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Analysis of water distribution network under pressure deficient conditions through Emitter Setting

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Abstract

Pressure-driven analysis (PDA) of water distribution networks necessitates assessing the supplying capacity of a network within the minimum and required pressure ranges. Pressure-deficient conditions happen due to the uncertainty of nodal demands, failure of electro-mechanical components, diversion of water, aging of pipes, permanent increase in the demand at certain supply nodes, fire demand etc. As the Demand-driven analysis (DDA) solves the governing equations without any bound on pressure head, it fails to replicate the real scenario particularly when the network experiences pressure deficient situations. Numerous researchers formulated different head-discharge relations and used them iteratively with demand driven software, while some other approaches solve them by incorporating this relation within the analysis algorithms. Several attempts have been made by adding fictitious network elements like reservoirs, check valves, flow control valves, emitters, dummy nodes and pipes of negligible length (i.e., negligible pressure loss), to assess the supplying capability of a network under pressure deficient conditions using demand driven simulation software. This paper illustrates a simple way to assess the supplying capacity of demand nodes under pressure deficient conditions by assigning the respective emitter co-efficient only to those nodes facing pressure deficit condition. The proposed method is tested with three bench-mark networks and it is able to simulate the network without addition of any fictitious network elements or changing the source code of the software like EPANET.

Keywords: Water distribution network, Demand-driven analysis, Pressure-driven analysis, Emitter, Fire demand.

1.0 Introduction

Analysis of water distribution systems under pressure-deficient conditions presents a challenging research area as understanding and simulating the real scenario is complex. It is well known that DDA simultaneously solves the mass balance and energy balance equations to determine the flow in each pipe for a given network topology and configuration. However, such DDA solution does not represent an exact behaviour of the system when it is under pressure-deficient conditions or if a bound on service pressure is assigned. It is possible to notice the negative pressure in DDA whenever the total loss of head occurring from source to node exceeds available source head. This mainly happens when the demand assigned to a node is higher than what the pipes incident to that node actually can carry based on the available source head. To compute the actual outflows from the nodes within given pressure bounds, modifications are needed either in the source code of demand driven simulation engine (e.g., Cheung et al. 2005) or by adding additional fictitious components like reservoirs, check valves, flow control valves, emitters, dummy nodes and very short pipes to the demand nodes (e.g., Ozger 2003; Ang and Jowitt 2006; Rossman 2007; Suribabu and Neelakantan 2011; Jinesh babu and Mohan 2012; Gorev and Kodzhespirova 2013;

Sivakumar and Prasad 2014; Morley and Tricarico 2014; Abdy Sayyed et al. 2014 and 2015; Sivakumar and Prasad 2015; Suribabu 2015; Mamizadeh and Sharoonizadeh 2016; Suribabu et al. 2017; Mohmoud et al. 2017; Pacchin et al.2017).

Mohmoud et al. (2017) addressed the shortcoming of each of these methods for evaluating outflow in the case of large networks and under extended period simulation (EPS).They have developed a new way to handle PDA using EPANET in single iterative type after an introduction of a check valve, a flow control valve and a flow emitter for both steady state and EPS.

2.0 Pressure Driven Analysis-Literature Review

In the beginning, pressure-deficient condition was considered as a rare phenomenon and/or a typical problem in operational scenario. However, when concern on reliability gained importance, the failure scenarios were analysed and thus analysis of pressure-deficient conditions became popular. Two approaches are popular for analyzing pressure deficient condition. In the first approach a specific pressure-demand relationship is embedded in the source code of the simulator (requires changing of source code). Some of the important studies using this approach by several authors are presented in tabular form below (Table 1).

Apart from the above tabled researches, Liu et al. (2011), and Siew and Tanyimboh (2012) adopted different methodologies to obtain node heads in EPANET. Giustolisi et al. (2011) developed and used new Excel based software called WDNetXL. Generally, the limitations of this approach (Mahmoud et al. 2017) are: (1) they require a change in algorithm and program code, (2) the computer codes are not available, (3) requires iterations, (4) most of them demonstrated on sample networks, and (5) they exhibit difficulty in handling extended period simulation.

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Some of the researchers in the recent years attempted pressure deficient analysis using EPANET (popular freeware demand driven model) by introduction of a few artificial or imaginary components like reservoir, flow control valve, check valve, emitter, but without node head-flow relationships. These researches claim less number of iterations and the recent researches claim single iteration (no iteration). The works using components in demand driven model for pressure deficient analysis are presented in Table 2.

Literature review indicates that the approach of using demand-driven engine to get the pressure-driven results is getting more attention. It is due to computational convenience and promising trend of development. Hence, this research is also planned to focus on this approach. This paper proposes a simple approach to suit both single period and EPS but without addition, deletion, opening and closing of network elements. Proposed method requires only assigning emitter co-efficient and altering nodal elevation by incorporating minimum pressure head with existing elevation. Though the method is an iterative type, it can be easily implemented irrespective of the size of network.

3.0 Background of Emitter based approaches

EPANET 2 (Rossman 2000) hydraulic simulation engine contains a special element called Emitter that behaves as a sprinkler head at the node and delivers an outflow proportional to available pressure head. Rossman (2007) discussed the possibility of building the pressure driven network analysis (PDNA) proposed by Ang and Jowitt (2006) in EPANET hydraulic solver using this emitter feature. Further, Suribabu (2015) proposed a method to use emitter as a replacement to the connection of fictitious reservoirs to all the demand nodes (DNs).

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Here, the emitter determines the possible supply at all deficient nodes based on its available pressure head. The flow from the emitter is expressed as follows (Rossman 2000):

$$Q = K_e p^n \tag{1}$$

Where Q is nodal outflow, K_e is the emitter co-efficient, n is the emitter exponent and p is pressure. Rossman (2007) suggested that the value of emitter co-efficient can be calculated according to the properties of the pipe that connects the node and the artificial reservoir (i.e., diameter, length and Hazen-William co-efficient), in order to make it equivalent to the approach of Ang and Jowitt (2006). Another emitter based approach was proposed by Abdy Sayyed et al. (2015) which is a non-iterative method by connecting a check valve (CV), a flow control valve (FCV) and an emitter to the demand nodes. Further, they have shown that emitter equation is identical with Wagner (1988) for $H_j^{req} \geq H_j^{min}$, if emitter co-efficient K_e and exponent γ are taken as follows:

$$K_e = \frac{Q_j^{req}}{\left(H_j^{req} - H_j^{Min}\right)^{\gamma}} \tag{2}$$

$$\gamma = \frac{1}{n_j} \tag{3}$$

Where the nodal elevation of the emitter set nodes should be:

$$NEL_j = EL_j + H_{\min} \tag{4}$$

Rossman (2000) also suggested that to get maximum flow at minimum pressure at demand nodes, the emitter co-efficient shall be assigned as 100 times of the respective nodal demand. Hereafter it is referred as K_{e100}(Co-efficient of discharge).

$$K_{e100} = 100 \times Q_j^{req} \tag{5}$$

In Abdy Sayyed et al. (2015), the FCV is used to fulfil the maximum flow constraint and the CV is employed to avoid flow reversal. Single iteration pressure driven analysis (SIPDA) proposed by Mohmoud et al. (2017) adopted the same sequence of network elements as that

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of Abdy Sayyed et al. (2015) approach. But, SIPDA adds the sequence of network elements and modifies their nodal elevations only to those nodes experiencing pressure-deficit. Pacchin et al. (2017) used another new sequence of elements (General Purpose Valve (GPV), Check Valve (CV) and artificial Reservoir) to evaluate outflow from the node under pressure-deficient conditions. Pacchin et al. (2017) applied the proposed approach and other similar methods to two real water distribution networks and concluded that their proposed method and Abdy Sayyed et al. (2015) are able to produce correct the behaviour of the network under pressure deficient condition. However, the drawback of these methodologies is the need to include two dummy nodes per node which further increases the number of components and the topology complexity of the network. Though addition of elements make single snapsort analysis, its incorporation to each demand nodes make network too complex in topology. It consumes lot of time of the network modeller unless separate integrated component is created with setting option in the existing software.

4.0 Assumptions

Many investigators (Bhave 1981; Germanopoulos 1985; Wagner et al. 1988; Reddy and Elango 1989, 1991; Chandapillai 1991; Fujiwara and Ganesharajah 1993; Tucciarelli et al. 1999; Tanyimboh et al. 2001; Wu et al. 2009; Tanyimboh and Templeman 2010) have suggested different head-flow relations for assessing the supplying capability of nodes under pressure-deficient conditions. Figure 1, presents an interpretation of the head-flow relations.

Given the variables defined in Figure 1, there are different assumptions that the modeller can make:

- The more general case is the one in which no assumption is made on Z, H_{min}, H_{req}. In this case the minimum possible head on a node is its elevation Z, and if hydraulic

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conditions do not permit, then the node is isolated representing not only that demand in the node must be zero, but also that there is no flow in the adjacent pipes (i.e. no-siphonic flow is considered). If the head is between Z and H_{min}, then the demand at the node is still zero, but now flow in the adjacent pipes can happen if hydraulic conditions downstream permit it. If the head is between H_{min} and H_{req}, then the demand at the note is only partially fulfilled even though the appliance(s) are completely open; this is modelled with a transition curve which can take different forms (e.g, Germanopoulos 1985; Bhave 1989; Salgado-Castro 1988; Wagner et al. 1988; Fujiwara and Li 1998; Tanymboh and Templeman 2010) although Germanoupoulos (1985) emitter equation is commonly accepted as the most physically appropriate. If the head is above H_{req}, then the pressure in the appliance is enough to fulfil the required demand and therefore the appliances are assumed be partially closed to receive only the required demand; this means that a demand driven analysis of the node is suitable.

- Assume $Z < H$ (assume the actual junction elevation is below any possible value of H). This case assumes that the water cannot ever reach the Node Isolation Zone. Models that accept negative pressures in the system and flows downstream on these nodes are either making this assumption, or assuming syphonic flow conditions (as long as the absolute pressure is above vapour pressure).
- Take $H_{min} = Z$. This case assumes that once there is some pressure in the node, there is some outflow. This assumption is valid when the node elevation actually represents the elevation of the lowest water demand appliance among all of the appliances lumped in it.
- Take $H_{req} = H_{min}$. This case assumes that once the head is above the minimum head (i.e., pressure in the emitter is above zero) the outflow is equal to the required flow or,

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failing that, the maximum hydraulically-possible flow. This assumption can be modelled using Rossman (2000) approximation of using a emitter coefficient of $100 \cdot Q_{Req}$.

The method proposed in this study requires no assumptions on Z, H_{min}, H_{req}, although it can deal with any of the previously mentioned ones. This means the only assumptions made in the proposed pressure driven analysis (PDA) are as follows:

1. Though available pressure is greater than required pressure, the outflow at demand nodes does not exceed its design demand. This is a very basic assumption made by municipal engineering at the project formulation stage.
2. No outflow is possible at demand node if available pressure is less than minimum service pressure.
3. Pressure dependent outflow between required and minimum pressures takes the form as shown in Fig. 1 and for the corresponding condition the percentage of valve opening is defined by the curve.
4. Water distribution network is considered as a non-air-tight system. Hence, no siphonic flow is possible in the network.
5. Emitter co-efficient is considered based on either eq. 2 or 100 times the nodal demand to estimate the outflow at minimum residual pressure (Eq. 5).

5.0 Proposed method

The present study, proposes a simple approach by setting emitter co-efficient and changing the elevation of the nodes that have been identified as pressure-deficient through few simulation runs of DDA. The proposed approach completely eliminates the serial inclusion of fictitious network elements at any node of the system. The entire procedure is illustrated by a flow chart shown in Fig. 2.

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For a given condition, the network initially should be simulated using EPANET 2, identifying the maximum pressure-deficient node and setting its demand as zero. This process should be implemented repeatedly until all the nodes get $H_{avl} \geq H_{req}$. Now, it is to be noted here that all non-zero nodes could deliver the design demand. Then, increase the elevation of zero-set nodes to H_{min} (ie. EL_j+H_{min}) and calculate the emitter co-efficient to be assigned to those nodes. Next, the network is simulated again. If a negative flow takes place at any emitter-set node, then remove the emitter value of those nodes and perform again DDA and interpret the results. Now there are chances of H_{avl} in some nodes going below H_{min} as the coefficient of the emitter with negative flows has been set to zero. Now such nodes cannot behave as sources. Hence, if pressure in some nodes gets less than minimum pressure, then again set the zero demand and change the nodal property as mentioned above and simulate the network. The analysis ends only if no negative flow exists and none of the non-zero demand nodes experience H_{avl} less than H_{min}. At the end of the analysis, if any nodes show negative pressure, then close the pipes incident to those nodes and simulate again to get final solution. The procedure is illustrated further by a flow chart (Fig.2).

5.1 Example 1

A single-fixed source head two-loop network with six demand nodes and eight links (proposed by Ang and Jowitt (2006) for PDA) is considered to illustrate the proposed approach (see Fig.3). Each pipe is 1000 m long with a Hazen-Williams coefficient of 130. The nodal demand for each node is 25 L/s. DDA shows the full delivery of design demand at respective elevation under normal conditions. To test the proposed algorithm, three scenarios are considered: (i) closing of pipe 3 (ii) Fire demand of 50 L/s at node 2 and (iii) Fire demand of 50 L/s at node 7. Table 3provides both DDA and proposed PDA results for all three scenarios. Equation 5 is used to simulate the pressure-flow relation (equivalent to a difference

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between required and minimum pressures below 0.001 m if using eq. 2) with an emitter exponent of 0.54.

DDA shows negative pressure at all the demand nodes except node 2 while pipe 3 is isolated from service (Scenario 1). Node 4 is observed as maximum negative pressure node and its nodal demand is set as zero. Again hydraulic simulation is carried out to verify whether all nodes turned into pressure above zero. But, still node 6 is facing higher pressure deficit condition among nodes 3 to 7 and its demand is set as zero. After setting emitter co-efficient to both node 4 and 6, the hydraulic analysis shows a negative flow at node 4 and a negative pressure at node 7. By disconnecting pipes incident to node 4 and removing its K_e the other outflows are computed. This scenario requires five demand driven analyses to obtain PDA results. Further, same result is obtained using SIPDA proposed by Mohmoud et al. (2017) after disconnecting incident pipes to node 4. SIPDA took three DDA run after addition of artificial links between network elements and five nodes.

In the next case (scenario 2), a fire demand of 50 L/s is created at node 2. The total demand at node 2 is changed as 75 L/s. As this node is nearer to the source, there is more possibility to satisfy the extra demand. But, DDA analysis indicates negative pressure to all the nodes as the total demand of that node is increased three times the design demand (i.e., two times higher than the existing demand). Nodal demand at node 3 and 7 is modified as zero sequentially after noticing negative pressure. Now, network shows pressure greater than H_{min} at these nodes. Hence, it is possible to deliver partially the flow to those nodes with zero demand set . Now Emitter co-efficient is set both to nodes 3 and 7 and network is simulated. No negative pressure or negative flow is detected at these two nodes. But, pressure at node 5 has become negative. By changing nodal demand and setting emitter co-efficient at node 5 provided a final result after simulation. It can be seen that network is able to supply full fire demand at node 2, full supply at node 4 and 6, and partial supply at node 3, 5 and 7. SIPDA

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provided the same result while emitter co-efficient is taken as 2500. Analysis by SIPDA necessitates addition of serial fictitious network elements to all the demand nodes as all the nodes experienced negative pressure upon 50 L/s fire demand at node 2.

In the third scenario, a fire demand of 50 L/s at node 7 is added and the network is simulated. Application of proposed approach and SIPDA provided the same results.

5.2 Example 2

The network 1 is used as it is for further analysis by setting reservoir elevation as 135 m instead of 100 m. The minimum and required pressures at all the demand nodes are designated as 15 m and 30 m respectively. DDA analysis indicates that network can supply design demand from all the demand nodes at required pressure level of 30 m. SIPDA and the proposed approach requires Emitter co-efficient, K_e. For demand 25 L/s with H_{req} = 30 m and H_{min} = 15 m, the emitter co-efficient is obtained as 5.80 L/s/m$^{0.54}$. The same value is utilised for both approaches to simulate the behaviour of network under link 3 isolation.

PDA analysis is carried out by proposed approach. DDA needs to be run five times and results obtained are presented in Table 4. Proposed method indicates full supply of design demand at nodes 2 and 3 while the remaining nodes are able to supply only partial demand. For the same case study, SIPDA makes partial supply at nodes 4, 6 and 7 while recorded pressure is in between H_{min} and H_{req}. Though the pressure at node 5 is below H_{req}, SIPDA indicates the full supply of demand instead of partial supply. SIPDA result at this node violates the assumption of partial supply in between minimum and required pressure.

Further, by closing two links 3 and 6, the network is simulated and DDA shows pressure below minimum at nodes 4, 5, 6 and 7. By applying proposed approach, actual demands and pressures are evaluated and presented in Table 4. Under pipes 3 and 6 failure condition,

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network is able to supply full design demand at nodes 2 and 3. The remaining nodes are able supply partial demand only.

5.3 Example 3

A multisource pumped water distribution network presented by Jinesh babu and Mohan (2012) is considered for further testing of the proposed approach. Fig. 4 shows the network layout consisting of two pumps with capacity of 125 kW each instead of 125 hp considered by Jinesh babu and Mohan (2012) and designed to deliver 2/3rd of total demand. These two pumps, P1 and P2 pump the water from two sources, S1 and S2 respectively whose elevations are 100 m each. The remaining 1/3rd of total demand shall be drawn from reservoir, S3 whose elevation is 200 m and one flow control valve is provided between reservoir S3 and node 7 in order to control the flow to 1/3 of total demand. A demand pattern with four intervals is considered with demand factors (DFs) of 0.2, 1.0, 0.6 and 0.8 which represent time intervals of 0.00 to 6.00, 6.00 to 12.00, 12.00 to 18.00 and 18.00 to 24.00 h respectively. The optimal speed of pumps for respective time interval needs to be set as 0.584, 1.0, 0.842 and 0.927. Hazen-Williams roughness co-efficient of 130 is assumed for all the pipes. As Jinesh babu and Mohan (2012) did not specify on upper and lower service pressure limit to the network, it is assumed in the present study that the required and minimum pressure needed for each demand node as 30 m and 15 m respectively. Table 5 presents the pipe and nodal properties of the network. Table 6 shows the required nodal outflows at four time steps.

Pump 1 failure case is analysed to examine the proposed approach. The results of EPS analysis for four time steps are presented in Table 7.This scenario produces partial flow at several nodes in all time steps. It is to be noted that in first and second time steps, all nodes supply some water whereas in the next two time steps, node 1 is unable to deliver even partial flow. Two nodes at time steps 1 and 2 indicates pressure greater than H_{req} with full supply conditions and all remaining nodes have H_{avl} between H_{min} and H_{req}. While in case of time step 3 and 4 no nodes are noticed with H_{avl} greater than H_{req}. This indicates that the proposed approach is able to simulate the pressure based flow when the network is energized by pumps apart from gravity flow by reservoir. The network is able to supply 71.17 %, 69.34%, 70.99% and 71.37 % of its total design demand at respective time steps. But, it is to be noted here that the drop in supply under failure of component is not uniform to all the nodes. While optimizing the network, the various components of the network should be sized in such a way that, to a possible extent, all nodes get affected uniformly under failure of any component so that equity can be maintained under failure scenarios. To achieve this PDA is becoming very important.

5.4 Example 4

To examine the applicability of proposed approach on a large size benchmark network, a Modena Network (MOD) given by Centre for Water Systems, University of Exeter (Wang et al. 2015) is considered. Its layout is shown in Fig. 5 and it consists of 317pipes, 268 demand nodes, and four reservoirs with fixed head within 72.0 m to 74.5 m. In the present work, the layout, its diameter and Hazen-Williams roughness coefficient of 130 are considered as it is given with the network. The minimum and required pressures are assumed as 10 m and 20 m respectively. Supply from Reservoir ID 272 is stopped fully by isolation of a pipe connecting reservoir and nearest node. DDA indicates pressure deficit (i.e., below H_{req}) in 171 demand nodes. Using EPANET Toolkit, the proposed approach is implemented and the results are presented in Fig.6. Actual outflow versus design demand plot (Fig.6) shows the number of full supply and partial supply nodes. The trajectory of points lying along diagonal indicates full supply nodes and points lying below the diagonal points denote partial supply against design demand. It is found from PDA that network is able to supply 89.1 % of total demand

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while supply from reservoir ID 272 is ceased. Out of 268 nodes, 90 nodes are able to make partial supply to the consumers and remaining nodes could make the design supply. Fig. 7 presents the distribution of nodal pressure under no-component failure condition. The DDA indicates that pressure at all the nodes is above H_{req} and hence full design supply is possible. Fig. 8 indicates the distribution of nodal pressures when there is no supply from reservoir ID 272. The DDA shows the negative pressure at several nodes. From Fig.6 and Fig.9, it is evident that proposed approach predicts nodal outflow corresponding to the pressure in all the nodes above H_{min}.

Further, supply from reservoir ID 270 is closed and proposed approach is applied. It is noticed that DDA has shown 232 nodes as pressure deficient nodes. In absence of supply from reservoir ID 270, the network is able to supply 78.46% of total design demand. From Fig 10, it is possible to notice that large number of supply nodes getting affected in absence of Reservoir ID 270. 49% of total nodes could deliver full design supply and remaining could make only partial supply. Table 8 presents the total outflow from the network obtained by isolation of selected pipes. It is evident from results that the proposed approach is able to find the nodal outflow under any pipe failure condition apart from pipe connecting the source.

6.0 Conclusion

Pressure driven analysis (PDA) of water distribution network estimates realistic outflow at all demand nodes while network is under pressure deficient conditions. Use of available network components like reservoir, valves and emitter to simulate pressure based outflow is found to be simple approach as it could be implemented easily for small networks without change of source code of commercial software. But, the major bottleneck in adopting such an approach is that large number of artificial components needs to be added to either all demand nodes or deficient nodes. This increases the complexity of network configuration and also burden to computation part. The proposed approach does not utilize the artificial components other than emitter. Emitter is not a physical component to be added at the demand nodes. Instead it requires an appropriate co-efficient to activate the emitter and estimate the outflow based on available pressure at the node. By changing the nodal properties to those nodes categorized as pressure deficit, the pressure based outflow is able to evaluate by proposed iterative approach using emitter option alone. From the analysis of the results, it is evident that proposed approach can be easily implemented for various pressure limits.

Competing Interests

The authors declare that they have no conflict of interest.

References

Abdy Sayyed, M. A. H., and Gupta, R.: Predicting deficient condition performance of water distribution networks, J. Civil Eng. Infrastruct., 46, 2, doi: 10.7508/ceij.2013.02.004, 2013.

Abdy Sayyed, M. A. H., Gupta, R., and Tanyimboh, T. T.: Modelling pressure deficient water distribution networks in EPANET, *Procedia Eng.*, 89, doi:10.1016/j.proeng.2014.11.487, 2014.

Abdy Sayyed, M.A.H., Gupta, R., and Tanyimboh, T.T.: Noniterative application of EPANET for pressure dependent modelling of water distribution systems, *Water Resour. Manage*., 29, 9 doi:10.1007/s11269-015-0992-0, 2015.

Ang, W.K., and Jowitt, P.W.: Solution for water distribution systems under pressure-deficient conditions, J. Water Resour. Plan. Manage., 132,3, doi.org/10.1061/(ASCE)0733-9496(2006)132:3(175), 2006.

Ang, W.K., and Jowitt, P.W..: Closure to 'Solution of water distribution systems under pressure-deficient conditions' by W.K. Ang and P.W. Jowitt." *J. Water Resour. Plan. Manage.*, 133,6, doi:10.1061/(ASCE)0733-9496(2007)133:6(571), 2007.

Baek C.W., Jun, H.D., and Kim, J.H.: Development of a PDA model for water distribution systems using harmony search algorithm, KSCE J. Civ. Eng. 14, doi:10.1007/s12205-010-0613-7.

Bhave, P.R.: Node flow analysis of water distribution systems, *J. Transp. Eng.*, 107, 4, 1981.

Chandapillai, J.: Realistic simulation of water distribution system, *J. Transp. Eng.*,117(2), doi:10.1061/(ASCE)0733-947X(1991)117:2(258), 1991.

Cheung, P. B., Van Zyl, J. E., and Reis, L. F. R.: Extension of EPANET for pressure driven demand modeling in water distribution system, Computing and Control for the Water Industry, 1, 2005.

Fujiwara, O., and Ganesharajah, T.: Reliability assessment of water supply systems with storage and distribution networks, *Water Resour. Res.*, 29, 8, doi:10.1029/93WR00857, 1993.

Fujiwara, O., and Li, J. : Reliability analysis of water distribution networks in consideration of equity, redistribution and pressure dependent demand, *Water Resour. Res*., 34, 7, doi:10.1029/98WR00908, 1998.

Germanopoulos, G.: A technical note on the inclusion of pressure-dependent demand and leakage terms in water supply network models, *Civ. Eng. Syst.*, 2, 3, doi: 10.1080/02630258508970401, 1985.

Giustolisi, O., Savic, D. A., Berardi, L., and Laucelli, D.: An Excel based solution to bring water distribution network analysis closer to users, Proc., Computer and Control in Water Industry, Exeter Press, Exeter, U.K, 2011.

Gorev, N.B. and Kodzhespirova, I.F.: Noniterative Implementation of Pressure-Dependent Demands Using the Hydraulic Analysis Engine of EPANET 2, Water Resour Manage., 27, 3623, doi:10.1007/s11269-013-0369-12013, 2013.

Jinesh Babu K.S., and Mohan, S.: Extended Period Simulation for Pressure-Deficient Water Distribution Network, *J. Comput. Civ. Eng.* 26,4, doi:10.1061/(ASCE)CP.1943-5487.0000160, 2012.

Jun, L., and Guoping, Y.: Iterative methodology of pressure dependent demand based on EPANET for pressure-deficient water distribution analysis, J. Water Resour. Plann. Manage.,139, 1, doi: 10.1061/(ASCE) WR.1943-5452.0000227, 2013.

Liu, J., Yu, G., and Savic, D.: Deficient-network simulation considering pressure-dependent demand, Sustainable Solutions for Water, Sewer, Gas, and Oil Pipelines (ICPTT 2011), ASCE, Reston, VA, 2011.

Mahmoud, H.A., Aavic, D., and Kapelan, Z.: New pressure-driven approach for modeling water distribution networks, J. Water Resour. Plann. Manage., 143, 8, doi:10.1061/(ASCE)WR.1943-5452.0000781, 2017.

Mamizadeh, J. and Shaoonizadeh, S.: Application of modified complementary reservoir approach in analysis of water distribution networks under pressure deficient conditions, *Urban Water.*, 14, 4, doi:10.1080/1573062X.2016.1171884, 2016.

Morley, M. S., and Tricarico, C.: Pressure driven demand extension for EPANET (EPANETpdd), Technical Rep. 2008, Univ. of Exeter, Exeter, U.K, 2014.

Ozger, S.: A semi-pressure-driven approach to reliability assessment of water distribution networks, Ph.D. dissertation, Department of Civil and environmental Engineering, Arizona State University, Temple, Ariz, 2003.

Pacchin, E., S. Alvisi, and M. Franchini, M.: A new non-iterative method for pressure-driven snapshot simulations with EPANET, *Procedia Engineering*, 186, doi:10.1016/j.proeng.2017.03.219, 2017.

Reddy, L. S., and Elango, K.: A new approach to the analysis of water starved networks, J. Indian Water Works Assoc., 23, 1, 1991.

Reddy, L.S., and Elango, K.: Analysis of water distribution networks with head dependant outlets, *Civ. Eng. Syst.*, 6, 3, 1989.

Rossman, L.A.: EPANET programmer's Toolkit Manual. Water Supply and Water Resources Division, National Risk Management Research Laboratory, U.S. Environmental Protection Agency, Cincinnati, 2000.

Rossman, L.A.: Discussion of 'Solution of water distribution systems under pressure-deficient conditions' by W.K. Ang and P.W. Jowitt., *J. Water Resour. Plan. Manage.*, 133,6, doi:10.1061/(ASCE)0733-9496(2007)133:6(566.2), 2007.

Salgado-Castro, R.O.: Computer modelling of water supply distribution networks using the gradient method, Ph.D thesis. Univ. of Newcastle Upon Tyne, U.K, 1988.

Sharoonizadeh, S., Mamizadeh, J. and Sarvarian, J.: Comparison of solution methods for analyzing water distribution networks under pressure-deficient Conditions, J. of Wat. Sup.: Res. and Tech.—AQUA, 65,4,doi: 10.2166/aqua.2016.084, 2016

Siew, C., and Tanyimboh, T. T.: Pressure-dependent EPANET extension, J. Water Resour. Manage., 26, 6, 2012.

Sivakumar, P., and Prasad, R. K.: Simulation of Water Distribution Network under Pressure-Deficient Condition. *Water Resour. Manage.*, 28, 10, doi:10.1007/s11269-014-0677-0 2014.

Drink. Water Eng. Sci. Discuss., https://doi.org/10.5194/dwes-2018-23
Manuscript under review for journal Drink. Water Eng. Sci.
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Open Access Drinking Water Engineering and Science Discussions

Sivakumar, P., and Prasad R.K.: Extended period simulation of pressure-deficient networks using pressure reducing valves, *Water Resour. Manage.*, 29, doi:10.1007/s11269-014-0907-52015, 2015

Suribabu, C.R.: Emitter based approach for estimation of nodal outflow to pressure deficient water distribution networks under pressure management, *Scientia Iranica A*, 22, 55, 2015.

Suribabu, C.R., Neelakantan, T.R., and Sivakumar, P.: Improved complementary reservoir solution to evaluate nodal outflow under pressure deficient conditions, *ISH J. Hydraulic Eng.*, 23, 3, doi:10/1080/09715010.2017.1298060, 2017.

Suribabu, C.R., and Neelakantan T.R.: Balancing reservoir based approach for solution to pressure deficient water distribution networks, *Int. J. Civ. Struct. Eng.* 2, 2, 2011.

Tanyimboh, T.T., and Templeman, A.B.: Seamless pressure-deficient water distribution system model, *Proc. of the Inst. of Civil Engrs, Water Manage.* 163, 8, doi: 10.1680/wama.900013, 2010.

Tanyimboh, T.T., Tabesh, M., and Burrows, R.: Appraisal of source head methods for calculating reliability of water distribution networks, *J. Water Resour. Plan. Manage.*, 127, 4, doi:10.1061/(ASCE)0733-9496(2001)127:4(206), 2001.

Tucciarelli, T., Criminisi, A., and Termini, D.: Leak analysis in pipeline systems by means of optimal valve regulation, *J. Hydraul. Eng.*, 125, 3, doi:10.1061/(ASCE)0733-9429(1999)125:3(277), 1999.

Wagner, J.M., Shamir, U., and Marks, D.H.: Water distribution reliability: Simulation methods. *J. Water Resour. Plan. Manage.*, 114, 3, doi:10.1061/(ASCE)0733-9496(1988)114:3(276),1988.

Wang, Q., Guidolin, M., Savic, D. and Kapelan, Z.: Two-Objective Design of Benchmark Problems of a Water Distribution System via MOEAs: Towards the Best-Known

Drink. Water Eng. Sci. Discuss., https://doi.org/10.5194/dwes-2018-23
Manuscript under review for journal Drink. Water Eng. Sci.
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Open Access Drinking Water Engineering and Science Discussions

Approximation of the True Pareto Front, *J. Water Resour. Plan. Manage.*,, 141, 3, doi:10.1061/(ASCE)WR.1943-5452.0000460, 2014, .

Wu, Z.Y., Wang, R.H., Walski, T.M., Yang, S.Y., Bowdler, D., and Baggett, C.C. : Extended global-gradient algorithm for pressure-dependent water distribution analysis, *J. Water Resour. Plan. Manage.*, 135, 1, doi:10.1061/(ASCE)0733-9496(2009)135:1(13) 2009.

Drink. Water Eng. Sci. Discuss., https://doi.org/10.5194/dwes-2018-23
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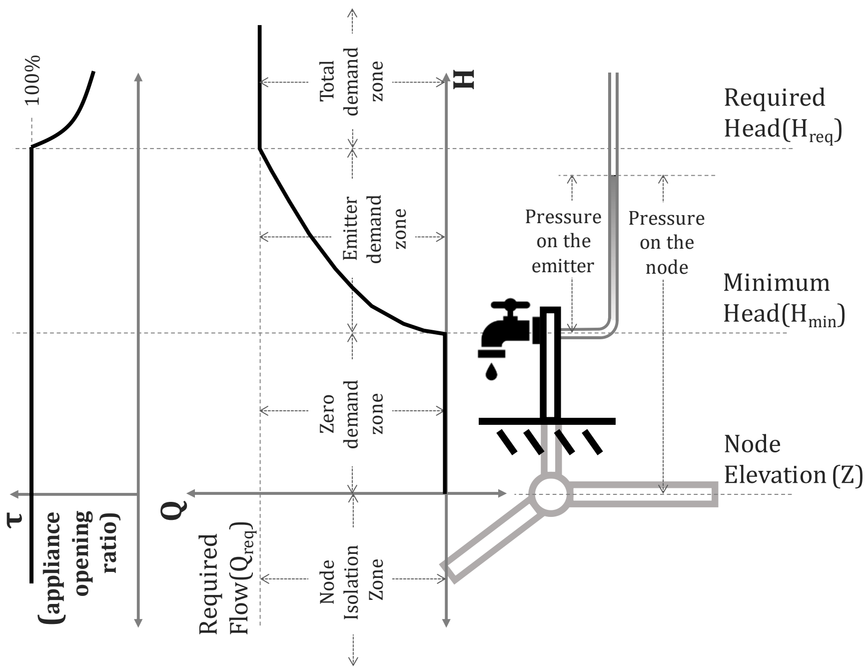

Fig.1 Interpretation of the nodal demand vs. head curve

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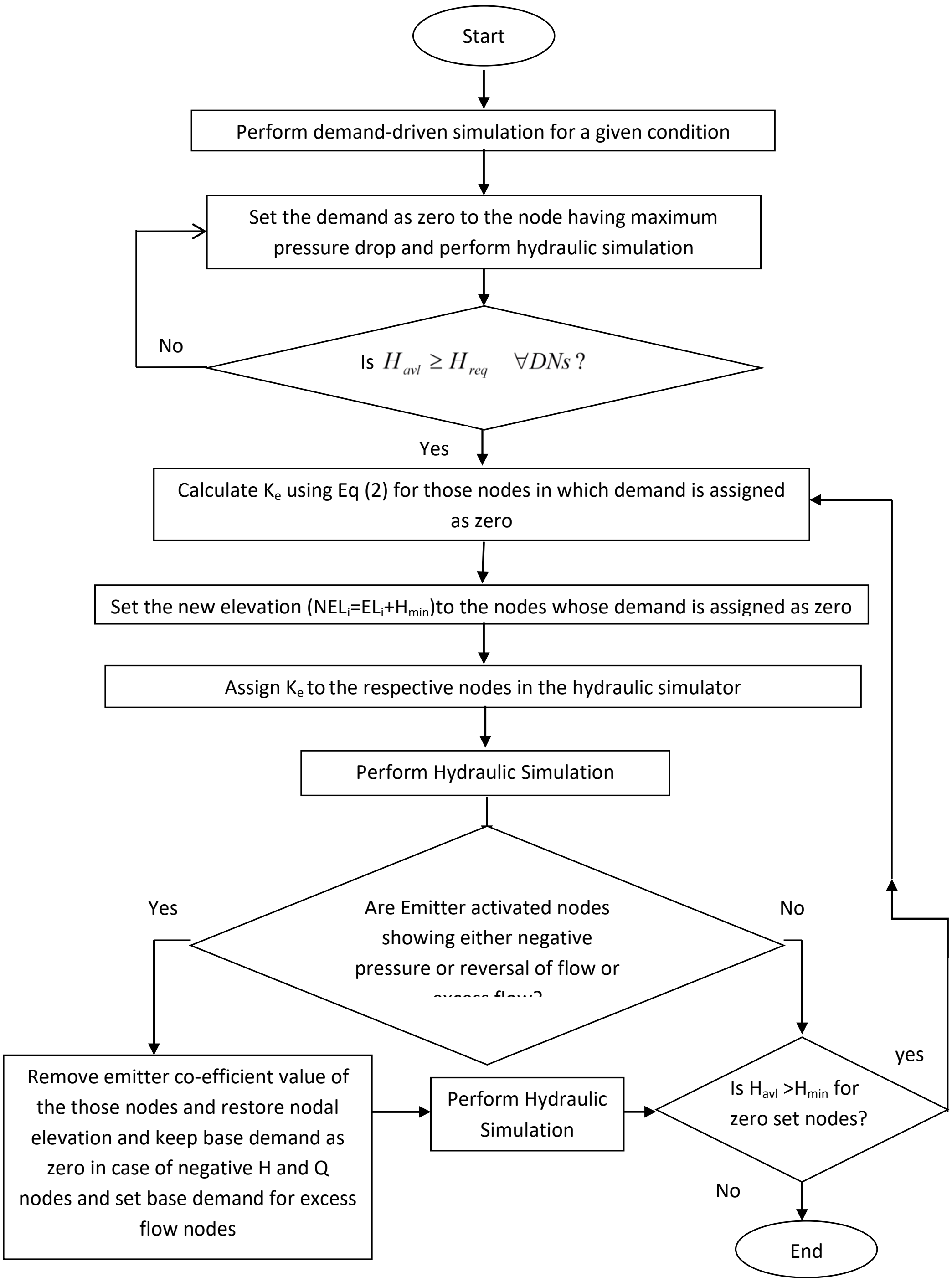

Fig. 2 Flow chart illustrate the computational steps involved in the proposed approach

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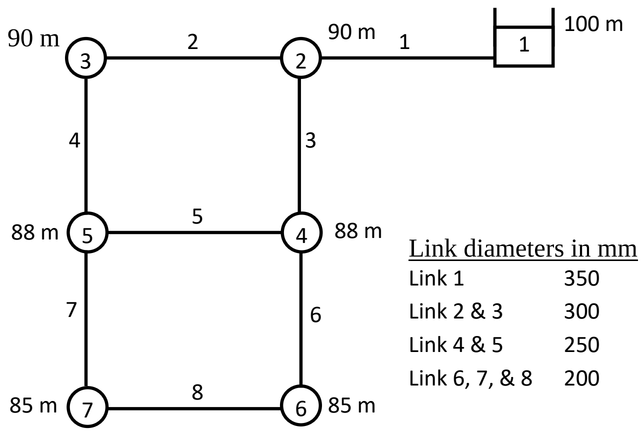

Fig. 3 Layout of the Two-Loop network (Example 1 and 2)

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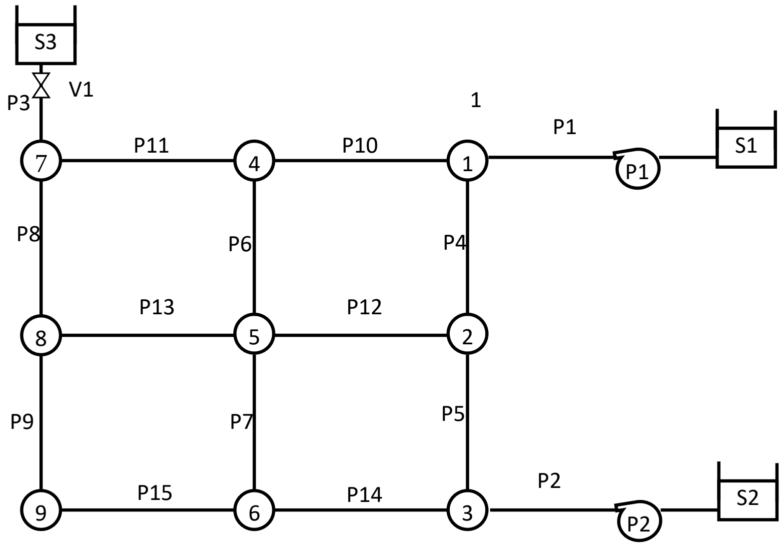

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538 Fig. 4 Layout of multisource pumped network (Example 3)

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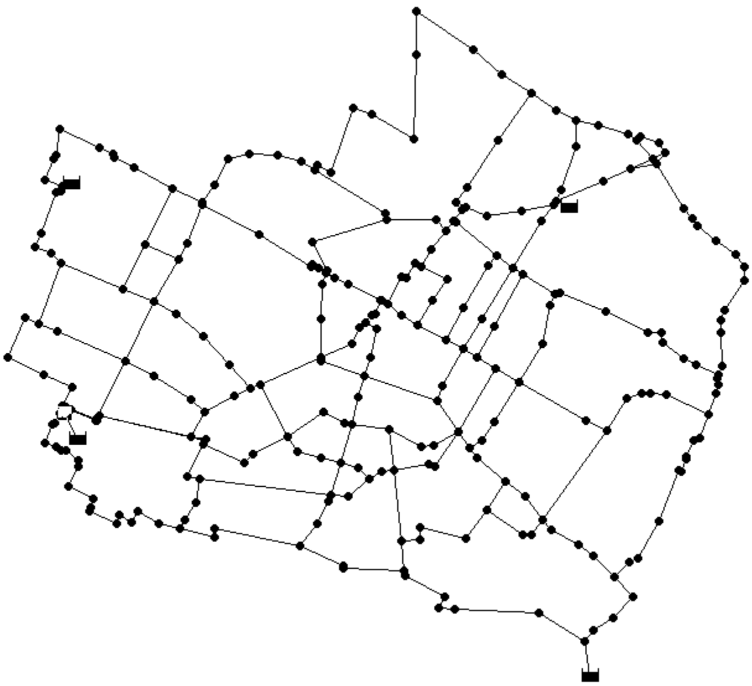

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541 Fig. 5 Layout of Modena Network (Example 4)

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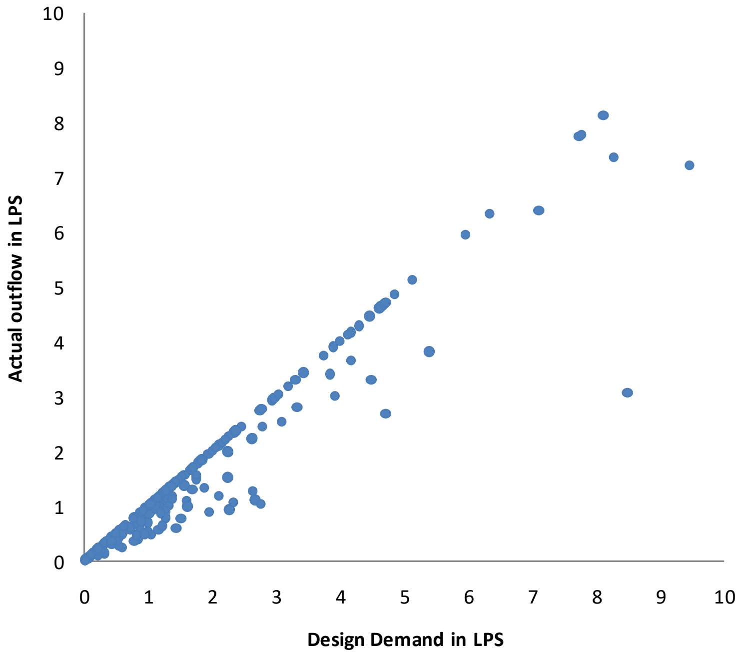

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545 Fig. 6 Actual outflow against design demand under no supply from Reservoir ID 272

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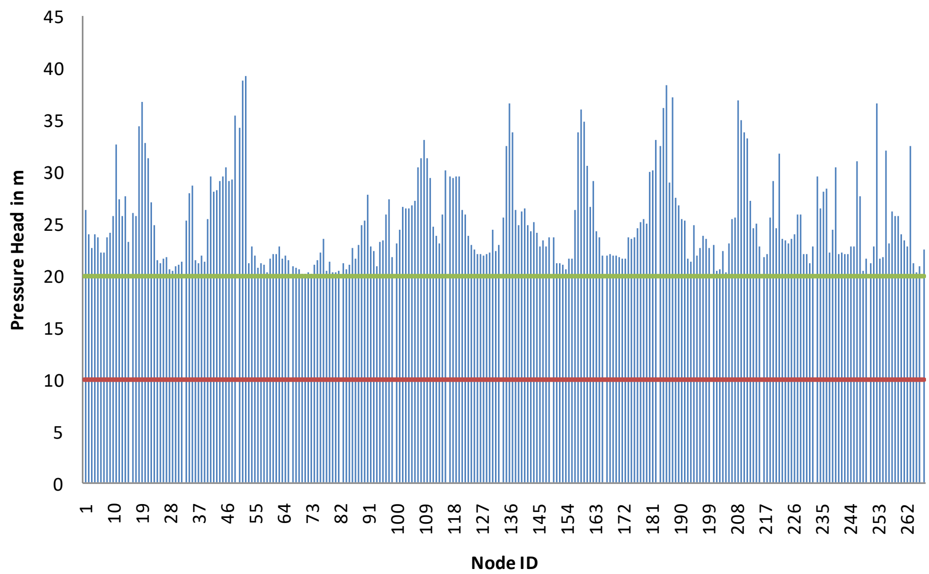

547 Fig. 7 Nodal pressure head under no component failure condition

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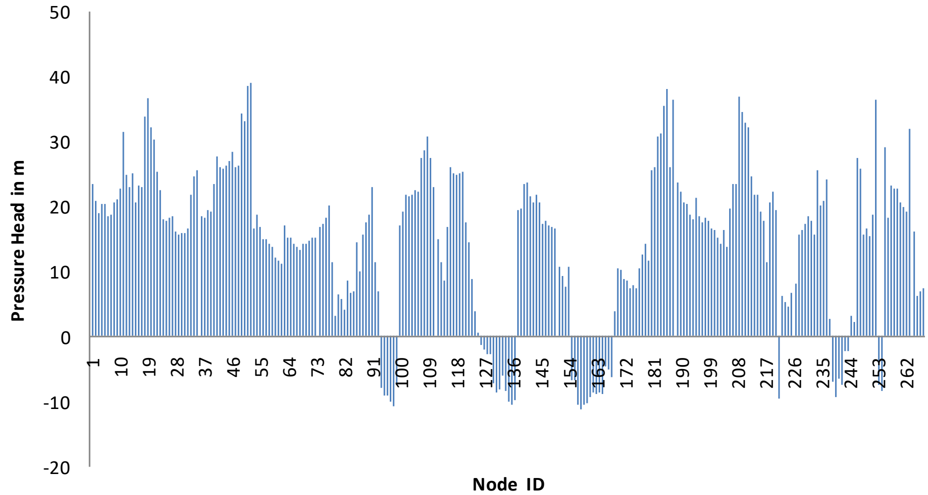

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550 Fig.8 Nodal pressure when Reservoir ID 272 disconnected (DDA)

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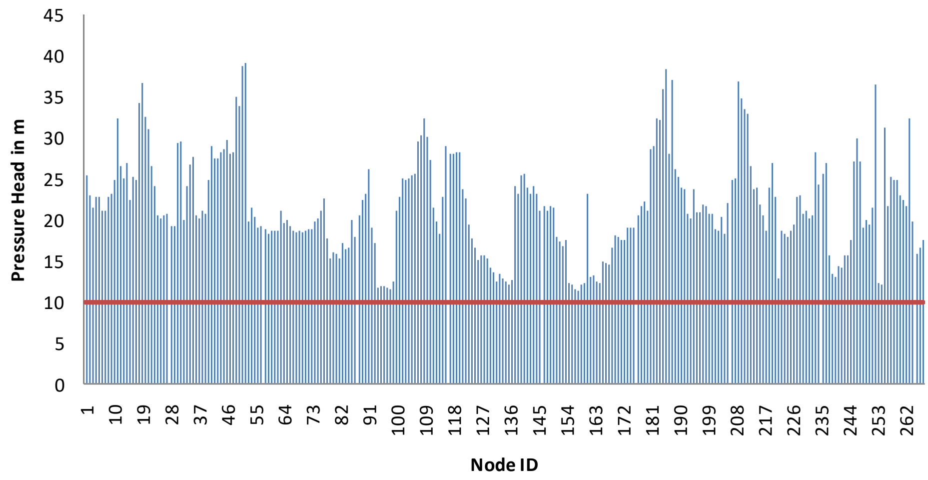

Fig. 9 Nodal pressure when Reservoir ID 272 disconnected (PDA)

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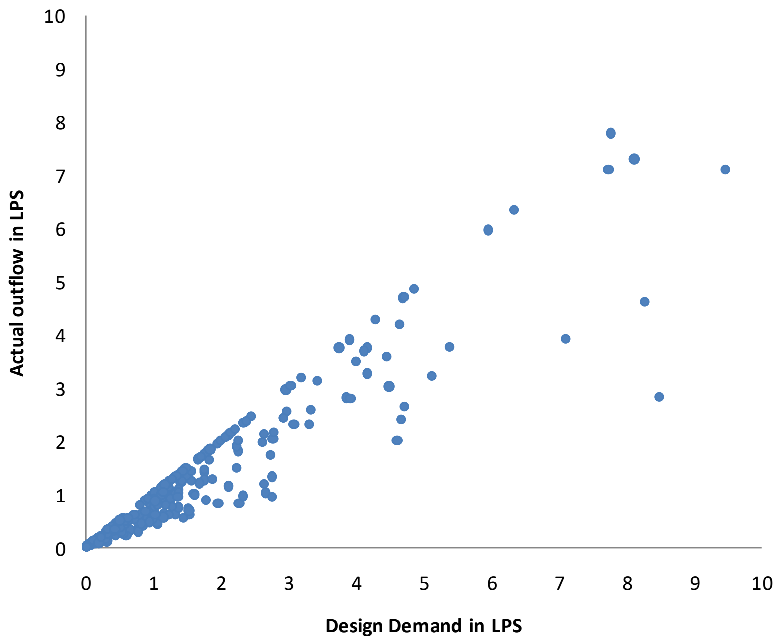

Fig.10 Actual outflow against design demand when no supply from Reservoir ID 270

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Table 1 Various Head – Flow relationship for PDA

S.No.	Author(s) & year	Year	Head-flow equation	Remark
1	Bhave	1981	$\begin{cases} q_j^{avl} = q_j^{req} (adequate\ flow),\ if\ H_j^{avl} \geq H_j^{\min} \\ 0 < q_j^{avl} < q_j^{req}\ (partial\ flow),\ if\ H_j^{\min} = H_j^{avl} \\ q_j^{avl} = 0 (no\ \ flow), if\ H_j^{avl} \leq H_j^{\min} \end{cases}$	First attempt for pressure deficient analysis using simultaneous head-flow equations along with energy and mass balance equations.
2	Germanopoulos	1985	$q_j^{avl} = q_j^{req}(1 - 10^{-c_j[(H_j^{avl} - H_j^{\min})/(H_j^{des} - H_j^{\min})]})$	C_j – node constant.
3	Wagner et al.	1988	$\begin{cases} q_j^{avl} = q_j^{req},\ if\ H_j^{avl} \geq H_j^{\min} \\ q_j^{avl} = q_j^{req} \left(\frac{H_j^{avl} - H_j^{\min}}{H_j^{des} - H_j^{\min}} \right)^{1/n},\ if\ H_j^{\min} < H_j^{avl} < H_j^{des} \\ q_j^{avl} = 0,\ if\ H_j^{avl} \leq H_j^{\min} \end{cases}$	n – Exponent constant (its value often taken as either 1.85 or 2).
4	Reddy and Elango	1989, 1991	$q_j^{avl} = S_j \left(H_j^{avl} - H_j^{\min} \right)^{0.5}$	S_j – node constant.
5	Chandapillai	1991	$H_j^{avl} = H_j^{\min} + K_j (q_j^{avl})^n$	K_j - constant; n – exponent;
6	Fujiwara and Ganesharajah	1993	$\begin{cases} q_j^{avl} = q_j^{req}\ for\ H_j^{avl} \geq H_j^{des} \\ q_j^{avl} = q_j^{req} \left(\frac{\int_{H_j^{\min}}^{H_j^{avl}} (H_j^{avl} - H_j^{\min})(H_j^{des} - H_j^{avl}) dH}{\int_{H_j^{\min}}^{H_j^{avl}} (H_j^{avl} - H_j^{\min})(H_j^{des} - H_j^{avl}) dH} \right),\ if\ H_j^{\min} < H_j^{avl} < H_j^{des} \\ q_j^{avl} = 0\ \ (no\ \ flow),\ \ if\ H_j^{avl} \leq H_j^{\min} \end{cases}$	
7	Tucciarelli et al.	1999	$\begin{cases} q_j^{avl} = q_j^{req},\ if\ H_j^{avl} \geq H_j^{\min} \\ q_j^{avl} = q_j^{req} \sin^2 \left(\frac{H_j^{avl}}{H_j^{\min}} \right),\ if\ 0 < H_j^{avl} < H_j^{\min} \\ q_j^{avl} = 0,\ if\ H_j^{avl} \leq 0 \end{cases}$	
8	Tanyimboh et al.	2001	Same as the equation of Wagner et al. (1988)	Drove Wagner's (1988) equation from Chandapillai (1991) equation. Using this attempted to find reliability of node as well as the network.
9	Wu et al.	2009	$\begin{cases} q_j^{avl} = 0,\ if\ H_j^{avl} \leq 0 \\ q_j^{avl} = q_j^{req} \left(\frac{H_j^{avl}}{H_j^{des}} \right)^{1/n},\ if\ \ H_j^{avl} < H_j^{thr} \\ q_j^{avl} = q_j^{req} \left(\frac{H_j^{thr}}{H_j^{des}} \right)^{1/n},\ \ if\ H_j^{avl} \geq H_j^{thr} \end{cases}$	H_j^{thr} - threshold pressure above which the demand is independent of nodal pressure.
10	Tanyimboh and Templeman	2010	$q_j(H_j) = q_j^{req} \frac{\exp(\alpha_j + \beta_j H_j)}{1 + \exp(\alpha_j + \beta_j H_j)}$ $\alpha_j = \frac{-4.595 H_j^{des} - 6.907 H_j^{\min}}{H_j^{des} - H_j^{\min}}$ $\beta_j = \frac{11.502}{H_j^{des} - H_j^{\min}}$	
11	Jun and Guoping	2013	Considered volume driven demand, pressure driven demand and leaks.	Modified EPANET for nodal outflows

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				based on pressure-dependent demand formulations and leakage models (EPANET-MNO).
12	Morley and Tricarico	2014	Modified source code of EPANET by introducing emitters.	Each emitter is assigned with its own empirical exponent. Convergence issues when applied to complex or larger WDNs.

594 **Table 2 Use of artificial components in PDA**

S.No.	Author(s) & year	Year	Component used in demand driven analysis	Remark
1	Ang and Jowitt	2006	Artificial reservoir and artificial pipe at each node	First (iterative) demand driven application for pressure deficient analysis. Popularly known as PDNA (Pressure-Deficient Network Algorithm)
2	Baek et al.	2010	Nil	Instead of iterative procedure, used an optimization model. DDA model and head-flow relationships were also used.
3	Suribabu and **Neelakantan**	2011	Artificial complementary reservoir and artificial pipe only at pressure deficient nodes	This approach used is known as CRS (Complementary Reservoirs Solution) method. *Second author is the PI of this proposal*.
4	Jinesh Babu and Mohan	2012	Artificial reservoirs, artificial flow control (to control flow to artificial reservoirs), check valves (to avoid negative pressure) and artificial pipe at pressure deficient nodes	Demonstrated limitation of the Ang and Jowitt (2006) method. Reduced the number of iterations required significantly. Popularly known as Modified PDNA (MPDNA).
5	Gorev and Kodzhespirova	2013	Artificial reservoirs, artificial flow control valves, artificial check valves and additional artificial pipes.	Results obtained in a single hydraulic run, Supports only parabolic type of node head-flow relationship.
6	Sivakumar and Prasad	2014	Artificial reservoirs, artificial flow control valves, artificial check valves and artificial pipe	Highlighted limitations of the Ang and Jowitt (2006) method. Reduced the number of iterations required significantly. Could not simulate partial flow between the minimum and the desired pressure head levels.
7	Abdy Sayyed et al.	2013, 2014, 2015	Replaced the artificial reservoir and artificial pipe with a flow emitter	Works excellent for steady-state analysis. Did not consider minimum pressure head level.
8	Sivakumar and Prasad	2015	Artificial reservoirs, artificial flow control valves, artificial check valves and additional artificial pipes.	Compared MPDNA with different head-flow relationships. Proposed modifications to MPDNA. No need for iterative procedures.
9	Suribabu	2015	Emitter	Compared Emitter based PDA with other PDA based on Head-Flow relations
10	Mamizadeh and Sharoonizadeh	2016	Among the two methods, in one method, the components added are same as in CRS approach of Suribabu and *Neelakantan (2011)*. Added a flow control valve in another method.	Proposed two modified versions of CRS method (MCRS) to overcome certain drawbacks.
11	Sharoonizadeh and Mamizadeh	2016	Compared PDNA, MPDNA, CRS and MCRS methods.	Concluded that MPDNA and MCRS methods are better,
12	Suribabu et al.	2017	Artificial reservoirs and artificial pipes.	Improved CRS method proposed.
13	Mahmoud et al.	2017	Artificial check valve, artificial flow control valve, artificial flow emitter, dummy node and artificial pipes at each pressure deficient node	Single-iteration pressure driven analysis (SIPDA). Uses Wagner et al. (1988) node head-flow relationship.

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Table 3 Step by step analysis results showing nodal outflows and pressure at each level of simulation

	Demand (L/s) and Available pressure (m)					
Simulation	Node 2	Node 3	Node 4	Node 5	Node 6	Node 7
			Pipe 3 closed condition			
1 (pipe 3 closed)	25.00 (3.57)	25.00 (-6.14)	25.00 (-23.17)	25.00 (-19.76)	25.00 (-22.31)	25.00 (-22.06)
2 (Zero demand to node 4)	25.00 (5.42)	25.00 (-1.01)	0.00 (-9.21)	25.00 (-8.18)	25.00 (-9.28)	25.00 (-9.25)
3 (Zero demand to node 6)	25.00 (6.97)	25.00 (3.20)	0.00 (0.66)	25.00 (0.87)	0.00 (3.05)	25.00 (2.43)
4 (Set K_e to node 4 and 6)	25.00 (6.82)	25.00 (2.80)	-18.34 (0.00)	25.00 (0.05)	20.94 (0.00)	25.00 (-0.03)
5 (Remove k_e at node 4 and close the pipes incident to the node)	25.00 (6.94)	25.00 (3.11)	Isolated	25.00 (0.70)	0.54 (0.00)	25.00 (0.00)
			50 L/s Fire demand at node 2			
1 (Set demand at node 2 as 75 L/s)	75.00 (-0.95)	25.00 (-3.12)	25.00 (-2.21)	25.00 (-2.87)	25.00 (-3.09)	25.00 (-3.11)
2 (Set Zero demand at node 3)	75.00 (1.45)	0.00 (0.50)	25.00 (0.60)	25.00 (0.21)	25.00 (-0.15)	25.00 (-0.16)
3 (Set Zero demand to node 7)	75.00 (3.57)	0.00 (3.03)	25.00 (3.88)	25.00 (3.72)	25.00 (5.46)	0.00 (6.09)
4 (Change nodal property for nodes 3 and 7)	75.00 (1.16)	6.25 (0.00)	25.00 (0.38)	25.00 (-0.05)	25.00 (0.00)	21.96 (0.00)
5 (Change nodal property for node 5)	75.00 (1.17)	6.81 (0.00)	25.00 (0.41)	24.06 (0.00)	25.00 (0.00)	22.26 (0.00)
			50 L/s Fire demand at node 7			
1 (Set demand at node 7 as 75 L/s)	25.00 (-0.95)	25.00 (-4.66)	25.00 (-5.45)	25.00 (-6.88)	25.00 (-14.46)	75.00 (-17.56)
2 (Set Zero demand at node 7)	25.00 (5.42)	25.00 (3.88)	25.00 (5.37)	25.00 (5.01)	25.00 (6.87)	0.00 (7.44)
3 (Change nodal property at node 7)	25.00 (3.18)	25.00 (0.87)	25.00 (1.64)	25.00 (0.93)	25.00 (0.10)	29.93 (0.00)

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Table 4 Step by step analysis results showing nodal outflows under two pressures

	Demand (L/s) and available pressure (m)					
Simulation	Node 2	Node 3	Node 4	Node 5	Node 6	Node 7
			Pipe 3 closed condition			
1 (pipe 3 closed)	25.00 (38.57)	25.00 (28.86)	25.00 (11.83)	25.00 (15.24)	25.00 (12.69)	25.00 (12.94)
2 (Zero demand to node 4)	25.00 (40.42)	25.00 (33.99)	0.00 (25.79)	25.00 (26.82)	25.00 (25.72)	25.00 (25.75)
3 (Zero demand to node 6)	25.00 (41.97)	25.00 (38.00)	0.00 (35.66)	25.00 (35.87)	0.00 (38.05)	25.00 (37.43)
4 (Change nodal property for nodes 4 and 6 assign K_e = 5.8)	25.00 (39.85)	25.00 (32.42)	15.75 (21.36)	25.00 (23.32)	17.39 (22.64)	25.00 (22.64)
5(Change nodal property for nodes 5 and 7 assign K_e = 5.8)	25.00 (40.17)	25.00 (33.32)	18.14 (23.26)	20.47 (25.34)	19.88 (24.74)	20.04 (24.93)
			SIPDA			
C_d = 5.8	25.00 (40.02)	25.00 (32.91)	17.22 (22.50)	25.00 (24.42)	19.15 (24.13)	19.29 (24.26)
			Proposed approach for isolation of Link 3 and 6			
1 (pipe 3 and 6 isolated)	25.00 (38.57)	25.00 (28.86)	25.00 (14.04)	25.00 (15.24)	25.00 (1.86)	25.00 (5.41)
2 (Set demand at node 6 as zero)	25.00 (40.42)	25.00 (33.99)	25.00 (25.62)	25.00 (26.82)	0.00 (26.27)	25.00 (26.27)
3(Set demand at node 7 as zero)	25.00 41.97	25.00 38.20	25.00 34.67	25.00 35.87	0.00 38.87	0.00 38.87
4 (Change nodal property at nodes 6 and 7 assign K_e = 5.8)	25.00 (39.99)	25.00 (32.89)	25.00 (23.02)	25.00 (24.22)	14.66 (20.57)	16.45 (21.89)
5(Change nodal property at nodes 4 and 5 and assign K_e = 5.8)	25.00 40.34	25.00 33.78	20.66 25.51	21.54 26.35	15.99 21.54	17.94 23.09

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601 Table 5 Nodal and Pipe properties of multisource pumped network

Node ID	Elevation (m)	Demand (m^3/hr)	Pipe No.	Length (m)	Diameter (mm)
1	165	100	1	1000	457.2
2	160	150	2	1000	508.0
3	155	120	3	500	355.6
4	150	120	4	1000	203.2
5	150	200	5	1000	203.2
6	155	100	6	1000	355.6
7	160	100	7	1000	152.4
8	160	330	8	1000	355.6
9	160	240	9	1000	254.0
			10	1000	355.6
			11	1000	152.4
			12	1000	152.4
			13	1000	152.4
			14	1000	406.4
			15	1000	406.4

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Table 6 Design demand during different time steps for multisource pumped network

Node ID	Demand in m^3/hr			
	Time step 1	Time step 2	Time step 3	Time step 4
1	20	100	60	80
2	30	150	90	120
3	24	120	72	96
4	24	120	72	96
5	40	200	120	160
6	20	100	60	80
7	20	100	60	80
8	66	330	198	264
9	48	240	144	192

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Table 7 Nodal outflows under pump 1 failure condition for Multisource pumped network

	Nodal outflow (m^3/hr) and Available pressure (m)									
Time step	N 1	N2	N 3	N 4	N 5	N 6	N 7	N 8	N 9	Total flow
1	4.26	18.17	20.78	24	40	17.26	12.79	41.82	30.38	209.46
	15.86	20.93	26.49	30.86	30.86	26.44	21.57	21.44	21.43	
2	33.82	99.66	120.00	40.84	68.17	100.00	91.07	266.61	192.22	1012.39
	17.01	22.04	31.33	17.02	17.04	30.27	27.62	25.11	24.94	
3	0.00	45.50	65.63	68.71	114.49	53.81	43.29	133.79	96.73	621.94
	13.79	19.24	27.64	28.76	28.75	27.26	23.20	22.26	22.18	
4	0.00	52.68	90.02	86.83	144.66	73.05	61.60	183.49	132.54	833.58
	12.51	18.27	28.32	27.46	27.45	27.67	24.24	22.65	22.52	

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612 Table 8 Total outflow from Modena network selected links isolation condition

Link ID	Pipe Diameter (mm)	Deficit nodes as per DDA	Total outflow LPS
11	100	1	406.9321
22	200	63	400.8348
50	150	26	404.3639
68	200	115	391.5420
100	150	57	390.9427
157	300	180	362.8878
158	300	182	361.7787
224	125	11	406.7551
242	125	14	405.1062
250	100	0	406.9399
291	350	245	277.6133
292	350	247	264.3850