SUPPLEMENTAL MATERIALS

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How to Model an Intermittent Water Supply: Comparing Modeling Choices and Their Impact on Inequality

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Supplemental Text

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Text S1. Extended methods for modelling pressure dependence in EPANET

The pressure dependence of demand in many IWS modelling methods is enforced with artificial elements. A given method may use an emitter, a minor loss or a major loss (e.g., via pipe length or diameter) to achieve the desired flow resistance.

Emitter sizing

Flow through an emitter in EPANET flows according to:

Eq. S1. Flow through an emitter in EPANET

$$Q = C_E H^{\alpha}$$

Where Q is the flow out of the emitter (to the consumer), C_E is the emitter's coefficient and α is the emitter's exponent. We assumed, following (Abdy Sayyed et al. 2015) that $\alpha = 0.5$.

Eq. S2. Emitter coefficient for head-flow relationship in FCV-EM

$$C_E = \frac{Q_{des}}{(H_{des} - H_{min})^{\alpha}}$$

Minor loss sizing

The minor (local) head losses in EPANET behave according to:

Eq. S3. Minor Headloss Equation in EPANET

$$h_{minor} = K_{minor} \frac{8Q^2}{g\pi^2 D^4}$$

Where h_{minor} is the minor head loss and K_{minor} is the minor loss coefficient. Accordingly, we can mimic the desired head-flow relationship by selecting:

Eq. S4. Minor Loss coefficient to match the head-flow relationship in FCV-Res and PSV-Tank

$$K_{minor} = (H_{des} - H_{min}) \frac{g\pi^2 D^4}{8Q_{des}^2}$$

Where K_{minor} is the pipe's minor loss coefficient, D is the artificial pipe's diameter (selected arbitrarily as 350 mm, following Sivakumar et al. (2020), and Q_{des} is the consumer's desired flow rate. Only one pipe of the artificial element arrangement is assigned a minor loss coefficient.(Gorev and Kodzhespirova 2013)

Length sizing

The Hazen-Williams equation can be rearranged to solve for the desired major loss associated with the pipe's length (or diameter). We implemented length-based major losses according to:

Eq. S5. Pipe length to match major losses to the head-flow relationship in CV-Tank and CV-Res

$$L = (H_{des} - H_{min}) \frac{C^{1.852} D^{4.87}}{10.67 Q_{des}^{1.852}}$$

Where L is the artificial pipe's length, C is the Hazen-Williams Coefficient (Selected as 130 in this paper), and D is the artificial pipe's diameter (selected as 350 mm for all consumers).

Tank Sizing

In addition to pressure dependent flows achieved with the above loss elements, volume limited methods employed a tank with diameter:

Eq. S6. Tank Diameter for CV-Tank and PSV-tank

$$D_{tank} = \sqrt{\frac{4V_{des}}{\pi \, h_{tank}}}$$

Where D_{tank} is the tank's diameter, and h_{tank} is the tank's maximum useable height (set at 1 metre in this paper).

Table S1. Classification of 30 studies that proposed or employed hydraulic modelling methods for IWS networks

Platform	Consumer Withdrawal Model	Study	IWS Phases Modelled			Notes
			Filling	Pressurized	Draining	
EPANET	Unrestricted	(Batish 2003) (Ang and Jowitt 2006) (Mohapatra et al. 2014)		✓		
	Volume-Restricted	(Batterman and Macke 2001) (Ingeduld et al. 2006) (Fontanazza et al. 2007) (Cabrera-Bejar and Tzatchkov 2009) (Ameyaw et al. 2013) (Taylor et al. 2019) (Sivakumar et al. 2020)		✓		
	Flow-Restricted	(Jinesh Babu and Mohan 2012) (Siew and Tanyimboh 2012) (Gorev and Kodzhespirova 2013) (Sivakumar and Prasad 2014, 2015) (Abdy Sayyed et al. 2015) (Mahmoud et al. 2017) (Paez et al. 2018) (Neelakantan and Rohini 2021)		✓		1
	Flow- & Volume-Restricted	(Suribabu et al. 2022)		✓		
EPA-SWMM	Volume-Restricted	(Segura 2006) (Cabrera-Bejar and Tzatchkov 2009) (Shrestha and Buchberger 2012)	✓	✓		
		(Campisano et al. 2019a) (Gullotta et al. 2021)	✓	✓	✓	

EPA-SWMM	Flow-Restricted	(Kabaasha 2012) (Dubasik 2017) (Campisano et al. 2019b)	✓	✓		
Custom	Volume-Restricted	(De Marchis et al. 2010)	✓	✓		2
		(Mohan and Abhijith 2020)	✓	✓	✓	2, 3
	None	(Lieb et al. 2016)	✓			2

1 Proposed for Pressure-Deficient Continuous Water Supply networks but has been repurposed for IWS
2 Source code not available
3 Issues with mass conservation

Table S2. Description of Compared Pressurized IWS (EPANET) methods

Consumer Withdrawal Model	Method	Based on	Artificial Elements	Pressure-dependence
Flow-Restricted	EPANET-PDA	Native to EPANET	None	-H_{min}, H_{des} and $1/n$ input natively
	FCV-Res	(Gorev and Kodzhespirova 2013)	-Flow Control Valve (FCV) -Artificial Reservoir	-Reservoir raised by H_{min} -FCV set to Q_{des} -H_{des} *and* n set in Local Loss Coefficient
	FCV-EM	(Abdy Sayyed et al. 2015)	-Flow Control Valve (FCV) -Node with Emitter	-Emitter raised by H_{min} -FCV set to Q_{des} -emitter exponent = $1/n$ - H_{des} set in emitter coefficient
Volume-Restricted	CV-Tank	(Batterman and Macke 2001) (Taylor et al. 2019)	-Pipe with Check Valve (CV) -Tank of Volume V_{des}	-Tank raised by H_{min} -Distributed Losses adjusted to simulate H_{des}, Q_{des} *and* n
	PSV-Tank	(Sivakumar et al. 2020)	-Pressures-Sustaining Valve (PSV) -2 Connecting Nodes (Dummy) -2 Pipes with CV -Tank of Volume V_{des}	-PSV set to H_{min} -H_{des}, Q_{des} *and* n set in Local Loss Coefficient
Unrestricted	CV-Res	(Mohapatra et al. 2014)	-Pipe with CV -Artificial Reservoir	-Reservoir raised by H_{min} -Distributed Losses adjusted to simulate H_{des}, Q_{des} *and* n

Detailed notes on how to size components for a given pressure-dependence, see section Text S1.

Table S3. Detailed implementation of flow-restricted and unrestricted methods as used in this study

Method	**Artificial Pipe**					**Artificial Node**	**Artificial Valve**		**Artificial Reservoir**	**Emitter**	
	D (mm)	**L (m)**	**HW Coeff.**	**K_{minor}**	**Status**	**Elevation**	**Type**	**Setting**	**Elevation**	**Elevation**	**Coefficient**
EPANET-PDA	-	-	-	-	-	-	-	-	-	-	-
FCV-Res	350	0.1	130	Eq. S4	CV	z_{orig}	FCV	Q_{des}	$z_{orig} + H_{min}$	-	-
FCV-EM	350	0.1	130	0	CV	z_{orig}	FCV	Q_{des}	-	$z_{orig} + H_{min}$	Eq. S2
CV-Res	50	Eq. S5	130	0	CV	z_{orig}	-	-	$z_{orig} + H_{min}$		

Where z_{orig} is the elevation of the original demand node and all else defined as before.

Table S4. Detailed implementation of volume-restricted methods as used in this study

Method	Artificial Pipe(s)					Artificial Node(s)	Artificial Valve		Artificial Tank		
	D (mm)	L (m)	HW Coeff.	K_{minor}	Status	Elevation	Type	Setting	Elevation	Diameter	Height (m)
CV-Tank	50	Eq. S5	130	0	CV	-	-	-	$z_{orig} + H_{min}$	Eq. S6	1
PSV-Tank[1]	350	0.1	130	Eq. S4 & 0	CV	z_{orig}	PSV	H_{min}	$z_{orig} - 1$	Eq. S6	1

[1] Where the two pipes differed, values are ordered upstream to downstream. One value means the same in both pipes.

Table S5. Execution time of IWS simulations using all 6 EPANET-based methods in milliseconds per run (Average of 1,000 timed runs). The similarity of run times between 4-hr and 12-hr simulations in some scenarios likely indicates the solvers use of more iterations to resolve the increased prevalence of pressure-dependent behaviour in the shorter, lower pressure simulations.

Network	Supply Duration (hr)	Flow-Restricted			Volume-Restricted		Unrestricted
		FCV-EM	FCV-Res	EPANET-PDA	CV-Tank	PSV-Tank	CV-Res
1	4	4.18	3.91	2	3.29	5.44	2.76
	12	4.33	3.9	1.99	3.43	5.41	2.77
2	4	6.75	6.13	2.62	4.98	8.58	4.05
	12	6.44	6.13	2.67	4.99	8.54	4.1
3	4	23.69	21.69	8.8	17.61	31.84	13.82
	12	24.46	22.33	8.79	17.19	32.81	13.84

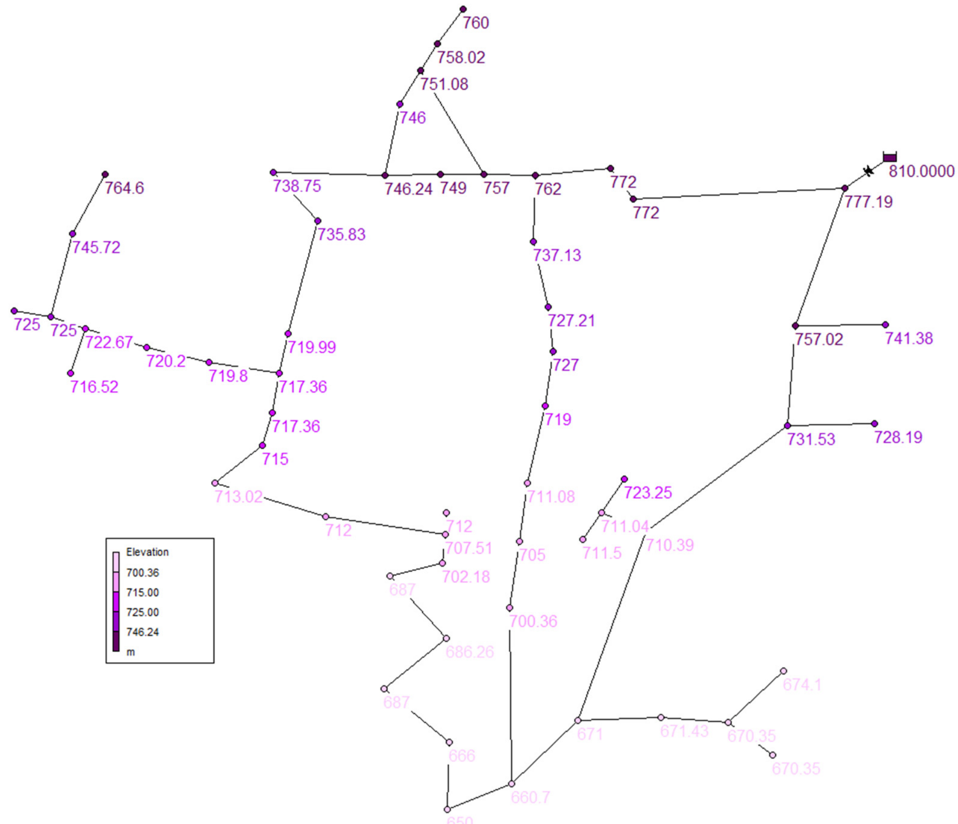

Fig. S1. Network 1 Layout and elevations as proposed by (Campisano et al. 2019b).

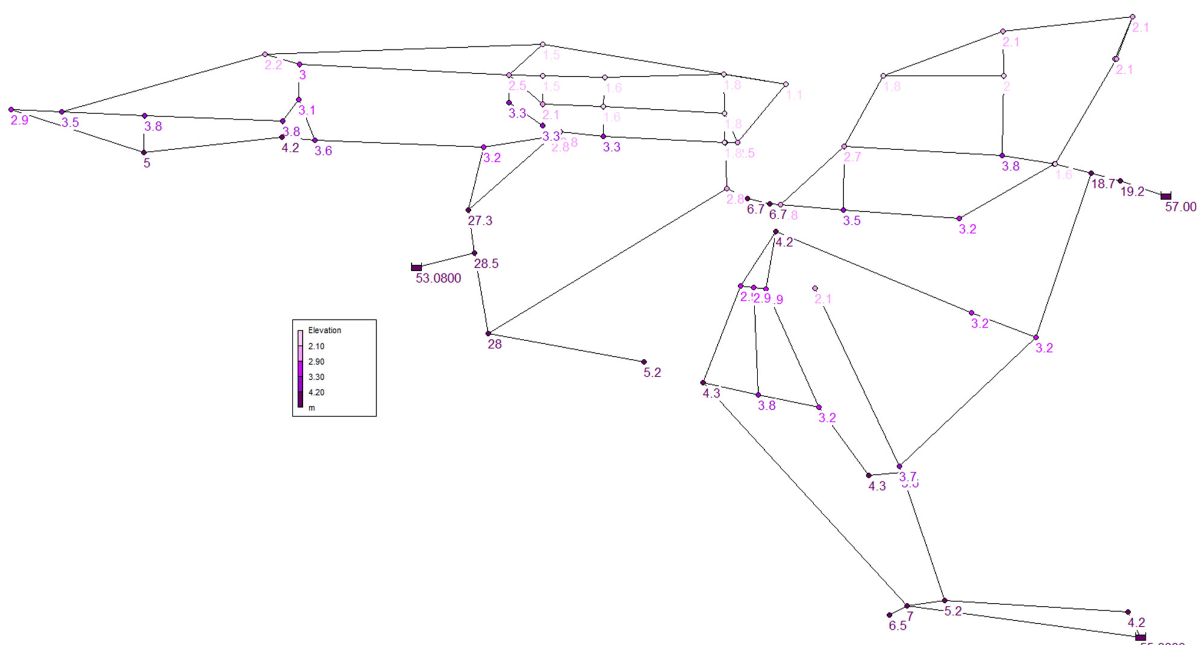

Fig. S2. Network 2 Layout and elevations as proposed by (Bragalli et al. 2012).

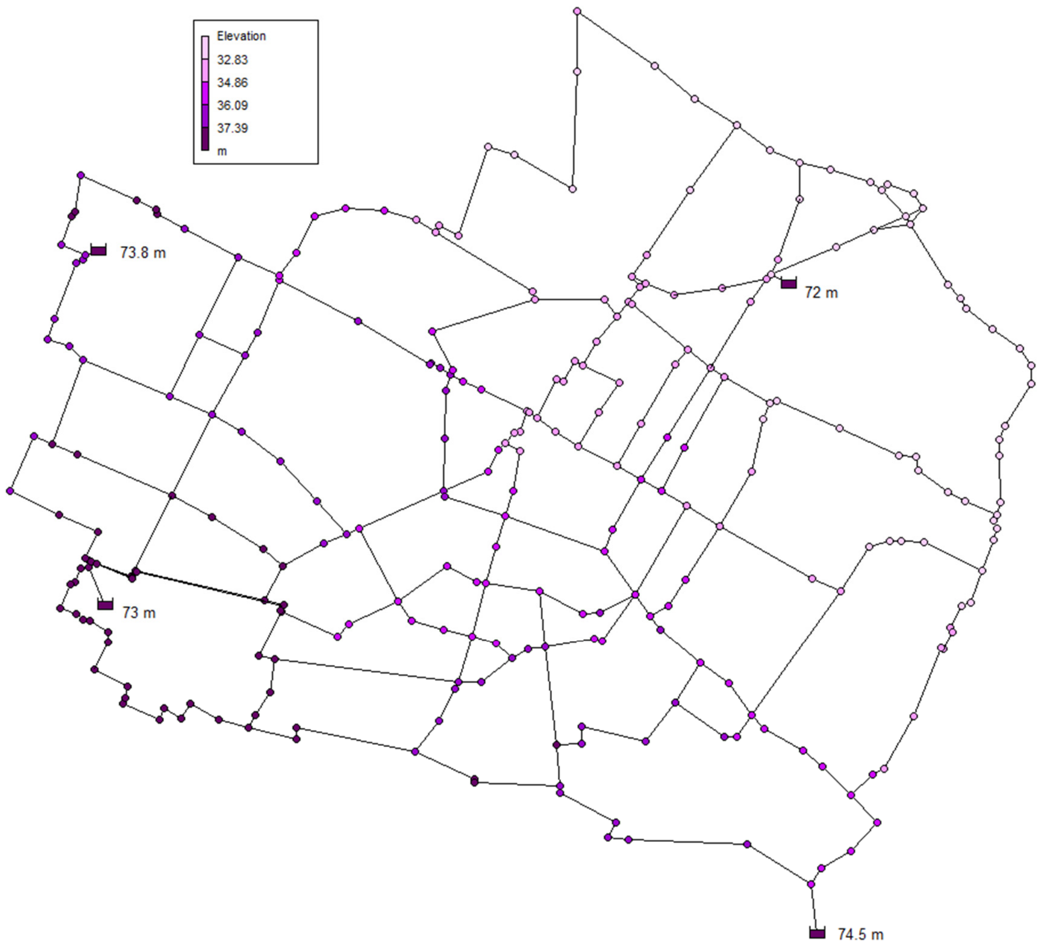

Fig. S3. Network 3 Layout and elevations as proposed by (Bragalli et al. 2012).

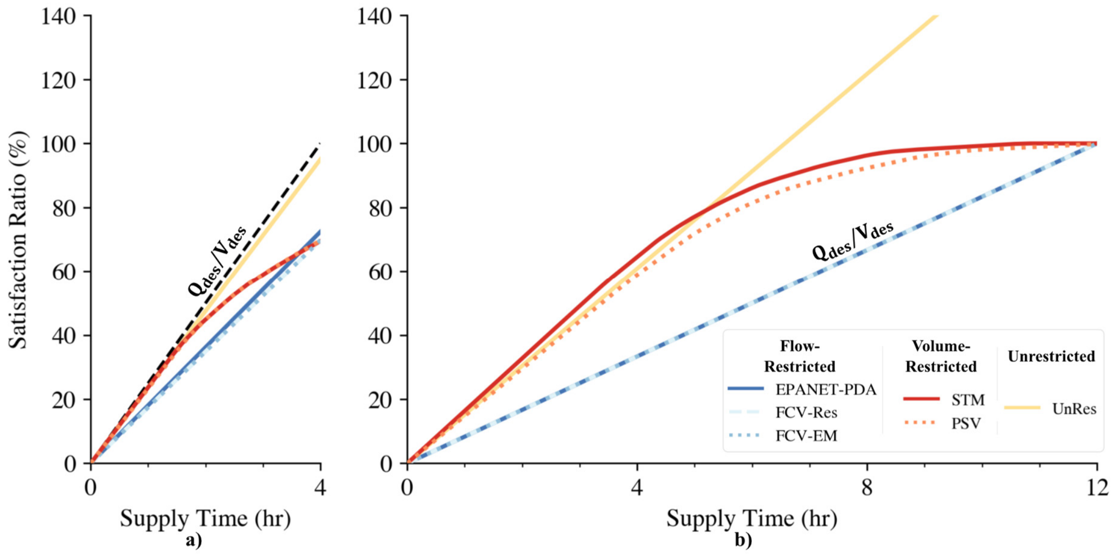

Fig. S4. The mean demand Satisfaction Ratio (delivered/desired volume) in Network 1 during a supply of a) 4 hours/day and b) 12 hours/day when consumers are modelled using flow-restricted methods: EPANET's PDA (Blue), FCV-Res (Dashed Light Blue), and FCV-EM (Dotted Light Blue), volume-restricted methods: Simple Tank (Red) and PSV (Dotted Orange), and unrestricted methods: such as Res (Yellow). Corresponding figure: Fig. 1.

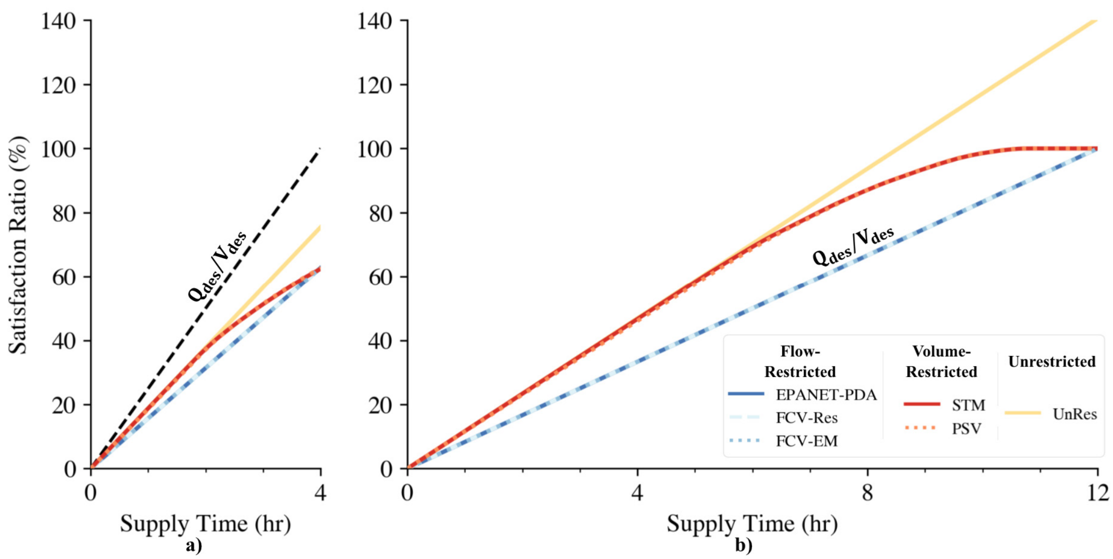

Fig. S5. The mean demand Satisfaction Ratio (delivered/desired volume) in Network 2 during a supply of a) 4 hours/day and b) 12 hours/day when consumers are modelled using flow-restricted methods: EPANET's PDA (Blue), FCV-Res (Dashed Light Blue), and FCV-EM (Dotted Light Blue), volume-restricted methods: Simple Tank (Red) and PSV (Dotted Orange), and unrestricted methods: such as Res (Yellow). Corresponding figure: Fig. 1.

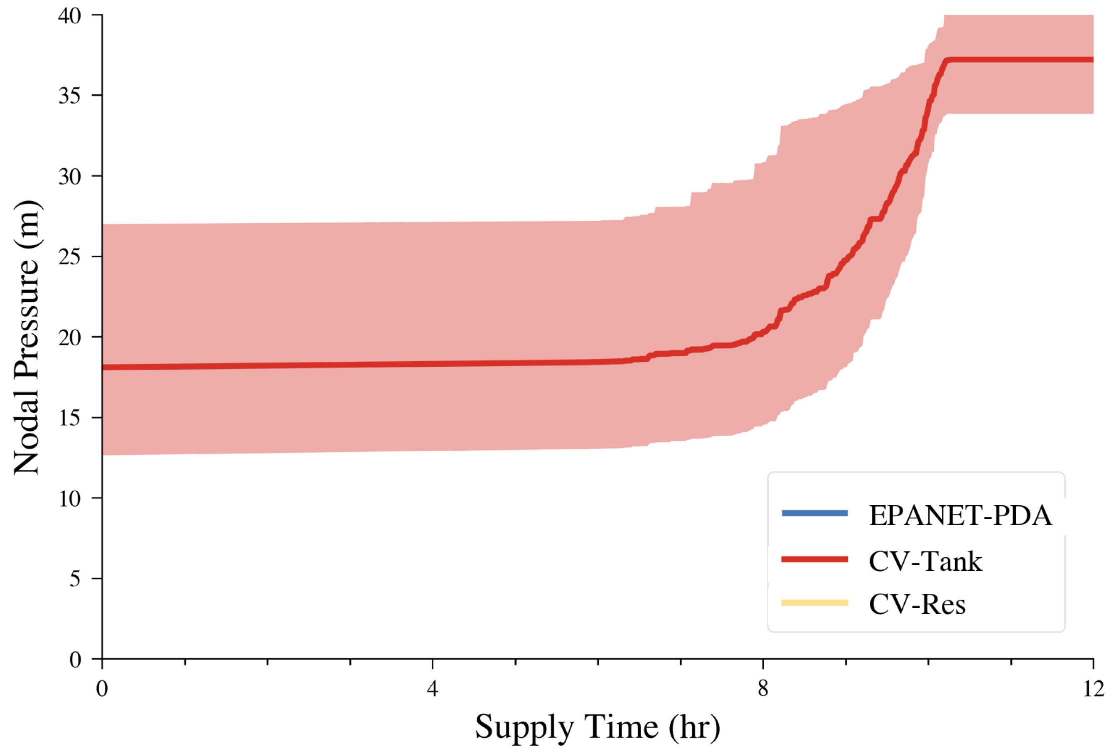

Fig. S6. Mean Nodal Pressure (Solid) and its 10^{th} to 90^{th} Percentile range (Shaded) for an unrestricted, a volume-restricted and a flow-restricted method in Network 3.

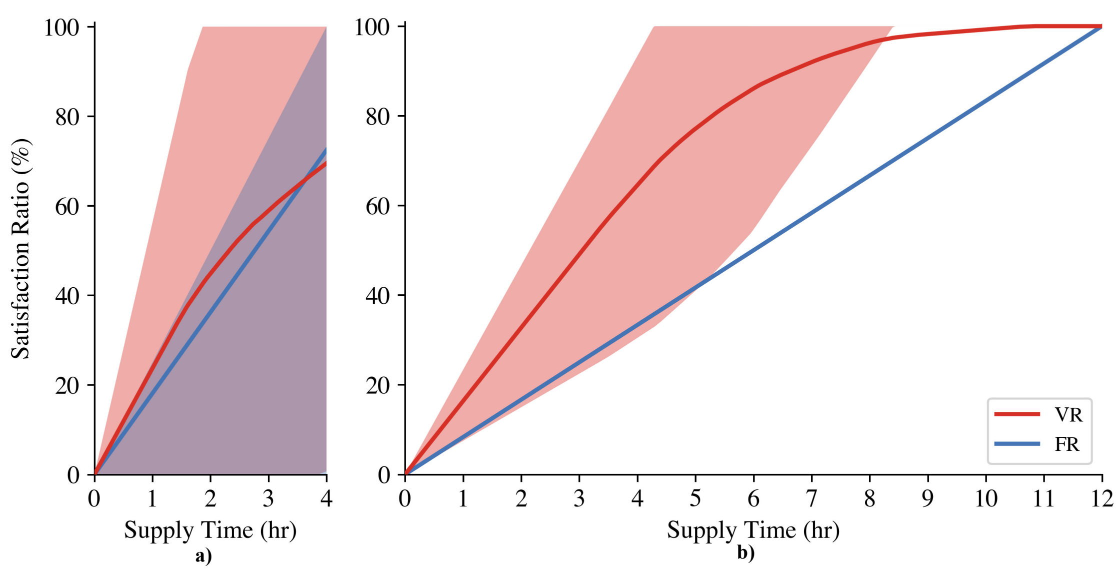

Fig. S7. Mean satisfaction ratio (Solid line) and satisfaction ratio ranging from the 10^{th} to 90^{th} percentile consumers (shaded) in Network 1 for a Flow-Restricted (FR) and a Volume-Restricted method (VR) over a a) 4-hr supply duration and b) 12-hr supply duration. Corresponding figure: Fig. 3.

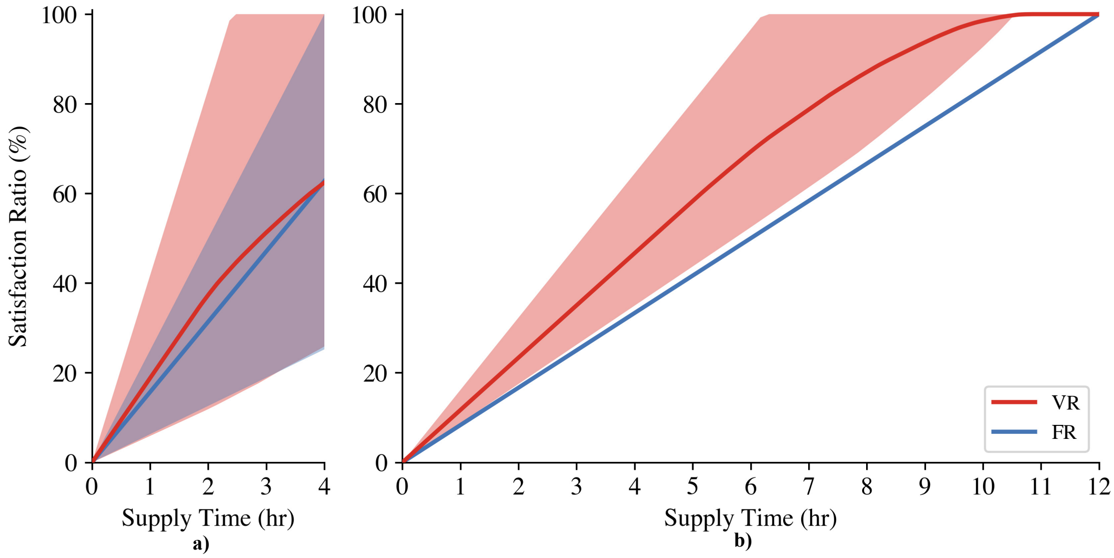

Fig. S8. Mean satisfaction ratio (Solid line) and satisfaction ratio ranging from the 10th to 90th percentile consumers (shaded) in Network 2 for a Flow-Restricted (FR) and a Volume-Restricted method (VR) over a a) 4-hr supply duration and b) 12-hr supply duration. Corresponding figure: Fig. 3.

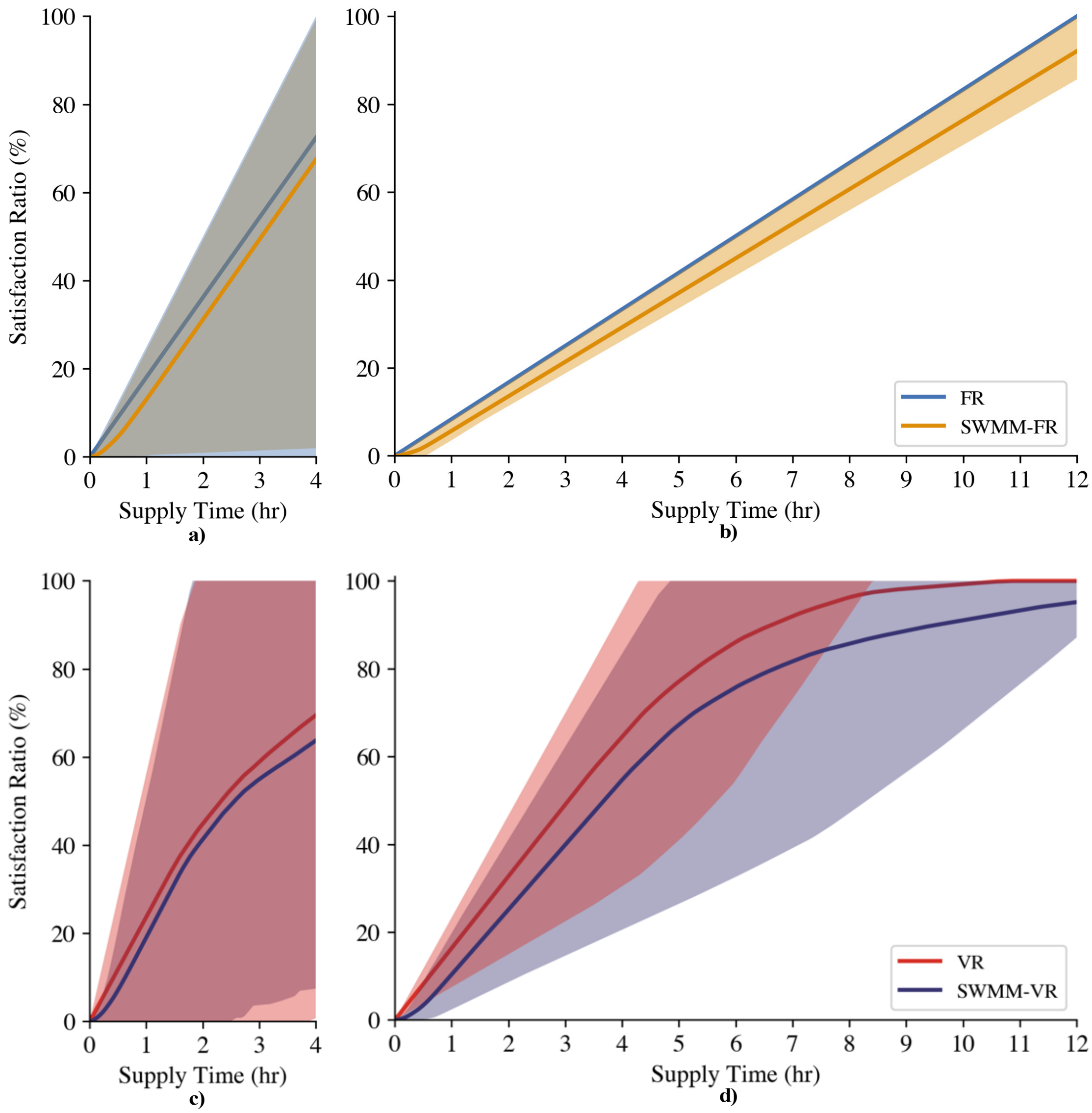

Fig. S9. Predicted mean satisfaction ratio and its range (10th-90th) in Network 1 with a flow-restricted method ignoring filling (FR) and including filling (SWMM-FR, and a volume-restricted method ignoring filling (VR) and including filling (SWMM-VR) under a 4 hours/day supply (a and c) a 12 hours/day supply (b and d). Corresponding figure: Fig. 4.

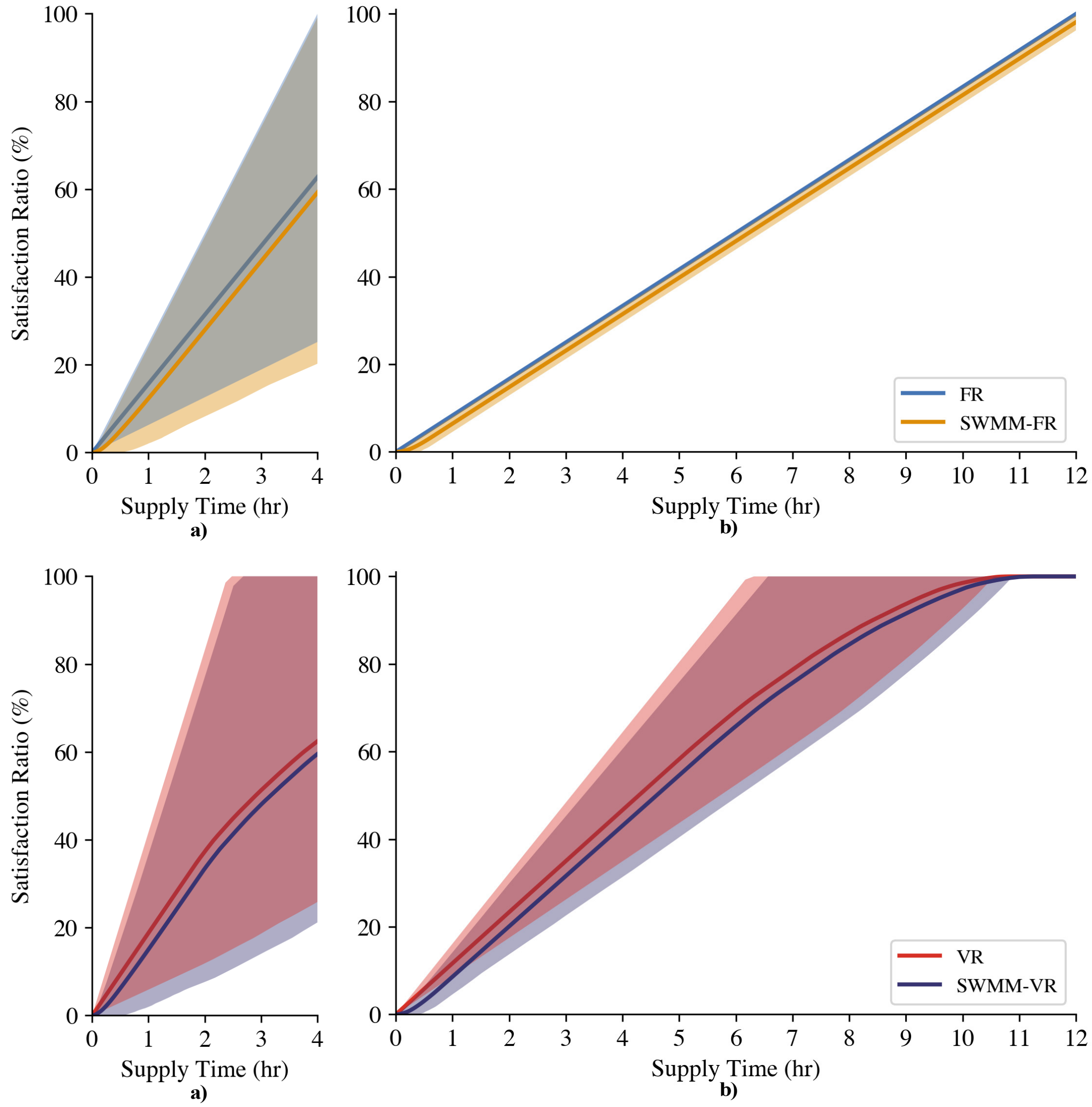

Fig. S10. Predicted mean satisfaction ratio and its range (10th-90th) in Network 2 with a flow-restricted method ignoring filling (FR) and including filling (SWMM-FR, and a volume-restricted method ignoring filling (VR) and including filling (SWMM-VR) under a 4 hours/day supply (a and c) a 12 hours/day supply (b and d). Corresponding figure: Fig. 4.

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