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An assessment of the artificial modelling elements approach to the pressure-driven analysis of water distribution networks

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ABSTRACT

EPANET 2.2 is a newly introduced upgraded version of EPANET 2 that can be used for both pressure-driven analysis (PDA) and demand-driven analysis (DDA) of water distribution networks. Moreover, it has certain limitations concerning the minimum and required pressure head parameters used for PDA, which leads to inaccurate simulation results. Another limitation of the PDA option of EPANET 2.2 is its inability to simultaneously consider pressure-dependent demands with pressure-independent fire demands. In this article, the reason for the spurious convergence is identified, and it is shown that the spurious convergence of EPANET 2.2 can be addressed by extending the energy balance convergence criterion to include the virtual demand links employed in the EPANET 2.2 formulation of PDA. On the other hand, interest in the methods that use artificial modelling elements in EPANET 2 for PDA is increasing rapidly. The implementation of the method presented in this paper (termed the alternative PDA approach) allows an extended period simulation of large networks with complex demand patterns, multiple tanks, reservoirs, pumps, valves, and thousands of pipes. Two benchmark networks and two real-world networks were analysed by both the alternative PDA approach and EPANET 2.2 and the results were compared.

Key words: alternative pressure-driven analysis, EPANET 2.2, pressure-deficient network, simulation models, water distribution network

HIGHLIGHTS

- Spurious convergence of EPANET 2.2 is demonstrated and addressed.
- Differences in the characteristic pressures of pressure-dependent demands are accounted for fully.
- Integration of multiple demand types at a node is seamless.
- Advantages of the alternative pressure-dependent analysis method are demonstrated.
- Effectiveness on very large complex real-world systems is demonstrated clearly.

1. INTRODUCTION

EPANET 2 (Rossman 2000a) is one of the most popular hydraulic solvers available in the public domain for the demand-driven analysis (DDA) of the water distribution network (WDN) in which the demand at a node is assumed fully satisfied irrespective of the pressure head at that node. Many researchers tried to use it for the analysis of WDN under pressure-deficient conditions, where available nodal flows are related to available pressure, and therefore, demands could be supplied fully, partially, or not at all.

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A common way to use EPANET 2 for pressure-driven analysis (PDA) is by adding artificial elements to the demand nodes (DNs), such as flow control valves (FCVs), pressure-reducing valves, low resistance pipes with check valves (CVs), general-purpose valves, pressure-sustaining valves (PSVs), throttle control valves (TCVs), emitters, reservoirs, and tanks.

Some of the analysis methodologies based on artificial elements require iterative use of EPANET 2. Some are non-iterative in nature and, consequently, can be implemented using the graphical user interface (GUI) of EPANET 2. It is noted that other computationally highly efficient and robust advanced formulations are available in the literature, including the globally convergent Newton–Raphson method (Tanyimboh & Templeman 2010) and EPANET-PDX (pressure-dependent extension) (Siew & Tanyimboh 2012), which introduced a pressure-dependent nodal outflow function in the constitutive equations of EPANET 2.

Recently, a modified version of EPANET 2, EPANET 2.2 (Rossman *et al.* 2020) has been introduced to include PDA, which can be done using the GUI. However, EPANET 2.2 assumes that the characteristic pressures of pressure-driven outflows, $P_{\min}$ and P_{req}, are the same for all DNs. $P_{\min}$ is the pressure head below which the outflow at a demand node is zero while P_{req} is the pressure head above which the outflow at a demand node is the same as the demand. Moreover, EPANET 2.2 assumes that a node can have only one type of demand (Gorev *et al.* 2021), which is simplistic and unrealistic.

By contrast, in real-world networks, besides multiple demand types with their respective independent demand multipliers (Seyoum & Tanyimboh 2014), $P_{\min}$ and P_{req} may be different in different zones or at different nodes (Gupta & Bhave 1996). In addition, a particular pressure-dependent demand node may have to supply a fixed (pressure-independent) fire demand in certain circumstances (Wu *et al.* 2009). Therefore, in general, due to the complex nature of a network's topography, topology, and multiple demand types, EPANET 2.2 is not able to simulate pressure-deficient networks satisfactorily, thus yielding unrealistic results. Additionally, it is shown herein that its convergence can be spurious.

A similar analysis as in EPANET 2.2 was used in EPANET 2.0 with emitters by Pathirana (2010) for PDA. An identical required pressure head was assumed for all DNs irrespective of the nodal elevations and demands. The use of global parameters for the minimum and required pressure heads are seldom practical for analysing real-world networks having different nodal elevations and pressure head requirements. It is thus a serious limitation and should be addressed urgently (Muranho *et al.* 2020).

Chandapillai *et al.* (2012) and Jinesh Babu (2021) developed an alternative PDA approach in EPANET 2 and 2.2 in which the network was simulated using emitter functions only, without applying any additional artificial modelling elements in the DDA model of EPANET. The EPANET 2 toolkit functions (Rossman 2000b) were used to implement the simulations in a C^{++} software platform by Jinesh Babu (2021). When the pressure drops below $P_{\min}$ at any node, the node acts as a source node and starts supplying water to the network. This situation is not correct, self-evidently. Therefore, the hydraulic analysis was repeated with the emitter coefficients at those nodes set to zero. Thus, the approach requires additional runs and is, accordingly, iterative, computationally inefficient and cumbersome.

By contrast, Abdy Sayyed *et al.* (2015) placed an artificial CV before the emitter to prevent back flow and the PDA solution was achieved in a single run. Mahmoud *et al.* (2017) in their single-iteration PDA approach suggested placing strings of artificial elements only at pressure-deficient nodes so as to reduce the computational time. However, it requires an initial run of DDA to identify the pressure-deficient nodes and has a limitation in its application for extended period analysis, wherein pressure-deficient nodes may change at different periods (Gupta *et al.* 2018).

Sivakumar *et al.* (2020) used artificial elements to run PDA in a single run in the case where, in contrast to EPANET 2.2, the pressures $P_{\min}$ and P_{req} may be different at different nodes and a node may have a pressure-independent fire demand in addition to its pressure-dependent normal consumption demand. However, the artificial elements were added manually, which can hardly, if at all, be done for large networks with thousands of components and/or for complex demand patterns. This paper presents an implementation of the methodology of Sivakumar *et al.* (2020) that allows an extended period simulation (EPS) of large networks with complex demand patterns. The implementation is termed the alternative pressure-driven analysis (APDA) approach.

During the analysis of the example networks considered in this study, it was found that the PDA option of EPANET 2.2 may show spurious convergence. The paper formulates and demonstrates a way to avoid this.

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2. METHODOLOGY

2.1. Node head–flow relationship in EPANET 2.2 and an alternative PDA

Both in EPANET 2.2 and APDA, the following nodal outflow vs. nodal pressure relationship is used (Wagner *et al.* 1988):

$$q = \begin{cases} q_{req}, & P > P_{req} \quad \text{(required outflow)} \\ q_{req}\left(\dfrac{P - P_{\min}}{P_{req} - P_{\min}}\right)^{n}, & P_{\min} \le P \le P_{req} \quad \text{(partial outflow)} \\ 0, & P < P_{\min} \quad \text{(zero outflow)} \end{cases} \tag{1}$$

where q is the actual nodal outflow; q_{req} is the demand; P is the nodal pressure; n is the pressure exponent set equal to 0.5 for both APDA and EPANET 2.2 in this study.

In EPANET 2.2, the pressure-dependent demands (PDDs) are simulated as the flows in virtual links that connect each demand node to a virtual reservoir whose total head is equal to the demand node elevation plus the pressure $P_{\min}$. For the PDD virtual links, EPANET 2.2 uses the following head loss vs. flow relationship:

$$h_{Lj} = \begin{cases} R_{\text{high}} q_j, & q_j \le 0, \\ (P_{req} - P_{\min})\left(\dfrac{q_j}{q_{req}}\right)^{\alpha}, & 0 < q_j < q_{req}, \\ P_{req} - P_{\min} + R_{\text{high}}(q_j - q_{req}), & q_j \ge q_{req} \end{cases} \tag{2}$$

where h_Lj is the head loss across the virtual link connected to the node j, q_j is the virtual link flow (the available outflow at the node j), R_{high} is the large resistance factor (10^8), and α is the flow exponent.

The relationship (2) is an inverse of Wagner's equation (Wagner *et al.* 1988) modified to make it a function of q_j differentiable everywhere except for the points $q_j = 0$ and $q_j = q_{req}$, while virtually limiting q_j to the interval $[0, q_{req}]$. The flow exponent α is the reciprocal of the pressure exponent in Wagner's equation.

2.2. Alternative pressure-driven analysis using EPANET 2

Though EPANET 2.2 aims to improve the hydraulic simulation using PDA, assigning identical pressure heads $P_{\min}$ and P_{req} at all the nodes is unsound. By contrast, the APDA approach demonstrated extensively here simulates the WDNs with different $P_{\min}$ and P_{req} values at DNs according to the nodal elevations, demands and head loss requirement for any secondary network.

Here is the outline of the procedure. A string of artificial elements as shown in Figure 1 is connected to each of the DNs and the pressure-dependent outflow is found as the flow in the artificial string. The string consists of an artificial flow control valve (AFCV) with a setting equal to the demand q_{req}, a fictitious node (FN), an artificial pipe (AP) of negligible friction loss with a CV and an artificial reservoir (AR). The AFCV serves to implement the required-outflow portion of Wagner's relationship (2). To implement the zero-outflow portion, the AR total head is the sum of the elevation (E_{DN}) and minimum required pressure head ($P_{\min}$) of the demand node (reverse flow is prevented by the CV). The partial-outflow portion is implemented by choosing the AP minor loss coefficient.

Because the pressure-dependent outflow at a demand node is simulated as the flow in the artificial string, the demand appearing in the mass balance equation for that node is set equal to zero. However, if a node has a pressure-independent fire demand in addition to a pressure-dependent normal consumption one, the demand appearing in the mass balance equation is set equal to the fire demand. A pressure-dependent fire demand is simulated as another additional artificial string connected to the demand node.

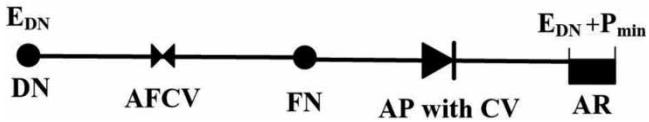

Figure 1 | Implementation of APDA using artificial modelling elements.

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Herein, the ability of APDA to consider different $P_{\min}$ and P_{req} properties at different nodes is illustrated further, aiming particularly to highlight the absence of this invaluable feature in EPANET 2.2.

In this study, the artificial elements were added to the data input (.inp) files of EPANET 2.0 using a simple MATLAB routine. The artificial elements added in such a way are displayed in the data browser window only without encumbering the network map. The artificial element addition and fire demand specification algorithm is as follows:

1. Add artificial elements to the network. To do this:
   - 1.1 Create an auxiliary file.
   - 1.2 In the first line of the auxiliary file, indicate the length, diameter and roughness of the artificial pipes.
   - 1.3 Add to the auxiliary file the content of the [JUNCTIONS] section of the original EPANET 2.0 input file.
   - 1.4 For each group of nodes with fixed P_{req} and $P_{\min}$, insert a line with those values of P_{req} and $P_{\min}$ just above that group.
   - 1.5 If a node has a pressure-dependent fire demand (regardless of whether its normal consumption base demand is zero or not), add at the beginning of its line an 'f' (to tell the MATLAB routine to generate an artificial string for the fire demand too) and the values of the fire demand pressures P_{req} and $P_{\min}$.
   - 1.6 Run the MATLAB routine to add artificial elements and generate a new input file.
2. Open the new input file and specify fire demands, if any. To do this, use the Demand Editor of the Property Editor for Junctions. Each fire demand must have a time pattern, whose identifier must begin with a 'd' for a pressure-dependent fire demand and with an 'i' for a pressure-independent one. This will tell the modified EPANET 2.0 used in APDA whether the fire demand is to be treated as an artificial string ('d') or used in the nodal mass balance equation as it is ('i').

A detailed description of the modified EPANET 2.0 is available in the Supplementary Information.

2.3. Extended period simulation

In an EPS, the AFCV settings and the AP minor loss coefficients must be varied according to the demand time pattern. In Sivakumar *et al.* (2020), the AP minor loss coefficients were specified as an EPANET 2.0 input parameter that cannot be varied in the course of the simulation (the dimensionless minor loss coefficient defined as the ratio of the minor head loss to the velocity head). Because of this, only demand multipliers equal to 1 and 0 were possible in EPS. Paez *et al.* (2018) used artificial throttle control valves (ATCVs) placed downstream of the AFCVs and specified the time dependence of the AFCV settings (the demands) and the ATCV settings (the loss coefficients) using EPANET 2 control statements. However, this increases the number of artificial elements and, in the case of large networks and/or complex demand patterns, can hardly be done manually, as a result of which the possibility of using the GUI would be of little, if any, advantage.

APDA uses an EPANET 2.0 code modified to vary the AFCV settings and the AP minor loss coefficients according to the demand pattern. From Equation (1) at $n = 0.5$, for the partial-outflow portion, we have:

$$P - P_{\min} = \frac{P_{req} - P_{\min}}{q_{req}^2} q^2 \tag{3}$$

In the partial-outflow portion, the AFCV is open, and thus the head at the FN (the AP start) is equal to the demand node head $P + E_{DN}$. Since the total head of the AR (the AP end) is $P_{\min} + E_{DN}$, the difference $P - P_{\min} = (P + E_{DN}) - (P_{\min} + E_{DN})$ on the left-hand side of Equation (3) is the difference between the heads at the AP start and end, which is equal to the AP head loss. Hence it follows from Equation (3) that to implement Wagner's relationship (2), the AP minor loss coefficient, i.e., the proportionality coefficient between the minor head loss and the squared flow, must be equal to $(P_{req} - P_{\min})/q_{req}^2$. The pressures $P_{\min}$ and P_{req} are not among the input parameters of EPANET 2.0. In its modified version used in APDA, the difference $P_{req} - P_{\min}$ appearing in the AP minor loss coefficient is specified as the elevation E_{FN} of the FN between the AFCV and the AP. This way to specify $P_{req} - P_{\min}$ as an input parameter is possible for the following reason. In EPANET 2, the elevations only serve to find the pressures from the computed heads, and thus, if a node is not an emitter or has no pressure-regulating devices connected to it its elevation does not matter.

At each time step of EPS, the modified EPANET 2.0 sets the AFCV settings to the current demands and computes the AP minor loss coefficients from the current demands and the differences $P_{req} - P_{\min}$ specified as the FN elevations. For each demand node, the output parameter 'actual demand' is the nodal outflow, i.e., the flow in the artificial string of the normal consumption demand plus the flow in the artificial string of the pressure-dependent fire demand, if any, or plus the pressure-independent fire demand, if any. A flowchart of the EPS algorithm of APDA is shown in Figure 2.

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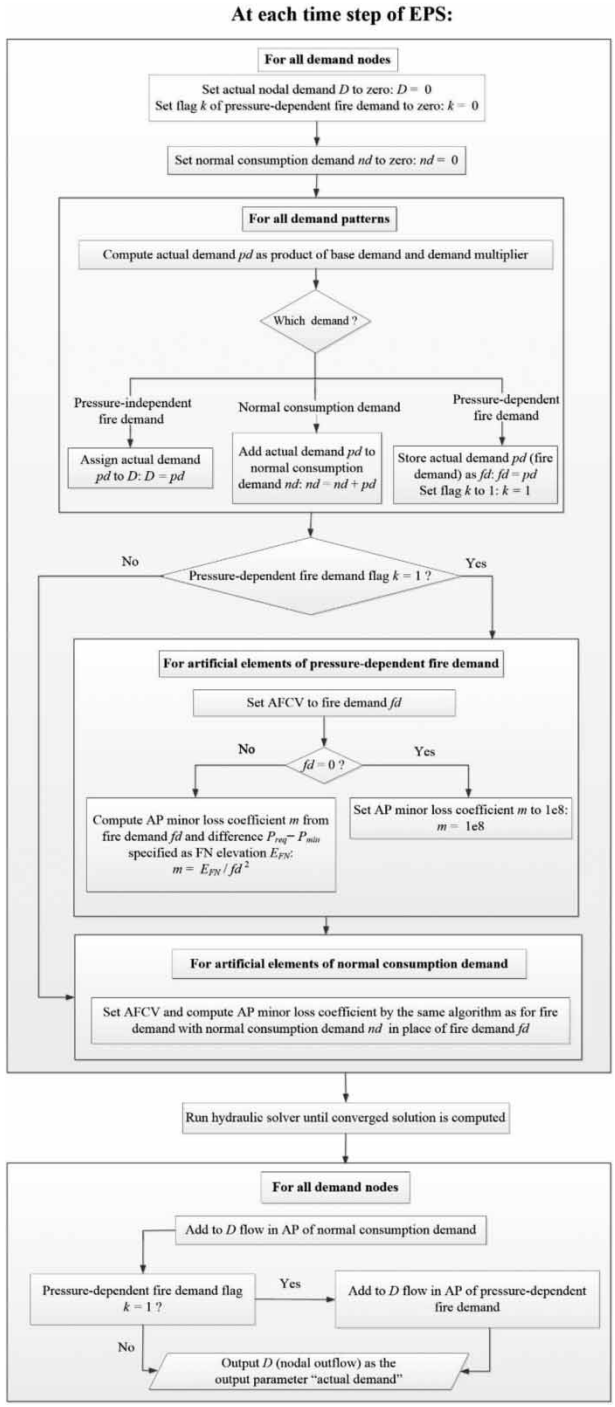

Figure 2 | Flowchart of the EPS algorithm of APDA.

2.4. Convergence criteria

EPANET 2.2 uses the following three criteria to determine when the iterations have converged to an acceptable solution:

(i) The relative change δ in the link flows, i.e., the sum of all link flow changes divided by the sum of all the flows in all links (both real and virtual), must be smaller than a specified dimensionless tolerance δ_{stop} as in the convergence criterion of EPANET 2.0.

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(ii) The maximum error $\Delta h_{\max}$ in satisfying the energy balance equation for all links (except for closed links and active pressure-reducing valves and PSVs) must be smaller than a specified tolerance h_{stop}.
(iii) The maximum flow change $\Delta q_{\max}$ among all links (both real and virtual) must be smaller than a specified tolerance q_{stop}.

EPANET 2.2 does not apply criterion (ii) to virtual demand links. As will be shown below, this may result in spurious convergence. This suggests that this criterion should be extended to virtual demand links too.

Reasoning similar to that in Section 2.3 Extended Period Simulation shows that the difference of the heads at the start and the end of the virtual link connected to node j is $P_j - P_{\min}$ where P_j is the pressure at node j. Because of this, the energy balance equation for the virtual link is:

$$P_j - P_{\min} = h_{Lj} \tag{4}$$

where h_{Lj} is the virtual link head loss given by Equation (2).

Clearly, it makes sense to check the satisfaction of Equation (4) only in the power function portion of the virtual link head loss vs. flow relationship (its two other portions are artificial, and their purpose is to allow the EPANET 2.2 hydraulic solver to be applied to virtual demand links too). Thus, criterion (ii) may be extended to virtual demand links as follows: for each virtual demand link where the computed pressure head and outflow meet the condition $P_{\min} \le P_j \le P_{req}$ and $0 \le q_j \le q_{req}$, the error in satisfying the energy balance equation, i.e., the difference of its left- and right-hand sides, must also be less than the tolerance h_{stop}. Thus:

$$\max\left|P_j - P_{\min} - (P_{req} - P_{\min})\left(\frac{q_j}{q_{req}}\right)^{\alpha}\right| \equiv \Delta h_{vir\max} < h_{stop}; \quad P_{\min} \le P_j \le P_{req}; \quad 0 \le q_j \le q_{req} \tag{5}$$

3. APPLICATION OF METHODOLOGY TO EXAMPLE NETWORKS

Four different networks have been considered: (1) to compare the PDA results of APDA with EPANET 2.2 in similar conditions; (2) to show that APDA can handle both pressure-dependent and pressure-independent demand in PDA, which EPANET 2.2 cannot; (3) to compare PDA results by APDA with those obtained with inappropriate use of EPANET 2.2 for PDA by considering same $P_{\min}$ and P_{req} instead of different $P_{\min}$ and P_{req} values at different nodes; (4) to show the effectiveness of APDA for PDA on large size networks with thousands of elements, multiple flow and pressure-regulating devices, pumps, tanks, reservoirs and EPS; and (5) to demonstrate spurious convergence in EPANET 2.2. All the networks were analysed on a laptop having a system configuration of 11th Gen Intel(R) Core (TM) i7-1165G7, 2.80 GHz processor with 16.0 GB RAM and 64-bit Windows 10. The EPSs were performed with a hydraulic time step of 1 h. The EPS was run for 12 or 24 h periods, wherever applicable. All the simulations were performed with a default accuracy of relative link flow change of 0.001 for APDA, except Case Study 4. The tolerances in relative link flow change, maximum head loss error and maximum link flow change, respectively, were 0.001, 0.001 m and 0.001 m^3/h for Case Studies 1A and 1B and 0.001, 0.001 m and 0.001 L/s for the other case studies. The computational, i.e., CPU, times to run all the simulations for all the case studies were less than 1 s unless otherwise specified.

3.1. Case study 1A

3.1.1. Spurious convergence of EPANET 2.2

Network 1 (Figure 3) has been used by many researchers (Gupta & Bhave 1996; Sivakumar & Prasad 2014) for validating their proposed methodology, especially for PDA. The network details are identical to Sivakumar *et al.* (2020) unless otherwise specified. The Hazen–Williams roughness coefficient of all pipes is 130. The hydraulic gradient level (HGL) of the supply node (SN) was varied here from 100 to 123.76 m to allow a comparison between the results of APDA and EPANET 2.2. The minimum pressure head $P_{\min}$ and required pressure head P_{req} for all DNs are 7 and 25 m, respectively.

The simulation results obtained by both methods are provided in Table 1. Assumed HGL at the SN is given in column 1, available heads and available outflows at DNs 1–4 are given in columns 2–5 and columns 6–9, respectively. Total outflow, percentage deficiency in meeting total demand, number of iterations and difference between APDA and EPANET 2.2 based on available outflow at DN_3 are given in columns 10–13, respectively. Both APDA and EPANET 2.2 results are provided side by side for easy comparison. The values given in parentheses are for EPANET 2.2.

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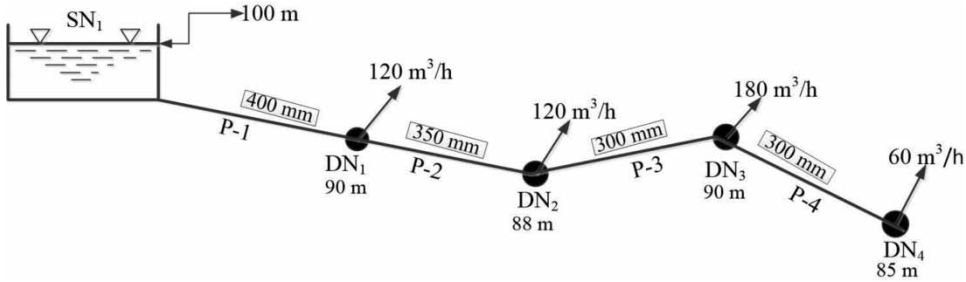

Figure 3 | Serial WDN of Case Study 1 (Gupta & Bhave 1996). *Note*: Additionally, a fire demand of 180 m^3/h is introduced at DN 4.

It can be observed from Table 1 that the available pressure head and available outflow at DNs gradually increase as source HGL increases from 100 to 123.76 m for APDA. Both APDA and EPANET 2.2 provided essentially identical results of available pressure head and available outflow with HGL of SN from 100 to 120 m.

However, it is interesting to discuss the results of EPANET 2.2 for outflows and available pressure heads when HGL at SN is increased from 120 to 120.1 m, and thereafter. Even by increasing the HGL at source from 120 to 120.1 m, an HGL drop is shown at all the DNs for EPANET 2.2, which obviously is not correct. Furthermore, EPANET 2.2 gives an outflow equal to the demand (i.e., 180 m^3/h) for node 3, whereas the available pressure head at node 3 is less than the required pressure head of 25 m. In fact, EPANET 2.2 showed that the demands of all the nodes are satisfied at an HGL of 120.1 m at the SN, even though a deficiency in pressure is observed at node 3. With a further increase in the HGL of SN from 120.10 to 123.75 m, EPANET 2.2 showed an increase in HGL at all the DNs. The pressure deficiency at node 3 decreased to 0 at the source HGL of 123.76 m.

Further, it is worth noting that the iteration count for APDA decreases from 5 to 2 for SN HGLs between 120.10 and 123.76 m whereas in EPANET 2.2 it is 2. The reason for only two iterations by EPANET 2.2 is that the demand at node 3 is considered satisfied even though there is a pressure head deficiency, when the HGL of SN is 120.10 m and above. In APDA, the iteration count reaches 2 only when all the demands and required pressures have been satisfied. It can be concluded from the obtained results that APDA follows the nodal outflows vs. nodal pressure head relationship correctly in all conditions. However, EPANET 2.2 did not.

Table 2 shows the relative link flow change for the whole network, the maximum head loss error for the pipes, the maximum link flow change and the maximum head loss error for the virtual demand links (the first three are used in the EPANET 2.2 convergence criteria) for the first five iterations, considering the total head at the reservoir as 120.10 m. As can be seen from Table 2, the spurious convergence of EPANET 2.2 at iteration 2 for δ_{stop} =0.001, h_{stop} =0.001 m and q_{stop} =0.001 m^3/h is avoided when criterion (ii) is extended to the virtual demand links as indicated above in the convergence criteria section. It can also be seen from Table 2 that with the extended criterion (ii), for the above-indicated values of δ_{stop}, h_{stop} and q_{stop} EPANET 2.2 produces an acceptable solution at iteration 5. In particular, the computed pressure and available outflow at node 3 are 22.076 m and 164.733 m^3/h, respectively, compared to 22.07 m and 164.77 m^3/h for APDA. For further analysis of the results of this case study and the other case studies, convergence criterion (ii) is also applied to virtual demand links to avoid spurious convergence and ensure the results achieved are accurate.

3.1.2. Comparison of APDA and EPANET 2.2 in the number of iterations

Subsequently, a fire demand of 180 m^3/h was added to the existing base demand of 60 m^3/h at DN_4 for 4 h from 04:00 to 08:00. The HGL of SN was set to 120 m. All the base and fire demands were simulated as PDDs. At all the DNs P_{min} and P_{req} were taken as 7 and 25 m, respectively. The total simulation period was 12 h. The available pressure heads at DNs 1–4 obtained during the fire demand were 26.35, 23.87, 16.44 and 19.30 m. The available outflows were, respectively, 120, 116.16, 130.32 and 198.44 m^3/h by APDA as well as EPANET 2.2. The actual outflow of 198.44 m^3/h at DN_4 represents the sum of the base and fire demand of 49.60 and 148.84 m^3/h, respectively. Though identical results are obtained by using both methods, APDA required only 25 iterations, while EPANET 2.2 required 52 iterations with convergence criterion (i) alone ($\delta_{stop} = 0.001$) and 65 iterations with all three convergence criteria ($\delta_{stop} = 0.001$, $h_{stop} = 0.001$ m and $q_{stop} =$ 0.001 m^3/h).

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Table 1 | Available nodal pressure heads and outflows of network 1 from APDA and EPANET 2.2

	Available pressure head at DNs (m)				Available outflow at DNs (m^3/h)							
HGL at SN (m)	DN_1	DN_2	DN_3	DN_4	DN_1	DN_2	DN_3	DN_4	Total outflow from SN (m^3/h)	Unserved demand (%)	Iterations	Difference in the node 3 outflow between APDA and EPANET 2.2
1	2	3	4	5	6	7	8	9	10	11	12	13
100.00	9.52 (9.52)	10.96 (10.96)	8.49 (8.50)	13.41 (13.41)	44.92 (44.91)	56.33 (56.32)	51.88 (51.88)	35.80 (35.79)	188.94 (188.90)	60.64 (60.65)	7 (7)	0.00
105.00	13.94 (13.94)	14.78 (14.78)	11.72 (11.72)	16.59 (16.59)	75.55 (74.53)	78.90 (78.88)	92.18 (92.17)	43.80 (43.79)	289.43 (289.37)	39.70 (39.71)	6 (6)	0.01
110.00	18.39 (18.39)	18.64 (18.64)	15.03 (15.03)	19.86 (19.86)	95.50 (95.47)	96.54 (96.52)	120.23 (120.20)	50.72 (50.71)	362.98 (362.90)	24.38 (24.40)	6 (5)	0.02
115.00	22.86 (22.86)	22.54 (22.54)	18.37 (18.37)	23.16 (23.16)	112.66 (112.63)	111.52 (111.49)	143.11 (143.09)	56.87 (56.86)	424.16 (424.07)	11.63 (11.65)	5 (5)	0.01
120.00	27.46 (27.46)	26.67 (26.67)	21.99 (22.00)	26.76 (26.76)	120 (120)	120 (120)	164.34 (164.30)	60 (60)	464.34 (464.30)	3.26 (3.27)	5 (5)	0.02
120.10	27.56 (27.40)	26.76 (26.37)	22.07 (21.34)	26.84 (26.11)	120 (120)	120 (120)	164.77 (180.00)	60 (60)	464.77 (480.00)	3.17 (0)	5 (2)	9.24
120.20	27.66 (27.50)	26.85 (26.47)	22.15 (21.44)	26.92 (26.21)	120 (120)	120 (120)	165.20 (180.00)	60 (60)	465.20 (480.00)	3.08 (0)	5 (2)	8.96
120.30	27.75 (27.60)	26.94 (26.57)	22.23 (21.54)	27.00 (26.31)	120 (120)	120 (120)	165.64 (180.00)	60 (60)	465.64 (480.00)	2.99 (0)	5 (2)	8.67
120.40	27.85 (27.70)	27.03 (26.67)	22.31 (21.64)	27.08 (26.41)	120 (120)	120 (120)	166.07 (180.00)	60 (60)	466.07 (480.00)	2.90 (0)	5 (2)	8.39
120.50	27.94 (27.80)	27.12 (26.77)	22.39 (21.74)	27.16 (26.51)	120 (120)	120 (120)	166.50 (180.00)	60 (60)	466.50 (480.00)	2.81 (0)	5 (2)	8.11
121.00	28.42 (28.30)	27.56 (27.27)	22.79 (22.24)	27.56 (27.01)	120 (120)	120 (120)	168.64 (180.00)	60 (60)	468.64 (480.00)	2.37 (0)	4 (2)	6.74
121.50	28.90 (28.80)	28.01 (27.77)	23.19 (22.74)	27.96 (27.51)	120 (120)	120 (120)	170.75 (180.00)	60 (60)	470.75 (480.00)	1.93 (0)	4 (2)	5.42
122.00	29.38 (29.30)	28.46 (28.27)	23.59 (23.24)	28.36 (28.01)	120 (120)	120 (120)	172.84 (180.00)	60 (60)	472.84 (480.00)	1.49 (0)	4 (2)	4.14
122.50	29.86 (29.80)	28.90 (28.77)	23.99 (23.74)	28.75 (28.51)	120 (120)	120 (120)	174.91 (180.00)	60 (60)	474.91 (480.00)	1.06 (0)	4 (2)	2.91
123.00	30.34 (30.30)	29.35 (29.27)	24.39 (24.24)	29.15 (29.01)	120 (120)	120 (120)	176.96 (180.00)	60 (60)	476.96 (480.00)	0.63 (0)	4 (2)	1.72
123.50	30.81 (30.80)	29.80 (29.77)	24.79 (24.74)	29.56 (29.51)	120 (120)	120 (120)	178.99 (180.00)	60 (60)	478.99 (480.00)	0.21 (0)	4 (2)	0.56
123.75	31.05 (31.05)	30.02 (30.02)	24.99 (24.99)	29.76 (29.76)	120 (120)	120 (120)	179.99 (180.00)	60 (60)	479.99 (480.00)	0.0021 (0)	3 (2)	0.01
123.76	31.06 (31.06)	30.03 (30.03)	25.00 (25.00)	29.77 (29.77)	120 (120)	120 (120)	180.00 (180.00)	60 (60)	480.00 (480.00)	0 (0)	2 (2)	0.00

Note: Values within bracket are obtained from EPANET 2.2.

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Table 2 | Case study 1A: errors at the first five iterations of EPANET 2. 2 for a reservoir total head of 120.10 m

	EPANET 2.2 convergence indicators			
Iteration number	**δ**	**Δh_{max} (m)**	**Δq_{max} (m^3/h)**	**$\Delta h_{vir\ max}$ (m)**
1	0.479347	–[a]	–[a]	–[b]
2	0.00000	0.0000	0.0000	3.662
3	0.037617	–[a]	–[a]	0.12
4	0.001496	–[a]	–[a]	1.9e-4
5	2e-6	0.0000	0.0009	2.6e-5

[a]Not indicated in the full status report of EPANET 2.2 (Δh_{max} and Δq_{max} are indicated only if the EPANET 2.2 main convergence criterion is met, i.e., if $\delta < \delta_{stop}$).
[b]The condition $P_{min} \le P_j \le P_{req}$ and $0 \le q_j \le q_{req}$ is not met for any virtual link.

3.1.3. Non-uniform P_{min} and P_{req} values and multiple demand categories

As discussed earlier in the introduction, networks with different P_{min} and P_{req} values cannot be simulated accurately by EPANET 2.2. Moreover, a pressure-independent demand at a node with a pressure-dependent one cannot be simulated by EPANET 2.2. APDA can handle all the combinations. Two cases are now being considered. In the first case (Case 1), all the network parameters, including fire demand are the same as in the preceding example, except that P_{req} at DN_3 is 20 m instead of 25 m (Sivakumar *et al.* 2020). However, in Case 2, P_{req} is assumed to be 25 m for all DNs and fire demands. Further, the fire demand is considered as pressure-independent and the base demand as pressure-dependent. The obtained results of PDA for Case 1 are compared with the results of Case 2. The results obtained for available pressure heads and outflows at DNs 1–4 for the two cases are given in Table 3. The following can be noted from the results:

(1) DNs 2–4 showed a partial supply due to the shortfall in the required pressure head in both cases.
(2) The pressure-independent fire demand is fully met. The shortfall in the required pressure affected the supply of base demand in both cases.
(3) Available flows are observed to decrease from 136.68 to 122.13 m^3/h at node 3, where the required pressure is increased from 20 to 25 m.
(4) The total supply from the source has also decreased.

The differences in the results achieved by APDA are substantial even for this small network with a small variation of the values at a single demand node.

3.2. Case study 1B

3.2.1. EPS of serial WDN

Now, the nodal demands are varied with respect to different time periods. Four variable demand factors were assumed for modelling purposes as 0.2, 1.0, 0.6 and 0.8 each of 6 h duration for the time periods from 00:00 to 06:00, 06:00 to 12:00, 12:00 to 18:00 and 18:00 to 24:00 h, respectively. Considering the demand factors, the demands of each time period for nodes 1–4 are shown in columns 2–5 of Table 4. The HGL of SN is taken as 100 m and P_{min} and P_{req} for all the nodes are 7 and 25 m, respectively. The available outflows for four time periods obtained from APDA and EPANET 2.2 for nodes 1–4 are the same and given in Table 4.

Table 3 | Available outflows during the fire demand period when fire demand is pressure-independent and base demand is pressure-dependent of case study 1A

Node no.	Minimum pressure head (m)	Required pressure head (m)	Available pressure head (m)	Available outflow (m^3/h)	Available fire flow (m^3/h)
1	7* (7)	25* (25)	26.00* (26.14)	120.00* (120.00)	–
2	7* (7)	25* (25)	22.95* (23.32)	113.00* (114.30)	–
3	7* (7)	20* (25)	14.49* (15.28)	136.68* (122.13)	–
4	7* (7)	25* (25)	16.82* (17.57)	44.32* (45.99)	180* (180)

Note: Values in asterisk (*) and within bracket () are for Cases 1 and 2, respectively.

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Also, the available outflows for the above nodes are given in Table 4 for P_{req} at DN_3 as 20 m while the rest of the nodes are 25 m. As can be seen from the results presented in Table 4, the available outflows are reduced at DN_3 when the required pressure head at that node is considered 25 m instead of 20 m. These results demonstrate that the inappropriate application of identical P_{min} and P_{req} values for all the DNs in EPANET 2.2 leads to inaccurate results.

Furthermore, a fire demand of 180 m^3/h is introduced at DN_4 in addition to its base demand for 24 h to identify the pressure-deficient nodes during the four time periods. Assume the HGL of SN is 119 m and the pressure head P_{min} is 7 m for all nodes and P_{req} is 25 m for nodes 1, 2 and 4 and 20 m for node 3. When fire demand is independent of pressure head (i.e., fire demand is constant for 24 h), observe the pressure-deficient nodes with available outflow as shown in Figure 4(a). Similarly, Figure 4(b) shows the results for pressure-dependent fire demand. Further, the available fire flow at DN_4 is 180, 142.55, 163.32 and 152.53 m^3/h for the first, second, third and fourth periods, respectively. The available fire flow depends on the demand factors of the base demand. It is observed from the results that the nodal base demand satisfaction is slightly more when fire demand is pressure-dependent compared to pressure-independent. Thus, the APDA methodology is flexible and allows unequal values of the minimum and required pressure heads at various DNs when necessary, considering both constant and variable demand patterns.

3.3. Case study 2: Two-source branched WDN

A real-world two-source branched WDN (Figure 5) is considered next. Itanagar WDN is specifically adopted for the present analysis due to the topography of the nodal elevations. The nodal and link details regarding elevation, demand, lengths and diameters of pipes and other parameters of WDN elements are briefly described in Sivakumar & Prasad (2014, 2015) to which the reader may refer for the details.

The simulations especially focused on Zone III where nodes are situated at different elevations. DNs 42 and 37 have the highest and lowest elevations of 390.705 and 242.60 m, respectively. All the DNs are lumped DNs, where the demands of several consumers are combined. P_{req} is 30 and P_{min} is 12 m for all nodes. The analysis is performed first in EPANET 2.2. The elevations and base demands of DNs of Zone III are shown in Table 5.

All DNs of Zone III except node 42 obtained the demands with the available pressure heads of 92.34, 156.65, 102.63, 107.53, 158.19, 164.25, 109.30 and 75.26 m for the nodes 27, 28, 30, 34, 36, 37, 39 and 41, respectively, by EPANET 2.2. Node 42 received a partial demand satisfaction of 7.29 L/s with an available pressure head of 22.32 m. The required iterations are only seven for the snapshot simulation for EPANET 2.2.

Table 4 | Results of APDA for variable demand pattern of case study 1B

	Demand (m^3/h) at nodes			
Time period (h)	**DN_1**	**DN_2**	**DN_3**	**DN_4**
(1)	(2)	(3)	(4)	(5)
00:00 to 06:00	24	24	36	12
06:00 to 12:00	120	120	180	60
12:00 to 18:00	72	72	108	36
18:00 to 24:00	96	96	144	48
	Available outflow (m^3/h) when $P_{min} = 7$ m and $P_{req} = 25$ m for all nodes by APDA and EPANET 2.2			
00:00 to 06:00	9.75	12.56	14.43	7.94
06:00 to 12:00	44.92	56.33	51.88	35.80
12:00 to 18:00	28.28	36.04	38.33	22.82
18:00 to 24:00	36.84	46.59	46.50	29.54
	When $P_{min} = 7$ m for all nodes and $P_{req} = 20$ m for node 3 and 25 m for the rest of the nodes by APDA			
00:00 to 06:00	9.74	12.55	16.93	7.94
06:00 to 12:00	44.69	55.86	58.35	35.44
12:00 to 18:00	28.19	35.85	44.19	22.67
18:00 to 24:00	36.68	46.25	59.28	29.29

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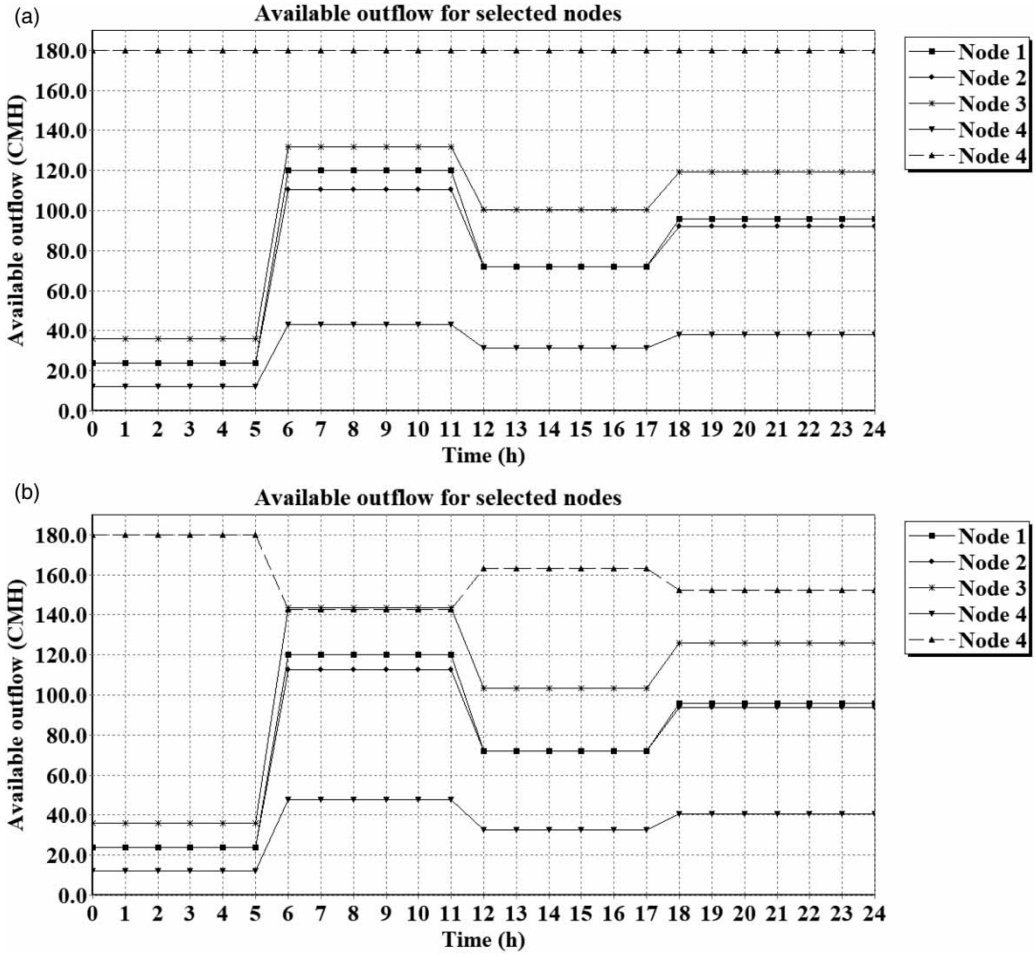

Figure 4 | Available outflow for selected nodes of Case Study 1B (a) when fire demand does not depend on pressure and (b) when fire demand is pressure-dependent. *Note:* CMH in ordinate represents m^3/h; legend of node 4 shows the available outflow and fire demand, respectively.

Then, APDA is carried out considering the P_{req} and $P_{\min}$ are taken as 12 and 7 m for node 42; and 30 and 12 m for the remaining nodes (Sivakumar *et al.* 2020) respectively. By contrast, for APDA, the outflow at node 42 is observed to be fully met. The required iterations are only six for the snapshot simulation for APDA.

Next, a case of fire demand is considered. Here, node 42 is considered a critical node due to its location and demand (Sivakumar & Prasad 2015; Sivakumar *et al.* 2020). A fire demand of 10 L/s is required in addition to its base demand of 9.624 L/s for 4 h from 04:00 to 08:00. During the fire demand simulations, link 52 is kept open because the total demand increases when a fire demand is added at any node of Zone III.

Table 5 shows the effect of fire demand at node 42 when simulated by two kinds of pressure conditions, i.e., pressure-independent and pressure-dependent. It is observed from the results that all nodes obtained the demand fully except node 42. When fire demand is simulated in pressure-independent condition, node 42 draws 10 L/s irrespective of the pressure head but the nodal base demand is not satisfied (i.e., 0.758 L/s). Both demands are partially supplied when fire demand depends on pressure.

3.4. Case study 3: Gittikhadan Zone of Nagpur WDN

Another real-world single source combined branched and looped pipe network system has been considered, as shown in Figure 6. Gittikhadan Zone of Nagpur WDN has a SN with an HGL of 335.84 m and the network comprises 141 DNs whose elevations range between 295.5 and 320 m with base demands between 0.2 and 29.913 L/s, 179 pipes and 38

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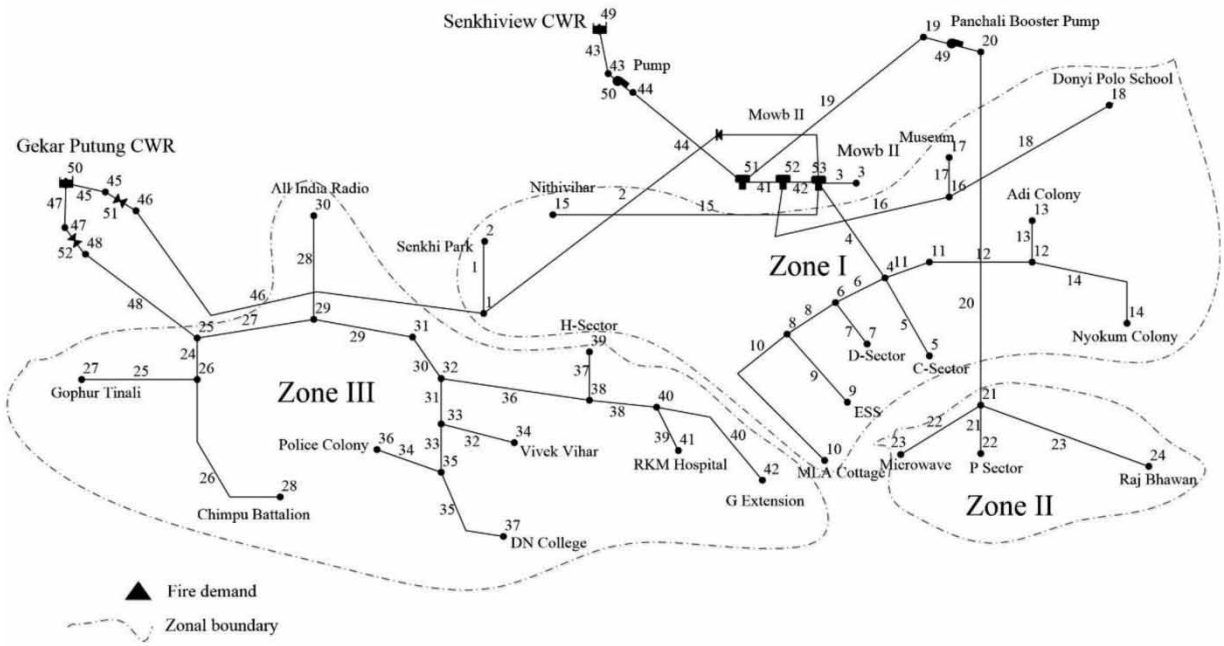

Figure 5 | Two-source Itanagar WDN (Sivakumar & Prasad 2014).

Table 5 | The available pressure heads and actual outflows at DNs of Itanagar WDN with a fire demand of 10 L/s at node 42

				Available pressure head and actual outflow			
				Pressure-independent		Pressure-dependent	
Zone	Node no.	Elevation (m)	Nodal base demand (L/s)	Head (m)	Flow (L/s)	Head (m)	Flow (L/s)
III	27	328.870	7.990	80.261	7.990	81.349	7.990
	28	258.260	4.154	144.574	4.154	145.662	4.154
	30	316.775	5.012	89.617	5.012	90.791	5.012
	34	297.220	5.895	93.324	5.895	94.607	5.895
	36	253.530	3.834	143.978	3.834	145.261	3.834
	37	242.600	4.205	150.043	4.205	151.325	4.205
	39	304.260	3.030	94.474	3.030	95.814	3.030
	41	338.000	8.254	60.305	8.254	61.658	8.254
	42	390.705	9.624	7.031	**0.758** (10)	8.418	**5.127** (5.327)

Note: Values in bold and parentheses represent partial-flow and available fire flow, respectively.

loops. The Hazen–Williams coefficient values of all the pipes are 130. The node and link details can be seen in Gupta & Bhave (2007).

The network is divided into four zones. Zone I consists of DNs 2–15; Zone II has DNs 16–54, 81, 115–140 and 142; Zone III has DNs 82–113 and 141; and Zone IV has DNs 55–80 and 114. The minimum residual (service) pressures of 7.0, 12.0 and 17.0 m are required at ferrule points for supply to one, two and three-storey buildings, respectively, as stated in the Manual on Water Supply and Treatment (CPHEEO 1999), India. All four zones are simulated by APDA with their respective $P_{\min}$ and P_{req} values. Zone I has several types of buildings, i.e., one, two, three and higher-storied buildings, in which some of the consumers will take water in sumps. Therefore, $P_{\min}$ and P_{req} values are taken as 2 and 22 m, respectively. Zone II consists of single-storey buildings having $P_{\min}$ and P_{req} as 7 and 10 m, respectively. Zone III is mixed, with single and double-storied buildings having $P_{\min}$ and P_{req} values as 7 and 15 m, respectively; and Zone IV consists of mixed single, double and three-storied buildings with $P_{\min}$ and P_{req} values as 7 and 20 m, respectively.

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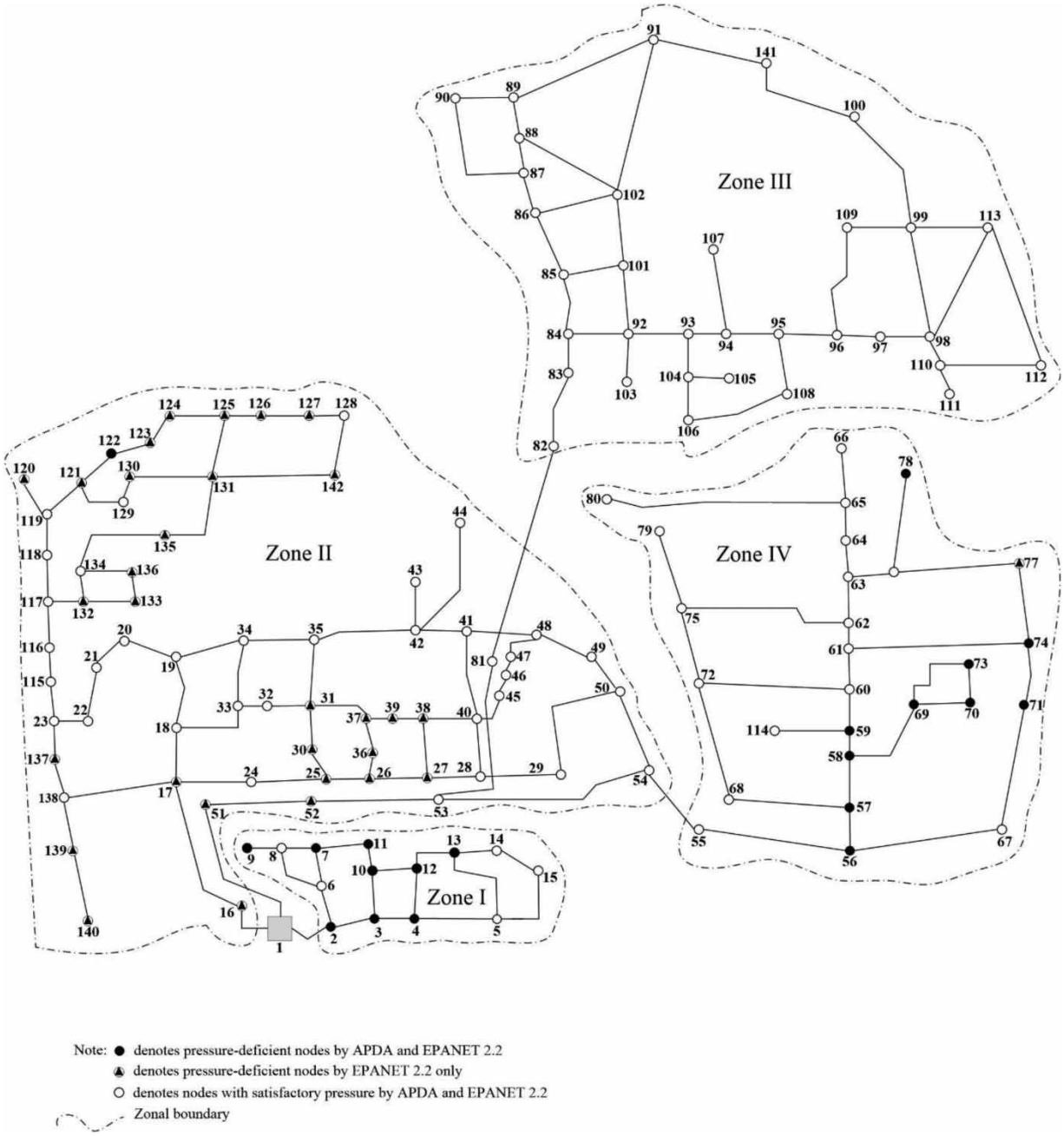

Figure 6 | The pressure-deficient nodes of the Gittikhadan Zone of Nagpur WDN by APDA and EPANET 2.2.

The obtained results are illustrated in Figure 6. The required iterations were 8 and 6 by APDA and EPANET 2.2, respectively. The available pressure heads and nodal outflows at all DNs are given in Supplementary material, Table S1. Out of 141 nodes, 19 nodes are observed as pressure-deficient by APDA. There are 9 (nine) pressure-deficient nodes in Zone I; 1 (one) in Zone II; and 9 (nine) in Zone IV.

EPANET 2.2 was used to simulate the network with $P_{\min}$ and P_{req} values as 2 and 22 m, respectively, in all four zones as it cannot handle different values for individual zones and nodes. The EPANET 2.2 simulation showed 50 nodes as pressure-deficient compared to 19 for APDA. For EPANET 2.2, there are 9 pressure-deficient nodes in Zone I; 31 in Zone II; and 10 in Zone IV. Zone III is observed to meet demands fully by both EPANET 2.2 and APDA.

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3.5. Case study 4: BSWN network 2

To verify APDA for much larger networks, with thousands of nodes and links, a large public-domain network, BSWN Network 2, was considered. The network has 12,523 nodes, including 10,552 DNs, two reservoirs, two tanks, 14,822 pipes, four pumps, four FCVs and one PSV. For the problem to be a PDA problem rather than a DDA one, all demands were multiplied by a factor of five as in Elhay *et al.* (2016). To demonstrate further the efficacy and practical utility of APDA, unlike Elhay *et al.* (2016), all valves, pumps and variable demand patterns were retained. To compare APDA and EPANET 2.2, the latter was run with the convergence criterion (i) alone (the common criterion of EPANET 2.2 and 2.0); both APDA and EPANET 2.2 were run with $\delta_{\text{stop}} = 0.00001$ (the minimum allowed stopping tolerance in EPANET 2).

A 24-h EPS was run by considering $P_{\min} = 7$ m and $P_{req} = 25$ m for all the DNs. The results are presented in Table 6, which shows the number of iterations, the number of pressure-deficient nodes and the relative demand deficit, i.e., the sum of the demand deficits at the pressure-deficient nodes divided by the sum of the demands at those nodes. As can be seen from the table, the results for EPANET 2.2 and APDA are essentially identical. The FCV VALVE-14826 was changed by timer control

Table 6 | BSWN network 2: EPS results for EPANET 2.2 and APDA

	EPANET 2.2			APDA		
Time (h:min:s)	Iterations	Number of pressure-deficient nodes	Relative demand deficit (%)	Iterations	Number of pressure-deficient nodes	Relative demand deficit (%)
0:00:00	9	5,578	35.93	36	5,578	35.93
1:00:00	8	3,462	38.76	43	3,462	38.76
1:07:59[a]	–	–	–	18	3,111	39.20
1:08:00[b]	7	3,111	39.20	–	–	–
2:00:00	7	3,804	38.12	15	3,804	38.12
3:00:00	8	5,729	35.64	7	5,729	35.64
4:00:00	10	7,976	35.98	27	7,976	35.98
5:00:00	12	9,737	43.69	8	9,737	43.69
6:00:00	23	10,011	50.27	9	10,011	50.27
7:00:00	39	9,936	48.05	58	9,936	48.05
8:00:00	53	9,742	43.86	88	9,742	43.86
9:00:00	12	9,748	43.97	4	9,748	43.97
10:00:00	12	9,644	42.74	37	9,644	42.74
11:00:00	12	9,606	42.26	34	9,606	42.26
12:00:00	28	8,785	37.86	59	8,785	37.86
13:00:00	10	8,395	36.55	30	8,395	36.55
14:00:00	10	8,534	37.15	4	8,534	37.15
15:00:00	9	8,725	37.77	6	8,725	37.77
16:00:00	10	9,229	40.04	8	9,229	40.05
17:00:00	11	9,838	45.43	8	9,838	45.43
18:00:00	45	9,911	48.77	9	9,911	48.77
19:00:00	42	9,996	52.18	9	9,996	52.18
20:00:00	25	9,955	51.35	29	9,955	51.35
21:00:00	12	9,782	45.16	80	9,782	45.16
22:00:00	10	9,180	39.87	52	9,180	39.87
23:00:00	8	5,877	36.11	72	5,877	36.11
24:00:00	9	4,953	36.03	22	4,953	36.03

[a]FCV VALVE-14826 changed by timer control (APDA).
[b]FCV VALVE-14826 changed by timer control (EPANET 2.2).

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at 1:08:00 for EPANET 2.2 and at 1:07:59 for APDA, and the relative demand deficit at 16:00:00 was 40.04% for EPANET 2.2 and 40.05% for APDA. Thus, the results are essentially the same. The total number of iterations and the CPU time were 772 and 5 s for APDA and 441 and 2 s for EPANET 2.2. It is worth emphasising, though, that APDA is intended primarily for cases where EPANET 2.2 is inapplicable. In particular, EPANET 2.2 cannot simulate networks where nodes have both a pressure-dependent and a pressure-independent outflow. To simulate this situation, a 24 h EPS was also run for a fixed fire demand (pressure-independent outflow) of 15 L/s at JUNCTION-39 from hour 0 to 1, JUNCTION-5435 from hour 6 to 7, JUNCTION-2922 from hour 10 to 11, and JUNCTION-9012 from hour 15 to 16 in addition to their normal consumption demands. For all four fire demand simulations combined, the APDA total number of iterations and CPU time were 857 and 5 s, respectively.

As a result of the fire demand at JUNCTION-39, the pressure at that node decreases from 25.493 to 23.858 m, i.e., the node becomes pressure-deficient ($P_{req} = 25$ m), and its normal consumption outflow decreases from 0.720 to 0.697 L/s. With the fire demand at the node, the number of pressure-deficient nodes increases from 5,578 to 5,633, but the relative demand deficit slightly decreases from 35.93 to 35.92%. This decrease is due to the fact that the denominator (the sum of the demands at the pressure-deficient nodes) increases more than the numerator (the sum of the demand deficits): the former increases from 3,208.88 to 3,236.63 L/s, while the latter increases from 1,152.90 to 1,162.58 L/s.

With the fire demand at JUNCTION-5435, the pressure at that node decreases from 28.179 m to 25.601 m, i.e., remains higher than P_{req} and thus its normal consumption outflow remains unchanged (1.412 L/s). The number of pressure-deficient nodes increases from 10,011 to 10,017 and the relative demand deficit increases from 50.27 to 50.35%.

With the fire demand at JUNCTION-2922, the pressure at that node decreases from 17.202 to 15.704 m (both lower than P_{req}) and the normal consumption outflow decreases from 0.547 to 0.505 L/s. The number of pressure-deficient nodes increases from 9,644 to 9,654 and the relative demand deficit increases from 42.74 to 42.91%.

With the fire demand at JUNCTION-9012, the pressures at that node both without and with the fire demand (26.431 and 25.811 m, respectively) are higher than P_{req}, and thus its normal consumption outflow does not change (0.290 L/s). The number of pressure-deficient nodes increases from 8,725 to 8,766, and the relative demand deficit increases from 37.78 to 37.87%.

This case study demonstrates the efficacy of APDA in an EPS of large networks with thousands of nodes and links and, as discussed earlier, artificial elements are easy to add for networks of any size. Moreover, the CPU times for all the examples of the BSWN network considered were not greater than 5 s.

4. DISCUSSION AND CONCLUSIONS

As demonstrated by Case Study 1A, the PDA option of EPANET 2.2 may show spurious convergence even though EPANET 2.2 has two optional convergence criteria in addition to the convergence criterion of EPANET 2.0. This may be remedied by extending the optional convergence criterion based on the error in satisfying the energy balance equations to virtual demand links for which the computed head loss and flow lie in the power function portion of the head loss vs. flow relationship.

It is observed from the study that APDA is more flexible compared to the PDA option of EPANET 2.2. Moreover, APDA requires only one run or execution of EPANET 2. EPANET 2.2 is not capable of carrying out PDA for WDNs in which the minimum and required pressure heads at different nodes are different due to differences in elevation and losses in secondary networks. Also, EPANET 2.2 cannot consider pressure-dependent and pressure-independent demands simultaneously. Though the APDA approach has many advantages over EPANET 2.2, it has a limitation of increasing the size of the network due to the inclusion of a string of artificial elements at each demand node. Also, the results show it is effective even on large networks with multiple reservoirs, tanks, pumps, flow and pressure control valves, thousands of pipes, and multiple demand types at the same node and EPS. It is thus anticipated that additional improvements of PDA in EPANET 2.2 will be undertaken to overcome the weaknesses discussed in this article.

AUTHOR CONTRIBUTIONS

P.S. and N.B.G conceptualised the study; P.S. and N.B.G. developed the methodology; N.B.G did software analysis; P.S., N.B.G., S.N., C.R.S, R.G. and T.T.T did formal analysis. All authors supervised the study, wrote, reviewed and did editing; P.S. and N.B.G wrote the original draft. All authors have read and agreed to the published version of the manuscript.

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DATA SUPPORTING

All data are illustrated in the manuscript.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information, including a detailed description of the modified EPANET 2.0. The modified EPANET 2.0 (including the MATLAB routine to prepare an input file with artificial elements) is available from the corresponding author upon request.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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