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Research Note

Emitter based approach for estimation of nodal outflow to pressure deficient water distribution networks under pressure management

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Abstract. The hydraulic network solver simulates the behavior of a water distribution network for a given set of geometric and hydraulic parameters, such as pipe length, pipe diameter, tank size, pump capacity, demand, and pipe roughness, etc. Over the years, many researchers have developed a number of hydraulic simulation models (software) for the analysis and design of water distribution networks, most of which are based on Demand Driven Analysis (DDA). This paper reviews the existing approaches and examines the usefulness of the emitter feature that is available in the hydraulic network solver (EPANET) as a tool for the pressure driven model. The emitter based method determines the possible supply at all deficient nodes, based on the availability of energy at that node by introduction of an emitter. This method, along with three existing approaches, has been applied to three benchmark networks, and important findings from the study, in terms of convergence and numerical results, are presented. The framework of the head-flow based approaches and the proposed method is carried out using the toolkit feature available in the EPANET hydraulic solver.

1. Introduction

Water distribution systems connect the source of a water supply to the consumer using hydraulic components, such as tanks, reservoirs, pumps, pipes and valves. The analysis and design of such a system is carried out for various demands and under various operating conditions. The size of the pipes and other hydraulic components should be able to provide hydraulic heads greater than those of the minimum required at all demand nodes. If the size of the pipes forming the network is inadequate, then, the analysis may show pressure heads below the acceptable for service. In the event of an unexpected failure, the network may not be able to supply some or all nodal demands at the desired service pressure. A similar situation may also arise when the network is analyzed for fire demand, besides the base demand. Such a condition of the network is called the pressure deficient condition. Traditional methods of analysis of water distribution networks infer that nodal demand is always satisfied, regardless of the nodal pressure head available in the distribution system. This approach is called demand-driven analysis and is used by almost all hydraulic network solvers. This formulation is valid only when the hydraulic pressure at all nodes is adequate, so that demand is independent of pressure [1]. The analysis of water distribution systems under pressure-deficient

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conditions is a subject of interest and importance for water utilities around the world [2]. Assessing the nodal supply capacity under deficient conditions is essential for the reliability assessment of the network and the preparation of operation strategies for valve settings in order to provide a partial supply at deficient nodes and evolve possible equitable distribution of water. Demand driven analysis solves the governing expressions (mass balance and energy principle) for the analysis of flow for a water distribution network. But, it does not represent the exact, or even quasi, behavior of the system when the system is under pressure deficit conditions. This happens due to a total loss of head occurring from the source to the node exceeding the available source head. In such a situation, the head loss from the source to the outlet is overestimated on account of unrealistic outflow expected at the demand node. Hence, an appropriate supply should be evaluated by considering the available pressure head at the delivery node to overcome the pressure deficiency. To solve this problem, an additional condition is required to limit the outflow based on pressure availability in the distribution system. Several researchers have suggested different methods for evaluation of outflow at nodes under pressure deficient conditions. Over the past three decades, a significant amount of research has been taking place into the development of optimization algorithms and models for an optimal design of water distribution networks, due to its computational and engineering complexity [3-21]. A module based on demand driven analysis is widely coupled with an optimization algorithm to explore pipe diameters that satisfy the hydraulic-head requirements with the least cost. The requirements of pressure driven analysis does not arise for new network designs, as the pipe diameter and size of other components are adjusted to satisfy the hydraulic-head requirements with the least cost. For component failure analysis, demand driven analysis can yield nodal pressures that are lower than the required minimum, or, sometimes, even become negative [22]. This paper presents a review of various existing methods in addition to their implementation strategies using an EPANET [23] hydraulic solver and also endeavors to examine the possibility of employing an emitter feature, available in the EPANET hydraulic simulation engine, for predicting the behavior of deficient network performance.

2. Methodologies

To compute the actual outflow of nodes under pressure deficient conditions, a head and flow based relation is commonly used iteratively to obtain the outflow. Alternatively, some researchers have used artificial reservoirs to obtain the outflow under such circumstances. Many investigators have suggested different flow-head based relations for assessing the supplying capability of nodes under pressure deficient circumstances. Most popularly, the method proposed by Wagner et al [24] is commonly used to simulate the actual flow. Todini [25] expanded the demand driven global gradient algorithm for pressure dependent analysis. Recently, Giustolisi et al. [26,27] used a generic function proposed by Wagner et al. [24] and integrated with a global gradient algorithm for analyzing pressure deficient networks.

The pressure driven approach treats demand as the random variable and recognizes the dominance of pressure by defining a relationship between the supply and the pressure at each node. In a pressure-deficient network, a relationship exists between the flow and pressure at a demand node, termed the Node Head-Flow Relationship (NHFR). During simulation, NHFR at different nodes must be satisfied, along with equations for the conservation of mass and energy for the network as a whole [28]. Such an analysis can be carried out by embedding a Nodal Head-Flow Relationship (NHFR) in the governing system of equations [29]. Probably, Bhave [28] was the first to provide a systematic solution, named Node Flow Analysis (NFA), for the analysis of deficient networks that determine nodal supply considering the head-discharge relationship, which is given by:

$$\left.\begin{array}{l} q_j^{avl} = q_j^{req}\,(\text{adequate} - \text{flow})\,, \quad \text{if} \quad H_j^{val} \geq H_j^{\min} \\[2ex] 0 < q_j^{avl} < q_j^{req}\,(\text{partial flow})\,, \quad \text{if} \quad H_j^{avl} = H_j^{\min} \\[2ex] q_j^{avl} = 0(\text{no flow}), \quad \text{if}, \quad H_j^{avl} \leq H_j^{\min} \end{array}\right\} \tag{1}$$

where q_j^{avl} is the flow available at node j, q_j^{req} is the flow required at node j, H_j^{val} is the available head at j, and $H_j^{\min}$ is the minimum required head at node j under normal working conditions.

In NFA, the minimum pressure and available nodal heads, and also the required and available nodal flows, are considered simultaneously. Later, Germanopoulos [30] presented an empirical relationship to determine the nodal outflow as follows:

$$q_j^{avl} = q_j^{req}\left(1 - 10^{-c_j\left[(H_j^{avl} - H_j^{\min})/(H_j^{des} - H_j^{\min})\right]}\right), \tag{2}$$

where C_j is the node constant.

The actual outflow at the node is calculated iteratively at which each level of iteration requires one complete demand driven analysis. Reddy and Elango [31] proposed a head dependent analysis for an uncontrolled outlet with reference to residual heads available at the node. The relationship is given below:

$$q_j^{avl} = S_j\left(H_j^{avl} - H_j^{\min}\right)^{0.5}, \tag{3}$$

where S_j is the node constant.

Use of this expression requires either a calibrated or reasonable assumed node constant. Wagner et al. [24] proposed a generic formula that relates the head and flow as given below:

$$\left.\begin{array}{l} q_j^{avl} = q_j^{req}\,(\text{adequate} - \text{flow}), \quad \text{if} \quad H_j^{val} \geq H_j^{\min} \\[2ex] q_j^{avl} = q_j^{req} \left(\frac{H_j^{avl} - H_j^{\min}}{H_j^{des} - H_j^{\min}}\right)^{1/n} (\text{partial flow}), \\ \text{if} \quad H_j^{\min} < H_j^{avl} < H_j^{des} \\[2ex] q_j^{avl} = 0(\text{no flow}), \quad \text{if}, \quad H_j^{avl} \leq H_j^{\min} \end{array}\right\} \quad (4)$$

where n is the exponent constant (its value often taken as either 1.85 or 2).

Wagner et al. [24] suggested the use of a parabolic relationship between nodal flow and nodal head for pressure-deficient situations. Accordingly, they suggested three separate relationships, as shown in Eq. (4), for adequate-, partial- and no-flow situations. It is, however, worth noting that even though they have suggested a parabolic relationship between nodal flow and nodal head for partial-flow situations, they use this relationship only once to find out the available nodal flow for the obtained nodal head. Thus, they do not truly use the head-flow relation at the partial-flow node. It is to be noted that Wagner et al. [24] described NHFR using two heads, $H_j^{\min}$ and H_j^{req}, and, recently, Abdy Sayyed and Gupta [32] compared the results obtained by modeling a serial and a looped network with these two different NHFRs. Chandapillai [33] proposed a relationship between the actual nodal outflows and heads in response to a minimum head as:

$$H_j^{avl} = H_j^{\min} + K_j(q_j^{avl})^n. \quad (5)$$

Fujiwara and Ganesharajah [34] proposed the relationship between the pressure head and discharge in the demand nodes as expressed in Box I.

Gupta and Bhave [29] reviewed different methods used for predicting the performance of a water distribution system under pressure deficient conditions. It was found that the NFA approach based on Wagner et al. [24] predicted the behavior of the serial network example better than the other two approaches, namely Bhave [28] and Germanopoulos [30].

Tanyimboh et al. [35] showed the derivation for the Wagner head-flow relation by rearranging Eq. (5) within the limitation of $q_j = q_j^{avl}$ for $H_j = H_j^{des}$. Furthermore, Tanyimboh et al. [35] presented a modified relation for the same expression relating the source head and outflow at the demand node. Tucciarelli et al. [36] suggested a pressure dependent leakage relation as follows:

$$\left.\begin{array}{l} q_j^{avl} = q_j^{req}, \quad \text{if} \quad H_j^{avl} \geq H_j^{\min} \\[2ex] q_j^{avl} = q_j^{req} \sin^2\left(\frac{H_j^{avl}}{H_j^{\min}}\right), \quad \text{if} \quad 0 < H_j^{avl} < H_j^{\min} \\[2ex] q_j^{avl} = 0(\text{no flow}), \quad \text{if} \quad H_j^{avl} \leq 0 \end{array}\right\} \quad (7)$$

Tabesh et al. [37] used the head-dependent flow term of Wagner et al. [24] in the continuity equations by choosing the nodal piezo-metric heads as unknown parameters, and the resulting set of equations, along with the energy equations, are solved iteratively using the Newton-Raphson method. Kalungi and Tanyimboh [38] presented a new hydraulic simulation model based on pressure driven simulation, for assessing the redundancy of water distribution systems. The novelty of their approach is that the proposed network analysis technique includes the introduction of a key partial flow node and the use of a joint head flow system of equations. They defined key partial flow nodes as nodes whose outflows affect the outflow at other nodes. Ozger [39] presented the Semi-Pressure Driven Analysis (SPDA) framework using EPANET toolkits for predicting the performance of a network under partially failed conditions and the same is used for reliability assessment of the network. Ozger [39] was perhaps the first man to use artificial reservoirs for analysis of pressure deficient networks. Subsequently, Ozger and Mays [40] used SPDA for reliability assessment, in association with an optimization model, for optimal location of isolation valves considering reliability aspects. Ang and Jowitt [22] introduced a novel methodology, called PDNA (Pressure-Deficient Network Algorithm), which uses a repeatedly demand-driven model. The novel feature of this method is that it does not use the head-flow relationship to adjust the demand but uses the addition or deletion

$$\left.\begin{array}{l} q_j^{avl} = q_j^{req} \quad \text{for} \quad H_j^{avl} \geq H_j^{des} \\ q_j^{avl} = q_j^{req} \left(\frac{\int_{H_j^{\min}}^{H_j^{avl}} (H_j^{avl} - H_j^{\min})(H_j^{des} - H_j^{avl})dH}{\int_{H_j^{\min}}^{H_j^{avl}} (H_j^{avl} - H_j^{\min})(H_j^{des} - H_j^{avl})dH}\right) (\text{partial flow}), \quad \text{if} \quad h_j^{\min} < H_j^{avl} < H_j^{des} \\ q_j^{avl} = 0(\text{no flow}), \quad \text{if} \quad H_j^{avl} \leq H_j^{\min} \end{array}\right\} \quad (6)$$

Box I

of artificial reservoirs. Rossman [41] discussed the possibility of building the PDNA proposed by Ang and Jowitt [22] in an EPANET hydraulic solver using an emitter feature. Suribabu and Neelakantan [42] introduced a new iterative method using EPANET for this problem through connecting a complementing reservoir at the node. The basis of the method is to supplement the flow equivalent to the shortfall from a complementary reservoir into the pressure deficient nodes. It is to be noted that the iterative execution of EPANET 2 with artificial reservoirs introduced at any demand nodes with insufficient pressure to carry out pressure-deficient network analysis proposed by Ozger and Mays [40], Ang and Jowitt [22] and Suribabu and Neelakantan [42] employed the NHFR suggested by Bhave [28]. Jinesh Babu and Mohan [43] modified the algorithm that Ang and Jowitt [22] proposed in order to carry out head dependent modeling in a single execution of the unmodified EPANET 2 algorithm.

Recently, Wu et al. [1] proposed a Pressure Dependent Demand (PDD) function as below, which is integrated with the global gradient algorithm. Tanyimboh and Templeman [44] presented a continuous function between the outflow and pressure head to overcome the convergence difficulties prevailing in the existing discrete functions. A Newton-Raphson algorithm is used to solve the set of governing equations of the network analysis with the proposed continuous function. Baek et al. [45] presented a pressure driven analysis model by integrating a hydraulic simulator with the Harmony Search algorithm. The optimization model minimizes the difference between assumed and calculated heads at the demand nodes. Head-flow relationships suggested by Wagner et al. [24] and Chandapillai [33] are used to determine the proper head at each demand. Gorev and Kodzhespirova [46] suggested a non-iterative algorithm for pressure-deficient network simulation considering the NHFR described by the two heads. They considered modeling with artificial pipes, having assigned a suitable resistance to simulate partial flow conditions. Siew and Tanyimboh [47] presented the extension of the EPANET hydraulic simulator by incorporating pressure dependent demands. They integrated the head-flow function developed by Tanyimboh and Templeman [44,48] with the global gradient method. The line search and back tracking procedure are used to enhance the algorithm's performance. Shirzad et al. [49] conducted laboratory and field experiments to estimate the outflow from the faucet with respect to the available pressure. It is highlighted that the relationship between the flow at the node and the pressure at that node is more complicated, due to varying operations of the faucet, the difference in elevation of the faucet and node levels, and the complexity of the piping between them. Further, study reveals that the pressure discharge relation proposed by Wagner et al. [24] is found to closely match with experimental results. Jun and Gouping [50] used the EPANET toolkit iteratively to modify the nodal outflow obtained based on Pressure Dependent Demand Formulation (PDDF). Recently, Sivakumar and Prasad [51] developed a head-discharge relationship based on the working principle of M-PDNA [43] and also illustrated means of applying M-PDNA with the EPANET Toolkit function using the EPANET simulation engine.

In this paper, the generic relationships between head and flow proposed by Germanopoulos [30], Wagner et al. [24] and Tucciarelli et al. [36] are used to simulate the outflow for pressure deficient networks. It is referred to herein as the head-flow based approach for pressure driven analysis (HFPDA-I, II and III, respectively). These three relationships are selected based on three different criteria, namely, the empirical exponential form, the parabolic form, and the sine function.

The evaluation of outflow at deficient nodes using the emitter feature available in the EPANET hydraulic solver is referred to as the Emitter based Approach for Pressure Driven Analysis (EPDA). The performance of EPDA and HFPDA is examined using three sample networks by creating a pressure deficiency through isolating a link. The first example is a simple single loop network having the same nodal elevations with different nodal demands. The second example is a single source two-loop network having different nodal elevations and the same nodal demands for all nodes. The framework of HFPDA and EPDA is built using the Toolkit feature available in the EPANET hydraulic solver.

3. Head-flow based approach for pressure driven analysis (HFPDA)

The head-flow relation proposed by Germanopoulos [30], Wagner et al. [24] and Tucciarelli et al. [36] are used to simulate flow using the EPANET Demand Driven Analysis (DDA) for a pressure deficient network. The following are the steps taken to evaluate the outflow at the nodes:

1. Solve the network by isolating a link.
2. Set the nodal demand to zero if the nodal pressure is negative, otherwise assume nodal pressure value (close to $H_{\min}$).
3. Calculate q_{avl} using any one of the expressions, as given in Eqs. (2), (4) and (7).
4. Simulate the network after changing nodal demand (q_{avl}).
5. Update the value of q_{avl} according to the new H_{avi}, and simulate the network with updated q_{avl}.

6. Repeat steps 4 and 5 until $[\sum_{i=1}^{nd} (H_{avl,i}^{n-1} - H_{avl,i}^{n})^2] < 1 \times 10^{-9}$ or H_{avl} for the node above $H_{\min}$.

where n is the number of iterations and nd is the number of demand nodes.

While solving the pressure deficient network, it is very common for the analysis to show non-serviceable pressure or even negative pressure at a few nodes, using demand driven software, According to the head-flow functions, the demand should be set to zero for the node/nodes with a pressure head below the minimum/serviceable value. When it is set at the very first iteration of pressure driven analysis to all affected demand nodes, then at the end of the first iteration, none of the nodes will experience a deficit scenario. In turn, those deficit nodes will have pressure above the serviceable pressure. This shows that one or more identified deficit nodes could probably supply part of the designed/required demand. Hence, it is required to verify the condition of the network progressively by setting the nodal demand to zero, starting from a node that faces maximum pressure deficit. When the pressure in the deficient nodes reaches a positive value after setting its demand to zero, the head-flow function can then be used iteratively till the specified convergence is achieved. This is further illustrated through sample networks.

4. Emitter based approach for pressure driven analysis (EPDA)

Pressure management becomes imperative when pressure deficiency arises in the water distribution network. Estimation of outflow at deficient nodes and arriving at better operating policies under such circumstances are found to be complex. This paper presents utilization of the Emitter option available in the EPANET hydraulic solver for finding a solution to the pressure deficient network under pressure management. Emitters are devices connected with nodes that model the flow through a nozzle or orifice. Generally, emitters are used to model flow through sprinkler systems and irrigation networks. In water distribution system modeling, emitters are used to simulate the leakage in a pipe connected to a node and to compute a fire flow at the node (the flow available at some minimum residual pressure). The emitter feature available in EPANET can be used for pressure dependent flow analysis. Rossman [41] illustrates how the emitter in EPANET can be used equivalently as artificial reservoirs of PDNA, provided an appropriate emitter coefficient is used. Sivakumar and Prasad [51] highlighted that the working of Emitter devices in the EPANET engine follows the uncontrolled head-discharge relationship defined by Reddy and Elango [31]. In the present work, the Emitter option of the EPANET is applied only to those nodes identified through demand driven analysis. Hence, an uncontrolled outflow situation does not arise in the proposed methodology.

If the head-flow loss relation chosen for the pipes within the EPANET hydraulic solver is the Hazen-Williams equation, then the flow rate can be expressed as follows:

$$Q = K_e p^n, \tag{8}$$

where $K_e = C_{HW} D^{2.63} (cL)^{-0.54}$; $p = H - E$; and $n = 0.54$.

The above expression for outflow at the node is used as the emitter equation in EPANET in which K_e is the emitter co-efficient and n is the emitter exponent. The value of the emitter co-efficient should be selected according to the property of the pipe considered, namely, diameter, length, and Hazen-William coefficient that connects the node and the artificial reservoir. The value of $c = 1.209 \times 10^{10}$, if the units for H, E, and L are in meters, Q in L/s and diameter in mm. Ang and Jowitt [22] used a pipe of size 350 mm, length 0.1 m and C_{HW} - 130 to connect the artificial reservoirs with the nodes. The artificial reservoir can be replaced by the emitter device by setting its co-efficient and exponent to 7949.4 and 0.54, respectively [41].

The emitter based approach presented here aims to find the outflows at all deficient nodes. When the pressure deficient network is solved by demand driven analysis, it may show a greater number of nodes under pressure deficient conditions. This is due to an overestimation of the head loss from the source to the outlet for the sake of satisfying the unrealistic outflow expected at the demand node. But, in reality, it may not be so. The proposed method ensures supply of the designed demand to all non-deficient nodes and partial supply to deficient nodes. By reducing the outflow at a few or all non-deficient nodes, the partial demand can be supplied to the deficient nodes. Outflow in all nodes is based on the availability of energy at that node. The design demand at the node will be fully satisfied only if sufficient energy is available. The availability of energy at a particular node depends not only on the source, but also on how the supply is drawn in either the en-routed nodes or neighboring nodes. Hence, it is essential to have an approach that satisfies the required (design) outflow at all non-deficient nodes and that, overall, imitates reality as closely as possible. The stepwise procedure is as follows:

1. Isolate the pipe (close the link) and run the hydraulic analysis. Check the pressure at all nodes. If the pressure at all nodes is above $H_{\min}$, it is a non-deficient network, with respect to isolation of that link. Otherwise, it is considered deficient.

2. Identify a node that experiences maximum pressure deficiency and set the nodal demand to zero. Perform the hydraulic analysis.

3. Repeat step 2 until no node experiences a pressure deficit.

4. If the last updated pressure deficient node possesses residual pressure in excess of $H_{\min}$, then, set its nodal elevation as $H_{\min}$ and emitter co-efficient as 7949.4 in the EPANET hydraulic solver. Again, perform the hydraulic analysis.

5. Check the pressure at all nodes. If the pressure at all demand nodes is above or equal to $H_{\min}$, then, terminate, and the solution has been obtained. Else, if the pressure at some node/nodes is below $H_{\min}$, then, identify elevation of the node at which maximum pressure deficit occurs, and set this elevation to the last updated pressure deficient node. Perform hydraulic analysis, and the resulting solution are final.

The procedure is further illustrated through the flow chart shown in Figure 1.

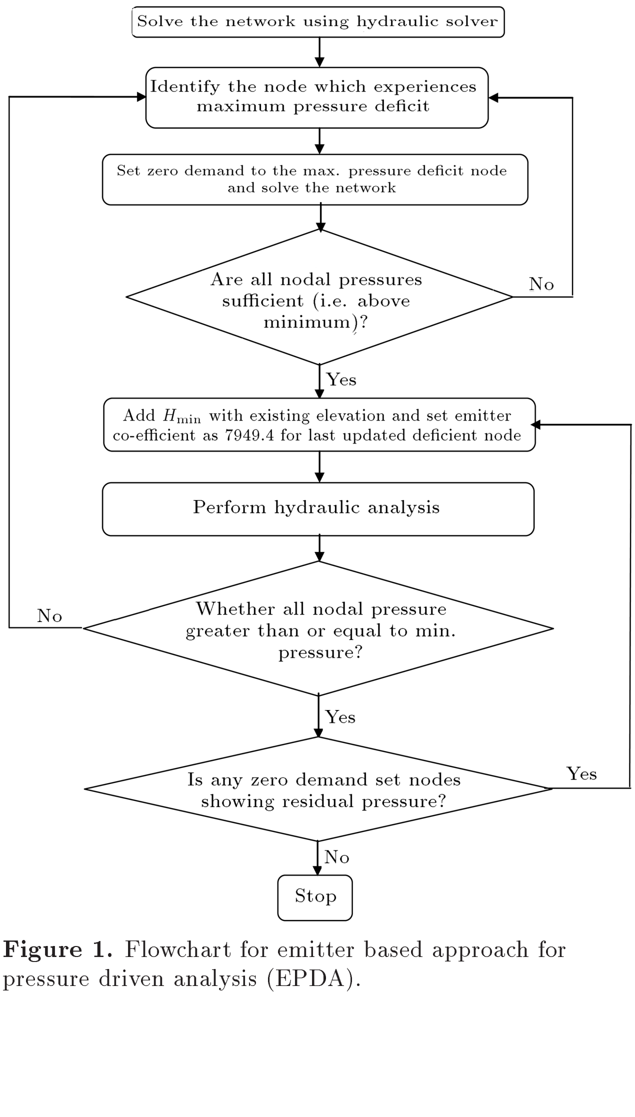

Figure 1. Flowchart for emitter based approach for pressure driven analysis (EPDA).

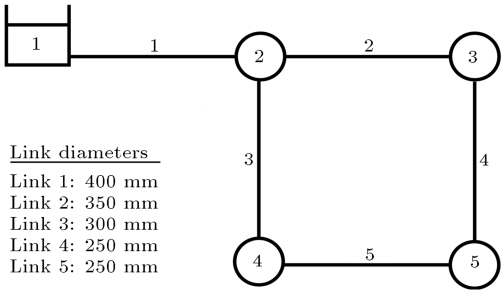

Figure 2. Single source one loop network.

5. Case studies

5.1. Example 1. Single loop network

Figure 2 shows a simple, single-source, one-loop network. The network consists of a reservoir, four demand nodes and five links. The elevation of the source reservoir is 20 m and all demand nodes are at zero elevation. The diameter of each link is shown in Figure 2. Each link is 1000 m long, and the Hazen-Williams coefficient is 100 for all the links. The minimum pressure head needed at each demand node is 15 m. The demands for nodes 2 to 5 are 20, 20, 25 and 35 L/s, respectively, under normal operating conditions. Under normal conditions, the demand driven analysis shows the pressure head at all nodes equal to, or above, 15 m. Pressure-deficient conditions can be created in this network by isolating any one of links 2, 3, 4, and 5. Table 1 shows the results obtained by the demand-driven method (by EPANET) for normal operations and pressure-deficient conditions with isolation of links 2, 3, 4 and 5, one at a time. It can be seen from Table 1 that the isolation of link 2 creates the deficiency in pressure at nodes 3, 4 and 5. According to the generic relations, nodes 3, 4 and 5 should be set to zero demand. Performing hydraulic analysis again with a new set of demands shows the pressure head above the minimum pressure of 15 m at all nodes. Since it shows the pressure at all nodes above 15 m, the identified deficit nodes could supply a portion of the demand. Now, the actual demand for nodes 3, 4 and 5 can be calculated using the generic relation between the head and flow, and its values are found to be equal to the required demand. The above mentioned steps are presented in Table 2. It is clear from the results of the fourth run (Table 2) that no improvement of results are feasible, since new demands are the same as those of the required demand. It is understood that the generic relation cannot be applied as it is in the given format. Further, it is clear that some portion of demand can be supplied from the deficit nodes due to the availability of some pressure in excess of that required in the node. Assessing the availability of such residual pressure at various deficient nodes poses a major challenge to the pressure driven model.

Table 1. Outflows and pressure head for one-loop network under single link failure.

Method	Status	Outflows (L/s) and pressure head (m)				
		Node 2	Node 3	Node 4	Node 5	Total outflow
Demand driven	No link failure	20 (17.43)	20 (16.46)	25 (15.64)	35 (15.00)	100
	Link 2 isolated	20 (17.43)	20 (0.84*)	25 (10.52*)	35 (2.13*)	100
	Link 3 isolated	20 (17.43)	20 (14.17*)	25 (2.36*)	35 (4.31*)	100
	Link 4 isolated	20 (17.43)	20 (17.18)	25 (13.37*)	35 (9.74*)	100
	Link 5 isolated	20 (17.43)	20 (15.80)	25 (16.63)	35 (12.16*)	100

Table 2. Simulated results for link 2 isolation of single loop network.

Method	Simulation status	Outflows (L/s) and pressure head (m)				
		Node 2	Node 3	Node 4	Node 5	EPANET run counter
Pressure driven	No link failure	20 (17.43)	20 (16.46)	25 (15.64)	35 (15.00)	1
	Link 2 isolated	20 (17.43)	20 (0.84*)	25 (10.52*)	35 (2.13*)	2
	Set demand at nodes 3, 4 and 5 as zero	20 (19.87)	0 (19.87)	0 (19.87)	0 (19.87)	3
	Set demand at nodes 3, 4 and 5 as 20, 25 and 35, respectively	20 (17.43)	20 (0.84*)	25 (10.52*)	35 (2.13*)	4

Gupta and Bhave [29] illustrated application of the head-flow relation for pressure dependent analysis in which, initially, nodal head (H_{avl}) is assumed for deficient nodes and, subsequently, nodal-head correction is applied at each state of iteration. Repeated application of the generic relation with nodal correction is needed until q_j^{avl} values obtained in the Nth and $(N-1)$th iterations are identical. Gupta and Bhave [29] used the Hardy-Cross Head Correction method for solving NHFR, along with continuity equations represented in terms of unknown heads. The NFA results are obtained in a single run. The SPDA, PDNA and EPDA are iterative and require assumptions in each run of the EPANET. The methodology of Gupta and Bhave [29] is free from any assumption. In the present work, instead of nodal correction, q_{req} for deficient nodes has been corrected.

Table 3 presents the solution based on pressure dependent analysis for isolation of links 2 to 5. The iterations within EPANET are referred to herein as inner iterations. The default values adopted for this study, for the maximum amount of trials and accuracy in EPANET, are 40 and 0.001, respectively. It can be seen from Table 3 that the number of outer iterations are more in cases of head-flow based approaches. Further, it is to be noted from the results that the number of hydraulic simulations for PDNA and EPDA is minimum. The main advantage of the emitter based approach is that no addition and deletion of the reservoir is required. Hence, no change in the topology of the network is resulted. For the head-flow based approach, a reasonable assumption of the initial available pressure head is essential, and it requires a higher number of hydraulic analyses to converge.

It is clear from the results that PDNA and EPDA could maximize the outflow under pressure deficient conditions for this example. In the case of the head-flow based approach, the relation proposed by Wagner et al. [24] could maximize the outflow within the termination criteria specified. The head-flow relation of Germanopoulos [30], with nodal constant c_j as 2, took a lower number of simulation runs, but fails in maximizing outflow within the specified termination criteria. From Table 3, it is evident that the head-flow relation of Tucciarelli et al. [36] uses a higher number of hydraulic simulations to satisfy the specified termination criteria.

5.2. *Example 2. Two-loop network*

This example is a single-source, two-loop network presented by Ang and Jowitt [22] for pressure driven analysis. The network consists of a reservoir, six demand nodes and eight links, as shown in Figure 3. The nodal elevations and link diameters are presented with the layout. The length and Hazen-Williams coefficient for each link is 1000 m and 130, respectively. The nodal demand for each node is 25 L/s. Under normal conditions, the demand driven analysis shows that nodal pressure heads are greater than the minimum required pressure head of zero, i.e. the outflow at the

Table 3. Simulated results for isolation of links for single loop network.

Methods	Status	Outflows (L/s) and pressure head (m)					No. of EPANET runs
		Node 2	Node 3	Node 4	Node 5	Total outflow	
HFPDA-1	Link 2 is isolated	20 (18.83)	2.25 (15.03)	25 (16.40)	18.25 (15.05)	65.50	40
HFPDA-2		20 (18.82)	0.32 (15.00)	25 (16.37)	20.36 (15.00)	65.68	230
HFPDA-3		20 (18.82)	1.50 (14.99)	25 (16.37)	19.19(15.00)	65.69	2839
PDNA		20 (18.82)	0 (15.00)	25 (16.37)	20.68 (15.00)	65.68	3
EPDA		20 (18.82)	0 (15.00)	25 (16.37)	20.68 (15.00)	65.68	4
HFPDA-1	Link 3 is isolated	20 (18.74)	20 (17.47)	2.75 (15.03)	25.30 (15.06)	68.05	95
HFPDA-2		20 (18.73)	20 (17.45)	0.44 (15.00)	27.85 (15.00)	68.28	326
HFPDA-3		20 (18.73)	20 (17.45)	1.75(14.99)	26.54(15.00)	68.29	3572
PDNA		20 (18.73)	20 (17.45)	0.00 (15.00)	28.29 (15.00)	68.29	3
EPDA		20 (18.73)	20(17.45)	0.00(15.00)	28.29(15.00)	68.29	4
HFPDA-1	Link 4 is isolated	20 (17.93)	20 (16.85)	25 (17.13)	23.98 (15.05)	88.98	27
HFPDA-2		20 (17.92)	20 (16.83)	25 (17.12)	24.19 (15.00)	89.19	53
HFPDA-3		20 (17.92)	20 (16.83)	25 (17.12)	24.21 (15.00)	89.21	1259
PDNA		20 (17.92)	20 (16.83)	25 (17.12)	24.19 (15.00)	89.19	4
EPDA		20 (17.92)	20 (16.83)	25 (17.12)	24.19 (15.00)	89.19	3
HFPDA-1	Link 5 is isolated	20 (18.20)	20 (17.95)	25 (16.05)	17.57 (15.03)	82.57	40
HFPDA-2		20 (18.19)	20 (17.94)	25 (16.03)	17.71 (15.00)	82.71	70
HFPDA-3		20 (18.19)	20 (17.94)	25 (16.03)	17.74 (14.99)	82.74	1452
PDNA		20 (18.19)	20 (17.94)	25 (16.03)	17.71 (15.00)	82.71	4
EPDA		20 (18.19)	20 (17.94)	25 (16.03)	17.71 (15.00)	82.71	3

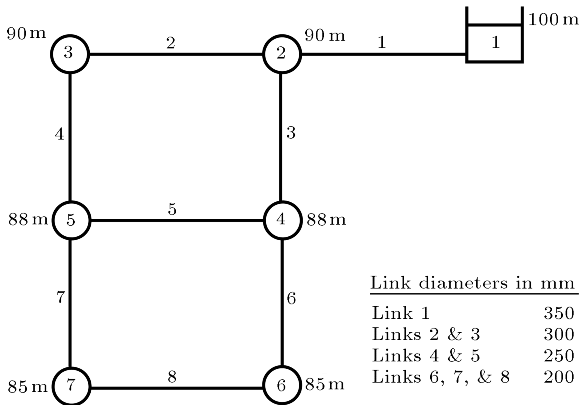

Figure 3. Layout of single-source two-loop network.

respective nodal elevation. The isolation of links 2 to 7 makes the system as the pressure deficient conditions.

It can be seen from Tables 4(a) to 4(f) that PDNA and EPDA provided the same results for isolation of all the links, except for links 2 and 3. The PDNA result for isolation of links 2 and 3 shows a negative pressure head with no outflow. But EPDA for the same cases do not show any negative pressure at any nodes, even for nodes with no outflow. This distinct result can be viewed from a different perspective. If negative pressure at no supply node is accepted hydraulically, then, the results of PDNA for isolation of links 2 and 3 should be considered a valid solution. Practically, all withdrawal from that node should cease. This is possible only if this node is a supply node for a minor distribution network, or any branches beginning from that node. If this is the case, then it is possible to isolate it from the main distribution using a control valve. Conventionally, the demand occurring along the link is lumped at the nodes for convenience of design. In such a case, the node takes in the air and the continuity of flow to the down gradient nodes is wrecked.

From an engineer's point of view, the negative pressure in the node will not be observed on site, as the pipes are usually not air-tight. Furthermore, even if the pipes are air-tight, any consumer opening a tap will render the pipes not air-tight. The solution of EPDA for the isolation of any link shows the positive pressure at all demand nodes. Specifically, for isolation of links 2 and 3, the total outflow is lesser than the outflow obtained using the PDNA approach. It can be observed from Tables 4(a) to 4(f) that for link 2 isolation, the EPDA solution shows lesser outflow at node 5; its value is 9.10 L/s and the corresponding

Table 4a. Simulated results for two-loop network with link 2 isolation.

Method	Status	Outflow (L/s) and residual pressure head (m) at						Total outflow (L/s)	Total no. of EPANET runs
		Node 2	Node 3	Node 4	Node 5	Node 6	Node 7		
HFPDA-1	2	25.00	0.00	25.00	19.32	25.00	25.00	119.32	Not converged
		5.79	-2.75	2.03	-0.75	0.06	0.11		
HFPDA-2		25.00	0.00	25.00	16.65	25.00	25.00	116.65	299
		5.97	-2.00	2.50	0.00	0.68	0.53		
HFPDA-3		25.00	0.00	25.00	16.75	25.00	25.00	116.75	8789
		5.90	-2.03	2.52	-0.03	0.65	0.51		
PDNA		25.00	0.00	25.00	16.65	25.00	25.00	116.65	5
		5.97	-2.00	2.50	0.00	0.68	0.53		
EPDA		25.00	0.00	25.00	9.10	25.00	25.00	109.10	5
		6.44	0.00	3.77	2.00	2.33	2.25		

Table 4b. Simulated results for two-loop network with link 3 isolation.

Method	Status	Outflow (L/s) and residual pressure head (m) at						Total outflow (L/s)	Total no. of EPANET runs
		Node 2	Node 3	Node 4	Node 5	Node 6	Node 7		
HFPDA-1	3	25.00	25.00	0.00	11.89	20.78	20.78	103.45	Not converged
		6.77	2.67	-0.96	-0.22	-0.14	-0.12		
HFPDA-2		25.00	25.00	0.73	10.25	19.40	22.53	102.90	Not converged
		6.80	2.76	-0.84	-0.05	-0.02	-0.02		
HFPDA-3		25.00	25.00	0.00	10.49	18.56	23.74	102.79	18193
		6.81	2.77	-0.77	-0.01	-0.01	-0.01		
PDNA		25.00	25.00	0.00	10.44	19.59	22.72	102.75	5
		6.81	2.78	-0.76	0.00	0.00	0.00		
EPDA		25.00	25.00	0.00	25.00	0.12	25.00	100.12	4
		6.96	3.18	0.62	0.83	0.00	2.39		

Table 4c. Simulated results for two-loop network with link 4 isolation.

Method	Status	Outflow (L/s) and residual pressure head (m) at						Total outflow (L/s)	Total no. of EPANET runs
		Node 2	Node 3	Node 4	Node 5	Node 6	Node 7		
HFPDA-1	4	25.00	25.00	25.00	10.36	25.00	25.00	135.36	81
		4.69	4.19	1.89	0.01	0.39	0.30		
HFPDA-2		25.00	25.00	25.00	10.39	25.00	25.00	135.39	543
		4.68	4.19	1.89	0.00	0.38	0.29		
HFPDA-3		25.00	25.00	25.00	10.39	25.00	25.00	135.57	11458
		4.67	4.18	1.86	-0.05	0.34	0.25		
PDNA		25.00	25.00	25.00	10.38	25.00	25.00	135.38	5
		4.68	4.19	1.89	0.00	0.38	0.29		
EPDA		25.00	25.00	25.00	10.38	25.00	25.00	135.38	3
		4.68	4.19	1.89	0.00	0.38	0.29		

Table 4d. Simulated results for two-loop network with link 5 isolation.

Method	Status	Outflow (L/s) and residual pressure head (m) at						Total outflow (L/s)	Total no. of EPANET runs
		Node 2	Node 3	Node 4	Node 5	Node 6	Node 7		
HFPDA-1	5	25.00	25.00	25.00	21.65	25.00	25.00	146.65	13
		3.84	0.92	3.62	0.01	1.22	0.94		
HFPDA-2		25.00	25.00	25.00	21.70	25.00	25.00	146.70	262
		3.83	0.91	3.61	0.00	1.21	0.93		
HFPDA-3		25.00	25.00	25.00	21.81	25.00	25.00	146.81	7441
		3.82	0.89	3.60	0.03	1.19	0.91		
PDNA		25.00	25.00	25.00	21.7	25.00	25.00	146.70	5
		3.83	0.91	3.61	0.00	1.21	0.93		
EPDA		25.00	25.00	25.00	21.70	25.00	25.00	146.70	3
		3.83	0.91	3.61	0.00	1.21	0.93		

Table 4e. Simulated results for two-loop network with link 6 isolation.

Method	Status	Outflow (L/s) and residual pressure head (m) at						Total outflow (L/s)	Total no. of EPANET runs
		Node 2	Node 3	Node 4	Node 5	Node 6	Node 7		
HFPDA-1	6	25.00	25.00	25.00	25.00	7.69	25.00	132.69	97
		4.88	2.84	4.84	3.28	0.04	0.04		
HFPDA-2		25.00	25.00	25.00	25.00	7.75	25.00	132.75	368
		4.87	2.83	4.83	3.27	0.00	0.41		
HFPDA-3		25.00	25.00	25.00	25.00	7.82	25.00	132.82	7798
		4.87	2.82	4.82	3.26	-0.04	0.37		
PDNA		25.00	25.00	25.00	25.00	7.75	25.00	132.75	5
		4.87	2.83	4.83	3.27	0.00	0.41		
EPDA		25.00	25.00	25.00	25.00	7.75	25.00	132.75	3
		4.87	2.83	4.83	3.27	0.00	0.41		

Table 4f. Simulated results for two-loop network with link 7 isolation.

Method	Status	Outflow (L/s) and residual pressure head (m) at						Total outflow (L/s)	Total no. of EPANET runs
		Node 2	Node 3	Node 4	Node 5	Node 6	Node 7		
HFPDA-1	7	25.00	25.00	25.00	25.00	25.00	9.63	134.59	79
		4.74	3.10	4.11	4.09	0.62	0.02		
HFPDA-2		25.00	25.00	25.00	25.00	25.00	9.63	134.63	299
		4.74	3.10	4.10	4.09	0.61	0.00		
HFPDA-3		25.00	25.00	25.00	25.00	25.00	9.76	134.76	4053
		4.73	3.09	4.09	4.07	0.54	-0.08		
PDNA		25.00	25.00	25.00	25.00	25.00	9.63	134.63	4
		4.74	3.10	4.10	4.09	0.61	0.00		
EPDA		25.00	25.00	25.00	25.00	25.00	9.63	134.63	3
		7.47	3.10	4.10	4.09	0.61	0.00		

outflow by PDNA is 16.65 L/s. This shows that the reduction in outflow at that particular node improves the pressure at several nodes. This clearly shows that outflow at a node is strongly interdependent on other demand nodes. The number of hydraulic simulations required for both PDNA and EPDA is almost the same, but it is considerably lower than the HFPDA.

The merit of EPDA and PDNA is that the accuracy based termination criteria are not required. PDNA requires repeated runs of the EPANET solver with artificial reservoirs added or deleted, as required, for either disallowing reverse flow from the artificial reservoirs back into the network or disallowing flow from the network into the artificial reservoirs to exceed nominal demand [52]. Babu and Mohan [43] presented a modified form of PDNA to get the PDNA solution in a single run using the EPANET toolkit, where they have used a flow control valve in addition to the artificial reservoir. Sivakumar and Prasad [51] presented another modification to M-PDNA, showing how M-PDNA can be used to simulate both pressure-sufficient and pressure-deficient conditions in a single hydraulic simulation without using the EPANET toolkit. Though the proposed approach needs repetitive use of EPANET, it does not require any topological modification of the network.

It can be seen from Tables 4(a) to 4(f) that the HFPDA could not converge to the positive pressure solution domain for certain cases. This is a main problem in head-flow based approaches. The flow correction carried out in the process of computation becomes ineffective after reaching a certain value. In such a circumstance, any minor change in the flow correction value may lead to a pressure drop to the nodes, which have already reached a threshold value. Hence, improvisation of the result is feasible only by changing the initially assumed pressure head. This further invites not only iterations, but also the necessity of trials in selection of the initial value. Tanyimboh and Templeman [44] pointed out that the discontinuity properties of the pressure-dependent demand functions and their derivatives can cause convergence difficulties in the computational solution of the system of equations.

Figure 4 shows the trajectory of convergence for outflow and the hydraulic gradient at node 5, in the case of HFPDA-2 for isolation of link 2. Figure 4 shows the importance of a higher degree of accuracy as a termination criteria (minimizing of error). It is clear from Figure 4 that the value of outflow is not decreasing uniformly from beginning to end of the iteration. At the early stages of iteration, there is a drastic change in the outflow and HGL values. From the experiments, similar observations were made at other nodal outflows and the pressure for isolation of link 2, and also pressure deficiency resulted for isolation

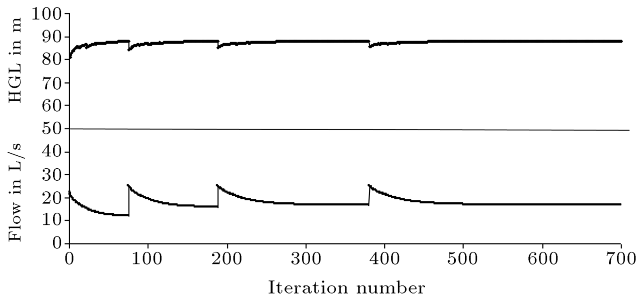

Figure 4. Trajectory of convergence for outflow and hydraulic gradient.

of other links. The required number of hydraulic simulations for HFPDA 3 is found to be more than HFPDA 1 and HFPDA 2 for all the cases considered in the study.

6. Discussion

The following general observations have been made from the results of PDA described in the present study:

1. Total outflow from the system is maximum and no node experiences negative pressure, even when outflow, as per Pressure Dependent Analysis (PDA), is found to be zero.
2. Total outflow from the system is maximum, and a node or few nodes experience negative pressure while estimated outflow from those nodes are zero.
3. Total outflow from the system is not maximum, and no demand node with zero outflow and pressure at all nodes are above or equal to minimum, even for deficient nodes.

If the solution obtained through PDA belongs in the first category, then, the network will practically be free from any air entrainment, even when the consumer tap is kept open. The second category depicts that the total outflow from the system will be maximum, but a negative pressure node with no supply may draw air through the consumer tap. Consequently, the consumer at the down gradient and at nearby nodes experiences air entrained outflow and sometimes interrupted outflow. As far as these two categories are concerned, the outflow at deficient nodes is determined by fulfilling the demand at non-pressure deficient nodes, corresponding to their designated demand. In the third category, the PDA predicts the partial outflow at all deficient nodes and also at some non-pressure deficient nodes. Overall, no pressure deficiency occurs at the cost of compromising the outflow at non-pressure deficient nodes. Hence, maximization of total outflow could not be achieved. Ang and Jowitt [22] described that the behavior of a water distribution system under pressure-deficient conditions is highly complex and non-instinctive. It is essential to understand the exact behavior of the network under abnormal working conditions. Real experimental research in the field could provide an answer to evaluate the exact behavior of the system.

7. Conclusion

Simulation of networks under low pressure scenarios should be based on PDA in order to consider the effects due to high demand. These include firefighting, burst pipes, pump failure, high demand over the designed peak demand and failure in supply from one (or more) source(s) in cases of multi-source systems. In the present study, some head-flow functions, including the emitter feature available in EPANET, and also the use of artificial reservoirs as proposed by Ang and Jowitt [22] are investigated as the outer model using the EPANET toolkit in terms of its convergence. Further, the results of the EPDA method have been compared and analyzed with solutions obtained, based on the head-flow based relation, for simulating a water distribution network under pressure deficient conditions. HFPDA takes a higher number of hydraulic simulations to converge within the specified degree of accuracy. A simple approach is presented for analysis of a deficient network in which additional nodes are added at each demand node, and the required demand, according to the various pressure levels, is taken as the base demand for simulation. The successive solution seeking procedure, based on repeated application of the hydraulic solver, is used to evaluate the outflow. Even so, the Wagner et al. [24] equation is increasingly used for evaluation of pressure dependent outflow; quantification of partial outflow under pressure deficient conditions will be effective only if the demand at various levels is known.

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Biography

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