Water Research 89 (2016) 107–117

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

Water quality modeling in the dead end sections of drinking water distribution networks

Ahmed A. Abokifa [a], Y. Jeffrey Yang [b], Cynthia S. Lo [a], Pratim Biswas [a, *]

[a] Department of Energy, Environmental and Chemical Engineering, Washington University in St. Louis, MO 63130, USA
[b] U.S. EPA, Office of Research and Development, National Risk Management Research Laboratory, Cincinnati, OH 45268, USA

ARTICLE INFO

Article history:
Received 24 June 2015
Received in revised form
8 October 2015
Accepted 8 November 2015
Available online 18 November 2015

Keywords:
Chlorine
Dead end pipe
Advection dispersion
Genetic algorithm
Stochastic demands
Spatial distribution
Correction factors

ABSTRACT

Dead-end sections of drinking water distribution networks are known to be problematic zones in terms of water quality degradation. Extended residence time due to water stagnation leads to rapid reduction of disinfectant residuals allowing the regrowth of microbial pathogens. Water quality models developed so far apply spatial aggregation and temporal averaging techniques for hydraulic parameters by assigning hourly averaged water demands to the main nodes of the network. Although this practice has generally resulted in minimal loss of accuracy for the predicted disinfectant concentrations in main water transmission lines, this is not the case for the peripheries of the distribution network. This study proposes a new approach for simulating disinfectant residuals in dead end pipes while accounting for both spatial and temporal variability in hydraulic and transport parameters. A stochastic demand generator was developed to represent residential water pulses based on a non-homogenous Poisson process. Dispersive solute transport was considered using highly dynamic dispersion rates. A genetic algorithm was used to calibrate the axial hydraulic profile of the dead-end pipe based on the different demand shares of the withdrawal nodes. A parametric sensitivity analysis was done to assess the model performance under variation of different simulation parameters. A group of Monte-Carlo ensembles was carried out to investigate the influence of spatial and temporal variations in flow demands on the simulation accuracy. A set of three correction factors were analytically derived to adjust residence time, dispersion rate and wall demand to overcome simulation error caused by spatial aggregation approximation. The current model results show better agreement with field-measured concentrations of conservative fluoride tracer and free chlorine disinfectant than the simulations of recent advection dispersion reaction models published in the literature. Accuracy of the simulated concentration profiles showed significant dependence on the spatial distribution of the flow demands compared to temporal variation.

1. Introduction

Disinfection is consistently applied as the final treatment step in typical drinking water treatment plants. All water utilities in the U.S. are required to maintain a residual disinfectant concentration throughout the distribution system to inhibit microbial re-contamination of treated drinking water. Chlorine, which is the most commonly used disinfectant worldwide, is a highly reactive oxidant that reacts with a variety of materials in both the bulk water and at the pipe wall as it transports through the distribution system pipes. In the last three decades, extensive research work was devoted to develop water quality models that simulate chlorine transport and decay in water distribution systems (Grayman, 2006). In the early work done by Biswas et al. (1993), a generalized model for steady state chlorine consumption that accounts for axial convection and radial diffusion was developed. It was the first model to appropriately account for chlorine decay at the pipe wall in addition to the bulk liquid phase. Rossman et al. (1994) developed a film mass transfer approach to account for radial chlorine transport and further reaction at the pipe wall. This 1-D advection-reaction model was incorporated in the water quality simulation module of the well-known software package EPANET (Rossman,

---

Abbreviations: ADR, advection dispersion reaction; CHBP, Cherry Hill Brushy Plains; CV, coefficient of variation; CF, correction factor; GA, genetic algorithm; GEP, gene expression programming; MOC, method of characteristics; SCCRWA, South Central Connecticut Regional Water Authority; RMSD, root mean square deviation.

* Corresponding author.
E-mail addresses: ahmed.abokifa@wustl.edu (A.A. Abokifa), yang.jeff@epa.gov (Y.J. Yang), clo@wustl.edu (C.S. Lo), pbiswas@wustl.edu (P. Biswas).

http://dx.doi.org/10.1016/j.watres.2015.11.025

Nomenclature

A	amplitude of inlet concentration sine wave (mg/L)
a	pipe radius (in)
C	instantaneous disinfectant concentration in the dead end (mg/L)
C^*	dimensionless disinfectant concentration = C/C_0
C_0	pipe inlet concentration (mg/L)
CV_{rms}	coefficient of variation of the root mean square deviation
E	longitudinal dispersion coefficient (m^2/sec)
E_T	Taylor's dispersion coefficient (m^2/sec)
D	molecular diffusivity (m^2/sec)
D_x^*	inverse of the radial Peclet number
Da	Damkohler number = $K\tau_0$
d	pipe diameter (in)
f^*	pipe friction factor
$f(r)$	radial flow distribution parameter
K	overall first order decay rate constant (sec^{-1})
k_b	decay rate constant for bulk flow (sec^{-1})
k_w	wall decay constant (m/sec)
k_f	mass transfer coefficient (m/sec)
L	pipe length (ft)
λ	period of the inlet concentration sine wave (hr)
N_{seg}	no. of withdrawal points along the axis of the dead end pipe
N_{meas}	No. of field measurements
Pe	axial Peclet number = uL/E
Q_b	base flow demand (L/hr)
R_w	overall wall demand (sec^{-1})
Re	Reynolds number
r	radial space coordinate (m)
r_h	pipe hydraulic mean radius (m)
τ_0	characteristic residence time (sec)
t	time (sec)
t_0	Lagrangian time scale = $a^2/16D$ (sec)
t^*	dimensionless time = t/τ_0;
u	average flow velocity in the pipe (m/sec)
W_d	wall demand parameter (m/sec)
x	axial space coordinate (m)
x^*	dimensionless axial distance = x/L

2000) which is widely used by water utilities worldwide. Although EPANET was able to accurately predict the field observed disinfectant concentrations for the water transmission mains, this was not the case for secondary branch pipes, the so called "dead-ends" at perimeters of a distribution system, where laminar flow conditions prevailed.

Distribution dead-end mains are characterized by intermittent low flow velocities and frequent stagnation times. They are well known problematic locations for the long and excessive residence times, leading to rapid water quality deterioration, disinfectant residuals disappearance and high potential for bacterial regrowth (Barbeau et al., 2005; Galvin, 2011). Few researchers gave special attention to water quality modeling in dead-ends, although they "often comprise 25% or more of the total infrastructure in a distribution system and tend to service a high percentage of the residential consumer base" as mentioned by Tzatchkov et al. (2002) based on the study of Buchberger and Lee (1999). For example, the Cherry Hill/Brushy (CHBP) plains water distribution network in New Haven, Connecticut has 32 dead-end links compared to 21 main trunk links out of total 103 pipes (Nilsson et al., 2005). Axworthy and Karney (1996) were the first to shed the light on the importance of considering dispersive transport in low flow velocity pipes as the advective transport models either would under- or over-predict the actual concentrations. Following this earlier work, several studies developed numerical 2-D convection-diffusion-reaction or 1-D advection-dispersion-reaction (ADR) models that efficiently simulate water quality under low flow conditions (Ozdemir and Ger, 1999, 1998; Islam and Chaudhry, 1998; Tzatchkov et al., 2002; Ozdemir and Ucak, 2002; Li et al., 2006; Basha and Malaeb, 2007). Spatial averaging of hydraulic parameters was employed in all these models by lumping multiple water uses into a single demand point assigned to a specified node on the network grid. For main water arteries, spatial aggregation is a good approximation because the ratio of the "on-pipe" demands compared to flows transmitted to downstream nodes is relatively small. However, this is not a good approximation for dead-ends, where all water demands are being directly withdrawn from the pipe at different spatial locations as shown in (Fig. 1-a). Applying spatial aggregation to dead ends will consistently overestimate the

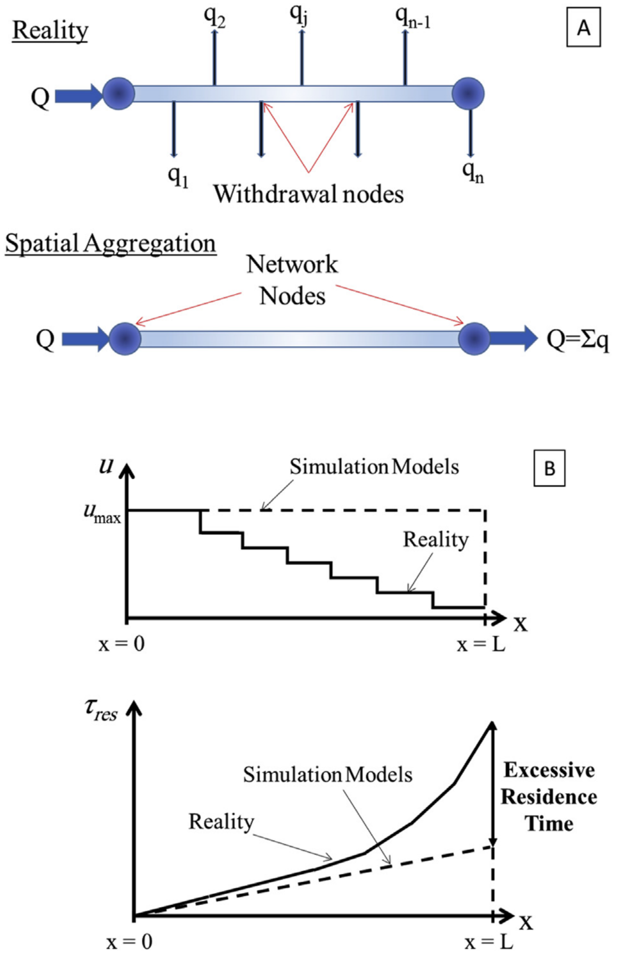

Fig. 1. **(A)** Spatial aggregation of flow demands compared to reality; **(B)** Over and under-estimation of average flow velocity (u) and residence time (τ_{res}) due to spatial averaging approximation.