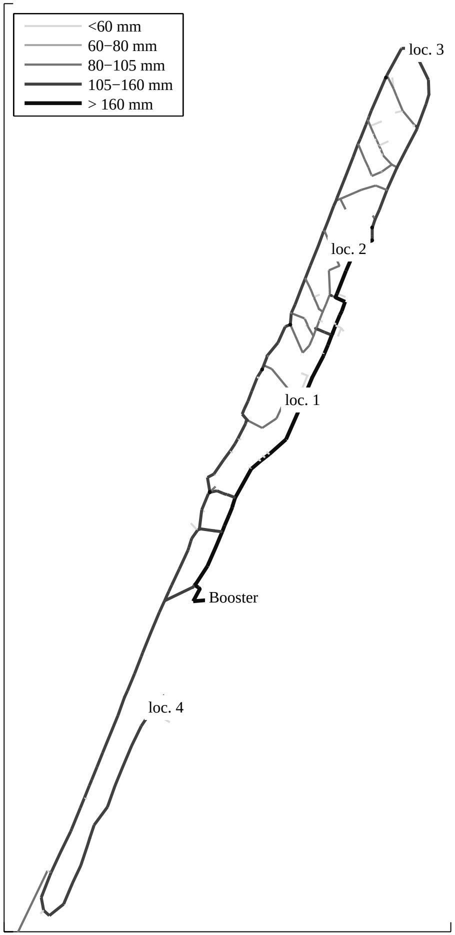

Fig. 1. Network layout.

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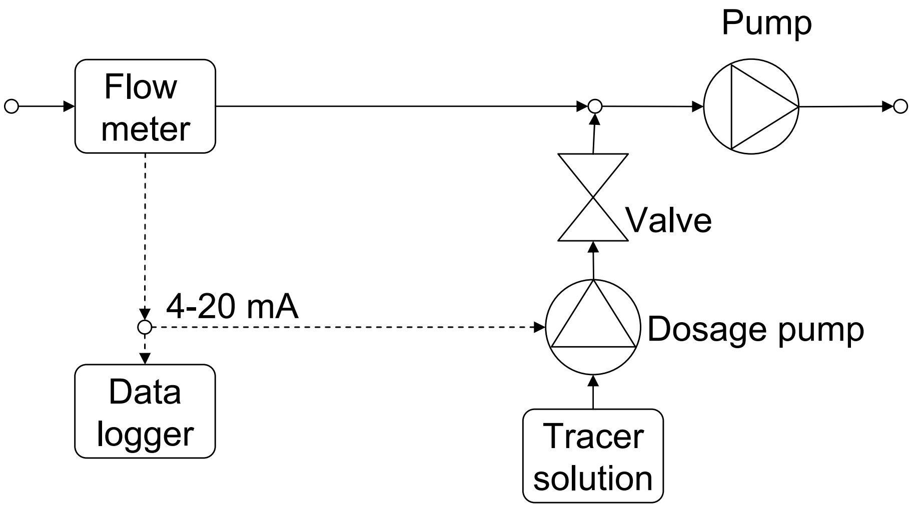

Fig. 2. Measurement setup for adding tracer solution.

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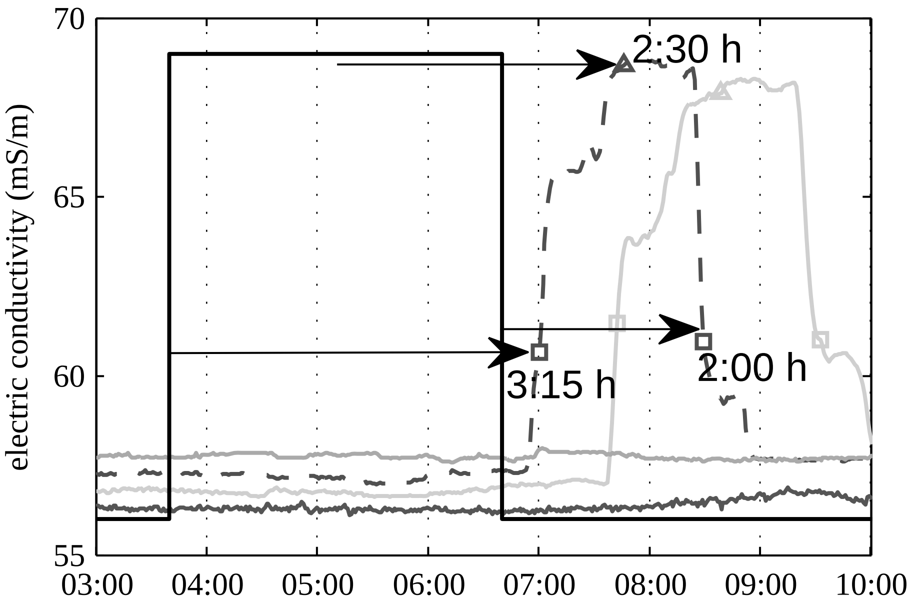

Fig. 3. Reconstructed EC at booster locations and measured EC at locations 1 and 2 (Wednesday, 3 September 2008) plus associated travel times.

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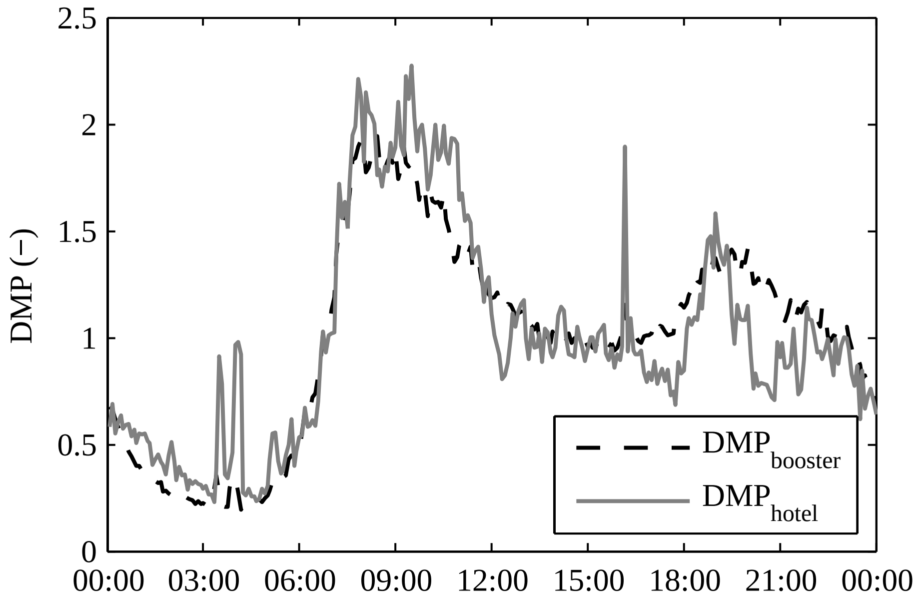

Fig. 4. Demand multiplier patterns as used in the $Model_{TD}$ and $Model_{BU}$.

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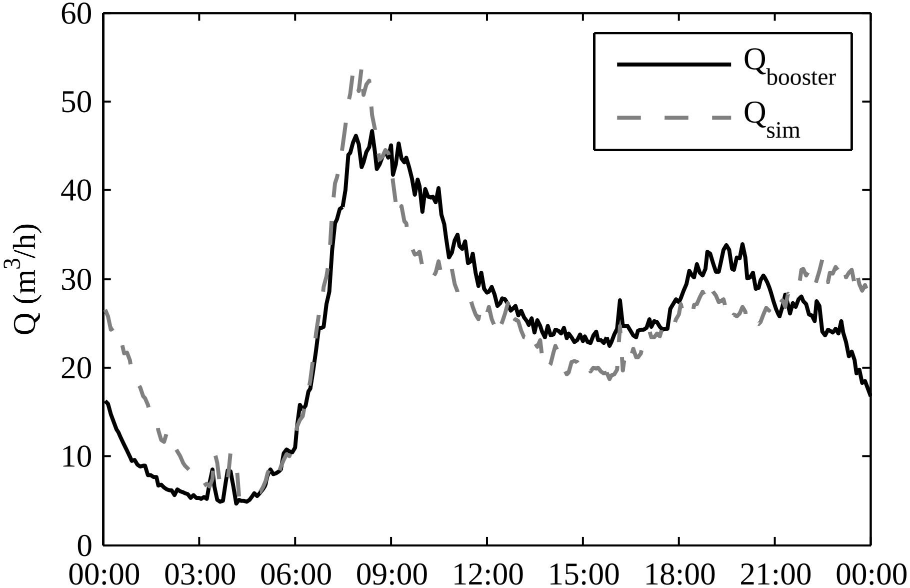

Fig. 5. Measured and simulated flows on a 5-min time scale.

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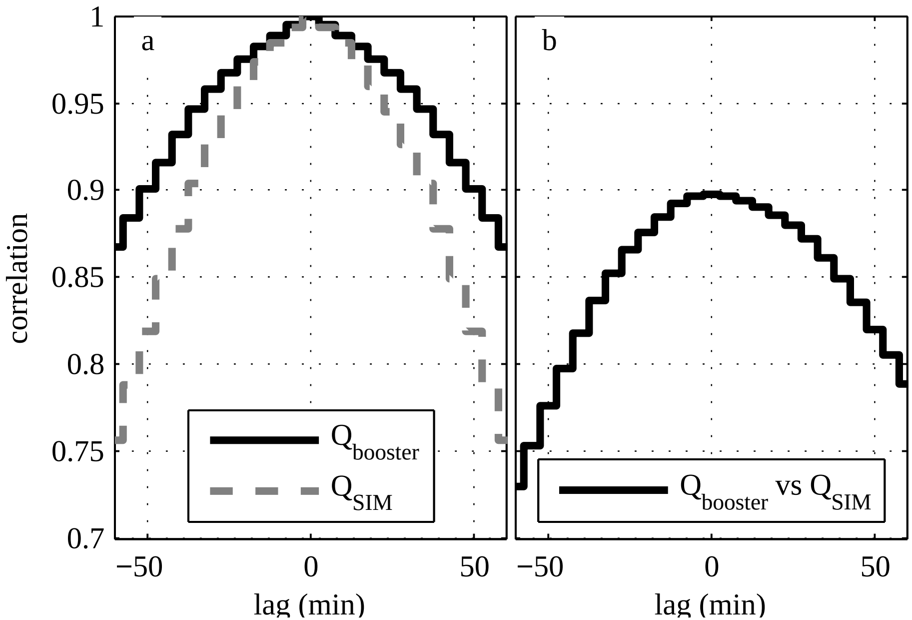

Fig. 6. **(a)** Auto-correlation of $Q_{booster}$ and Q_{SIM} and **(b)** cross-correlation between $Q_{booster}$ and Q_{SIM} for different time lags on a 5-min time scale.

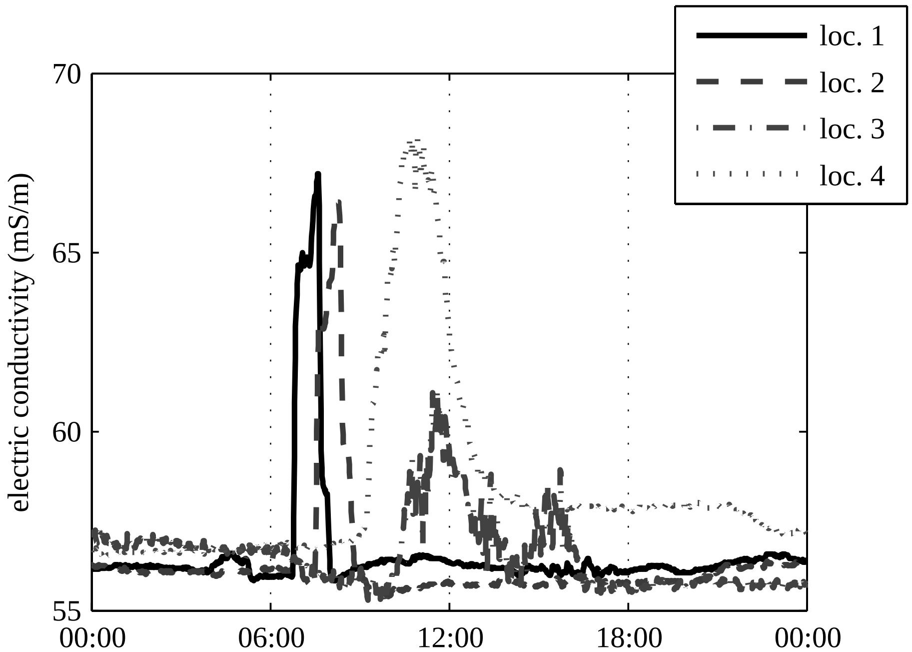

Fig. 7. Measured EC at locations 1–4 at Thursday, 4 September 2008. N.B. EC at location 4 has 24 h delay.

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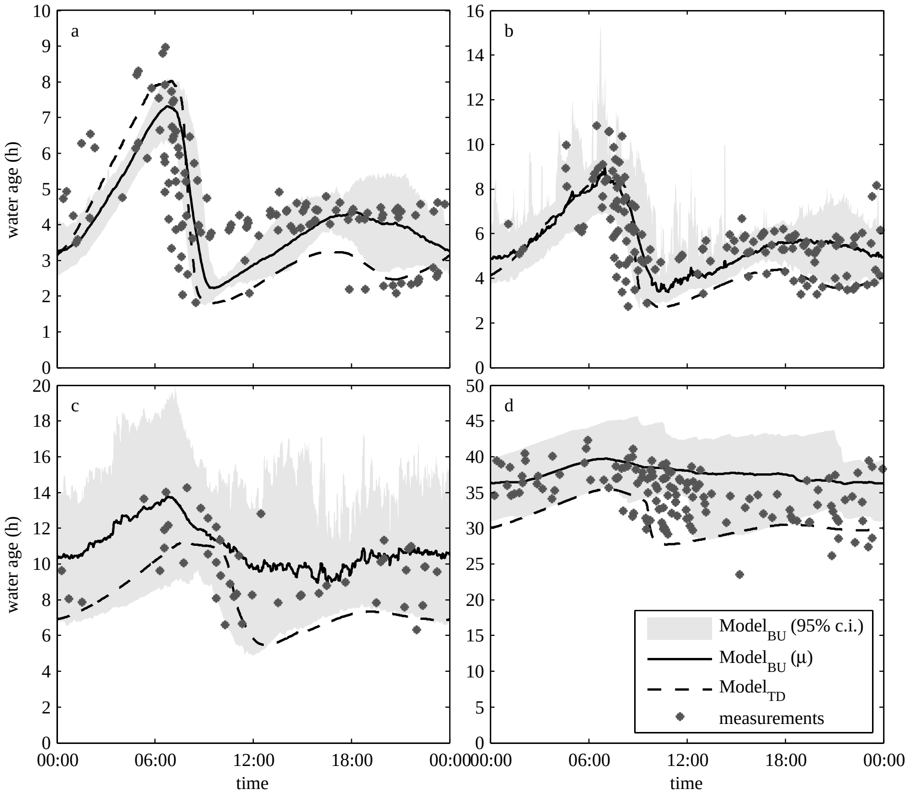

Fig. 8. Measured and modelled water age at location **(a)** 1; **(b)** 2; **(c)** 3 and **(d)** 4. N.B. the 95% confidence interval is due to variation, not to uncertainty.

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