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Method for Extended Period Simulation of Water Distribution Networks with Pressure Driven Demands

D. Paez[1] · **C. R. Suribabu**[2] · **Y. Filion**[1]

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Abstract This paper proposes a non-iterative method to perform the simulation of water distribution systems with pressure driven demands using EPANET2 without the need to use its programmer's toolkit. The method works for single period simulation (snapshot) and for extended period simulation (EPS) as well. It is based on the addition of a flow control valve (FCV), a throttle control valve (TCV), a check valve (CV) and a reservoir to each demand node in the network, in addition to a list of simple controls to modify the setting of the FCV and TCV in each time step. The main advantages of this approach are: 1. the source code of EPANET2 is not modified, 2. the toolkit functions are not needed for the simulation and they remain available for further uses, 3. the extended period simulation (EPS) is performed by EPANET2 and it carries tank levels, demand variation and other time-changing variables internally. The performance of the method is tested in two benchmark networks and a real size network with pumps, tanks and a 24 h demand pattern. The results show that the method computed the pressures and outflows accurately and that the computational time required is not significantly higher than a demand driven execution in most cases.

Keywords Pressure driven demand · EPANET · Non iterative · Control valves

1 Introduction

There are two main approaches to simulate the hydraulic behaviour of a Water Distribution Network (WDN): Demand Driven Analysis (DDA) and Pressure Driven Analysis (PDA). DDA assumes that the demand on each node is always satisfied independent of the hydraulic conditions of the network, which are actually the outputs to be calculated. This approach is

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✉ D. Paez
da.paez270@gmail.com

[1] Department of Civil Engineering, Queen's University, Kingston, ON, Canada

[2] Centre for Advanced Research in Environment, School of Civil Engineering, SASTRA University, Thanjavur, India

acceptable when the resulting pressures in the nodes are sufficient to deliver the demanded volume of water through the internal pipe system of the building and its water appliances. The most accepted method to make a DDA is using the global gradient algorithm proposed by Todini and Pilati (1988) and its implementation in EPANET 2 by Rossman (2000).

However, if the resulting pressures p are not sufficient, the demands Q_D are not fully supplied and only some flow Q is delivered. To model this partial supply, different authors have proposed different curves that relate p with Q (Bhave 1981; Germanopoulos 1985; Wagner et al. 1988; Fujiwara and Li 1998; Tanyimboh and Templeman 2010). From these relationships, the most established in the research literature is the one proposed by Wagner et al. (1988) (Eq. 1). They assign a potential relationship (with exponent n) between the pressure and the outflow, for any p between zero and the pressure required to ensure full supply of the demand (p_{req}). Experimental data from Shirzad et al. (2012) and Walski et al. (2017) show the validity of this function to model nodal demands under critical pressures.

$$\begin{array}{lll} & \text{Wagner's Relationship} & \text{Proposed implementation method} \\ Q= & \begin{cases} 0 & \textit{if } p\le 0 \\ Q_D\left(\dfrac{p}{p_{req}}\right)^n & \textit{if } 0<p\le p_{req} \\ Q_D & p>p_{req} \end{cases} & \begin{array}{l} \rightarrow\text{enforced by a Check Valve} \\ \rightarrow\text{enforced by a Throttle Control Valve} \\ \rightarrow\text{enforced by a Flow Control Valve} \end{array} \end{array} \tag{1}$$

To solve the PDA model of a WDN considering the flow-pressure relationship, three types of approaches have been proposed: 1. modifying the source code of the DDA simulator (typically EPANET2), 2. adding iteratively artificial elements to the nodes according to previous results using DDA, and 3. adding artificial elements to all demand nodes in the DDA model. Mahmoud et al. (2017) reviews the most important methodologies that follow the first approach (Cheung et al. 2005; Liu and Yu 2011; Giustolisi et al. 2011; and Siew and Tanyimboh 2012; among others) and identify five limitations that they can have: 1. Require underlying algorithm modifications, 2. Not in the public domain, 3. Require several iterations, 4. Demonstrated only on limited simple case studies, and 5. Unable to handle EPS analysis.

The second category of methods is based on adding artificial elements to the model as flow control valves (FCV), check valves (CV), pressure reducing valves (PRV), general purpose valves (GPV), emitters (E) or reservoirs (R). These methods add and remove if necessary their proposed artificial elements to the DDA model in each iteration until convergence (Ang and Jowitt 2006; Todini 2006; Suribabu and Neelakantan 2011; Mahmoud et al. 2017). However, the drawback of these methods is they may require many iterations in large networks and its implementation for EPS is complicated as the topology of the network must be changed in each time step.

The third category of methods, instead, add artificial elements to all demand nodes so the topology does not need to be modified iteratively. They include adding to each demand node series of elements as PRV-E (Bertola and Nicolini 2006), FCV-CV-R (Jinesh Babu and Mohan 2011; Sivakumar and Prasad 2014; Gorev and Kodzhespirova 2013), FCV-CV-E (Sayyed et al. 2014), and GPV-CV-R (Pacchin et al. 2017). All these methods find results that fulfill the flow-pressure function with an acceptable error for single period simulations. However, they all need complex code using EPANET2 programmer's toolkit to run EPS as the parameters for the added valves and reservoirs are a function of the demand in the node, which changes with time.

This manuscript presents a new pressure-driven simulation approach (part of the third category of methods mentioned above) that includes a throttle control valve (TCV) element which has never been considered before for PDA simulations. The TCV simulates a partially-closed valve with a minor head loss coefficient that can be changed in time, making it the first approach of the third category of methods that does not require any external call of EPANET2 toolkit, or any source code modification, to perform an EPS. The method solves completely the system of equations that drive a PDA (energy conservation, mass balance and flow-pressure relationship) while also ensures a persistence in time of all the state variables of the network for the EPS.

Two benchmark networks by Ang and Jowitt (2006) and Jinesh Babu and Mohan (2011) are used to compare the results, in single and extended period simulation respectively, against their PDA approaches. A third case study is used to show the performance of the methodology in a real network.

2 Method

The method proposed here adds, in order, a FCV, a dummy junction, a TCV, another dummy junction, a CV and a reservoir to each demand node of the network (see Fig. 1). As in all other methods presented before, the base demand of the demand node must be set equal to zero since the reservoir will be the one receiving the water now. The FCV is used to ensure that the delivered flow Q does not exceed the demand at the node. Therefore, the setting of the FCV is equal to the demand at the node Q_D. The downstream node is used just to connect the FCV with the TCV. The TCV, which is the novel element used by this method, is added to simulate the pressure-flow relationship when $0 < p < p_{req}$ by setting its head loss coefficient according to Eq. 2, which comes from rearranging Wagner's (1988) equation and equating the head loss in the valve with p:

$$\begin{gathered} p = \frac{p_{req} Q^2}{Q_D^2} \qquad with \quad n = 0.5 \\ \Delta H = K_{TCV} \frac{Q^2}{2gA^2} = p \\ K_{TCV} = \frac{g \pi^2 d^4 p_{req}}{8 Q_D^2} \end{gathered} \tag{2}$$

where ΔH is the head loss in the valve, K_{TCV} is the minor losses coefficient of the TCV, A is the cross sectional area of the valve ($A = \pi d^2/4$) and d is the diameter assigned to the valve. It must be noted that the previous equation is valid only if n is equal to 0.5. However, the authors do not consider this a major drawback as experimental results have shown that this exponent value is a valid assumption (e.g., Walski et al. 2017).

After the TCV, another dummy junction is added to connect it with the CV. The CV ensures that if the pressure in the node is less than zero, then there will not be any inflow (negative Q) from the connected reservoir (which represents the appliances lumped in that node, and therefore should not supply any flow). The parameters of the CV are set to produce negligible head losses when water is flowing in the right direction (short length and large diameter). Finally, this arrangement connects the reservoir with a constant head equal to the elevation of the demand node to make sure that the pressure head p is used entirely in the TCV (making

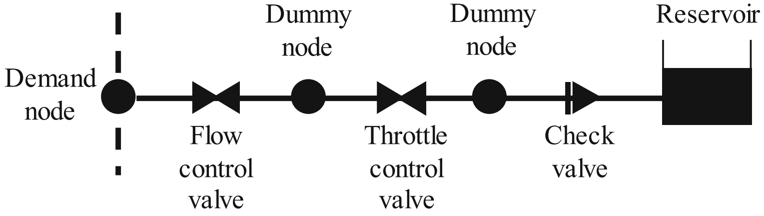

Fig. 1 Proposed artificial elements connected to a demand node

$\Delta H = p$). Table 1 summarizes the parameters for each artificial element while Eq. 1 shows the role of each added valve.

The above parameters' configuration works for single period simulations where Q_D is constant. However, in extended period simulations the demand varies with time according to the demand patterns:

$$Q_D(t) = Q_{D0} \cdot DP(t) \tag{3}$$

where Q_{D0} is the base demand of the node and $DP(t)$ is the demand pattern multiplier for time t.

This is where using a FCV and a TCV becomes advantageous, as they can be controlled using simple controls from EPANET2 allowing to consider demand time patterns by modifying their setting at each time step.

To do that, the demand time series $Q_D(t)$ for each node must be computed a priori. Then, two sets of simple controls are added for each demand node. The first set of controls modifies the setting of the FCV at each time step t, making it equal to $Q_D(t)$. The second set of controls modifies the setting of the TCV at each time step t, making it equal to:

$$K_{TCV}(t) = \frac{g\pi^2 d^4 p_{req}}{8(Q_D(t))^2} \tag{4}$$

This means that if a network model has a demand pattern of 24 time steps, each node adds 48 simple controls to it. Even though three extra links, three extra nodes and 48 controls per demand node may seem like an important modification to the model and its execution time, it is shown in the results that the computational time is not affected considerably in most cases.

Table 1 Parameters for artificial elements

Element	Parameter
Demand node	Base demand ←0
Flow Control Valve (FCV)	Diameter ←d_{large} (a large number, e.g, 1000) Setting (maximum flow) ←Q_D
Throttle Control Valve (TCV)	Diameter ←d (arbitrary diameter, e.g.,150 mm) Setting (minor headloss coefficient) ←K_{TCV} (Eq. 2)
Check Valve (CV)	Diameter ←d_{large} (a large number, e.g, 1000) Length ←L_{short} (a small number, e.g., 0.01)
Reservoir	Elevation ← Elevation of demand node
For extended period simulation	
Simple controls for FCV	Add new control for each time step t in the demand pattern: LINK FCV_Name $Q_D(t)$ AT TIME t
Simple controls for TCV	Add new control for each time step t in the demand pattern: LINK TCV_Name $K_{TCV}(t)$ AT TIME t

3 Case Studies

The proposed method is tested in three WDNs. The first case is the Multiple Source Looped WDN proposed by Ang and Jowitt (2006) and used by other researchers to test their algorithms for PDA under single period simulation (e.g., Jinesh Babu and Mohan 2011). The second case is Multiple Source Pumped WDN introduced by Jinesh Babu and Mohan (2011) and it is selected to compare the proposed PDA approach against their FCV-CV-R approach under extended period simulation. The full description of the first two case studies is included in the supplementary material. Finally, a real network, named “VC02”, from the WDNs database presented by Paez and Filion (2016), is used to compare DDA and PDA results for extended period simulation, to show how the solution completely conforms with the flow-pressure relationship, and finally to evaluate the computational time of an execution.

3.1 Multiple Source Looped WDN

Figure 2a shows nodes IDs and elevations in m, and pipe diameters in mm for this WDN. The demands under normal conditions are 25 L/s for all nodes. Ang and Jowitt (2006) performed a maximum flow analysis which according to Rossman (2000) can be simulated with an emitter coefficient of $100 \cdot Q_D$. (i.e. $p_{req} = 0.0001$m).

Table S1 in the supplementary material shows the flow and pressure results for normal conditions (without pressures below p_{req}), and for firefighting conditions with a 50 L/s extra demand on node J9. To simulate these conditions with the proposed method, the setting for the FCVs was 25 L/s for nodes J1 to J8 and 75 L/s for J9; the setting for the TCVs was 1.9358 for nodes J1 to J8 and 0.2151 for J9. The proposed method reaches the same results as Ang and Jowitt (2006) with differences under 0.01%.

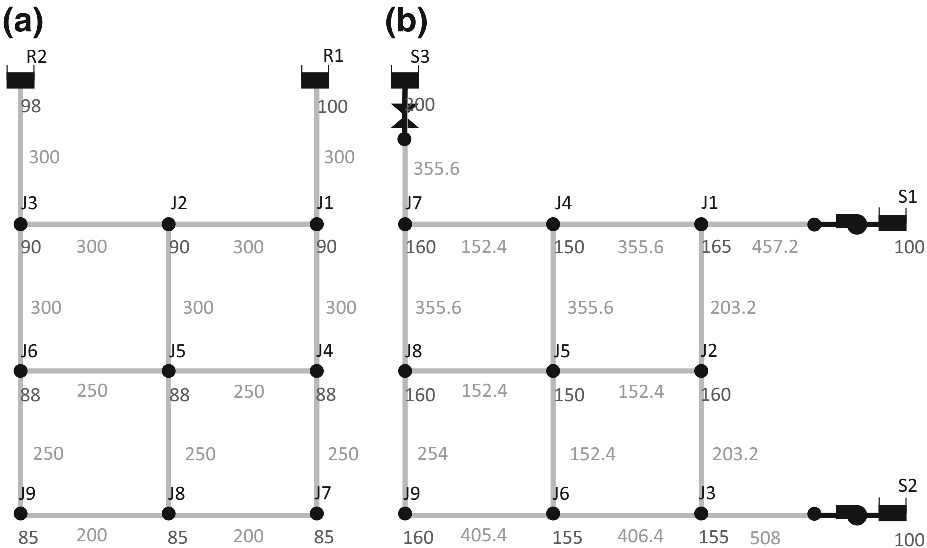

Fig. 2 Multiple Source Looped WDN (**a**) and Multiple Source Pumped WDN (**b**). Elevations in m and diameters in mm

3.2 Multiple Source Pumped WDN

The second case study is the Multiple Source Pumped WDN (Jinesh Babu and Mohan 2011) which has a demand pattern of 4 time steps and demands between 100 and 330 m^3/hr (see supplemental material). Similarly to the previous case study, Jinesh Babu and Mohan (2011) performed a maximum flow analysis for three pressure deficient scenarios: 1. Pump S1 failure, 2. Pump S2 failure, 3. Valve S3 shutdown.

Since the network model is in extended period simulation with four time steps and nine demand nodes, 72 simple controls where added to simulate the change in time of the settings for the FCV and the TCV. Table S2 in the supplementary material presents the setting values used for all the added controls.

Regarding the resulting hydraulic behaviour of the system both methodologies identify the same deficit nodes and only in those nodes the correspondent valves are activated. However, the outflows present an average difference of 5.4%. These differences are explained by the differences in the exponent used n and in the p_{req} used. Since Jinesh Babu and Mohan (2011) use a CV to control inflows but also to model the flow-pressure relationship, their approach has intrinsically an exponent $n = 0.54$ correspondent to the exponent of the head loss when Hazen-Williams equation is solved for Q. The second difference is that they do not consider explicitly the recommendation of Rossman (2000) for maximum flow analysis ($K = 100Q_D$). However, the proposed method always finds higher values of delivered water and therefore estimates better the maximum possible flows without negative pressures.

3.3 Large Real WDN (VC02)

The network VC02 (Paez and Filion 2016) has 284 demand nodes, 337 pipes, 1 reservoir, 4 tanks, 2 pumps, and a 24 h demand pattern. Figure 3 shows the layout and topography of the WDN as well as the demand pattern. The base demands of the network were modified to have a homogeneous value of 0.067L/s for a total mean demand of 19.03L/s.

To implement the proposed method, the input file was modified including 568 dummy nodes, 284 reservoirs, 852 links (284 FCVs, 284 TCVs and 284 CVs), and as the network model works for extended period simulation, 13,632 simple controls were added to modify the settings of the valves in each time step (using MS Excel to modify the *.inp file). Since the system was conveniently modified to have homogeneous demands, all FCVs and TCVs had

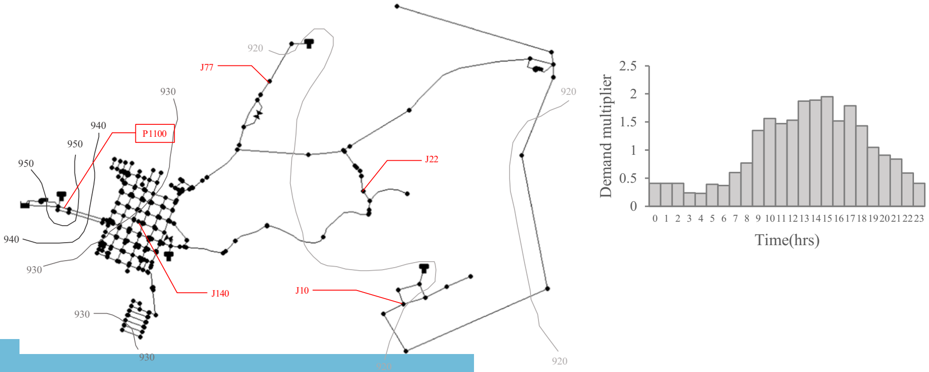

Fig. 3 VC02 network layout and demand pattern

the same time pattern for their settings (Fig. 4). For this network, d_{large} was taken as 1000mm while d was set as 150mm (more convenient considering the low demands); and L_{short} was still 0.01m. For this case p_{req} was set as 15m as it is a more realistic value than the ones used for previous examples.

The first execution of the network model was under normal conditions, where the DDA shows no occurrences of pressures below p_{req}. The results using the proposed PDA method also finds no occurrences of $p < p_{req}$ and the minimum registered pressure in the entire simulation is 15.66m which represents an error below 1% with respect to the DDA results. Figure 5 also shows a comparison of the system flow balance between DDA and PDA for the normal conditions. It can be seen that, although there are some differences, in no case they are significant (especially considering the many other sources of uncertainty in a WDN model).

To produce a pressure deficit scenario, pipe P1100 was closed simulating a failure (see Fig. 3). Nodes J140, J77, J22 and J10 were analysed in detail to see the differences between the DDA and the PDA. Figure 6 presents the pressure and demand time series for the four nodes under DDA and PDA. From the pressure time series, it is evident that node J140 is the most affected from the closure, while node J70 is the less affected one. This is due to the closeness between J40 and P1100 and the fact that they belong to the same hydraulic sector. On the other hand, J77 is located in a zone with lower elevation and is actually part of a different hydraulic sector as there is a pressure reduction valve upstream. Node J22 is also more affected because, despite its low elevation, it is still connected by two paths to the sector of P1100 and therefore its pressure is highly dependent on it. Lastly, node J10 is only slightly affected due to the presence of a pump between the node and P1100 that overcomes partially the pressure deficit.

With respect to the difference between the DDA and the PDA results, it is evident that results from DDA cannot be trusted in this kind of situation as it finds many negative pressures that are actually just pressures below p_{req}. This does not mean that PDA cannot find negative pressures, but it is able to assign a supplied flow of zero for those negative-pressure nodes (e.g., the node immediately downstream on P1100 has negative pressures during 19 of the 24 h simulated), and it can identify nodes with p between zero and p_{req}.

To show how the proposed method always fulfill the flow-pressure relationship, Fig. 7 plots the supplied flow vs. the pressure for all demand nodes in the network at times 6, 12 and 20. It can be seen that all the nodes fall into the flow-pressure curve with an average error below 0.5% and a maximum error below 1.5%.

Finally, since a single execution of the PDA method always took an indiscernible amount of time (less than 1.0 s), to test the computational cost of implementing this method two sets of

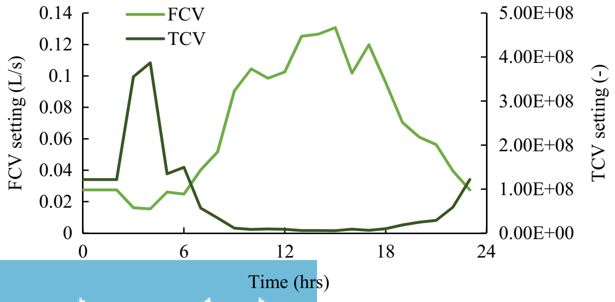

Fig. 4 FCV and TCV settings time series in VC02

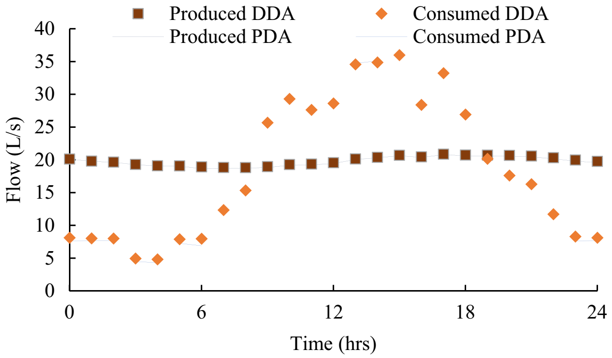

Fig. 5 System flow balance for VC02

500 executions in extended period simulations were carried on using VC02. The configuration of EPANET2 for the executions is presented in the Table S4 of the supplementary material.

The first set of executions was just a repeated execution of the network under normal conditions. The objective was to compare the extra computational time imposed by the additional elements and controls. The second set of executions was based on choosing randomly one pipe per execution to be closed. Figure 8 shows the computational time for all the executions. The DDA shows an average of 0.08 s per run without major variations for the normal conditions set. On the other hand, the proposed method takes in average 0.29 s per run for the normal conditions (PDA 1 on Fig. 8). Finally, when the proposed approach is used for pipe failure simulation (PDA 2), the average time is 0.41 s per run, although the model sometimes required more than 1.0 s to converge. These high computational time cases had in common that the closure of the pipe isolated a sector and therefore water could not reach some demand nodes, pumps and tanks.

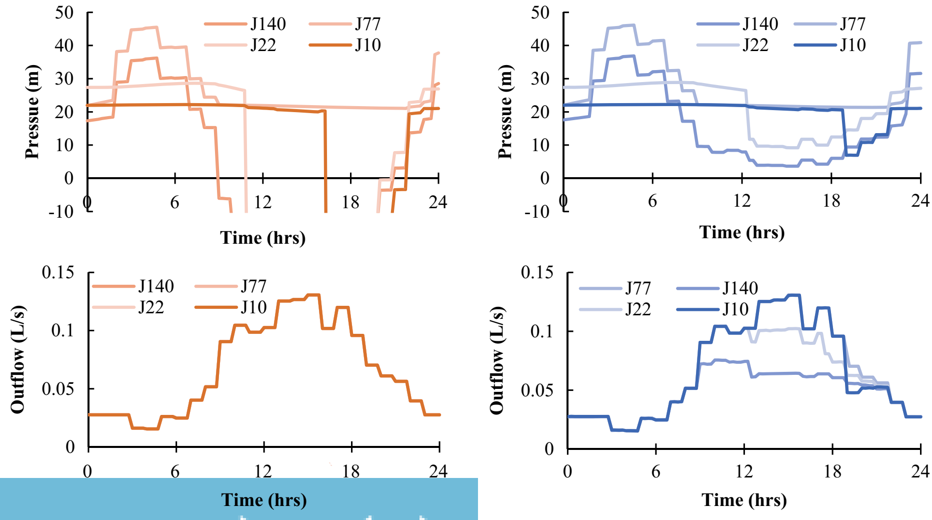

Fig. 6 Pressure and outflow time series for DDA (left) and PDA (right) of VC02

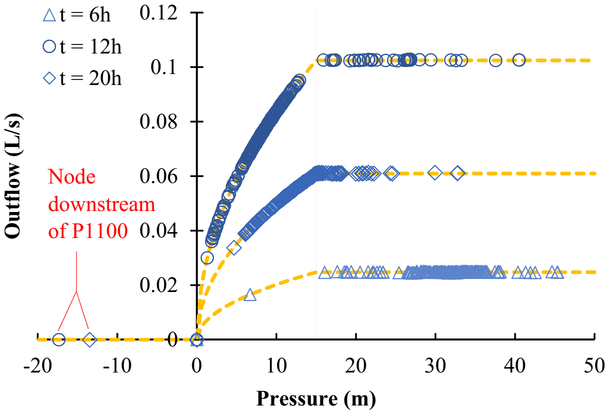

Fig. 7 Flow-pressure relationship for all nodes of VC02

4 Conclusions

A new method to perform pressure driven analysis on WDNs using EPANET2 is proposed. The method is based on adding a flow control valve, a throttle control valve, a check valve and a reservoir to each demand node. The method was tested in two benchmark networks and a third real, complex network. The results show that the proposed approach is able to simulate the network with pressure driven demands in extended period simulation without the need to modify EPANET2 source code or using its programmer's toolkit. The computational time is maintained within acceptable range for most cases.

Though an addition of series of hydraulic components to each node for converting DDA to PDA in EPANET2 makes initial burden to network modeller, this manuscript shows it is easy to implement a single hydraulic component called Pressure Driven Element with the combination of properties shown in Table 1 for future versions of the software.

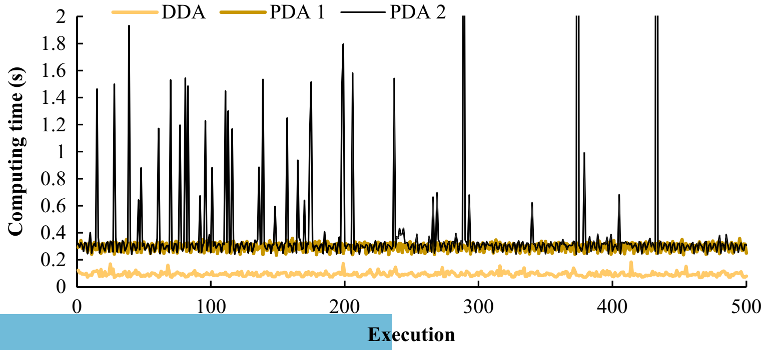

Fig. 8 Computational time for each extended period execution of EPANET2

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