2nd International Joint Conference on Water Distribution
Systems Analysis & Computing and Control in the Water Industry
Valencia (Spain), 18-22 July 2022
doi: https://doi.org/10.4995/WDSA-CCWI2022.2022.14067

COMPARISON BETWEEN THE TOP-DOWN AND BOTTOM-UP APPROACH FOR THE DIFFUSE-DISPERSIVE PHENOMENON ANALYSIS

Stefania Piazza[1], E. J. Mirjam Blokker[2], Mariacrocetta Sambito[3], Gabriele Freni[4]

[1,3,4] School of Engineering and Architecture, University of Enna "Kore", Cittadella Universitaria,
94100 Enna (Italy)
[2]KWR Water Research Institute, P.O. Box 1072, 3430 BB Nieuwegein (The Netherlands)

[1] *stefania.piazza@unikore.it,* [2] *Mirjam.Blokker@kwrwater.nl,* [3] *mariacrocetta.sambito@unikore.it,*
[4]*gabriele.freni@unikore.it*

Abstract

In order to detect deliberate or accidental contamination in drinking water distribution systems (DWDS), typically water quality sensors need to be installed in this system, and the data need to be analysed in order to feed alert systems and prevent the harm of contamination. This requires numerical (hydraulic and water quality) models that are as realistic as possible to support monitoring systems. Currently, water quality models used in the literature adopt an advective approach and simplified reaction kinetics, such as EPANET, which neglect diffusion-dispersion phenomena that are relevant in the presence of laminar and transient flow regimes. Another important aspect providing relevant uncertainty is related to the simplified estimation of sub-daily water demands that are commonly estimated from highly aggregated consumption data.

The present study aims to analyse diffusion-dispersive phenomena in a realistic DWDS model, which shows turbulent, transitional and laminar flows, and compare this to how such a DWDS would typically be modelled with a coarse estimate of demands. We are therefore considering two different demand allocation approaches (Top-down and Bottom-up).

In this paper the EPANET advective model and the diffusive-dispersive model, developed in a previous study, were used to better understand what the effect using the latter approach has within the DWDS as a function of two different types of demand allocation. To do this, the models results were compared to numerical tests that were performed on the real network of Zandvoort (the Netherlands) using a conservative tracer. For the 4 locations considered, it was noted that the diffusive-dispersive model responds well when using the bottom-up approach compared to the top-down approach. We found that in order to predict the tracer pattern, the Top-Down approach of demand allocation does not work well, even when an optimized diffusive-dispersive model is used. The bottom-up approach of demand allocation leads to far better results in predicting the tracer patterns, and with the diffusive-dispersive model the prediction improves even more. This means that in order to model water quality in a DWDS the first step should be to improve water demand models for this DWDS. This leads to an improved representation of flow regimes, and will most likely include laminar flows.

Keywords
Dispersion, TD and BU demand allocation, WDN, Water quality, Numerical analysis.

1 INTRODUCTION

Water distribution systems are made up of elements at risk, such as valves, pipes and tanks that could represent a preferential way for the intrusion of contaminants [1]. To better identify the occurrence of the contamination, the monitoring system must be able to reduce this risk [2], maximizing the detection efficiency and minimizing equipment costs [3]. To do this, simulation tools that manage to represent reality must support it.

Currently literature studies are based on hydraulic simulation tools, such as EPANET [4], which adopt a simplified approach regarding water quality, based on advective transport and some simplified reaction kinetics ([5], [6], [7]), neglecting the diffusive phenomena.

Although the use of simplified advective approach does not produce significant errors in the event that the DWDS is subject to a purely turbulent flow regime, they are not able to effectively model the behaviour of contaminants for laminar and transitional flow regimes, as shown by Piazza et al. (2020) [8].

Furthermore, the Top-down approach is the one conventionally used for allocating demand within DWDS and it is used in real applications. It consists of assigning a demand pattern of multiplier factors (typically taken from the drinking water production station) and correction factors (base demands) to all demand nodes (typically based on measured annual demands).

To ensure that a model is as representative of reality as possible, as well as being able to solve adequately the diffusive-dispersive processes [9], it must also be equipped with an accurate hydraulic model [10].

In this study the EPANET model and EPANET-DD (Dynamic-Dispersion) model, developed by Piazza et al. 2022 [9], were applied to the really existing network in Zandvoort (Netherlands), considering two different types of demand allocation (Top-down and Bottom-up). The Bottom-Up approach, unlike the Top-Down approach, consists in assigning different demand models to all nodes in the DWDS, according to the characteristics of the nodes. This was possible through the use of the SIMDEUM [11] which allows to generate stochastic demands according to the types of users analysed.

The aim of the present study is to analyse how the diffusive-dispersive process is influenced by the two different types of demand allocation. To do this, the numerical results were compared with those obtained from the experimental monitoring campaign carried out on the Zandvoort network in 2008 using a conservative tracer such as sodium chloride. Four locations were monitored, two of which are located near apartment buildings (Burg. Fennemaplein, De Ruyterstraat), the third is located in the basement of the hotel (NH hotel) and the fourth is located in the basement of a small apartment buildings of 15 residences (Sterflat Friedhoffplein).

2 MATERIALS AND METHODS

2.1 Case Study

The Zandvoort network was built in the 1950–1960s and consists of 5.7 km of Ø100 mm lined cast iron pipes and 3.5 km of Ø100 mm PVC pipes; it supplies 1000 homes, 2 hotels and 30 beach clubs. The area is supplied from one point with a fixed head through a booster pump; there are no tanks in the network (Figure 1). Inflows are monitored with an electromagnetic flowmeter with similar characteristics to those used in laboratory experiments and supplied flows are monitored with turbine flow meters compliant with MID directive (maximum error lower than 5%), variable depending on water meter age, diameter and installation. The water use in the network was determined by the historical flow patterns at the stimulation station, measured by the Provincial Water Company Noord-Holland (PWN), and the domestic water demand accounted for 70% of the total demand. Drinking water is distributed without any disinfectant, as is common in the Netherlands.

A tracer study with NaCl was performed between 2 September and 20 October 2008. During the study, the water service was guaranteed to the users and sodium chloride (NaCl) was used as a tracer, as it does not cause inconvenience or risks to the health of users and provides results of good precision and is low cost. The quantities of tracer used were such as not to compromise the characteristics of the water for normal use. The numerical simulations were carried out considering the same conditions used in Blokker et al. 2010 [11]. Electrical conductivity (EC) values were measured at 4 locations. The modeled results were compared with the experimental data obtained by the tracer study.

Figure 1. Layout of the Zandvoort water distribution network.

2.2 Numerical Model

The upgraded version of the EPANET model, used in Piazza et al. 2022 [9], which solved the dispersion / diffusion equations proposed by Romeo-Gomez and Choi (2011) [12] in quasi-stationary flow conditions, solving the hydraulic problem in steady-state flow conditions with the EPANET-MATLAB-Toolkit [13] and the equation of advection-diffusion-dispersion in dynamic flow conditions in the two-dimensional case with the classical random walk method [14].

The model allows to determine the position of the solute particles in the *x* and *y* directions using equations (1) and (2) as a function of the different flow regimes that occur inside the network, and the tracer concentration using equation (3).

$$x = x + \frac{3}{2} u_x \left(1 - \left(\frac{y}{\frac{d}{2}} \right)^2 \right) dt + \sqrt{2 \cdot E_{f\ or\ b} \cdot dt} \tag{1}$$

$$y = y + u_y dt + \sqrt{(E_f + E_b) \cdot dt} \tag{2}$$

$$C = \frac{C \cdot n}{\left(\frac{L}{\Delta x} \cdot \pi \frac{d^2}{4} \right)} \tag{3}$$

where

u_x and u_y	are the velocities along the two x and y axes respectively;
dt	is the duration of the contamination event;
d	is the pipe diameter;
E_f and E_b	are the forward and backward diffusion coefficients, respectively, as defined by Romero-Gomez and Choi (2011). In equation (1) they are a function of positive or negative flow direction.
$(C \cdot n)$	is the concentration per unit of particles;
L	is the length of the pipe;
Δx	is the section number of the pipe;
$\pi \frac{d^2}{4}$	is the cross-sectional area of the pipe.

The advective-diffusive-dispersive model, suitably calibrated (Eb = 0.05 m^2 / s and Ef = 0.3 m^2 / s), was applied to the real Zandvoort network (near Haarlem) in order to compare the results of the model with the values of the monitoring campaign [11] conducted between 2 September and 20 October 2008.

2.3 Experimental and Numerical Setup

Solute transport monitoring was carried out near two apartment buildings (locations 1 and 2), in the basement of a hotel (location 3) and in the basement of a small apartment building of 15 residences (location 4) (Figure 1). Monitoring was enabled by dosing sodium chloride (NaCl) within a booster location nearby the network inlet, raising the electrical conductivity (EC) from about EC=57 mS/m without dosage to about EC=68 mS/m. Short intermittent tracer events (3 hours) were performed with an inter-event time of 20 hours. The tracer study was carried out for 7 weeks, but here we reported only a few days (the event of 3 September 2008).

Electrical conductivity (EC) values were measured at 4 locations in the system, and two models were constructed that are distinguished by demand allocation: ModelTD (top-down) and ModelBU (bottom-up).

The first was allocated to all demand nodes with a correction factor DMP. This correction factor is the base demand and has been assigned based on the same demand category for all demand nodes, having a pattern time step of 15 min. The bottom-up demand allocation was done with the use of the end-use model SIMDEUM that considers a stochastic water demand pattern, obtaining a specific demand pattern as a function of the different types of demand nodes, having a pattern time step of 5 min [11]. In order to validate the ModelBU, in the study of Blokker et al. 2010 [11], 10 different SIMDEUM models were used and, in this work, only one was shown as an example. As leakage in the Netherlands is generally very low (2–4%) ([15]; [16]), no leakage is assumed in this network.

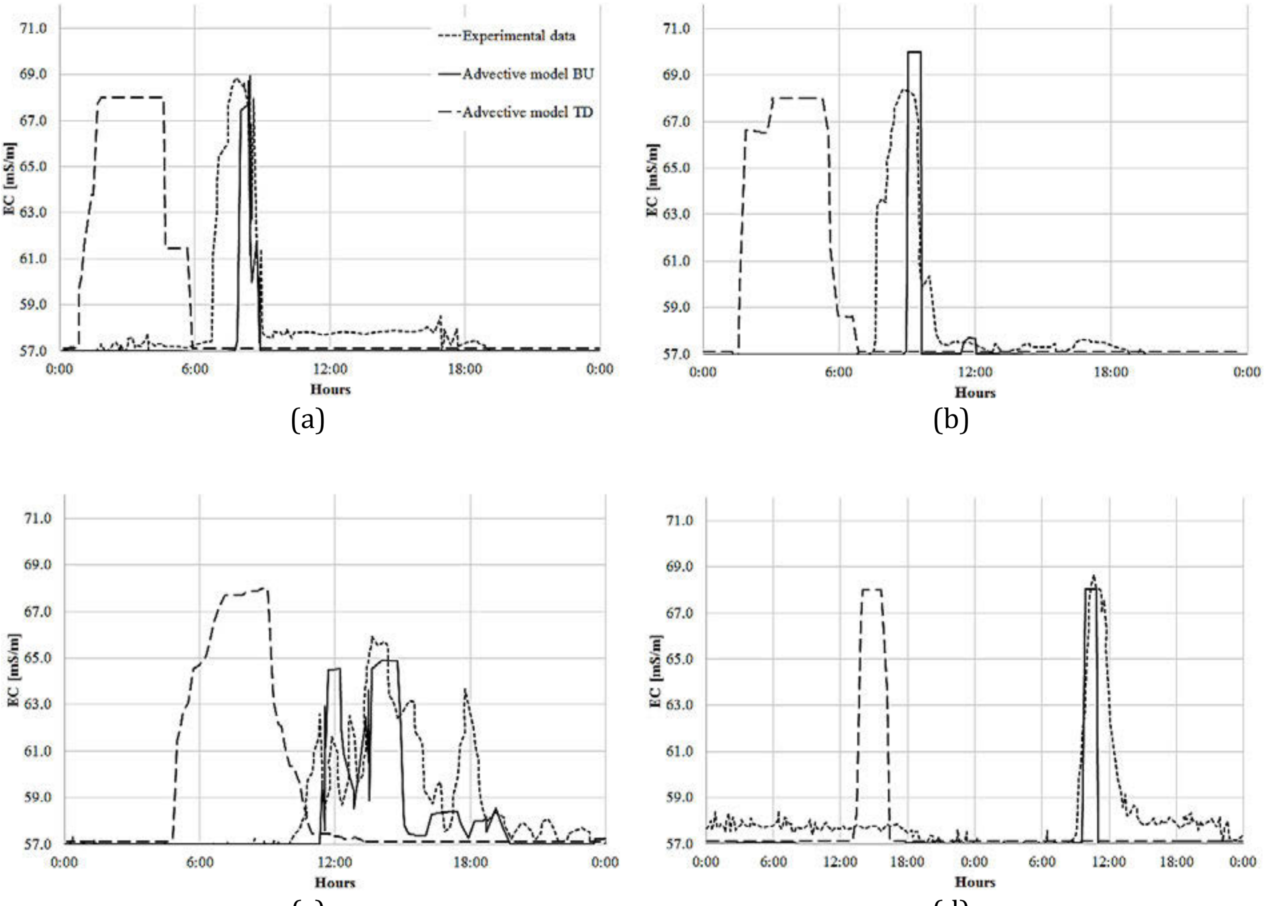
3 RESULTS

In Figure 2 and Figure 3 the numerical results obtained from the resolution of the advective and advective-diffusive-dispersive model respectively were compared, considering both the demand allocation approaches (Top-Down and Bottom-Up), with the electroconductivity (EC) measurements collected during a tracer experiment of 3 September 2008, present in Blokker et al. 2010 [11].

Note that the tracer inserted at the booster location on the 3rd September 2008 reached the locations Burg. Fennemaplein (Figure 2a), De Ruyterstraat (Figure 2b), NH hotel (Figure 2c) a few hours later, while it reached the Sterflat Friedhoffplein location (Figure 2d) one day late, around 9:00 am.

As known from the Figure 2 and the Table 1, in which the values of the Nash-Sutcliffe coefficient have been reported for the four monitored locations, it is observed that the EPANET advective model is not at all representative of the measured data, using both demand allocation models.

In fact, it is observed that the tracer event simulated using the Top-Down approach is significantly anticipated with respect to the real data and, once exceeded, is completely cancelled. In particular, for the location of Sterflat Friedhoffplein (Figure 2d) it should be noted that the advective model detects the event one day in advance. Furthermore, considering the Bottom-Up approach, the advective model tends to provide a much shorter event with a much smaller mass of the tracer reaching the user.



(a)

(b)

(c)

(d)

Figure 2. Comparison of EC measurements (Blokker et al., 2010) and simulated with only advection considering Top-down and Bottom-up approach for demand allocation for the 3rd September 2008 tracer event at Burg. Fennemaplein (a), De Ruyterstraat (b), NH hotel (c), Sterflat Friedhoffplein (d).

The inadequacy of the advective model in the real data representation is also highlighted by the values of the Nash-Sutcliffe coefficients which in this case are negative for both models (Table 1).

Table 1. Nash – Sutcliffe coefficient for the Top-down and Bottom-up approach for only advective (adv) and advective – dispersive – diffusive model (disp) for E_b = 0.05 m^2/s E_f = 0.30 m^2/s for the 3 September 2008 tracer event.

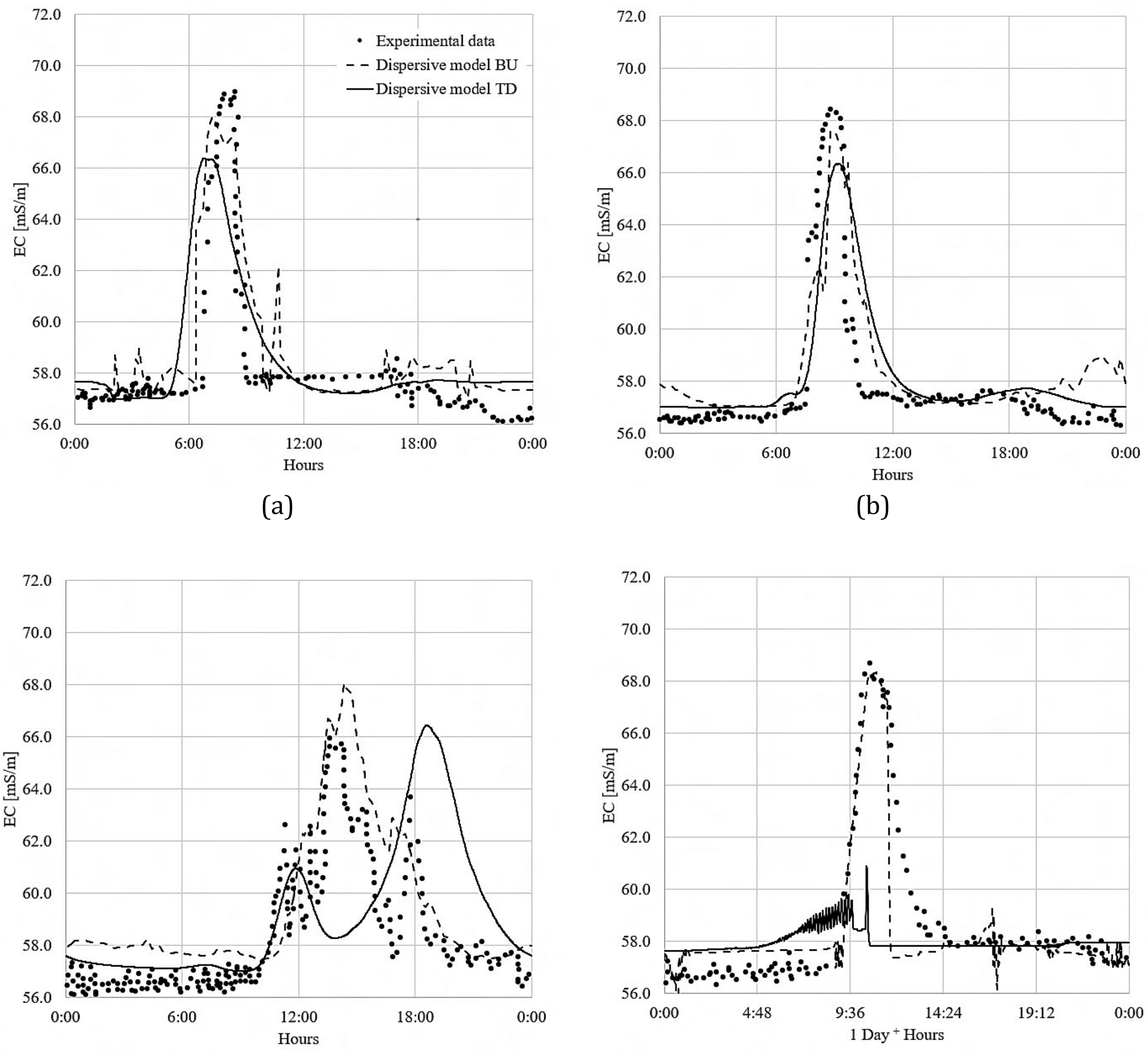
	Burg. Fennemaplein	De Ruyterstraat	NH Hotel	Sterflat Friedhoffplein
Top-Down N – S (adv)	-0.09	-0.12	-1.07	-0.50
Top-Down N – S (disp)	-0.04	0.78	-0.62	-0.44
Bottom-Up N – S (adv)	0.28	0.24	0.22	0.50
Bottom-Up N – S (disp)	0.79	0.88	0.68	0.71

In Figure 3 it is observed that the advective-diffusive-dispersive model is much more efficient in representing the experimental data in the case in which use the Bottom-Up model of allocation of demand.

Using the previously calibrated dispersion coefficients (E_b = 0.05 m^2/s E_f = 0.30 m^2/s), the model not only manages to centre the peak concentration, but is able to best represent the descending traits of the pollutogram. This can be seen from Table 1 in which the values of the Nash-Sutcliffe (N-S) coefficient, used to evaluate the adaptability between the simulated and measured data, are high and in some cases close to unity.

By comparing the experimental results with the data obtained using the Top-Down model of demand allocation, it is observed that the model adequately reproduces only the data relating to the location De Ruyterstraat (Figure 3b). In fact, in this case the model, although with lower peak values, reproduced the real event with an efficiency of 78%.

In all other cases, the model differs from the experimental data as it not only anticipates the real event (Figure 3a and Figure 3d), but is also unable to reproduce the shape of the event. This is more evident in the locations of Figure 3c, in which a double peak occurs, and Figure 3d, in which the curve is remarkably flattened. To confirm this, it is observed from Table 1 that the values of the Nash-Sutcliffe coefficient for the above locations are negative and therefore the model is not suitable for reproducing the real data.



(a) (b)

(c) (d)

Figure 3. Comparison of EC measurements (Blokker et al., 2010) and simulated with dispersion considering Top-down and Bottom-up approach for demand allocation (backward dispersion coefficient=0.05 m²/s and forward dispersion coefficient=0.30 m²/s) for the 3rd September 2008 tracer event at Burg. Fennemaplein (a), De Ruyterstraat (b), NH hotel (c), Sterflat Friedhoffplein (d).

4 CONCLUSIONS

The present study applied the EPANET and EPANET-DD model to the real network of Zandvoort (Netherlands), considering two different demand allocation models (Top-Down and Bottom-Up). The models were suitably calibrated from a hydraulic (EPANET and EPANET-DD) and quality (EPANET-DD) point of view. Different demand patterns were used depending on the demand allocation model considered: in the first case, a single pattern that was the same for all demand nodes was chosen with a pattern time step equal to 15 min; in the second case, the demand patterns were obtained through a SIMDEUM stochastic model as a function of the features of the demand node (residential house, hotel, etc.) having a pattern time step equal to 5 min.

Furthermore, the backward and forward dispersion coefficients respectively equal to of 0.05 m^2/s and 0.30 m^2/s were calibrated, using the trial-and-error heuristic method through the Nash-Sutcliffe efficiency coefficient.

The model results were compared with numerical tests performed on the network from 2 September to 20 October 2008 using a conservative tracer.

The analysis showed that by varying the demand allocation model, dispersive and diffusive processes are relevant in the simulation of solute propagation in water networks.

In fact, using the Top-Down approach for the demand allocation, considering both the advective model and the advective-diffusive-dispersive model, it is not able to represent real data in terms of time, as it produces an impulse that arrives several hours before the measured event. This effect is less accentuated by using the complete model. Furthermore, considering the latter model, it underestimates the peak concentration of the tracer and also generates a double peak at the NH Hotel location. Using this approach, only one of the monitored locations (De Ruyterstraat) was adequately modelled with an efficiency of 78%.

However, in all other cases, the ineffectiveness of the model was highlighted by the negative values of the Nash-Sutcliffe coefficient, which allows us to evaluate the predictive power of the models with respect to the measured data.

On the other hand, using the Bottom-Up approach for the demand allocation, the advective-diffusive-dispersive model is much more performing. In fact, not only it is able to centre the pollutogram peaks, but it is able to adequately model the shape of the event, with the Nash-Sutcliffe efficiencies coefficient ranging between 68% and 88%.

The study has highlighted that the use of diffusive-dispersive models coupled with demand patterns as close as possible to the real demand of the users, allows to obtain models that are very representative of reality (in terms of time and concentration peaks) and this it can be a valid modeling tool to be used upstream of optimization models to prevent illegal intrusions into water distribution networks.

REFERENCES

[1] M. Blokker, P. Smeets and G. Medema, "Quantitative microbial risk assessment of repairs of the drinking water distribution system," Microbial Risk Analysis, vol. 8, pp. 22-31, 2018.

[2] R. Murray, T. Haxton, R. Janke, W. E. Hart, J. Berry and C. Phillips, “Sensor network design for drinking water contamination warning systems: A compendium of research results and case studies using TEVA-SPOT,” EPA/600/R-09/141, Office of Research and Development, National Homeland Security Research Center, 2009.

[3] M. Weickgenannt, Z. Kapelan, M. Blokker and D. A. Savic, “Optimal Sensor Placement for the Efficient Contaminat Detection in Water Distribution Systems,” Water Distribution Systems Analysis, 2008.

[4] L. Rossman, “EPANET 2 Users Manual,” Environmental Protection Agency, 2000.

[5] A. Ostfeld and E. Salomons, “Securing Water Distribution Systems Using Online Contamination Monitoring,” Journal of Water Resources Planning and Management, vol. 131, pp. 402-405, 2005.

[6] O. N. Ozdemir and M. E. Ucaner, “Success of booster chlorination for water supply networks with genetic algorithms,” Journal of Hydraulic Research, vol. 43, no. 3, pp. 267-275, 2005.

[7] J. Guan, M. M. Aral, M. L. Maslia and W. M. Grayman, “Identification of Contaminant Sources in Water Distribution Systems Using Simulation–Optimization Method: Case Study,” Journal of Water Resources Planning and Management, vol. 132, pp. 252-262, 2006.

[8] S. Piazza, E. J. M. Blokker, G. Freni, V. Puleo and M. Sambito, “Impact of diffusion and dispersion of contaminants in water distribution networks modelling and monitoring,” Water Supply, vol. 20, no. 1, pp. 46-58, 2020.

[9] S. Piazza, M. Sambito and G. Freni, “Impact of water-quality modelling simplifications on the optimal positioning of sensors in looped water distribution networks,” Preprint (version1) available at Research Square, 06 April 2022.

[10] E. J. M. Blokker, J. H. G. Vreeburg, S. G. Buchberger and J. C. van Dijk, “Importance of demand modelling in network water quality models: a review.,” Drink. Water Eng. Sci., vol. 1, no. 1, pp. 27-38, 2008.

[11] E. J. M. Blokker, J. H. G. Vreeburg, H. Beverloo, M. Klein Arfman and J. C. van Dijk, “A bottom-up approach of stochastic demand allocation in water quality modelling,” Drinking Water Engineering and Science, vol. 3, pp. 43-51, 2010.

[12] P. Romeo-Gomez and C. Y. Choi, “Axial Dispersion Coefficients in Laminar Flows of Water-Distribution Systems,” Journal of Hydraulic Engineering, vol. 137, no. 11, pp. 1500-1508, 2011.

[13] D. G. Eliades, M. Kyriakou, S. Vrachimis and M. M. Polycarpou, EPANET-MATLAB Toolkit: An Open-Source Software for Interfacing EPANET with MATLAB, The Netherlands: Proc. 14th International Conference on Computing and Control for the Water Industry (CCWI), 2016, pp. 1-8.

[14] F. Delay, P. Ackerer and C. Danquigny, “Simulating Solute Transport in Porous or Fractured Formations Using Random Walk Particle Tracking: A Review,” Vadose Zone Journal, vol. 4, no. 2, p. 360–379, 2005.

[15] R. H. S. Beuken, C. S. W. Lavooij, A. Bosch and P. G. Schaap, “Low leakage in the Netherlands confirmed,” Ohio, USA, 2006.

[16] P. J. J. G. Geudens, “Water supply statistics 2007,,” Vewin, 2008.