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Modelling Pressure Deficient Water Distribution Networks in EPANET

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Abstract

Nodal outflows in a pressure deficient water distribution network depend on available nodal heads. Thus, node-head flow relationship exists at each node which are solved along with other appropriate equations for simulation. While using EPANET for such simulation, source code needs to be modified to obtain direct solution. The other way is to use EPANET iteratively wherein node head-flow relationships are satisfied externally. Herein, a simple non-iterative method is suggested in which artificial string of Check Valve, Flow Control Valve, and Emitter are added in series at each demand node to model pressure deficient water distribution network.

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Keywords: Algorithms; EPANET; Modelling; Pressure-deficient network analysis; Water Distribution; Water Pipelines;

1. Introduction

Traditional methods for analysis of looped water distribution networks assume that available nodal flows are equal to the nodal demands and obtain available pressure heads at different nodes. Available pressure heads less than the minimum required heads at one or several nodes show network's inability to supply the desired demands. Under such pressure-deficient conditions, the quantity of water a network can supply at different nodes is required in order to estimate short-fall in supply. Such an analysis has been used in tackling many network problems such as: assessing reliability [1-5] reliability-based design [6-9], calibration [10], vulnerability analysis [11], placement of isolation

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valves [12-13], and multi-objective network design [14]. Available flow at a node depends on available pressure. Hence, a relationship between flow and pressure at a node exists and is termed as node head-flow relationship (NHFR). During simulation, NHFR at different nodes must be satisfied along with node flow continuity and conservation of energy equations. Several methods have been suggested to simulate pressure-deficient networks in EPANET by considering the different types of NHFR. One way to solve this problem is to modify the source code of EPANET to get a direct solution which will satisfy the NHFRs. However, this is a difficult task. Another way to solve this problem is to iteratively use EPANET with the node head-flow relationships satisfied externally in each iteration. Also, modifications in the network with the addition of valves, artificial reservoirs and pipes have been suggested to mimic the behavior of pressure deficient network in better way and obtain the simulation results directly. A new methodology is proposed in this paper and its application is illustrated with two example problems taken from literature. The proposed method is found to simulate pressure-deficient network in EPANET with reasonable computational efficiency. Several methods have been developed to make use of widely used demand-driven hydraulic solver EPANET 2.0 [15] for simulation of pressure-deficient water distribution networks. Cheung *et al.*[16] modified the source code of EPANET by modifying the emitter status using the object oriented toolkit. Guidolin *et al.*[17] developed CWSNet as an open-source alternative to EPANET which is equipped with emitter. Siew and Tanyimboh [18] modified the source code of EPANET for pressure-deficient WDN analysis and termed this version as EPANET-PDX. Ozger and Mays [3], Ang and Jowitt [19], Suribabu and Neelakantan [20], Jun and Gouping [21] suggested iterative use of the EPANET hydraulic solver. Their methodology consists of introducing artificial reservoirs at the pressure deficient nodes. Ozger and Mays [3] and Ang and Jowitt [19] considered the flow to the artificial reservoir and determined how much water is available; while Suribabu and Neelakantan [20] considered the flow from the artificial reservoir to the pressure deficient demand node and determined how much water is required to meet the demand. Mansoor and Vairavamoorthy [22] used artificial reservoirs with ball valves that restrict the flow from reservoir under negative pressure conditions. Jinesh Babu and Mohan [23] used artificial reservoir along with artificial flow control valve that prevents surplus flow. Rossman [24] suggested using emitter component available in EPANET for pressure-deficient network simulation. Gorev and Kodzhespirova [25] considered an artificial string made up of a flow control valve, a pipe with a check valve, and a reservoir at each node. In this paper, approach of Gorev and Kodzhespirova [25] is modified. The modification includes use of emitter instead of pipe and artificial reservoir. The proposed approach simulates pressure-deficient water distribution networks in a *single run* of EPANET. The methodology is illustrated with examples from the literature.

2. Proposed Approach

The generalized equation for flow through emitter can be written as [15]

$$q_j^{\mathrm{avl}} = C_d\left(H_j^{\mathrm{avl}} - H_j^{\min}\right)^{\gamma} \tag{1}$$

$$C_d = q_j^{req} / \left(H_j^{des} - H_j^{\min}\right)^{\gamma} \tag{2}$$

in which C_d and γ are the emitter coefficient and exponent, respectively. For demand node j, q^{req}, q^{avl}, H^{des}, H^{avl} and H^{min} are, respectively: demand, available flow, required head, available head and the head below which the nodal flow is zero. It can be seen that substitution of Eq. 2 into Eq. 1 leads to the well-known form of the pressure-dependent nodal flow function proposed by Wagner *et al.* [26]. In a WDN where nodal demands of several consumers are lumped at a node, the value of γ depends on the characteristic of secondary network, i.e. relative locations of consumers' connections and head loss in secondary network [27].Emitter is used for sprinklers where outflow depends on available pressure and is uncontrolled. It is therefore proposed to consider an artificial string of a flow control valve (FCV), an emitter and a Check Valve (CV) as shown in Fig. 1. The FCV will restrict the flow to desired maximum, the emitter will simulate partial flow condition, and the CV at the demand node will restrict the negative flows. Thus the method involves modification to the network nodes, which may be done using the graphical user interface of EPANET. Alternatively, the toolkit and the standard file input/output streams on the platforms that support the toolkit may be used to reduce time and effort especially for large networks.

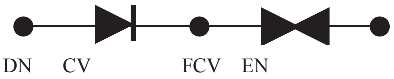

Fig. 1. Required connections at each demand node

3. Results and Discussion

3.1. Example 1

A serial network shown in Fig. 2 is taken from literature [27]. The source head at Reservoir is 100 m and required heads at nodes J_1 through J_4 are 90, 88, 90, and 85 m. The demands at nodes J_1 through J_4 are 120, 120, 180 and 60 m^3/h, respectively. In addition to normal demand, fire demand of 180 m^3/h is considered at node J_4. Each link is 1000 m long and has Hazen-Williams roughness coefficient of 130. The diameters for links P_1 through P_4 are 400, 350, 300 and 300 mm, respectively. Considering the same, the desirable head at nodes J_1 to J_4 would be 90.4, 88.4, 90.9 and 86.6 m, respectively. The emitter exponent is $\gamma = 0.5$.

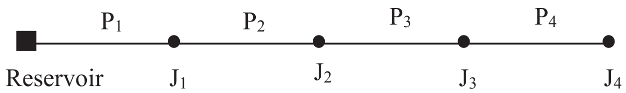

Fig. 2. System layout for Example 1

The serial network is modified by adding CV, FCV and emitter at each demand node as shown in Fig. 2 and analyzed in EPANET. CV is considered with negligible resistance, FCV is set to required demand. It is observed that demand at nodes J_1, J_2 and J_4 are fully met and outflow at node J_3 is 23.93 m^3/h (0.399 m^3/min). The available heads at J_1 to J_4 are 97.049, 93.633, 90.016, and 86.983 m, respectively. The outflow at node 3 obtained by Gupta and Bhave [27] was 22.38 m^3/h (0.373 m^3/min). The small difference may be due to differences in the systems of units used, unit conversion errors and differences in the convergence criteria.

3.2. Example 2

A looped water distribution network as shown in Fig. 3 is taken from literature [3]. The head at both the reservoirs RES_1 and RES_2 is 60.96 m. The network has 13 demand nodes and 21 pipes. Pipe number, length, diameter and Hazen-Williams roughness coefficient are given in Table1. Node number, elevation, and nodal demands are given in Table 2. The head at a node below which no water is available is taken as the elevation of the node. The required residual head at all demand nodes is 15 m. Thus, required head in NHFRs is taken as 15 m above node elevation. The emitter exponent is $\gamma = 2/3$ [27]. The results are summarized and compared in Table 2 for failure and subsequent closure of Pipe 3. Jinesh Babu and Mohan [23] obtained the most conservative estimate of total supply from the sources as 2390.96 m^3/h. Gorev and Kodzhespirova [25] estimated total supply from sources as 2749.65 m^3/h. The proposed method estimated total supply from sources as 2709.35 m^3/h. The solution by the proposed method is the same as that obtained by embedding the pressure dependent NHFRs in the system of equations [27]. The solution by Jinesh Babu and Mohan [23] does not model partial flow satisfactorily as it is based on H_j^{min} only; it does not consider H_j^{des}. In the solution by Gorev and Kodzhespirova [25] the shape of the pressure dependent nodal flow function is fixed. Modelling errors are therefore introduced, as there is no means to calibrate the relationship between the flow at a demand node and the pressure.

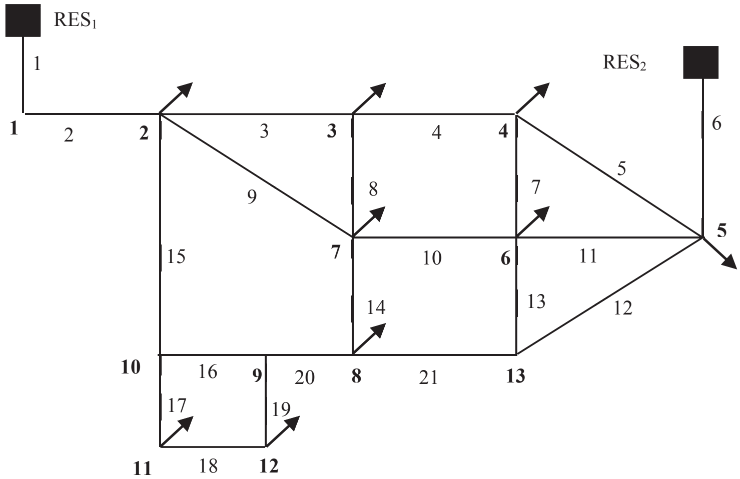

Fig. 3. Water distribution network for Example 2

Table 1. Pipe data for Illustrative Example 2

Pipe No.	Length (m)	Diameter (mm)	Roughness CHW
(1)	(2)	(3)	(4)
1	609.60	762	130
2	243.80	762	128
3	1524.00	609	126
4	1127.76	609	124
5	1188.72	406	122
6	640.08	406	120
7	762.00	254	118
8	944.88	254	116
9	1676.40	381	114
10	883.92	305	112
11	883.92	305	110
12	1371.60	381	108
13	762.00	254	106
14	822.96	254	104
15	944.88	305	102
16	579.00	305	100
17	487.68	203	98
18	457.20	152	96
19	502.92	203	94
20	883.92	203	92
21	944.88	305	90

Table 2. Node data for Illustrative Example 2 and analysis results for Pipe 3 failure

Node No.	Elevation	Demand	Jinesh Babu and Mohan [23]		Gorev and Kodzhespirova [25]		Proposed Approach	
			Available flow	Available HGL	Available flow	Available HGL	Available flow	Available HGL
	(m)	(m^3/h)	(m^3/h)	(m)	(m^3/h)	(m)	(m^3/h)	(m)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
RES_1	60.96	0.00	-1168.55	60.960	-1315.32	60.960	-1298.65	60.960
RES_2	60.96	0.00	-1222.41	60.960	-1434.33	60.960	-1410.70	60.960
1	27.43	0.00	0.00	60.590	0.00	60.500	0.00	60.510
2	33.53	212.40	212.40	60.438	212.40	60.310	212.40	60.325
3	28.96	212.40	212.40	46.869	**193.06**	41.353	**193.27**	41.980
4	32.00	640.80	**165.11**	47.000	**506.92**	41.387	**489.54**	42.016
5	30.48	212.40	212.40	50.446	212.40	46.823	212.40	47.252
6	31.39	684.00	**499.05**	46.390	**558.58**	41.393	**543.71**	42.020
7	29.56	640.80	640.80	46.565	**588.00**	42.190	**587.73**	42.736
8	31.39	327.60	**274.56**	46.390	**277.52**	42.154	**271.54**	42.710
9	32.61	0.00	0.00	53.551	0.00	51.357	0.00	51.597
10	34.14	0.00	0.00	55.013	0.00	53.288	0.00	53.473
11	35.05	108.00	108.00	51.527	**103.87**	48.925	**103.80**	49.183
12	36.58	108.00	**66.24**	51.580	**96.89**	48.654	**94.97**	48.950
13	33.53	0.00	0.00	48.360	0.00	44.252	0.00	44.761

Note: Partial nodal flows are shown bold.

4. Summary and Conclusions

Several researchers have suggested modifying the source code of EPANET. However, many municipalities lack the expertise for specialist work of this nature. Modification of network by incorporating artificial reservoirs to determine the system's performance under conditions of subnormal pressure underestimates the flows and requires iterative execution of EPANET 2. The method proposed by Gorev and Kodzhespirova [25] is based on an implicit pressure dependent nodal flow function that cannot be calibrated for different water distribution networks which, therefore, leads to modelling errors. The method proposed herein is very practical when used in conjunction with the EPANET toolkit.

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