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MODELLING CONSUMERS IN INTERMITTENT WATER SUPPLIES: A COMPARATIVE REVIEW OF EPANET-BASED METHODS

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Abstract

Intermittent Water Supply (IWS) networks, which pressurize for less than 24 hours/day, affect 1 billion people worldwide and are associated with increased water contamination and inequitable distribution. Due to these downsides, various methods to model consumers and understand their behaviour were proposed. We found more than 8 different methods of modelling IWS consumers, but we know of no comparative analyses of these methods nor their efficacy. This study comparatively reviews methods of modelling IWS consumers implemented in EPANET, due to their prevalence, reproducibility, and accessibility. Methods of modelling IWS consumers were found to fall into three groups based on their assumed consumer withdrawal behaviour: unrestricted, flow-restricted, and volume-restricted methods. We applied each method to three reference networks and compared the methods' performance after subjecting each reference network to common IWS improvement strategies, including changing the supply duration and/or source pressure. Flow-restricted methods assume consumers withdraw their demands at a constant rate, leading to unrealistic predictions when subjected to unexpected changes in supply conditions. Volume-restricted methods assume consumers withdraw at the highest, hydraulically feasible rate until their storage tanks fill. This assumption highlights pronounced inequality between consumers, as consumers advantaged by source proximity and/or elevation receive their demands faster and earlier. Our results demonstrate that the simulated behaviour of IWS depends substantially on the type of consumer model employed. Presented examples demonstrate that consumer model selection can change the simulation-predicted optimal strategies for coping with and improving IWS. IWS modelling methods should reflect the consumer behaviour in the modelled network and the model's intended use.

Keywords
Intermittent Water Supplies (IWS), Water Distribution Networks (WDN), Modelling, EPANET.

1 INTRODUCTION

Intermittent Water Supply (IWS) refers to water distribution networks that do not operate for 24 hours/day. This type of networks serves approximately 1 billion people around the world, mostly concentrated in the global south [1]. Intermittent operation is seldom in place by design but is often the result of utilities attempting to cope with water stress, lack of sufficient funds, and/or deterioration of infrastructure [2]. IWS networks distribute water inequitably among their consumers [3] and this inequality is exacerbated by their unplanned nature. IWS also degrades water quality during distribution [4]. Due to IWS' drawbacks, many IWS networks do not meet the specifications set for target 6.1 of the United Nations (UN) Sustainable Development Goals (SDG), which targets "universal and equitable access to safe and affordable drinking water for all" [5]. Thus, it is of high interest to improve service consistency and quality in IWS contexts if universal access to safely managed water supplies (SDG 6.1) is to be achieved.

To achieve SDG 6.1 and its national counterparts, utilities, researchers, and regulators have attempted to optimize intermittent operation to improve service and move towards continuous supply (e.g., [6]–[9]). But for IWS optimization efforts to yield practical value, optimizations must be founded on a modelling method that meaningfully represents consumer behaviours. Ideal representations of consumer behaviour would capture how consumers respond to IWS improvements such as changes in supply duration and/or pressure. Several methods have been proposed to capture the distinct features of IWS networks. These methods are heterogenous in their scope (steady-state operation vs. filling and draining of the network), their platform (open-source software like EPANET and SWMM vs. methods independent of available software) and their assumptions about consumer behaviour. Despite such diversity in modelling methods, we know of no qualitative or quantitative comparisons of these methods nor of their ability to usefully represent consumer behaviours and network conditions.

To provide guidance to utilities and researchers interested in modelling IWS, this paper aims to review and compare modelling methods that can be applied to IWS. We demonstrate each model's representation of consumers and their demand withdrawal behaviour in three test networks, subject to various practically motivated supply conditions. To do so, we:

1. Cluster similar methods of modelling IWS into groups based on their assumptions about the consumer (Section 2);
2. Summarize the test networks used, our methods and scenarios for comparison (Section 3);
3. Demonstrate how each method's assumptions about consumers affect the simulated network and the variations in consumer demands delivered (Section 4), and lastly;
4. Recommend methods best suited for utilities and researchers interested in improving IWS networks (Section 5).

2 LITERATURE REVIEW

The literature on IWS modelling, while relatively scarce, varies widely in scope, approach, and utilized tools. A majority of the reviewed literature (e.g., [10]–[13]) focuses on predicting the steady-state (post-pressurization) network conditions, while other efforts (e.g. [3], [14]) focus instead on describing the filling (pressurization) process. Several models of filling adapt the EPA's Storm Water Management Model (SWMM) (i.e., [14]–[17]) while others were constructed from scratch, providing greater flexibility in model construction often at the expense of reproducibility and ease of use (i.e., [3], [17], [18]). Of the steady-state modelling methods, most use EPANET due to its prevalence in modelling WDNs in general and its open-access nature. This review compares such EPANET-based methods of modelling IWS. A review of methods for modelling the filling of IWS networks – while important in ascertaining when consumers start receiving their demands (and therefore the total volume they can receive during a supply cycle)- is left for future work.

Some aspects of the steady-state performance of IWS can be modelled using methods that were not specifically formulated to represent IWS networks and/or consumers. We include such methods in our review, even though this inclusion may stretch such methods beyond their proposer's intent. One such category of methods aims to model pressure-dependent demands. In many IWS networks, consumer withdrawals are affected by pressures in the network [15]. This dependence of demand on adequate pressure distinguishes most IWS from their Continuous Water Supply (CWS) counterparts, where it is typically assumed that sufficient pressure is provided. Since EPANET was originally built to model CWS, its solver was not outfitted with a Pressure-Driven Analysis (PDA) option and operated exclusively on a Demand-Driven Analysis (DDA) basis, until 2020 [19].

Pressure-dependent demand in this context describes a method of modelling consumer withdrawals that includes the sensitivity of withdrawals to the available pressure in the network. In its general form, a pressure-dependent demand is typically defined by three regimes:

a) Below a minimum head threshold, no water flows to the consumer,

b) Above a desired head threshold, the consumer receives their desired demand,

c) Between the minimum and desired thresholds, flow to a consumer depends on the available head, and the minimum and desired head thresholds.

This pressure-dependence was first formulated as a relationship between head and flow rate by [20]. Wagner et al. [21] proposed the form used by the majority of later studies, an n^{th} root relationship:

$$Q_j = 0, \quad if\ H_j \leq H_j^{\min} \tag{1a}$$

$$Q_j = Q_j^{\text{des}}, \quad if\ H_j \geq H_j^{\text{des}} \tag{1b}$$

$$Q_j = Q_j^{\text{des}} \left(\frac{H_j - H_j^{\min}}{H_j^{\text{des}} - H_j^{\min}}\right)^{\frac{1}{n_j}}, \ if\ H_j^{\text{des}} > H_j > H_j^{\min} \tag{1c}$$

Where Q_j is the actual demand withdrawn at node j. Q_j^{des} is the desired consumer demand, and H_j, $H_j^{\min}$ and H_j^{des} are the head available at node j, the minimum required head for flow to start at node j, and the minimum head required to deliver the consumer's desired demand at node j, respectively, and n_j is an exponent that is characteristic of node properties [21].

Earlier efforts to implement this pressure dependence in EPANET included iterative approaches (e.g., [22], [23]), and modifying EPANET source code or extending its solver (e.g., [24], [25]). Later efforts achieved comparable results by using model elements native to EPANET to modify demand nodes and account for pressure dependence. These later approaches provided higher accessibility and ease of use since they can be used within EPANET's Graphical User Interface.

All methods of modelling steady-state IWS networks include Pressure-Dependent Demand (PDD). Methods differ, however, in their formulation of this PDD relationship and its implementation in EPANET, as well as their assumed consumer behaviour in withdrawing demands. We group IWS modelling methods based on three types of demand withdrawal assumptions: Flow-restricted, Volume-restricted, and Unrestricted methods (Figure 1).

2.1 Flow-restricted methods

Flow-restricted methods of modelling networks assume that as long as pressure is greater than the desired pressure ($H_j > H_j^{\text{des}}$), withdrawal flow rates are independent of pressure (i.e., Equation 1b). When these methods are employed to model IWS, their predictions correspond to consumers that consciously restrain their withdrawal to receive only what the modeller expects, which is often what they need. When modelling IWS, the expected withdrawal rate (i.e., desired demand Q^{des}) is often defined as the total daily demand volume, spread out over the supply duration. We found three distinct ways in which flow-restricted methods have been implemented in EPANET (Figure 1).

EPANET-PDA: As of 2020, EPANET has been outfitted with a Pressure-Driven Analysis (PDA) option built natively in the source code and GUI. Thus, we include "EPANET-PDA" as one of the flow-restricted methods in our analysis. The EPANET-PDA method is used in the current conference's Battle of Intermittent Water Supply (BIWS).

Prior to the release of the native PDA option, however, flow-restricted methods were implemented in EPANET using Flow Control Valves (FCVs) to restrict the maximum flow (Q^{des} in Equation 1b). FCVs In EPANET restrict flow from the original (demand-driven node) to a new node, either a reservoir (FCV-Res) or an emitter (FCV-EM).

FCV-Res: When an FCV is connected to a downstream reservoir (FCV-Res) flow at intermediate pressure heads (i.e., between $H_j^{\min}$ and H_j^{des}) is governed by the reservoir's elevation and the friction between the original node and the reservoir. The reservoir elevation is set to be above the original node's elevation by exactly the minimum required head (H_j^{min}) [26], [27]. Gorev and Kodzhespirova [27] improved on [26]'s convergence by adjusting the resistance of the connection between the original node and the reservoir, by setting the connecting pipe's minor loss coefficient as:

$$k_j = (H^{des} - H^{min})\frac{g}{8}\left(\frac{\pi D^2}{Q^{des}}\right)^2 \tag{2}$$

where k_j is the minor loss coefficient, D is the pipe diameter, and other variables as defined before.

FCV-EM: FCVs have also been used in conjunction with emitters, rather than reservoirs. In this case, the n^th root relationship (Equation 1c) is represented by the emitter's coefficient and the emitter's elevation is set to account for H_j^{min} similar to the reservoir [28]. The emitter's exponent is determined as:

$$C_d = \frac{Q^{des}}{(H^{des} - H^{min})^{\frac{1}{n_j}}} \tag{3}$$

Mahmoud et al. [29] modified this approach to selectively add the artificial elements only to pressure-deficient nodes to improve efficiency [29].

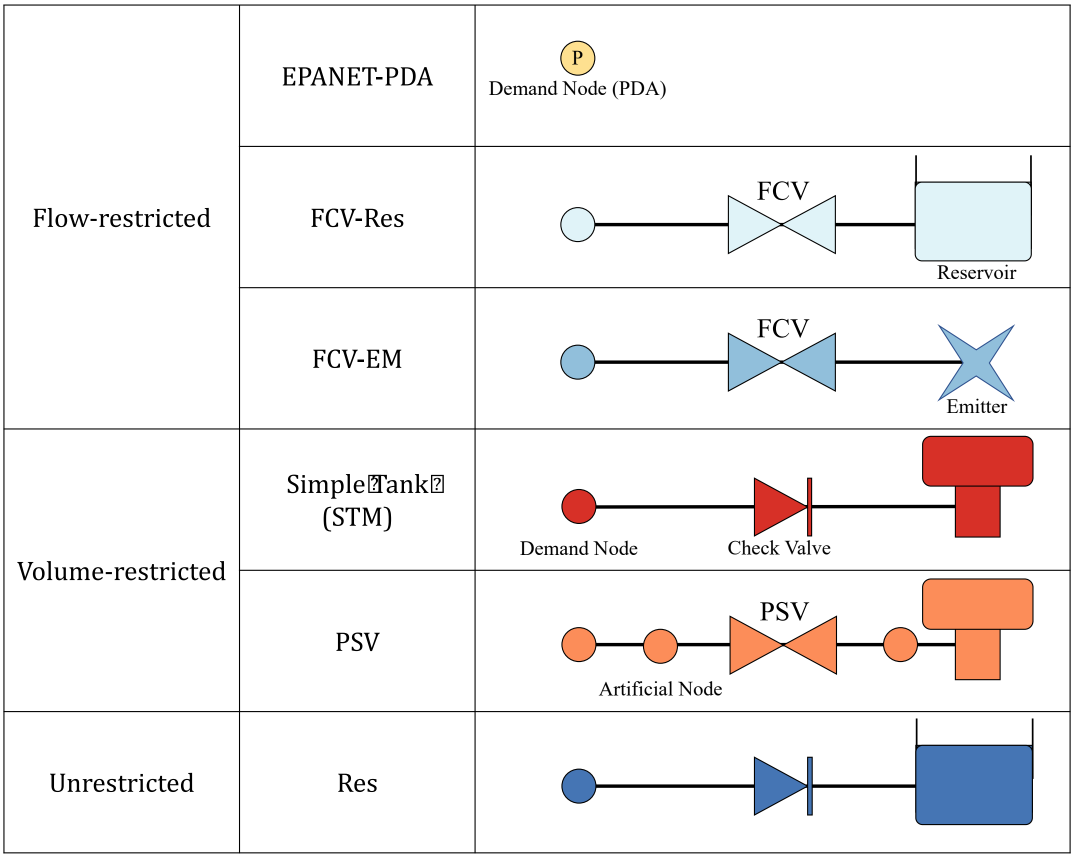

Figure 1: EPANET representation of flow-restricted methods: EPANET's native PDA option (EPANET-PDA), FCVs with downstream reservoirs (FCV-Res), and FCVs with downstream emitters (FCV-EM); volume-restricted methods: Simple Tank Method (STM) and Pressure-Sustaining Valve method (PSV); and the unrestricted method using reservoirs (Res).

To test these methods, we implemented FCV-Res in accordance with [27] due to its improved convergence and we implemented FCV-EM in accordance with [28] since all nodes in an IWS network should be treated as pressure-deficient. Both FCV methods were compared with EPANET's (newly) native PDA option. The EPANET representation of each of these flow-restricted methods is shown in Figure 1.

2.2 Volume-restricted methods:

IWS consumers typically compensate for expected supply interruptions by storing water [30], [31]. Consumer storage in IWS networks transforms (integrates) their desired flow rate into an equivalent desired volume, V^{des}, over the supply cycle (from the start of one pressurization to the next) [11]. Consumers with storage need not withdraw water at the same rate as they desire to use it. Instead, volume-restricted methods assume that consumers withdraw water at the highest rate they can (hydraulically determined by the pressure in the network and service connection resistance) until they have received their demanded volume, after which they shut off their connection Volume-restricted methods have been implemented in EPANET using its tank element to represent this volume restriction. Specifically, the tank's volume corresponds to the desired demand volume, V^{des}. We found two EPANET-based methods of implemented volume-restricted flow.

Simple Tank: The Simple Tank Method (STM) was first proposed by Batterman and Macke [10] and later systematized and adapted by Taylor et al. [11]. The use of simple tanks was also observed in [32] and suggested by [15]. In STM, consumers are represented as a tank with a volume equal to V^{des}, The tank's elevation is set as the sum of the original node's elevation and $H_{\mathrm{j}}^{\mathrm{min}}$, equivalent to the reservoir and emitter elevations in the FCV-Res and FCV-EM methods. Consumer tanks are set to a uniform, nominal height (often of 1 metre to simplify postprocessing). The pipe connecting the original demand node to the consumer tank is equipped with a check valve to prevent backflow and the pipe's minor loss is adjusted as in Equation 2. As each tank fills, its pressure head slowly increases, which slows the withdrawal rate.

PSV: Sivakumar et al. [33] expanded the STM by adding a Pressure Sustaining Valve (PSV) upstream of the tank to ensure the upstream pressure is constant at atmospheric pressure. The PSV enables a flow rate expected of a tank filling from the top – as opposed to STM's filling from the bottom. The result of this distinction is that tanks are subjected to a constant head differential in the PSV method, therefore the withdrawal rate is constant until the tank is full. Compared to the STM, tanks in the PSV method should have an elevation that is lower by the tank's height.

2.3 Unrestricted method(s)

Res: Lastly, Mohapatra et al. [13] adopted an approach that is neither restricted by volume nor flow rate. This "Unrestricted" method assumes that the consumer will withdraw at the maximum possible rate and maintain it for the entire supply. This is achieved by replacing the tank element (volume-restricted storage) in the STM method with a reservoir element (unrestricted storage). This formulation would hold true if consumers were known to leave their taps open regardless of withdrawal volumes.

3 METHODS

To compare each method's predictions of steady-state behaviour in IWS networks, we implemented each method in three reference networks (Figure 2). Network 1 (6 demand nodes) is a single source, two-loop network introduced by [22]. Networks 2 (3 reservoirs, 64 demand nodes) and 3 (4 reservoirs, 245 demand nodes) are models based on the WDNs of Pescara and Modena, Italy, respectively introduced by [34]. The networks are numbered in order of increasing complexity. To consistently compare the predictions and performance of the modelling methods, we harmonized their assumptions about the minimum and desired pressures ($H_{\mathrm{j}}^{\mathrm{min}}$ and H_j^{des}).

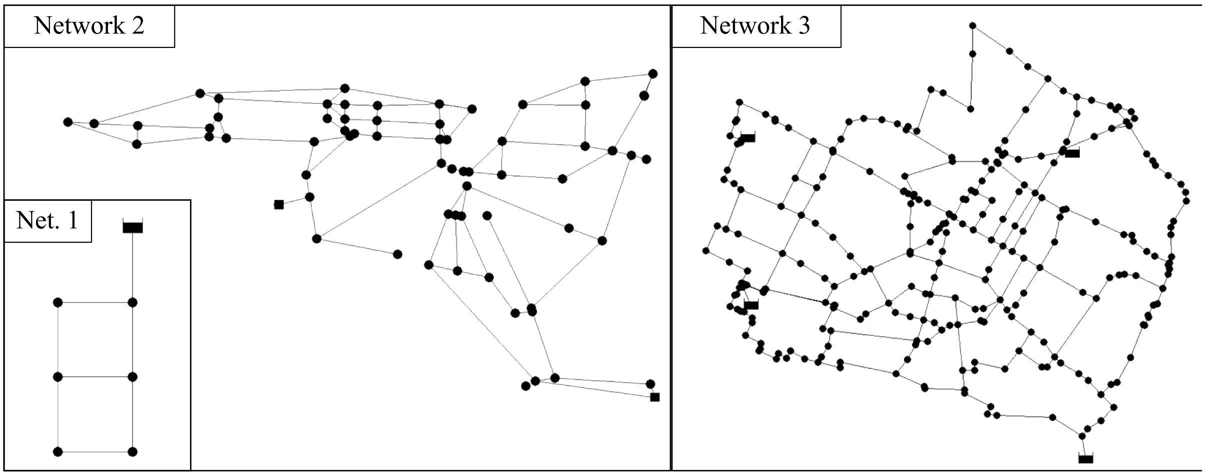

Figure 2: Networks used in method testing. Network 1 is a single-source, two-loop network with 6 Demand Nodes, Network 2 (Pescara, Italy) has 3 source reservoirs and 64 demand nodes, while Network 3 (Modena, Italy) has 4 source reservoirs and 245 demand nodes

In theory, the true value of these parameters depends on the degree of network skeletonization, and the resistance expected from the consumers' service connections. Literature on their appropriate value for various IWS contexts is starkly absent [35] and so these values are set at 0 and 10 metres for H_j^{min} and H_j^{des} respectively. The exponent n_j was set at 0.5 for all nodes in all methods and in all networks. These assumptions about pressure head thresholds and exponents match those used for the BIWS network.

In EPANET-PDA, values for H_j^{min} and H_j^{des} are directly input into EPANET's hydraulic options [36]. For the remaining methods, these values are represented in the connecting pipe's minor loss calculated as in Equation 2, except for FCV-EM where they are represented in the emitter's coefficient as in Equation 3. The value of Q^{des} used in equations 2 and 3 for all methods was set as the flow rate needed to satisfy consumer demands over the supply duration – which for most runs is 12 hours unless stated otherwise.

The analysis of all methods was conducted using the Water Network Tool for Resilience (WNTR) v. 0.4.1 [37] python package in Python 3 on a 2020 MacBook Pro M1. The speed of each method in each network was averaged across 1,000 timed runs. Instances where the difference in efficiency could potentially cause a considerable difference in user experience (time difference >50%) are noted below. To compare the predicted hydraulic behaviour of each method, we computed its predicted consumer demand satisfaction, S, defined as the ratio between the volume delivered to consumers and the total volume desired for all consumers during the supply cycle:

$$S = \frac{V^{sup}}{V_T^{des}} \tag{4}$$

where V^{sup} is the total volume supplied to consumers and V_T^{des} is the total demand volume for all consumers.

For volume-restricted methods, the total delivered volume was computed as the sum of the volumes stored in the tank at the end of supply, while for flow-restricted and unrestricted methods, it is computed as the product of the demand withdrawal rate and the supply duration. An equivalent satisfaction ratio for each node was computed in a similar fashion, to allow for an investigation of variance (if any) in demand delivered to consumers and subsequently, an investigation of supply equality. Consumers in a flow-restricted model are limited by their desired flow rate Q^{des}, which in imposes an upper limit on the average satisfaction ratio of the network defined by:

$$S \leq \frac{Q_T^{\text{des}}}{V_T^{\text{des}}} t \tag{5}$$

where Q_T^{des} is the sum of all desired demands and V_T^{des} is the sum of all desired demand volumes and t is the time since supply started (supply time).

A useful modelling method ought to be able to produce realistic results under "non-design" conditions, especially if modelling is to inform and guide the optimization of the operation and/or improvement of IWS networks (e.g., BIWS). We demonstrate and compare the methods' predictions under two such non-design conditions in which supply duration and pressure are varied.

Supply pressure is expected to be one such "non-design" condition of interest to utilities and/or researchers. Intermittent operation is often caused by water scarcity or insufficient funding [2], hence, low reservoir levels and/or energy shortages affecting pump operation are expected to frequently reduce source pressure. Thus, each method was also tested on each network under reductions of source pressure by 25, 50 and 75%, where source pressure was defined as the head differential between the highest reservoir and the highest demand node's elevation. Similarly, supply duration is expected to be a "non-design" condition of interest since variations in supply durations are common in IWS [38]. Here, while reference networks are configured assuming a supply duration of 12 hours, methods were tested under unexpectedly shortened supply (10 hours) and lengthened supply (14 hours) durations.

To exemplify the distinctions between the modelling methods, two scenarios of practical relevance to the operation/management of IWS are constructed. In the first scenario, a network (which satisfies consumer demands in 12 hours) is occasionally constrained to operate only for 10 hours a day (e.g., due to electricity blackouts). The utility is therefore considering a proposal to augment its source pressure during the 10 hours of supply (e.g., by installing an additional pump). In the second scenario, a network (which also satisfies in 12 hours) suddenly faces reduced source pressure (e.g., due to a pump failing). The utility is therefore considering a proposal to mitigate this reduced pressure by lengthening its supply duration (e.g., by running the operational pumps for longer).

Table 1: Description of the improvement scenarios used to compare modelling methods

Scenario	Problem	Improvement	Proposed Mitigation
1	Reduced to 10-hour supply 100% Source Pressure	Increase Source Pressure	10-hour supply 125% Source Pressure
2	12-hour supply Reduced to 25% Source Pressure	Lengthen Supply Duration	14-hour supply 25% Source Pressure

In each scenario, the hypothetical utility would evaluate the proposed mitigation based on the modelled gains (or lack thereof) in consumer demand satisfaction (Equation 4). Thus, we compared the decisions made by the utility in each scenario, depending on the modelling method they employed.

4 RESULTS & DISCUSSION

Based on the quantitative performance of the simulated modelling methods, we first compare method performance both within groups (e.g., flow-restricted methods) and between groups. Next, we inspect the predictions for the extreme consumers (10th and 90th percentiles) across different supply conditions (changed supply duration and pressure). Lastly, we investigate the implications of the different methods when used to model the improvement of IWS networks.

4.1 Types of IWS models

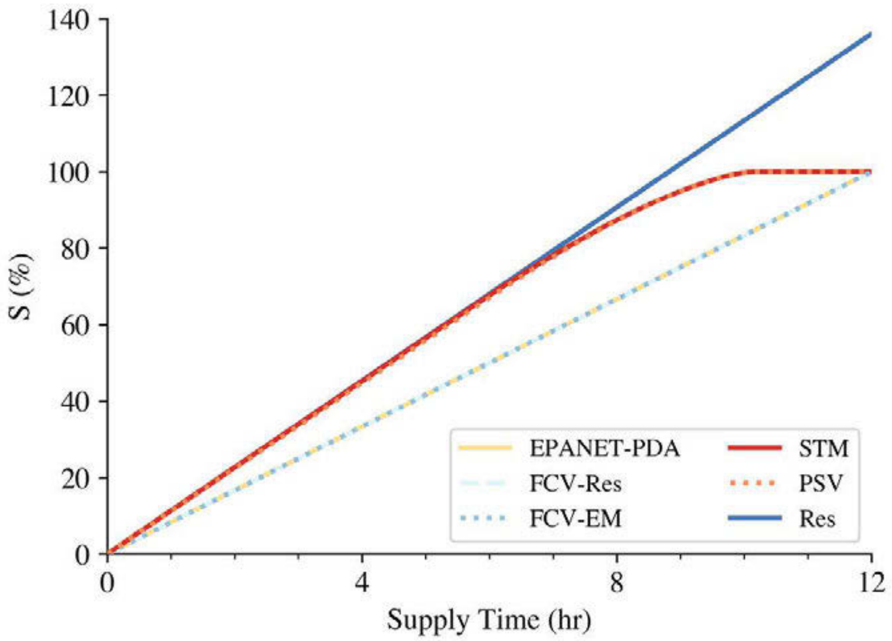

Figure 3: Demand satisfaction, S, in Network 3 vs. supply time for flow-restricted methods: EPANET-PDA (solid yellow), FCV-Res (dashed light blue) and FCV-EM (dotted light blue), and volume-restricted methods: STM (solid red) and PSV (dotted orange), and the unrestricted Res method (solid blue). The results of methods within the aforementioned groups are shown to be virtually identical on the aggregate level. A Significant difference is observed between groups as expected. Flow-restricted methods show a controlled rate bounded by the flow restriction; volume-restricted methods start withdrawing at a higher rate before levelling off due to tanks becoming full (volume restriction) while the unrestricted Res continues to withdraw at the maximum rate.

The average consumer satisfaction predicted by the simulated methods strongly supports our grouping of them (Figure 3). Flow-restricted methods exhibited controlled and constant withdrawal, as expected, since consumer withdrawals are bounded by the flow restriction. When supplied with ample pressure, flow-restricted consumer satisfaction follows a straight line defined by an intercept of zero and a slope equal to Q^{des}/V^{des} (e.g., see Figure 3). Flow-restricted methods produced nearly identical results (<0.01% difference) once assumptions around minimum pressure (H^{min}) and desired pressure and demand (H^{des} and Q^{des}) are harmonized. This close alignment between the historical methods of flow restriction (FCV-Res and FCV-EM) and the PDA option in EPANET 2.2 demonstrates the adequacy of earlier methods in representing pressure dependence. Of note, EPANET's PDA option is approximately 1.5 times faster in Network 1 and 2.5 times faster in Network 3. While the total runtime for all networks remains below 30 milliseconds per run, if a network with low skeletonization or a considerably larger scale is of interest (e.g., the BIWS network has 2,859 nodes compared to Network 3's 245), the computational cost would likely scale non-linearly, and the difference in modelling efficiency may become significant to the modeller.

Both unrestricted and volume-restricted methods predicted faster consumer withdrawals than flow-restricted methods while the average satisfaction in the network is relatively low (e.g., S <70% in Figure 3). Thereafter, some tanks start to become gull (i.e., the number of unsatisfied consumers dwindles), slowing average withdrawal rates. Both volume-restricted methods (STM and PSV) agreed closely on the average consumer satisfaction as long as pressures in the network were considerably higher than the tank heights as noted by [33], [35]. For example, their predictions were <0.7% different in Figure 3 where network pressures were 20-30 metres compared to tank heights of one metre.

The unrestricted Res method's predictions overshoot the desired demand for all consumers when supply durations are longer than hydraulically required to satisfy consumers. For example, when Network 3 was supplied for 12 hours, the average consumer satisfaction was 136% with a range of ~110-180% (Figure 3). The absence of restrictions on consumer storage may also lead to unrealistic results in networks where consumers have widely differing elevations and/or proximities to the source; hydraulically advantaged consumers could be predicted to receive much more than they can physically store, even if the average consumer satisfaction was <<100%.

All flow- and volume-restricted methods on the total satisfaction ratio of the consumers at the end of the planned supply, provided water is supplied for the expected duration (12 hours in Figure 3). Before the end of the planned supply, however, flow- and volume-restricted methods differ in the predicted consumer satisfaction levels. In networks where some consumers are hydraulically advantaged over others, consumer satisfaction (100%) is achieved faster because demand is hydraulically staggered. Advantaged consumers, in volume-restricted models, fulfil their demands earlier, enabling higher pressures for disadvantaged consumers. More generally, variance in withdrawal rates modelled by volume-restricted methods has important implications for the equality of consumer withdrawals in IWS networks.

4.2 Supply distribution between consumers and inequality

Flow- and volume-restricted methods predict similar average levels of consumer satisfaction across a range of pressures when the network is supplied for the expected duration. At very low pressure, when all pressures are lower than the desired head H_j^{des}, both methods also agree on the distributions of consumer satisfaction since all consumers are hydraulically limited to a rate lower than the flow restriction (e.g., Figure 4c). As pressures increase, consumer withdrawals are increasingly restricted in flow-restricted methods, which imposes an upper limit on the predicted variance in consumer satisfaction (e.g., Figure 4b vs. 4a). Flow-restricted methods, by construction, exhibit complete uniformity between consumers who receive sufficient pressures ($>H_j^{\mathrm{des}}$). Studies of flow variation due to pressures above the desired pressure were not intended, and subsequently are not captured, by flow-restricted methods.

IWS consumers have been observed to actively seek measures that enable them to withdraw their demands as fast as possible. One estimate suggests that 25% of consumers in IWS use private (suction) pumps to actively pull water out of the network faster than it would otherwise flow [39]. In many IWS networks, and especially where suction pumps are prevalent, consumers tend to withdraw and fulfil their demands as quickly as possible. In such contexts, volume-restricted methods more accurately account for rapid withdrawals and therefore demand distribution between consumers than their flow-restricted counterparts.

Water networks, and especially IWS networks, should be evaluated based on more than their average performance. Equality of access to safe and affordable drinking water features prominently in many national and global policy goals. To realize such goals, tools that enable us to understand and mitigate inequalities under IWS are needed. Volume-restricted methods of modelling IWS capture more of this inequality than their counterparts and are therefore more useful for utilities and researchers seeking operational opportunities to maximize equality in IWS networks.

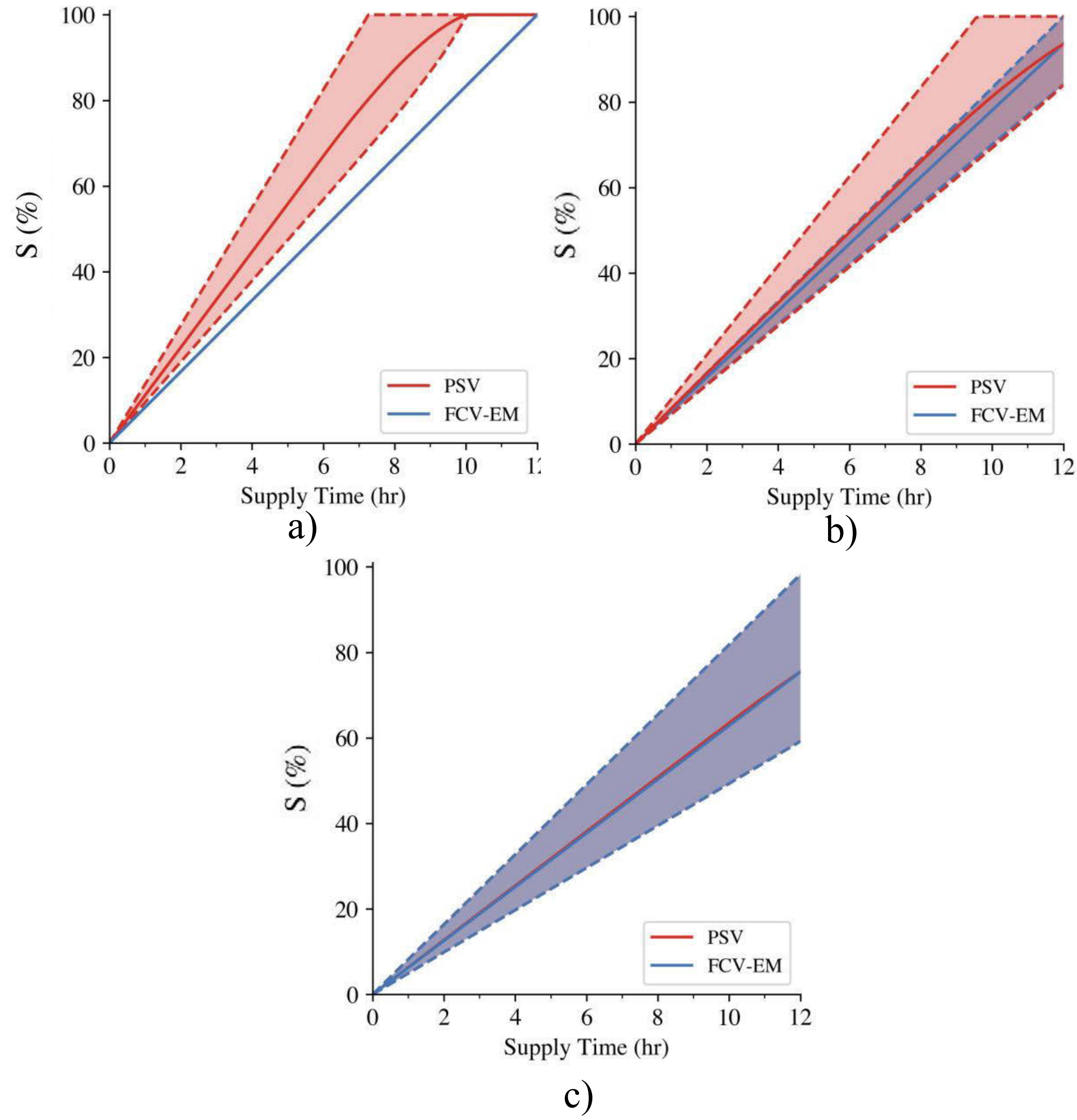

Figure 4: Comparing a flow-restricted (FCV-EM) and a volume-restricted (PSV) method. Mean (solid), 10th and 90th percentile (shaded) of consumers' demand satisfaction for Network 3 under a) 100% source pressure, b) 50% source pressure, and c) 25% source pressure. As the source pressure decreases, the variance between consumers' satisfaction increases. By construction, flow- and volume-restricted methods agree when all consumers are pressure deficient. When at least some consumers have pressures higher than H_j^{des}, volume-restricted methods predict greater inequality since they are not restricted by the upper bound of flow-limited methods (defined in Equation 5).

4.3 Modelling the improvement of IWS

The choice of modelling method can have important practical implications for utilities using models to evaluate possible operational changes. To demonstrate, we contrast how differently flow- and volume-restricted methods would evaluate the same strategies to improve network performance in two scenarios.

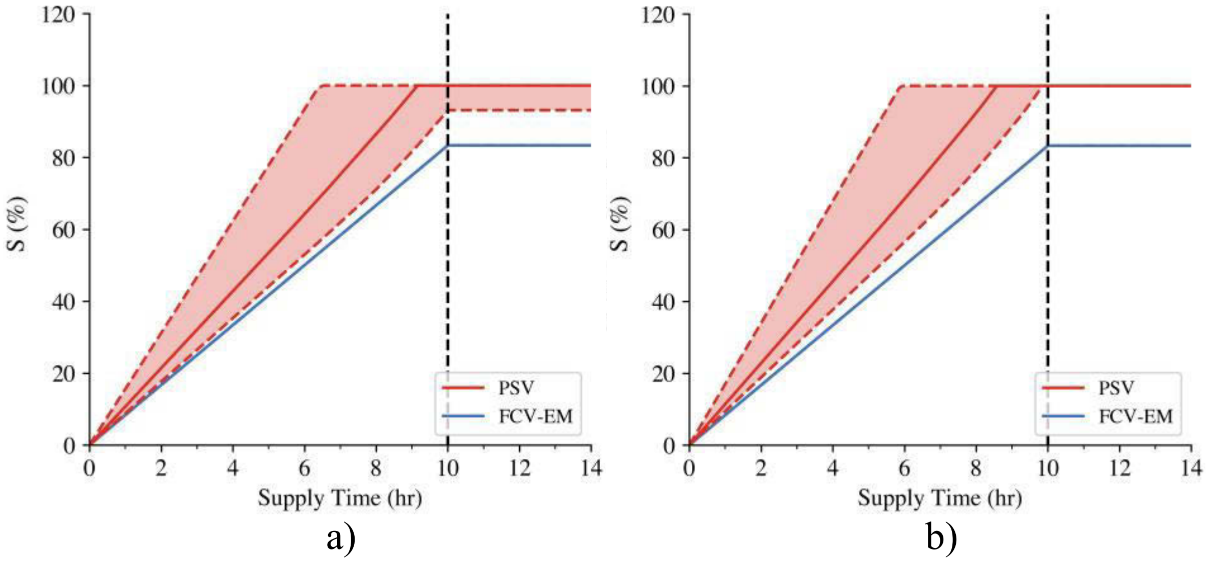

Figure 5: Comparing a flow-restricted (FCV-EM) and a volume-restricted (PSV) method. Mean (solid), 10th and 90th percentile (shaded) of consumers' satisfaction for Network 2 operating for a) 10 hours under normal source pressure and b) 10 hours under 125% source pressure. Dashed black line indicates the end of supply. Network 2 was configured assuming supply would last for 12 hours. Volume-restricted methods predict an increase in consumer satisfaction, while flow-restricted methods predict no change. The different assumptions about consumer behaviour made by the methods inform the utility towards opposing decisions.

In Scenario 1, a water utility is occasionally forced to operate their IWS network for 10 hours a day, instead of its normal 12 hours a day (Figure 5a). Both methods predict that after 10 hours of supply, the network is not yet satisfied. Flow-restricted methods predict that all consumers will be equally inconvenienced and receive only 83.3% (10/12) of their desired demand (Figure 5a). Contrastingly, volume-restricted methods predict that only a few disadvantaged consumers will bear the brunt of the shortage. To improve consumer satisfaction during these occasional restrictions in supply duration, the utility is considering augmenting its source pressure by 25%. Flow-restricted and volume-restricted methods differ drastically in their evaluation of this proposed pressure increase (Figure 5b). In this scenario, consumer withdrawals are constrained by supply duration, not pressure, since all consumers in the modelled network have pressures higher than their desired head H_j^{des}. As such, flow-restricted methods predict no improvement in consumer satisfaction (Figure 5b). Volume-restricted methods, however, predict that increased pressure would lead to higher consumer withdrawals and satisfaction (Figure 5b). Thus, the utility's choice of modelling method would change their evaluation of the proposed pressure increase; the proposed improvement could be deemed effective if a volume-restricted method was used, but ineffective if a flow-restricted method was used.

In the second scenario, a similar network that operates for 12 hours faces occasional pressure deficiencies (25% Source Pressure). Both flow- and volume-restricted methods agree on the unmitigated impact this pressure reduction would have on consumers, i.e., a portion of consumers cannot satisfy their demand (Figure 6a). To address this pressure deficit, the utility considers lengthening the supply to 14 hours per day to improve consumer satisfaction. Given the increased supply duration, volume-restricted methods predict that all consumers will be satisfied by the end of supply (Figure 6b). Flow-restricted methods, on the other hand, predict that some consumers will still see their demands unsatisfied, even when most consumers receive more than their desired demand (Figure 6b). Flow-restricted methods also predict that the total water supplied to consumers will be greater than their collective demand. In a water-scarce context, this predicted increase in total water supplied could discourage the utility from adopting the increase in supply duration. Similarly, any equality-focused utility might decide that supply durations longer than 14 hours are required based on a flow-restricted method when a volume-restricted method suggests otherwise.

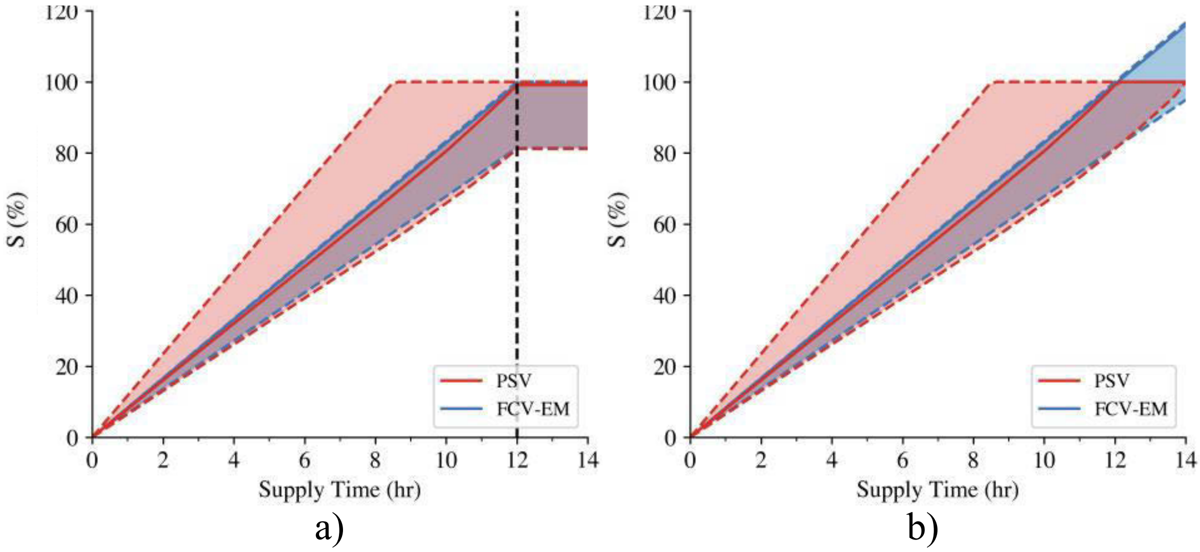

Figure 6: Comparing a flow-restricted (FCV-EM) and a volume-restricted (PSV) method. Mean (solid), 10th and 90th percentile (shaded) of consumers' demand satisfaction for Network 2 operating for r a) 12 hours under 25% source pressure and b) 14 hours under 25% source pressure. Dashed black line indicates the end of supply. Network 2 was configured assuming supply would last for 12 hours. While both methods predict a gain in consumer demand satisfaction, flow-restricted methods predict that some consumers remain unsatisfied and predict a higher outflow from the source.

In both scenarios, using a different type (group) of modelling method could lead the utility to a different decision. We suggest these scenarios highlight two major limitations of flow-restricted methods when modelling IWS. When most or all pressures in an IWS network are sufficient, flow-restricted methods artificially obscure inequality between consumer withdrawals (and potentially satisfaction). When IWS networks increase their supply duration beyond the duration used when setting flow0restriction settings, flow-restricted methods can predict withdrawn volumes larger than consumer demand. Thus, we recommend volume-restricted methods over flow-restricted ones in three IWS modelling circumstances:

1. When the equality of consumer withdrawals (rather than the average) is a key concern,
2. When network pressures are higher than (or expected to increase beyond) the desired pressure, and/or
3. When the effect of supply duration changes is of interest.

Conversely, we note that flow-restricted methods can enable the simulation of multiple supply cycles if set up with appropriate patterns and control rules (as seen in the BIWS network), which cannot be done in currently available volume-restricted methods. However, since flow-restricted methods do not model consumer storage, they are unable to capture how an unsatisfied demand in one cycle affects consumer behaviour over the following cycle (if such an interaction existed).

Hydraulic models of IWS can be used to evaluate and/or optimize opportunities to improve IWS network performance. Successful improvements to most IWS networks would result in increased pressure and supply duration. Hence, we strongly recommend that flow-restricted modelling methods be avoided when evaluating and/or optimizing IWS networks. If based on flow-restricted models, optimized IWS improvement strategies are likely to underestimate the withdrawal rates of advantaged consumers and underestimate inequality between consumers, and consequently may fail to correspond to optimal improvement strategies in physical IWS networks.

5 CONCLUSIONS & RECOMMENDATIONS:

The presented analysis emphasizes the importance of adopting a modelling method that fits both the modelling purpose and the nuances of consumers in IWS. Utilities and regulators should carefully assess the consumer behaviour in their context and select a modelling method that reliably portrays the behaviour. Based on the performance of the reviewed modelling methods, we suggest that:

- When IWS networks operate with supply durations shorter than needed for any consumers, unrestricted and volume-restricted methods agree and are best suited to simulate the hasty withdrawals we expect from unsatisfied consumers.
- When supply durations are perceived by consumers to be unreliable, flow-restricted methods are not recommended as consumers are unlikely to withdraw water slower than hydraulically possible.
- When network pressures are above the desired head for at least a few consumers, volume-restricted methods provide a more realistic prediction of consumer withdrawals. Otherwise, when network pressures are below the desired head for all consumers, all three methods are equivalent.
- When the phenomenon of interest occurs over multiple supply cycles, flow-restricted methods are the only EPANET-based method currently available
- When flow-restricted methods are preferred, the native PDA option supersedes the need for other FCV-based implementations

Research on the optimization and improvement of IWS networks is important and meaningful, especially when the modelling methods employed carefully represent the consumer's behaviour in IWS. We submit that flow-restricted methods are ill-suited to simulate IWS networks where pressures exceed the desired head for a considerable portion of consumers and thus are ill-suited to model an IWS network's transition to continuous supply.

Volume-restricted methods appear to allow for a wider range of non-idealized consumer behaviours. Unfortunately, to date, no EPANET-based volume-restricted approach can model an IWS network beyond the end of one supply duration. The development of volume-restricted methods that can simulate multiple cycles of intermittent operation, while conserving mass, would provide a more robust basis for optimizing and improving IWS networks and thus should be a priority for future work.

Future research should also be directed towards improving and validating assumptions about consumer behaviour, as well as developing modelling methods to capture these improved assumptions. Such research could significantly improve our ability to evaluate, improve and even optimize the performance of achieving SDG 6.1. Given that approximately 1 billion people (21% of piped water consumers) depend on intermittent supplies for their daily demands, research on IWS modelling is still relatively scarce. We commend the research done to date and call for more, urgently.

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