ABSTRACT

With infrastructure aging, sustained low/negative pressure events in distribution systems (DSs) may become more common. Therefore, more accurate numerical tools to predict hydraulic and water quality (WQ) behavior of DS under low/negative pressure conditions are needed to better identify areas where corrective/preventive actions are justified. A technique which allows combining pressure-driven hydraulic analysis and multi-species WQ model (i.e EPANET-MSX) is applied to investigate the impact of sustained pressure losses on hydraulic and WQ of a full-scale network. In this regard, chlorine residual and THMs concentrations are simulated during a severe sustained low/negative pressure event considering continuous intrusion of contaminated water. Cryptosporidium oocysts resulting from the ingress of sewage at low/negative pressure nodes was considered as conservative tracer. The impact of using different pressure demand relationships (PDRs) while performing pressure-driven analysis (PDA), is investigated on both the hydraulic and WQ behavior of the network during simulated sustained pressure deficient conditions (PDCs).

Keywords: Multi-species water quality model, pressure-driven analysis, continuous intrusion from sustained low-negative pressure events

1 Introduction

To ensure public health protection during pressure losses, appropriate emergency responses are required by water utility managers. Hydraulic and water quality modelling can be applied to predict the behavior of pressure deficient networks. To accurately simulate PDCs, a pressure-driven hydraulic analysis should be performed rather than the traditional demand-driven analysis (DDA). Different methods have been proposed in the literature to perform PDA [1, 2]. Some studies are based on iterative use of DDA, while others solve simultaneously the mass and energy conservation equations and an equation which express the relation between pressure and demand (PDR). In this regard, different PDRs have been proposed to perform PDA [3-5]. Some investigations on selecting a representative PDR have been performed [6, 7]; however, finding an appropriate PDR is a challenging task in the absence of field data.

A multi-species water quality model is required to be able to account for the interactions between microorganisms, disinfectant residual and different types of matrices. In 2007, EPANET-MSX which is a multi-species extension of EPANET was released. Yang et al. used EPANET-MSX to simulate the interactions between disinfectant decay and virus inactivation due to intrusion events [8]. Other researchers have applied this software to simulate contaminant intrusion for E. coli [9].
However, standard modeling tools are usually limited to either single species water quality analysis or the hydraulic analysis is only valid under normal operating conditions. Some researchers modeled water quality using pressure-driven hydraulic analysis for optimization models [10]. Also, the coupling of PDA and single species water quality analysis has been proposed for water quality reliability assessment [11, 12].

In this study, the impact of sustained low/negative pressure events on water quality variations by the help of a recently developed methodology is demonstrated. This modeling approach allows performing multiple species water quality modeling under sustained PDCs based on pressure driven hydraulic analysis results. The efficiency and applicability of this methodology are evaluated by simulating multiple water quality species in a single run under a significant sustained PDCs. As a proof of concept, and because modeling work is still ongoing, the water quality species included in this demonstration include chlorine, THMs and Cryptosporidium oocysts as a conservative tracer. Chlorine residual and THM spatial variations under sustained PDCs comparing to normal operating conditions are evaluated and the contamination transport throughout the DS due to continuous intrusion is investigated. The impact of using different PDRs, when performing PDA, on hydraulic and WQ parameters is also demonstrated.

2 Methodology

A full-scale distribution system with three WTPs is selected for the simulations and evaluating the performance of the proposed methodology. This network is comprised of 30,077 nodes which serves a population of about 400,000. There are no storage tanks or pump stations in the water network. As the entire network is hydraulically interconnected the supply zone of each WTP can be modified under PDCs based on the hydraulic conditions of the network.

2.1 Hydraulic analysis

To simulate sustained PDCs, pressure-driven hydraulic analysis is performed using the commercial software WaterGEMS®. Different PDRs can be defined in this software using pressure-demand piecewise linear curve. In this study, the impact of using two different PDRs when performing PDA, on hydraulic and water quality parameters are compared. Tanyimboh relationship can be defined as follows [3]:

\[
q_{j}^{\text{avl}} = q_{j}^{\text{req}} \frac{\exp(\alpha_j + \beta_j H_j)}{1 + \exp(\alpha_j + \beta_j H_j)} \quad \text{Eq. 1}
\]

where \(q_{j}^{\text{avl}}\) and \(q_{j}^{\text{req}}\) are available and required demand at node \(j\), respectively, \(H_j\) is available head. \(\alpha_j\) and \(\beta_j\) are parameters defined using field data while in the absence of field data, they can be estimated by \(\beta_j = 11.502/(H_j^{\text{des}} - H_j^{\text{min}})\) and \(\alpha_j = (-4.595H_j^{\text{des}} - 6.907H_j^{\text{min}})/(H_j^{\text{des}} - H_j^{\text{min}})\). In these equations \(H_j^{\text{min}}\) and \(H_j^{\text{des}}\) are minimum and desired pressure head, respectively. Wagner Equation [5] can be presented as follows when pressure head is between \(H_j^{\text{min}}\) and \(H_j^{\text{des}}\):

\[
q_{j}^{\text{avl}} = \left( \frac{H_j - H_j^{\text{min}}}{H_j^{\text{des}} - H_j^{\text{min}}} \right)^{1/2} q_{j}^{\text{req}} \quad \text{Eq. 2}
\]

In this study, \(H_j^{\text{min}}\) and \(H_j^{\text{des}}\) are considered to be 0 and 15 m, respectively, for all the nodes. Demand Satisfaction Ratios (DSRs) are calculated by dividing the available demand to the required demand at each node.

A continuous sustained low/negative pressure event (Scenario 1) is simulated by assuming that only one WTP out of three is online and the hydraulic and water quality behavior are compared with the normal conditions (Scenario 2) in which all 3 WTPs are working. A constant demand corresponding
to peak hour consumption in the studied distribution system is considered throughout the simulations for simplicity.

2.2 Water quality analysis

To enable performing multi-species water quality analysis during sustained low/negative pressure conditions a methodology is proposed which modify the EPANET input file based on the PDA results. This modified input file will then be used by EPANET-MSX for multi-species water quality analysis. More details on the developed technique (MSWQA-PDA) can be found in Hatam et al. (in press) [13].

To demonstrate the advantage of the proposed technique, chlorine residual, THMs and Cryptosporidium oocysts (simulated as a conservative tracer as chlorine has no effect on this microorganism) are predicted during sustained PDCs. The overall chlorine decay considers reactions in the bulk flow (\(k_b\)) and at the pipe wall (\(k_w\)) using a first-order reaction model \(\frac{dC}{dt} = -(k_b + k_w)C\). THMs are calculated using the following equation:

\[
\text{THM} = K_{tc}(C_0 - C) + \text{THM}_0
\]

in which \(C_0\) is the initial chlorine concentration at \(t=0\), \(C\) is the chlorine concentration (mg/L), and \(K_{tc}\) is the proportion of the chlorine bulk demand that leads to THM formation which is considered to be 41 µg/L per mg/L free Cl\(_2\) [14].

At this step, for simplicity, a conservative scenario is simulated by assuming continuous contaminant intrusion at all the nodes with pressure less than 1 m, within the range of water table levels in this system [15], due to a sustained pressure drop event in the DS. The concentration of Cryptosporidium oocysts in sewage is assumed to be equal to 26 oocysts/L (mean concentration) [16]. The contaminant is considered to be transported as a conservative tracer and no inactivation or interaction with other species is assumed. The intrusion flow rate \((Q_i)\) at each node is calculated using the orifice equation \((Q_i = C_d\pi(D^2/4)\sqrt{2gh_{ext} - h_{int}})\). The orifice diameter (D) is considered to be constant at all the nodes (1 mm) and the pressure head \((h_{ext})\) outside the pipe is considered to be equal to 1 m. The available demands for consumers are assumed to be zero at the intrusion nodes. The internal pressure head \((h_{int})\) at each node is calculated from the model.

Intrusion volume may affect the hydraulic conditions of DSs and an iterative procedure can be applied for calculating \(Q_i\) through orifice equation if large intrusion volumes are coming into the DS. In this paper, the impact of intrusion flow rates on pressure variations was considered by adding the intrusion flow rates into the model. However, the intrusion volumes were not then corrected using the adjusted pressure values as the differences were considered negligible in terms of both pressure and intrusion volume.

For water quality analysis an extended period simulation of 20 days was carried out to reach the equilibrium conditions of water quality parameters and the results were then reported for the last hour.

3 Results and discussions

The distribution of nodal demand satisfaction ratios is demonstrated in Figure 1 (a), using Tanyimboh equation. The results are grouped by the pressure values to facilitate the comparison, as required demands are completely satisfied at nodes with pressure more than 15 m. The median DSR for nodes under PDCs (P<=15) is 72% using Tanyimboh equation. For Wagner equation (results are not shown here) this value is 67% and, the mean is about 60% for both relationships. However, as it is shown in Figure 1 (b), using different PDRs can lead to different DSRs at some nodes in the network. For this scenario, the median, 75 percentile and maximum percentage of difference between the Tanyimboh and Wagner DSRs are 0.3%, 5% and 30%, respectively. Discrepancies in
the available demand can impact WQ by affecting the path through which the water passes to reach a node.

**Figure 1.** Distribution of (a) percentage of DSRs under pressure-deficient scenario when using Tanyimboh for two groups of nodes and (b) nodal DSRs absolute differences between different PDRs ($\Delta DSR = |DSR_{Tanyimboh} - DSR_{Wagner}|$) while performing PDA, for all the nodes. These results exclude nodes with no required demand.

Pressure values under normal operating conditions and pressure deficient conditions using traditional DDA and PDA (Wagner and Tanyimboh) are compared in Figure 2. Again the pressure values under PDCs calculated by Tanyimboh equation are used to discriminate nodes with pressure less than or equal to 15 m and nodes with pressure more than 15 m.

During normal conditions, pressure values are between 21 to 63 m while under PDCs the minimum pressure in the network is decreased to –7 m using PDA (either Wagner or Tanyimboh equation) (Figure 2). However, the results show that DDA incorrectly estimates the pressure values under PDCs especially for nodes experiencing PDCs ($P<=15m$) (pressures are between 2 to -27 m). Even though small pressure differences are observed between the use of the two PDRs (less than 1 m at all the nodes), they can affect the number of nodes prone to intrusion and volume of contaminated water which can enter into the DS. Therefore, water quality data will also be compared in the followings for these two PDRs to observe the importance of these discrepancies in the hydraulic parameters in water quality.

**Figure 2.** Comparison of pressure results calculated from PDA (Wagner and Tanyimboh) (modified EPANET input file) and DDA under pressure-deficient conditions and normal operating conditions (NOCs) (DDA)
The choice of a minimal pressure criteria is a critical factor when defining the nodes that may be susceptible to intrusion/backflow and areas which require corrective/preventive actions. Guidance to set these threshold pressure values remains poorly defined and do not consider the particular conditions of a specific network. Guideline reference values especially vary in their tolerance of low but positive pressures. Figure 3 shows the impact of different minimal pressure criteria choice (0, 5, 10 or 15 m) on the number of nodes at risk of intrusion/backflow for the simulated low/negative pressure event. It should be mentioned that the nodes which may need corrective/preventive actions also depend on the intrusion rate, the contamination level outside the pipe and fate and transport of microorganism throughout the network. The impact of using different PDRs on the number of nodes experiencing low pressure (based on different minimal pressure criteria) is shown in Figure 3. The differences are less than 1% for all the groups. However, as expected, DDA will overestimate the zones at risk of low pressure, potentially leading to unjustified boil water advisories. A more detailed discussion about the impact of different minimal pressure criteria on the number of nodes and geographical distribution of areas which may need corrective/preventive actions can be found in Hatam et al. (in press) [13].

![Figure 3](image.png)

**Figure 3. Number of nodes at risk of intrusion/backflow based on different minimal pressure criteria and different methods of estimation: traditional DDA and PDA (comparing Wagner and Tanyimboh)**

The multi-species water quality analysis based on PDA was used to model a continuous intrusion of Cryptosporidium oocysts at nodes with pressures <1 m. The impact of the simulated sustained PDCs on chlorine and THM concentrations are shown by comparing the results of each pressure group to the corresponding values during normal operating conditions (Figure 4). As an example, for nodes with zero or negative pressure, the median chlorine residual decreased due to sustained pressure losses from 1.2 to 0.4 mg/L. For nodes with low but positive pressure the median chlorine residual drop from 1.1 to 0.9 mg/L while for nodes with P>=15 m the median remains almost constant (~1 mg/L).
Figure 4. THM and chlorine concentration under normal and pressure deficient scenario, Tanyimboh equation used while performing PDA. Note: Median; Box: 25%-75%; Whisker: min-max

Cryptosporidium oocysts in contaminated ingress water at low/negative pressure nodes are transported throughout the DS, reaching more than 8,000 nodes at different concentrations (Figure 5). The theoretical intrusion flow rate entering the DS is estimated to be 2.5 lps (968 nodes) for Tanyimboh, and 3.7 lps (1343 nodes) for Wagner equations.

Figure 5. Number of nodes in the network for different ranges of Cryptosporidium concentration using Tanyimboh (blue) and Wagner (green) equations

For better comparison, chlorine residual at each node under PDCs is also compared with the corresponding values under NOCs and the distribution of these differences is shown in Figure 6 (a). The results showed that generally the water quality gets poorer due to the simulated sustained pressure drop. These differences are generally more significant for the groups of nodes with lower pressure. The median of chlorine differences decreased from 0.8 mg/L, (for nodes with P<=0) to zero (for nodes with P>15). It is important to note that these differences in chlorine residual are caused by changing hydraulic operating conditions (water age), during the simulated sustained PDCs. They do not take into account other possible causes of residual loss such as biofilm re-suspension and scouring of corrosion products caused by flow reversals. These other causes of residual loss can also become important and cause complete loss of residuals especially during unsteady flow conditions. It should be noted that in the current demonstration, the contamination intruded into the network during PDCs is considered to be non-reactive (conservative tracer). Therefore, its spatial and temporal distribution throughout the network is not affected by the nodal chlorine residuals, which is coherent with the high resistance of Cryptosporidium oocysts to chlorine.
Chlorine residual differences, under PDCs, based on the use of different PDRs (Wagner and Tanyimboh) at most of the nodes are small. As it is shown in Figure 6 (b), the median of differences is zero and about 90% of the nodes have chlorine differences less than 0.03 mg/L. This is while less than 4% of the nodes have chlorine differences higher than 0.1 mg/L while using different relationships.

![Figure 6](image.png)

**Figure 6.**(a) distribution of nodal chlorine residual differences between normal (DDA) and pressure deficient conditions (PDA, Tanyimboh) (b) distribution of nodal chlorine residual differences under pressure deficient conditions between Wagner and Tanyimboh equations

### 4 Summary and conclusions

A recently developed methodology which enables multi-species water quality model based on a pressure-driven approach was applied to investigate the impact of sustained pressure losses on water quality in a distribution system. In this regard, chlorine residual and THMs were simulated during a severe sustained PDCs concurrently with modeling continuous intrusion of sewage contaminated water (*Cryptosporidium* oocysts) at nodes with low/negative pressures. However, this study is based on several conservative assumptions such as a continuous intrusion of contaminants with no reactions; future developments of this research will address extending the developed methodology to simulate less conservative scenarios. Ongoing work includes the consideration of scenarios with reactive contaminants and intrusion events in the range of hours.

DDA does not estimate correctly the pressure values and overestimates the number of nodes with low pressures during PDCs, potentially leading to unjustified boil water advisories. Therefore, realistic PDA should be linked with water quality models to predict water quality in the systems under pressure losses. Some differences, although negligible at most of the nodes, were observed in the predicted nodal pressures and values of available nodal demand when using different PDRs while performing PDA. These differences can impact on water quality modeling during PDCs. Under the scenario considered, the intrusion volume was significantly higher (48%) using the Wagner PDR. Although, PDA produces much more realistic results as compared to traditional DDA during PDCs, the selection of the PDRs which are more representative of the network model can improve the PDA results.

### 5 References


