COMPARISON OF DEMAND DRIVEN AND PRESSURE DEPENDENT HYDRAULIC APPROACHES FOR MODELLING WATER QUALITY IN DISTRIBUTION NETWORKS

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Abstract

Water distribution hydraulic models have been used as a basis for water quality modelling in distribution networks. Experts recognized that a realistic hydraulic model is required to accurately simulate water quality. The aim of this paper is to compare Demand Driven Analysis (DDA) and Pressure Dependent Analysis (PDA) based hydraulic models for simulating water quality in networks for future enhancement of water quality models. The well known EPANET 2 and the newly developed EPANET-PDX (pressure dependent extension) have been used as the DDA and PDA models respectively. Water quality analysis was performed for normal and pressure deficient hydraulic conditions on a sample network from literature. The models provide identical results for normal pressure conditions, but different results for pressure deficient conditions. The differences for the case of pressure deficient condition are significant at the farthest nodes from the source during high pressure deficiency situation with low demand satisfaction condition.

Keywords
Demand driven analysis, pressure driven analysis, EPANET 2, EPANET-PDX, water quality modelling, water distribution network

1. INTRODUCTION

One of the main concerns in drinking water industry today is on maintaining water quality in distribution networks. Water quality deteriorates because of various complex chemical and microbiological activities taking place in the distribution system. One of the health concerns associated with water quality problem for instance is formation of potentially carcinogenic disinfection by products (DBPs) due to reaction of disinfectant with organic and inorganic substances in water. In order to predict and control water quality the use of water quality models has become vital for water utilities.

Water distribution hydraulic models have been integrated with water quality models to simulate different water quality parameters. Nevertheless hydraulic models need to be highly accurate before being used in conjunction with water quality models [1] and [2].

Demand Driven Analysis (DDA) and Pressure Dependent Analysis (PDA) are the two approaches to hydraulic modelling of a network. DDA assumes nodal flows are always satisfied at all demand nodes regardless of the available pressures at demand nodes [3]. Conversely PDA takes into consideration the pressure at demand nodes [4].

Several researchers emphasized the robustness of PDA for its capability in providing realistic results under different pressure conditions [4], [5], [6] and [7] and criticized the DDA approach due to its lack of accuracy under pressure deficient conditions such as pipe bursts, pump failures, temporary demand increase and system maintenance and repair restrictions.

The main purpose of this paper is to compare DDA and PDA approaches for modelling water quality in a network for future enhancement of water quality models. The paper is part of a recently started research on Water Quality Management and Optimization of Water Distribution Systems.

The well-known EPANET 2 and the newly developed EPANET-PDX [5] were used as DDA and PDA models respectively. To exemplify the capability of DDA and PDA approaches a water quality analysis was performed on a sample network under different pressure conditions. During the analysis effect of leakage was not considered. Results from the two models are compared and presented herein.

2. HYDRAULIC AND WATER QUALITY APPROCHES

EPANET 2 and EPANET-PDX are the two models used in the study as a DDA and PDA respectively. EPANET-PDX is an extension of EPANET 2 with a continuous nodal Pressure Dependent Demand Function [8] integrated into the Gradient Method [9] to form a model for both hydraulic and water quality modelling of a network under different pressure conditions during extended time periods. The Pressure Dependent Demand Function [8] which was integrated into EPANET-PDX is:

$$Qn_i(Hn_i) = Qn_i^{req} \frac{\exp(\alpha_i + \beta_i Hn_i)}{1 + \exp(\alpha_i + \beta_i Hn_i)} \tag{1}$$

where Qn_i and Hn_i are the flow and head at node i respectively. Qn_i^{req} is demand at node i. α_i and β_i are parameters determined using relevant field data. The basis for this function , as described in Figure 1, is nodal demand is satisfied in full when nodal head is equal to or greater than the desired head and zero when the nodal head is equal to or lower than the minimum head [4]. The demand satisfaction ratio (DSR) is $Qn_i (Hn_i)/Qni^{req}$.

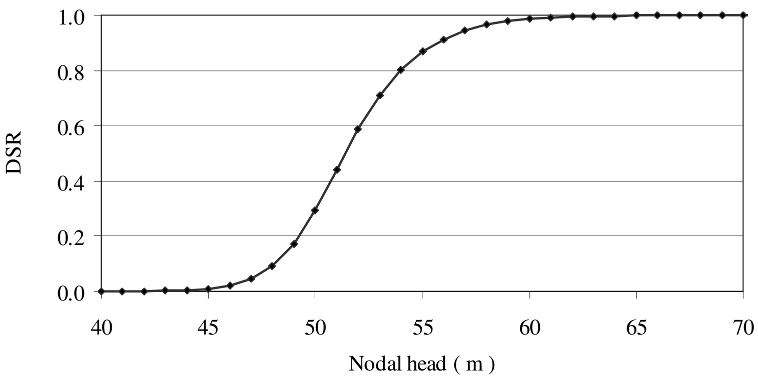


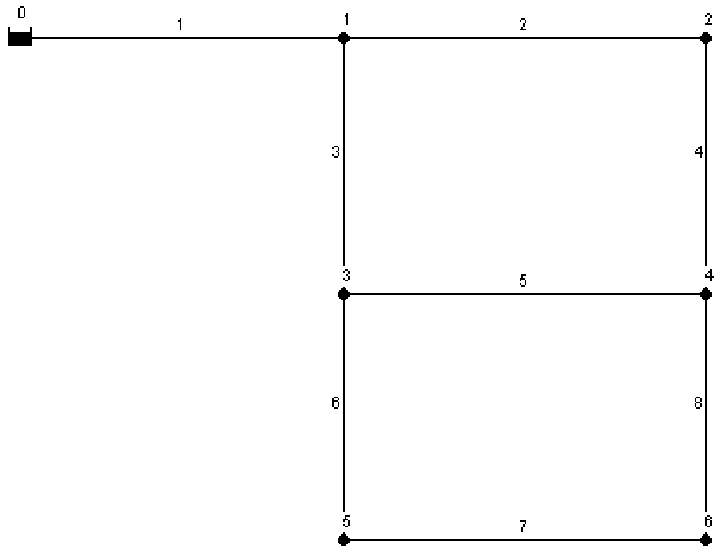
Figure 1. Pressure dependent demand function (node elevation =45 m, desired head=60m)

The governing equations for EPANET 2 water quality solver are based on the principle of conservation of mass coupled with reaction kinetics [10]. EPANET-PDX follows the same principle as it is developed in EPANET 2 environment; however, the basis for its hydraulic data needed for water quality analysis is the integrated pressure dependent demand function. The expressions for the conservations of mass during transport in pipes, mixing at junctions and mixing in storages facilities can be found in [10] and [12]. Details on reaction rate expressions for modelling decay and growth of substances can be found in [10].

A Lagrangian time based approach is used by EPANET 2's water quality solver to trace concentration of a series of segments of water in the distribution network [10]. The concentration of the segments is updated for any reaction that may have taken place over a time step. The accuracy of the Lagrangian time based approach is dependent on the choices of quality time step and concentration tolerance [12]. The concentration tolerance refers to the smallest change in concentration that will cause generation of new segments of water in a pipe [10].

3. EXAMPLE, RESULTS AND DISCUSSIONS

This section presents water quality results obtained from EPANET 2 and EPANET-PDX models for a steady state condition considering both normal and pressure deficient hydraulic conditions. A sample network [13] which is shown in Figure 2 is used for demonstrating the results. The network consists of a single source, 8 pipes of length 1000m and 6 demand nodes. The required residual head for all nodes was predetermined to be 15 m. The minimum heads for all nodes are taken to be equal to their respective elevations; the design heads are equal to elevation plus the required residual head of 15m. The source head was fixed at 90 m for normal pressure condition. Various source heads (60m, 65 m, 70m and 75m) were considered for pressure deficient conditions.



Node	Elevation (m)	Demand (l/s)
1	50	47.1
2	50	47.1
3	45	77.8
4	45	47.1
5	55	55.6
6	55	88.9

Pipe	Diameter (mm)	C
1	500	140
2	400	140
3	400	140
4	400	140
5	250	140
6	250	140
7	250	140
8	250	140

Figure 2. Sample network

The output of the water quality analysis comprised of water age [hrs], chlorine [mg/L] and Trihalomethane (THM) [$\mu g/L$]. For reactions in bulk solution and at pipe walls, the bulk and wall coefficients were assumed 1[day^{-1}] and 1.5[m/day] respectively based on literature [10]. For estimating chlorine decay, a constant chlorine dose of 1[mg/L] was applied at the source. For estimating THM concentration, the limiting concentration was assumed to be 80[$\mu g/L$] and the initial concentrations at all nodes were taken to be equal to 20[$\mu g/L$].

A 5 minute quality time step, which is much shorter than the minimum travel time in the network, was chosen for accurate simulation. A zero concentration tolerance has also been selected for accurate network simulation. As the network used here is of small size, considering zero concentration tolerance did not affect the network computation time.

Water quality analysis was carried out using EPANET 2 and EPANET-PDX models under normal pressure condition. The models provide identical results for all water quality parameters, i.e. water age, chlorine residual and THM concentrations as indicated in Figures 3 and 4 below.

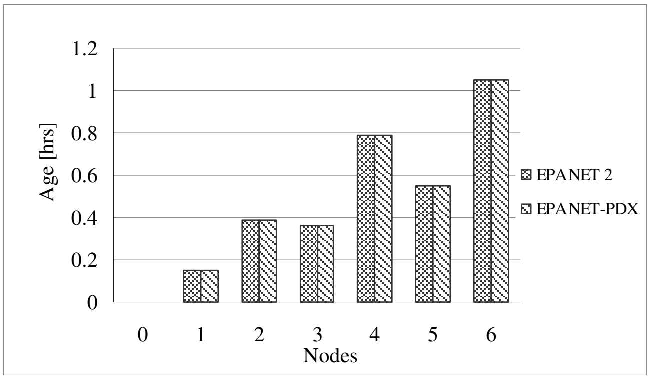


Figure 3. Water age for normal pressure condition

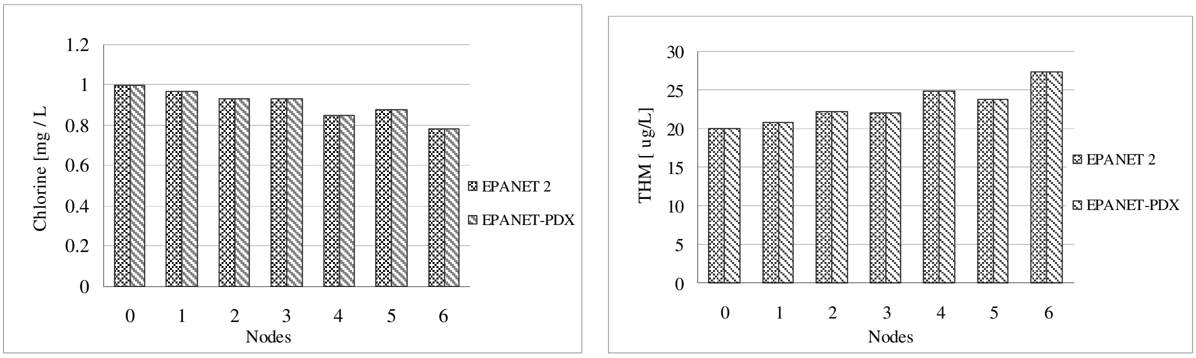


Figure 4. Chlorine residuals and THM concentrations for normal pressure condition

Pressure deficient conditions were created by reducing the source water level from 90 m to 75 m, 70 m, 65 m and 60 m to make the network satisfy only 92 %, 83%, 71% and 56 % of the total demand respectively. Water quality analysis for pressure deficient conditions indicates that EPANET 2 gives the same result as its normal pressure conditions. This illustrates EPANET 2 is incapable of handling the different pressure conditions realistically. By contrast EPANET-PDX considers the different pressure conditions and provides different results for normal and pressure deficient conditions. The overall comparison of the models for pressure deficient conditions is indicated in Figures 5, 6 and 7 below. Results from EPANET-PDX show higher values of water age, lower chlorine residual and higher THM concentration in all nodes compared to EPANET 2. This is because of the occurrence of low flow condition in the system (Figure 8) owing to the pressure deficiency. The low flow condition creates longer residence time in the network and ultimately contributes to more chlorine depletion and high THM growth. It is worthwhile to see in Figures 5, 6 and 7 that the differences in the model results of EPANET 2 and EPANET-PDX are significant at the farthest nodes from the source during high pressure deficiency with low demand satisfaction condition. In fact nodes which are far from the sources have normally long residence time in the network and thus require accurate model prediction. Long residence time contributes to deterioration of microbial and chemical water quality in the distribution network.

To verify the accuracy of EPANET-PDX results for pressure deficient condition a hydraulic feasibility [14] check was carried out using the actual nodal flows from EPANET-PDX as a new demand input into EPANET 2. Simulations for source heads ranging from 40m to 80m were performed. Nodal heads obtained from EPANET 2 were compared with those of EPANET-PDX. A correlation between the heads gives R^2 value of 0.9999995 as it is shown in Figure 9. This evidently confirms that EPANET-PDX results are accurate.

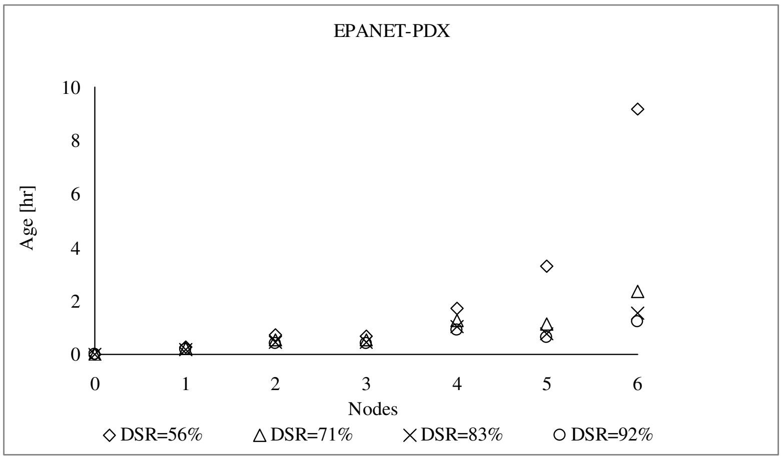


Figure 5. Water age for pressure-deficient conditions

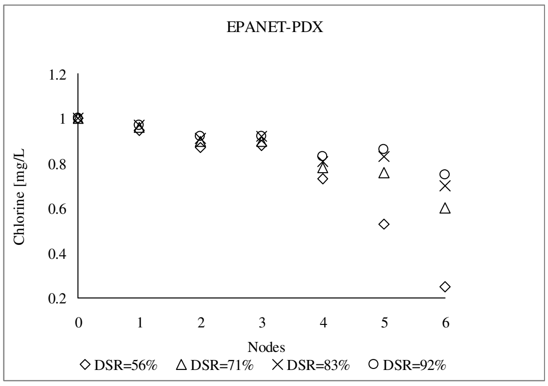


Figure 6. Chlorine residuals for pressure-deficient conditions

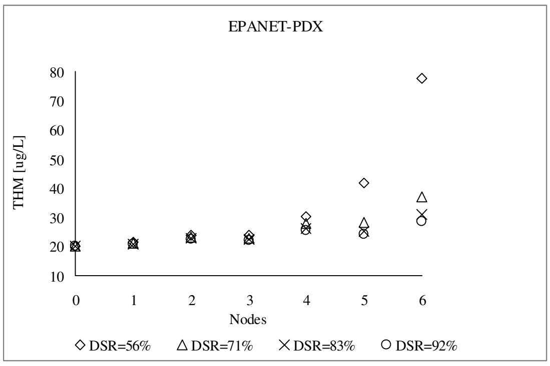


Figure 7. THM concentrations for pressure-deficient conditions

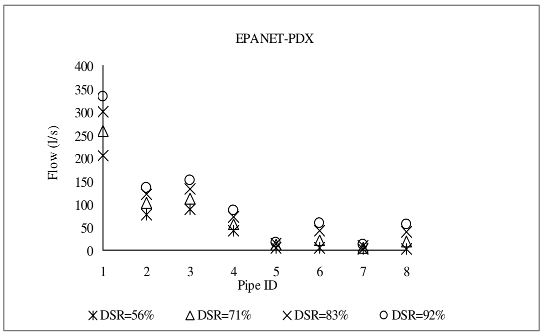


Figure 8. Pipe flows for pressure-deficient conditions

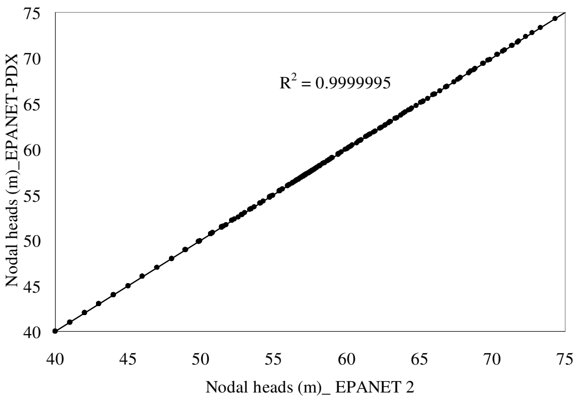


Figure 9. Hydraulic feasibility check for source heads from 40m to 80m

4. CONCLUSIONS

Comparison of EPANET 2 (DDA) and EPANET-PDX (PDA) models was performed for water quality analysis of a network under normal and pressure deficient hydraulic conditions. The performance of the models was tested on a sample network and the study shows that both EPANET 2 and EPANET-PDX provide identical results under normal pressure condition but different results during pressure deficient conditions. The differences during the pressure deficient conditions are significant at the farthest nodes from the source during high pressure deficiency situation with low demand satisfaction condition.

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