

EXTENSION OF EPANET FOR PRESSURE DRIVEN DEMAND MODELING IN WATER DISTRIBUTION SYSTEM

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Abstract

The use of mathematical models for simulating the physical behavior of water distribution systems becomes standard engineering tools of water utilities for applications such as design, calibration, rehabilitation and operation. Currently, there are several hydraulic simulation models and most of them are based on demand driven analysis (DDA). Recently, a number of studies have highlighted some of the limitations of demand driven analysis leading to remarks that such models may be inadequate when abnormal conditions are considered. In fact, demand flowrates are not only functions of time, since the node outflows occur via orifices (e.g. open taps or valves) and are thus dependent on the pressure in the system. Analysis that incorporates the relationship between demand and pressure are called pressure driven analysis (PDA). In this framework, functions assume fixed demand above a given critical pressure, zero demand below a given minimum pressure and some relationship between pressure and demand for intermediate pressures. In this paper, the authors describe an extension of the Epanet by OOTEN toolkit to directly include pressure driven demand modeling. The data structures and algorithms within Epanet source code are modified to adequate PDA modeling. To demonstrate the capability of PDA model manages the insufficiency of nodal pressure, failure conditions are assumed (fire flow). Results show that PDA can be more effective for simulating abnormal conditions than DDA. Finally, concluding remarks are presented.

Keywords: water distribution systems, simulation models, pressure driven modeling.

1. INTRODUCTION

Hydraulic models that simulate the behavior of water distribution systems (WDS) have become standard engineering tools of water utilities for applications such as design, calibration, rehabilitation and operation. The conventional approach also called demand driven analysis (DDA) assumes that demands are known functions at time and are independent of the pressure in the system [1]. Since the goal of a hydraulic model is to produce nodal pressures and link flows that satisfy fixed demand values at system nodes, water utilities have typically used practical guidelines or measured field data to estimate system demands in order to input within these simulation models. Most of simulation models based on DDA have usually presented reasonable solutions under normal conditions. However, such models may not be able to accurately reproduce the behavior of systems under abnormal conditions (negative pressure). Previous studies [2–6], some based on field investigations, have presented limitations related to the use of demand driven modeling and hence have highlighted some of the implications of pressure driven analysis (PDA). In fact, demand flowrates are not only functions of time, since the node outflows occur via orifices (e.g. open taps or valves), but also dependent on the pressure in the system. Currently, several approaches [7–12] based on PDA may be used to model the pressure/demand relation on water distribution systems. It assumes fixed demand above a given critical pressure, zero demand below a given minimum pressure and some proportional relationship between pressure and demand for intermediate pressures. Additionally, network studies [1, 3, 13] have adopted methods that use the classical formulation of orifices at system nodes in order to consider some pressure-demand relation on the modeling process. However, in some cases this framework may present deficiencies due to the water consumption capacity which is limited. In this paper, it is proposed an extension of the Epanet [14] to directly include pressure/demand functions into OOTEN toolkit [15] and so permitting that abnormal conditions can be realistically modeled. The data structures and algorithms within Epanet source code are modified to adequate PDA modeling. Here, the developed model is applied to simple example networks under failures conditions to demonstrate the capability of PDA modeling manages the insufficiency of nodal pressure. Moreover, performance and convergence characteristics are discussed. Results show that PDA can be more effective for simulating abnormal conditions than DDA.

2. BACKGROUND

Conventionally, DDA has been adopted as standard technique to solve the network problem. This technique assumes that the amount of required water along pipes is known and can be grouped at the point of demand (network

nodes). Thus, the system behavior in terms of the state variables (pressure and flows) is obtained solving governing equations with fixed demand values at nodes. In this type of analysis, any demand/pressure relationship is ignored and demands are always satisfied even when the nodal pressures are below zero [1]. Therefore, consumers can be supplied with water under low and even negative nodal pressures. Obviously, this assumption is unrealistic and represents the main deficiency of DDA approaches. However, if WDS are operating under normal conditions and their structural conditions are reasonable known, DDA models can be adopted as hydraulic appraisal tool. Assuming that real systems often present abnormal conditions, previous authors [7–12] have proposed models that consider the pressure/demand relation in order to reproduce the system behavior under failure conditions. PDA model assumes that if some pressure is available above of a minimum level, some water portion will be supplied at system node. This assumption seems to be more realistic than DDA. Some authors [1, 3, 16, 17] have formulated the problem as intermittent systems using the emitter coefficient which are implemented into Epanet. Using the classical formulation of orifices, Rossman [14] proposes emitter coefficients in Epanet as described:

$$q^{avl} = S(H^{avl} - H^{min})^\alpha \quad (1)$$

where q^{avl} is the available demand at a given node, S is a node constant that depends of consumer characteristics, H^{avl} and H^{min} are respectively the available nodal pressure and critical nodal pressure, and α is a exponent constant for orifices with a fixed cross-sectional area. Although this approach seems simple, it is limited by available piezometric level of the system leading to a water consumption to be proportional the available pressure. In some situations, this approach (Eq. 1) may produce undesired solutions due to unconstrained assumptions. For instance, it is clearly known that there is a maximum demand consumption (e.g. 300 L/day) for each residential consumer. Thus, researches [7–10] have suggested non-continuous discretized equations that estimate maximum, partial and minimum demand supply (pressure driven demand) depending of available head. The computing of pressure driven demand rate (q^{avl}) is conditioned to assumptions: (a) $H^{avl} \leq H^{min}$, (b) $H^{min} < H^{avl} < H^{des}$ and (c) $H^{avl} \geq H^{des}$. Assuming the a- and c-conditions, q^{avl} becomes respectively 0 and q^{req} (design demand). Considering b-condition, Wagner et al. [7] propose:

$$q^{req} \left(\frac{H^{avl} - H^{min}}{H^{des} - H^{min}} \right)^{\frac{1}{\alpha}} \quad (2)$$

where q^{avl} is the available demand at a given node, q^{req} is the fixed demand that is previously estimated, H^{min} is the threshold pressure below which no flow can be discharged, H^{des} is the desired pressure to satisfy the fixed demand (full demand), and α is an exponent usually between 1.5 and 2 (Wagner et al. [7] suggest $\alpha = 2$). Precisely, this exponent may be determined by calibration. Tucciarelli et al. [10] suggest:

$$q^{req} \sin^2 \left(\pi \frac{H^{avl}}{2H^{des}} \right) \quad (3)$$

where \sin is a mathematical function and π is attributed 3.14. In addition, Fujiwara et al. [9] present the pressure/demand rate as follows:

$$q^{req} \frac{(H^{avl} - H^{min})^2 (3H^{des} - 2H^{avl} - H^{min})}{(H^{des} - H^{min})^3} \quad (4)$$

3. PRESSURE-DRIVEN DEMAND MODEL

The introduction of the pressure driven analysis (PDA) within the conventional water network models is a complex task. Previous studies [4–6, 13, 18, 19] have suggested distinct implementation ways (iteratively or directly). Here, is presented an extension of EPANET to directly carry out pressure driven modeling. Thus, small modifications in conventional formulation are required.

3.1 OOTEN Programmer's Toolkit

The Object Oriented Toolkit for Epanet (OOTEN) is a code library that allows developers to customize EPANET's computational engine for their own specific needs. It was developed by Water Resources Group at Rand Afrikaans University under supervision of J. E. Van Zyl [15]. OOTEN is written in standard ANSI C++ code and can be incorporated in any compatible programming code. However, to perform pressure driven analysis by OOTEN, it is necessary to modify the conventional hydraulic model. Such adjusts should be directly made under C and C++ languages codes which are respectively used in Epanet and OOTEN. It is important to state that all extensions described here are not extended to Epanet desktop application.

Data Structure Modifications. Two new terms are added to Epanet input file. These modifications of data structure enumerated below are made for computing the pressure driven demand.

1. Introduction of **Emin**. This new global variable (**Emin**) is added to represent the threshold nodal head in the demand models. It is defined in header file "types.h" under type Snode.
2. Introduction of **Edes**. This new global variable (**Edes**) is added to represent the necessary minimum head to satisfy fixed nodal demands. It is defined in header file "types.h" under type Snode.

Pressure Driven Demand Algorithm. The conventional water network model is defined through a set of nonlinear and linear equations corresponding the energy and mass conservation. Epanet uses the gradient method based on Newton-Raphson technique for solving simultaneously this equation set. Without loss of generality, the conventional water network model can be described as follows:

$$\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & 0 \end{bmatrix} \begin{bmatrix} Q \\ H \end{bmatrix} = \begin{bmatrix} -A_{10}H_0 \\ q \end{bmatrix} \quad (5)$$

where A_{11} is the diagonal matrix which its elements represent head losses (pipes, pumps and minor loss), A_{12} is the reduced incidence matrix (only non-tank nodes), A_{10} is the reduced incidence matrix to the tank nodes, H_0 is the known head vector, A_{21} is the overall incidence matrix, q is the demand vector and Q and H are the state variable vectors (flow rate and head, respectively). More details about how building these matrices (A_{11} , A_{12} , A_{10} and A_{21}) may be verified in [13, 14, 19]. Solving the above problem (Eq. 5), two iterative equations are obtained:

$$H^{k+1} = -(A_{21}G^{-1}A_{12})^{-1}[A_{21}G^{-1}(A_{11}Q^k + A_{10}H_0) - A_{21}Q^k + q] \quad (6)$$

$$Q^{k+1} = (-G^{-1}A_{11} + I)Q^k - G^{-1}(A_{12}H^{k+1} - A_{10}H_0) \quad (7)$$

where $G = NA_{11}$, N is a diagonal matrix with its elements are defined by head loss exponent, I is an identity matrix, and k is the iteration operator. To introduce the PDD relationship in the water network general problem, it should be redefined the q term from Eq. (5) introducing implicitly the head variable H on it, as follows:

$$\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & 0 \end{bmatrix} \begin{bmatrix} Q \\ H \end{bmatrix} = \begin{bmatrix} -A_{10}H_0 \\ q(H) \end{bmatrix} \quad (8)$$

where $q(H)$ is computed using pressure driven demand models (Eqs. 2, 3, and 4). Applying both Taylor expansion series and the Newton-Raphson techniques on PDD problem (Eq. 8), it is possible to find iterative equations that represent the PDD simulation:

$$H^{k+1} = -(A_{21}G^{-1}A_{12} + D)^{-1}[A_{21}G^{-1}(A_{11}Q^k + A_{10}H_0) - A_{21}Q^k + q(H^k) - DH^k] \quad (9)$$

$$Q^{k+1} = (-G^{-1}A_{11} + I)Q^k - G^{-1}(A_{12}H^{k+1} - A_{10}H_0) \quad (10)$$

Epanet Code Modification. The general approach described by Eqs. (9 and 10) is the standard language for modeling PDD. The required changes for including pressure driven demands has been implemented at a low level, i.e. inside Epanet code. Two new functions are defined in "funcs.h" and implemented in "hydraul.c": **void newcoeffsPDM (int)** and **void pressuredrivendemand (float)**. The function *newcoeffsPDM* calculates the PDD and it is called into conventional function *netsolve (int *, float *)* which solves network nodal equations for heads and flows. In addition, the function *newcoeffsPDM* replaces the original function *newcoeffs()*.

Input File. The EPANET input file is modified to accommodate the pressure driven analysis modeling. The minimum and desired heads should be specified in input file (.inp) which the modifications are summarized below:

1. Specifying minimum head. The minimum head should be specified in the input file in the [JUNCTIONS] section. The variable name is **Hmin**.
2. Specifying desired head for each node. The desired head should be specified in the input file in the [JUNCTIONS] section. The variable name is **Hdes**.

4. APPLICATION AND RESULTS

To investigate the performance and limitations of the proposed PDA model, applications have been carried out under some WDS network models used on literature. The first network (1-network) shown in Fig. 1 includes 4 consumer nodes, 1 tank and 4 pipes with its data given in own illustration. This model was previously tested by [18, 20]. The

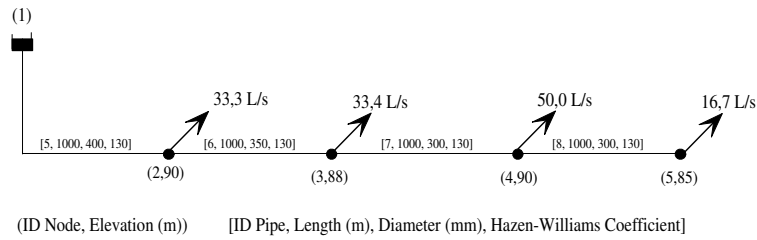


Fig. 1: 1-Network Model

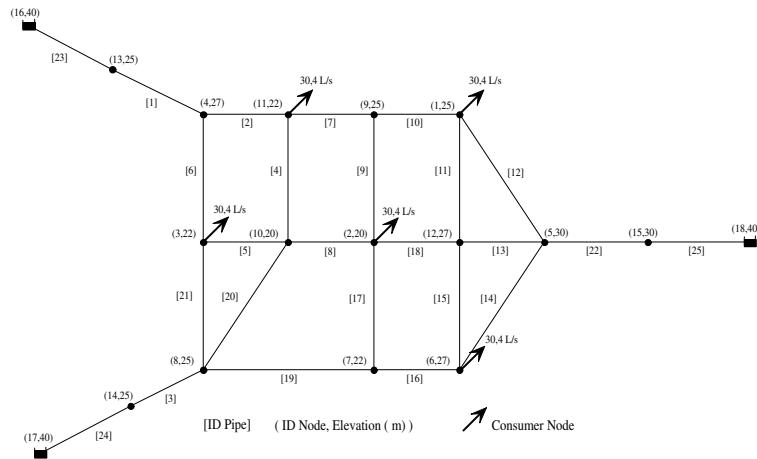


Fig. 2: 2-Network Model

Table 1: Simulation results of 1-network problem

ID Node	Demand Driven Analysis		Pressure Driven Analysis			
	Normal	Fire Flow	Normal		Fire Flow	
	Pressure	Pressure	Pressure	Demand	Pressure	Demand
2	7.31	5.13	8.81	22.1	8.29	21.4
3	6.27	0.71	9.5	23.0	8.16	21.3
4	1.24	-9.84	6.3	28.1	3.56	21.0
5	6.00	-7.88	11.2	12.5	7.36	40.4

second network model shown in Fig. 2 was proposed by [10]. It includes 15 junction nodes (5 consumer node), 3 tanks and 25 pipes. The 2-Network data are given in [10].

This section discusses and compares DDA and PDA methods. For this purpose, two operational conditions are assumed to 1-network problem. The first represents a normal operational condition. It is performed using network data described in Fig. 1 and tank level equal 100 m. The second condition reproduces a fire flow situation (abnormal). In this case, additional flow of 50 L/s is assumed at 5-node modifying the nodal demand to 66.7 L/s. The objective of this last condition is to produce negative pressures in 1-network model, permitting permits to assess the performance of both methods. Simulation results of this last case are shown in Table 1. Initially, it can be observed that both nodes 4 and 5 present pressure deficiencies when DDA simulates fire flow condition. From this simple test, it is demonstrated the DDA incapability of simulating abnormal conditions. For example, how can 4-consumer node supply water if the available pressure is negative (physically, it may be assumed zero)? Moreover, it is possible to state that negative pressures (4 and 5) are produced because the model needs to satisfy fully nodal demands. This same example (1-network problem) is simulated using PDA approach. The adopted demand model is based on Eq. 2. Minimum and desired pressure limits are respectively assumed 0 and 20 m. Comparing with more details the obtained solutions using DDA and PDA approaches (Table 1), it can be seen that PDA solutions have been more acceptable than DDA solutions mainly in terms of the available pressures. For example, a pressure of 1.24 m (from DDA simulations) obtained from DDA analysis difficultly supplies the required demand (50.0 L/s) at 4-node. Therefore, DDA fails when abnormal conditions are required. It is important to state that the mass balancing is satisfied for all cases.

In order to compare pressure driven demand models described here, the proposed model is applied to the 2-network problem (Fig. 2). Minimum and desired pressures are equally adopted 0 and 20 m as the above case. A fire flow (abnormal condition) is simulated. It assumes additional flow of 100 L/s at 1-node. Thus, the nodal demand at 1-node becomes 130.4 L/s. Results are summarized in Table 2. It can be noted that the DDA model are not capable to produce accurate results when the 2-network is submitted to the fire flow condition. Observe that the first column of this table refers to the results using DDA model. The available pressure at 2-node represents an unrealistic situation. Comparing described demand models in terms of total demand sum, it is possible verify that formulations proposed by Fujiwara et al. [9] (Eq. 4) and Tucciarelli et al. [10] (Eq. 3) present a similar performance. Instead, the model proposed by Wagner (Eq. 2) overestimates the demand values. Note that all nodal demands suffers supply constraints when network pressure deficiencies are simulated.

Table 2: Simulation results of 2-network problem

Index	Fire Flow (demand at node 1 = 130.4 L/s)						
	DDA	Wagner		Fujiwara		Tucciarelli	
	Pressure	Pressure	Demand	Pressure	Demand	Pressure	Demand
1	0.75	3.0	50.20	4.6	17.70	4.7	16.70
2	-23.84	8.3	19.60	9.5	14.00	9.5	13.90
3	6.72	7.7	18.80	7.9	10.50	7.9	10.30
4	2.55	2.9	0.00	3.0	0.00	3.0	0.00
5	-0.60	-0.1	0.00	0.0	0.00	0.0	0.00
6	0.63	2.7	11.20	3.0	1.80	3.0	1.60
7	5.63	7.7	0.00	8.0	0.00	8.0	0.00
8	4.60	4.9	0.00	5.0	0.00	5.0	0.00
9	0.00	3.3	0.00	4.6	0.00	4.7	0.00
10	3.99	9.1	0.00	9.7	0.00	9.8	0.00
11	3.25	6.6	17.40	7.7	10.00	7.7	9.80
12	0.70	2.7	0.00	2.9	0.00	2.9	0.00
13	5.00	5.0	0.00	5.0	0.00	5.0	0.00
14	5.00	5.0	0.00	5.0	0.00	5.0	0.00
15	0.00	0.0	0.00	0.0	0.00	0.0	0.00
			117.20		54.00		52.30

5. CONCLUSIONS

The Epanet method that reproduces the hydraulic behavior of water distribution networks is modified to simulate failures conditions. These modifications are based on pressure driven modeling technique. All code changes are written under low level which modify data structure, solving algorithms and input files. Two example network problems are adopted to assess the methodology. In addition, three demand models are tested. It is concluded that demand driven analysis fails when abnormal conditions are required. On the other hand, pressure driven analysis has presented desired solutions, showing a compensation among nodal demands and available pressures. In terms of investigated demand models, it can be stated that formulations proposed by Fujiwara and Tucciarelli present similar results in such applications. Although advantages of pressuredriven modeling are presented, it is necessary to verify this methodology in networks more complex under several failure conditions.

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