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HOUSEHOLD BEHAVIOUR AND ENERGY LOSS IN INTERMITTENT WATER SUPPLY NETWORKS

Hamidreza Mohabbat[1] and David D. J. Meyer[2]

[1,2] Centre for Global Engineering, Department of Civil & Mineral Engineering, University of Toronto, Toronto, ON, Canada

[1] *H.Mohabbat@mail.utoronto.ca*, [2] *David.Meyer@utoronto.ca*

Abstract

Intermittent water supply (IWS) networks are a problematic reality for over one billion people. Despite their drawbacks, IWS networks persist, and projects to convert them to continuous supply often fail. Here we explore one reason such projects might fail: the energy loss associated with IWS. Under IWS, water is delivered over a shorter period, increasing flow rates and thereby increasing energy losses. Could this energy loss prevent utilities from increasing their supply durations?

To explore this question, we built two IWS versions of the Modena water network in EPANET. All households were assumed to withdraw water either i) as hastily as possible or ii) as patiently as possible. Artificial tanks and emitters modelled household storage and network leakage, respectively. Artificial tanks filled quickly, mimicking hasty withdrawals. To model patient withdrawals, a flow control valve was installed upstream of the tank, distributing withdrawals evenly throughout the duration of water supply.

Simulations showed that when households withdraw hastily, energy losses strictly increase as the supply continuity of the network increases. Conversely, when households withdraw water patiently, energy losses increase initially, reach at least one maximum, and then decrease as supply continuity increases. Our results suggest that since energy losses often increase as utilities increase continuity, energy loss could obstruct some utilities from increasing supply continuity and from achieving continuous supply. We also found clear evidence that network behaviour strongly depends on the hastiness of household withdrawals. We also found that when networks with patient households are supplied with ample continuity, leakage can substantially influence the energy loss. We recommend additional theoretical and field research on IWS investigate the pace at which household withdrawals occur.

Keywords
Intermittent water supplies, water distribution networks, Global South, energy loss, artificial string, EPANET.

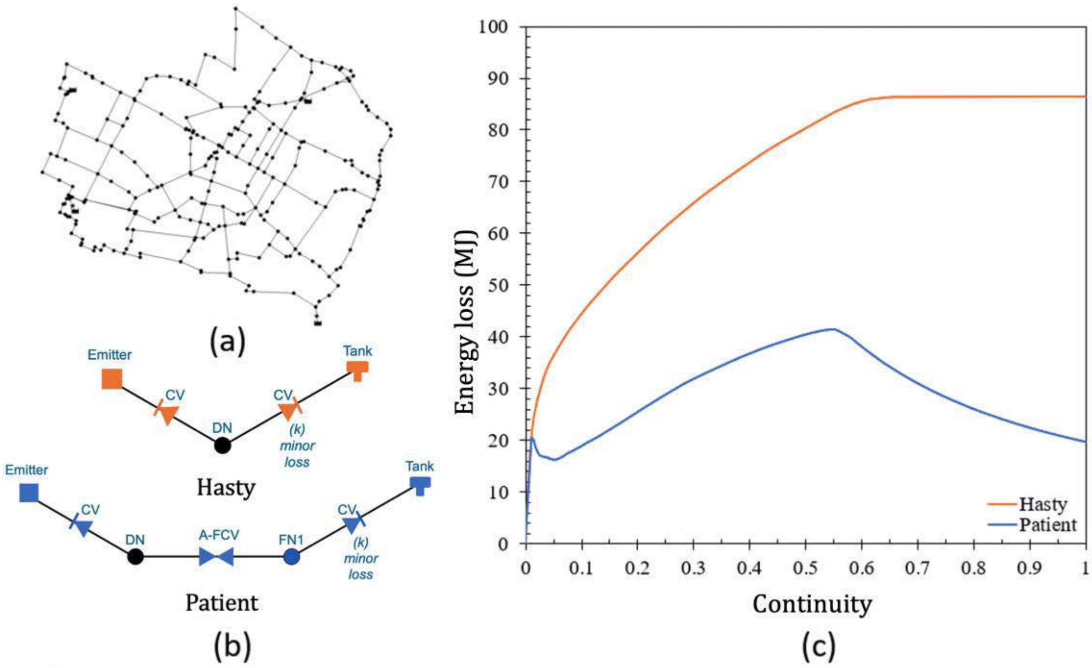


Figure 1 Visual Abstract, (a) Modena network before modification, (b) Artificial strings representing hasty and patient households in EPANET, (c) Energy loss versus water supply continuity in the modified Modena network, with hasty and patient households.

1 INTRODUCTION

Intermittent water supply (IWS) networks supply water for less than 24 hours per day, seven days a week [1]–[3]. Such networks serve over one billion people [4]. Many utilities resort to IWS when faced with water shortages [4] since intermittent operation can temporarily suppress leakage and consumer withdrawals [5]–[8]. Unfortunately, however, IWS worsens water quality and equality and complicates network hydraulics.

Given the drawbacks of IWS, many policies promote continuous water supply, or at least increasingly continuous supply (e.g., India launched new national 24x7 water policies and guidelines in 2021 and 2022 [9], [10]). But efforts to transition intermittent networks towards continuous supply often fail for varied and poorly understood reasons [11], [12]. To explain the persistence of IWS networks, some have suggested insufficient source water or treatment capacity, poor network management, and/or unsustainably high consumption [2], [13]. But to date, little attention has been given to energy losses in IWS networks.

We hypothesize, that energy losses are an important factor preventing some IWS networks from increasing their supply continuity. Under IWS, flow rates are high, which increases friction and induces a high rate of power loss in the network [14]. As an intermittent utility tries to increase its supply, flow rates and therefore power losses will decrease. But energy losses depend on the rate and duration of power loss. So as an IWS increases its supply duration, we expect power loss to decrease, but will that decrease outpace the increase in duration?

To evaluate potential barriers to 24x7 supply, previous research has often deployed hydraulic models of IWS [15]–[17]. These models included a variety of assumptions about how households respond to IWS [15]–[17]. Field research in IWS has consistently confirmed that households store water in response to IWS [2], [4], [18], but provides little detail on the rate at which household storage is filled. Without details on the rate of water withdrawals, flow and energy loss cannot be modelled.

This paper aims to provide quantitative evidence about the degree to which energy losses in IWS may thwart utility attempts to increase water supply duration. To do so we:

1. Propose two types of household withdrawal behaviour and construct EPANET models representing them;
2. Quantify how energy loss varies across simulations of these models for different supply durations;
3. Evaluate the degree to which energy losses may help explain the persistent of IWS; and
4. Assess the influence of the network leakage on energy loss.

2 DEFINITIONS AND MODELS

2.1 Water Supply Continuity Definitions

IWS networks vary in how often (frequency) they are pressurized and for how long (duration). We track the frequency of supply (e.g., every other day) by its inverse: the supply period (T). We define the average length of time during which a network is supplied with water as the supply duration (τ). Finally, we combine these metrics together to define the *supply continuity* (c) as the average percent of the time that a network supplies water: $c = \tau/T$. For instance, a network that provides water for a duration 4 hours ($\tau = 4\ hrs$) every four days would have a supply continuity of $c = 4\ hrs/4 * 24\ hrs = 4.2\%$, equivalent to the continuity of a network that runs for one hour ($\tau = 1\ hr$) every day.

2.2 Household Behaviour Types

Taylor et al. (2019) suggested that households in an IWS desire a certain volume of water per day, and as soon as they withdraw (i.e., satisfy) this demanded volume, they cease withdrawing water [8]. Through EPANET-based simulations, they showed that if an IWS network runs long enough, household demand becomes satisfied, and the qualitative behaviour of the network changes. In this paper, we denote the average percent of the time that an IWS must operate to satisfy households who withdraw water as fast as they can as the *satisfaction continuity,* c_s. For convenience, we similarly denote the supply duration required to satisfy such households as the *satisfaction duration*, $\tau_s = c_s T$.

Beyond the existence of a satisfaction threshold, little is known about the time-dependent and continuity-dependent behaviour of households in IWS. To explore the effects of household behaviour, we construct two models for how households withdraw water over time by imagining two types of household behaviour: hasty and patient.

Hasty households **withdraw water as fast as possible**; the received flow rate for a hasty household can be modelled as:

$$Q_{\text{Hasty}}(t) = \begin{cases} \frac{V_s T}{\tau_s} = \mathrm{Q_{max}} & \text{for } t < \tau_s \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

where V_s is the household's desired water demand per day and τ_s is the satisfaction duration – the minimum required supply duration for the network to satisfy a household who hastily withdraws water, e.g., by leaving all taps and tanks open [6]. The satisfaction duration, τ_s, depends on the supply period (T) and the satisfaction continuity (c_s), while c_s depends only on physical network attributes and the household satisfaction volume (V_s). Hasty households, by definition, withdraw water as fast as hydraulically possible and so we sometimes denote it as $\mathrm{Q_{max}}$.

Patient households **spread their demand over the supply duration;** hence, the received flow rate for a patient household depends on the continuity of the network. When the supply continuity is greater than the satisfaction continuity, a patient household utilizes the entire supply duration (τ) to withdraw its desired satisfaction volume: the daily desired volume, V_s, times the period of supply, T. When $c < c_s$, a patient household's withdrawal rate is equal to a hasty household's: both are limited by network hydraulics:

$$Q_{\text{Patient}}\,(t) = \begin{cases} \dfrac{V_s T}{\tau_s} = \mathrm{Q}_{\max} & \text{for } c < c_s \\ \dfrac{V_s T}{\tau} & \text{Otherwise} \end{cases} = \frac{V_s T}{\max(\tau_s, \tau)} \qquad (2)$$

To explore the difference between these behaviours, consider a household supplied with water daily ($T = 1$), with a satisfaction continuity of 25% and in a network with a supply duration of 18 hours ($\tau = 18$ hrs, so $c = 75\%$). In this example, the satisfaction duration is $\tau_s = c_s T = 25\% *$ 24 hours = 6 hors. During the first 6 hours of supply in this example, a hasty household would receive a flow rate of $V_s T/\tau_s$; thereafter (the remainder of the supply duration, 12 hours) the hasty household will neither demand nor receive any water. Contrastingly, a patient household would utilize the entire supply duration (18 hours) to withdraw its desired volume $V_s T$. In this example both household types are ultimately satisfied and the initial flow rate to a hasty household is three times larger than to a patient household (Figure 2).

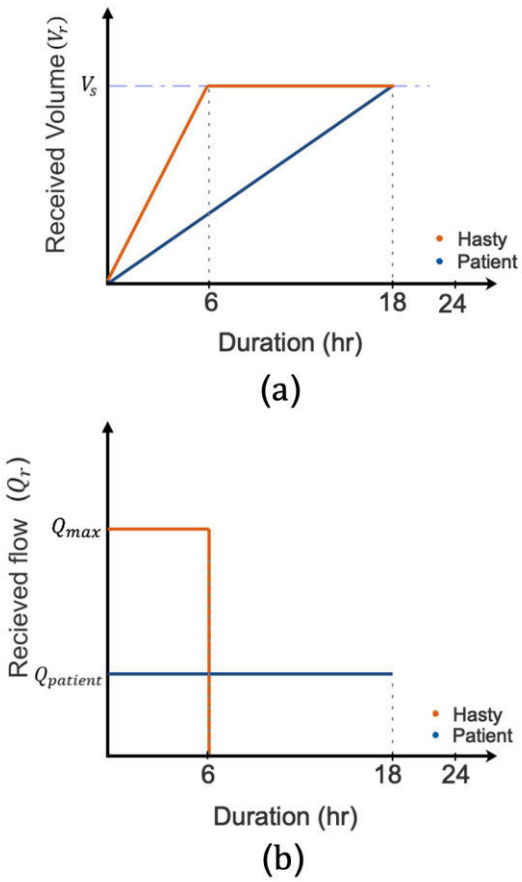


Figure 2 An example of how household type (hasty vs. patient) changes the received volume (a) and flow rate (b) over time in a network with daily supply of 18 hours/day and in which hasty households can be satisfied in only 6 hours.

If the network had operated for less than the required satisfaction continuity (c_s), neither of the households could have fulfilled their desired demand and both would withdraw water at maximum hydraulically feasible flow rate: $Q_{\max}$.

2.3 EPANET Construction

To explore the effect of hasty and patient households in a network, we converted a model of the Modena network (a continuous water supply, CWS) to behave like an intermittent one. Artificial tanks and emitters modelled household storage and network leakage, respectively. Artificial tanks filled quickly, mimicking hasty households. To model patient households, we installed artificial flow control valves upstream of the household tanks to distribute household withdrawals evenly throughout the supply duration.

2.3.1 Hasty Households in EPANET

Our EPANET model of hasty households is based on a method proposed by Batterman and Macke (2001), sometimes called the simple tank method (STM) [19]. Following the STM methodology, a CWS model can be modified to mimic an IWS by splitting demand at each of its nodes into hastily withdrawing households and leakage. Specifically, the STM adds two artificial strings per CWS demand node. Hasty households are represented by an artificial storage tank. Network leakage is represented by an artificial emitter. Both strings also include check valves to prevent reverse flow. The final composition of the strings is depicted in Figure 3.

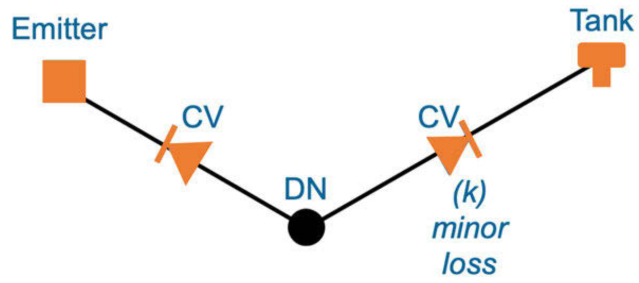


Figure 3 Schematic of the strings representing leakage and hasty households in EPANET, including the original demand node (DN) and two check valves (CV) connecting to an emitter and tank.

The parameters of the artificial strings depend on an assumed daily demand of an averageIWS household (V_s) and a network-wide leakage fraction [8]. The original demand of each CWS node is then split into leakage using an emitter and a tank-based representation of *N* hasty households, where *N* is determined based by the ratio of V_s to the demand at the CWS node (after subtracting leakage) [11]. By further assuming the hydraulic properties of a typical hasty household's service connection pipe and tank, the equivalent hydraulic attributes of *N* hasty households can be computed using formulations proposed by Batterman and Macke (2001) and summarized with increased specificity in Table A-2 [16]. The volume of each artificial tank is set to represent the combined demand of all *N* households represented by the original CWS node (detailed equations in Table A-2). The volume of these tanks corresponds to the households' combined daily demand, not the volume of their physical storage tanks.

Leakage is represented by an artificial string connecting an emitter to the original demand node (DN) via a check valve (Figure 3). The pipe is assumed to have a length of 1m, a roughness of 130 (Hazen-Williams), no minor losses, and a diameter equal to the average of connecting pipes at DN. The leakage flow through the emitter attached to demand node 'k' ($Q_{l,k}$) depends on the nodal pressure at the emitter (h_k), and the emitter discharge coefficient (C_k):

$$Q_{l,\mathrm{k}} = C_k h_k^{\alpha} \quad (3)$$

where α is the emitter's pressure exponent in the absence of network data, we assume $\alpha = 1$ [20]. Here, we set the emitter coefficient by i) assuming leakage is a defined portion (β) of the original demand node in the leak-free CWS, and ii) assuming pressure head is 30 m. Hence:

$$C_k = \frac{Q_{l,k}}{h_k^{\alpha}} \approx \frac{\beta Q_{T,k}}{\overline{h_n}} \approx \frac{\beta Q_{T,\mathrm{k}}}{30} \tag{4}$$

where $\overline{h_n}$ is the average pressure head through the network, β is the leakage portion, and $Q_{T,k}$ is the original node demand in the CWS state, measured in m^3/s.

2.3.2 Patient Households in EPANET

Patient households usually satisfy their demands at a lower, more controlled flow rate compared to hasty households. To mimic this withdrawal patience, we added a flow control valve (FCV) upstream of the artificial tank, keeping all other elements equivalent to the STM (Figure 4).

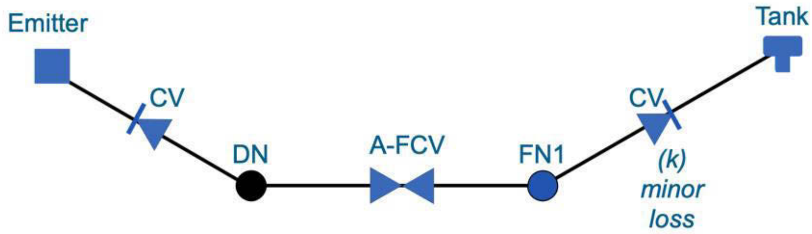


Figure 4 Schematic of the string representing leakage and patient households in EPANET, including the original demand node (DN), two check valves (CV), a fictitious node (FN) and an artificial flow control valve (A-FCV).

The flow setting for the described artificial valve is defined as:

$$Q_{FCV,k} = \frac{\overline{Q}_k T}{\tau} = \frac{0.85\ Q_{T,k} T}{\tau} \tag{5}$$

where $\overline{Q}_k$ is the household demand, here assumed as 85% of nodal demand in the leak-free CWS network ($Q_{T,k}$), and τ is the supply duration at which the network runs. As we are concerned with IWS networks that supply water at least occasionally, we assume τ>0.

In our accounting of energy losses, we focus on energy lost in the network (rather than in households' taps). As such, we do not include the head loss values occurring inside the A-FCVs in our computation of total energy loss.

2.4 Modena Network

The unmodified Modena network comprises 268 demand nodes, 317 pipes and four reservoirs [21]. The spatial household demand distribution for the original leak-free Modena network is depicted in Figure 5. Its EPANET data are publicly accessible on the Water Distribution System Research Database of the University of Kentucky [22]. We adapt the Modena network to minimize inter-reservoir flows by changing the reservoir connection pipes into check valves. Using the Water Network Tool for Resilience (WNTR 0.4.0) package in Scientific Python Development Environment (Spyder 5.0.5), hasty and patient versions of the Modena networks were generated [23].

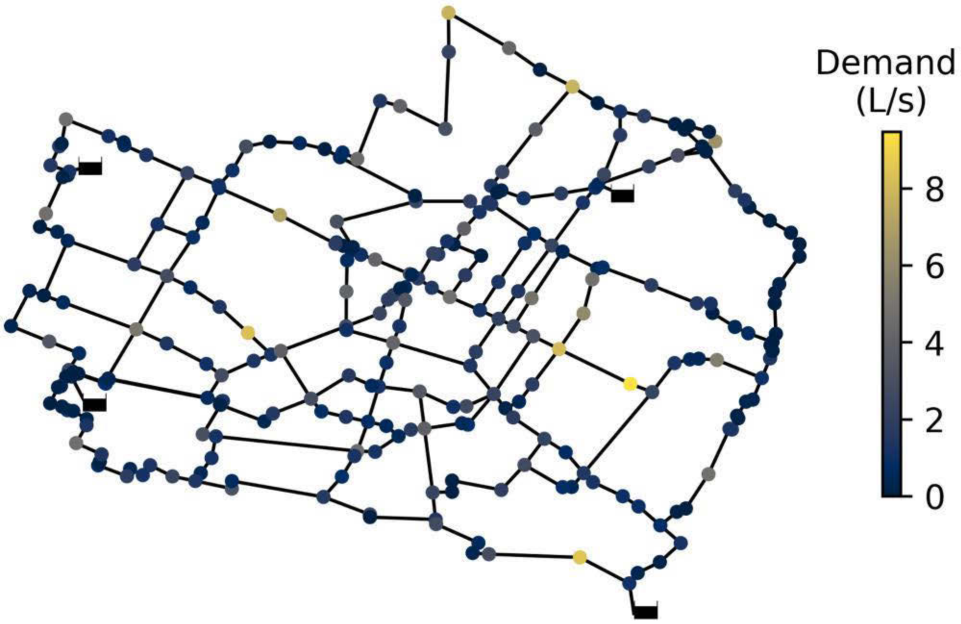


Figure 5 Spatial spread of Demand in Modena network (data originally published by [21])

2.5 Energy loss Calculation

To quantify the accumulated energy loss (E) during the supply duration (τ) in the hasty and patient Modena networks, energy loss was summed across all pipes (except the artificial flow control valves) and across all time steps:

$$E(\tau) = \gamma \sum_{t=0}^{\tau} \sum_{l=1}^{m} h_l Q_l \Delta t \quad (6)$$

where h_l, Q_l are the pipe-friction-induced head loss and flow rate in pipe l, Δt is the timestep (one minute), m is the number of pipes in the network, and τ is the supply duration (time during which the energy loss is accumulated). Note that E is the friction-induced energy loss and not the total energy supplied to the network.

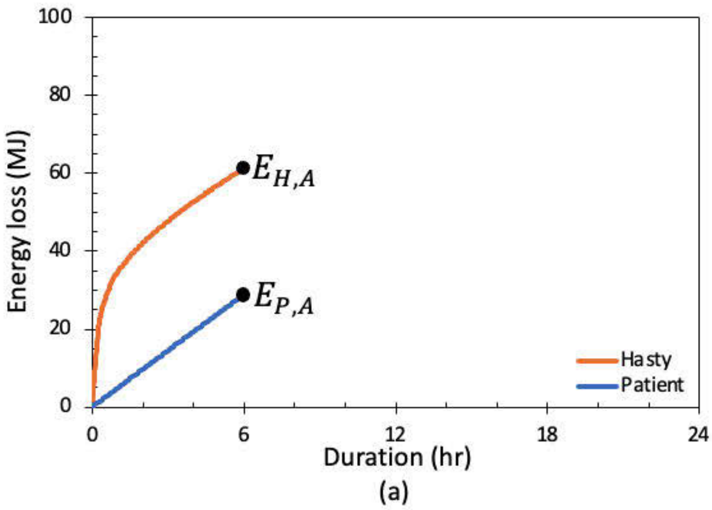
The energy loss caused by the short (1 m) pipes connecting emitters to demand nodes is included in this sum, but its contribution is minimal (<0.001%).

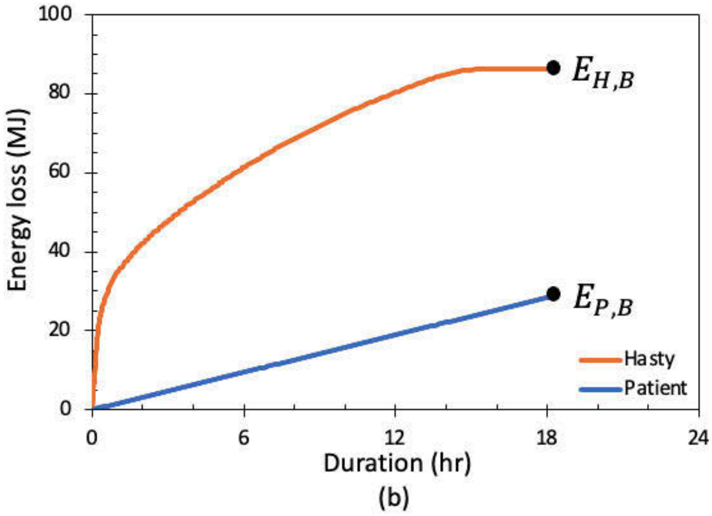
3 RESULTS AND DISCUSSION

3.1 Energy loss vs. duration and continuity

To explore how household type affects energy loss, we first plot energy loss over time for two specific scenarios: when households in the hasty and patient Modena networks know the network will operate for 6 hours (Figure 6a) and for 18 hours (Figure 6b) per day, corresponding to continuity levels of 25% and 75%. The energy loss curves for the hasty Modena network under the continuity of 25% (Figure 6a) and 75% (Figure 6b) coincide because hasty households race to withdraw as fast as possible, regardless of the continuity, resulting in coincident and monotonically increasing energy losses. Contrastingly, the energy loss curves for the patient Modena network have slopes that decrease as the continuity of the network increases from 25% to 75% because patient households reduce their flow rates in response to having a greater supply continuity.

While energy losses always increase over time for a given supply continuity (e.g., Figure 6b), when the total energy loss is compared to continuity, more complex trends emerge. The total (accumulated) energy loss at the end of each supply is represented by the points $E_{H,A}$ and $E_{P,A}$ for the hasty and patient households in Figure 6a and $E_{H,B}$ and $E_{P,B}$ in Figure 6b. We aggregate points like $E_{H,A}$ and $E_{P,A}$ across a range of continuity levels to plot the relationship between total energy loss and continuity (Figure 6c).





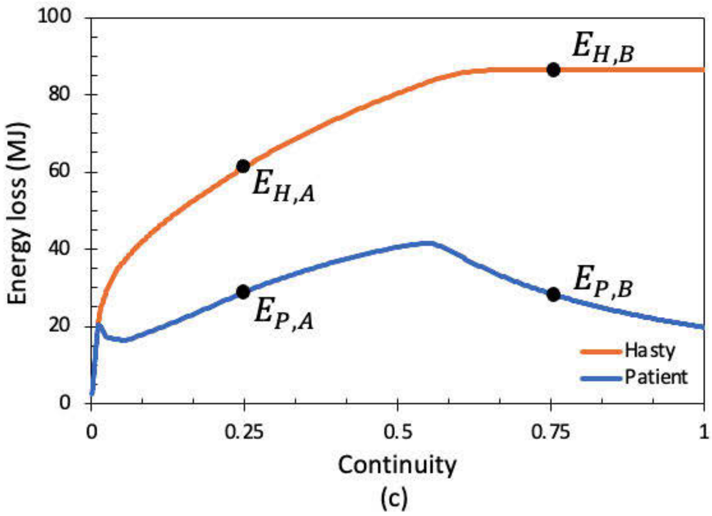


Figure 6 a, b: Cumulative energy loss against elapsed duration (time) in hasty and patient Modena networks when the network runs for 6 hours (a) and 18 hours (b) every day. c: Energy loss vs supply continuity for hasty and patient Modena networks. While energy loss increases monotonically with time for any given supply duration, patient households reduce flow rates at increased continuity levels, creating local maxima in the energy loss vs. continuity curve.

In both hasty and patient Modena networks, increasing continuity is associated with increasing energy losses when initial continuity values are <55% (Figure 6c). If the hasty Modena network began with 25% continuity, increasing to continuous supply (100% continuity) would increase total energy losses by 40% (Figure 6c). Similarly, if the patient Modena network increased from c=25%, energy loss would initially increase to a maximum of about 40% of their original value at their peak (at continuity≈55%; Figure 6c). However, after that peak energy loss, flow rates and energy losses would decrease with increasing continuity, ultimately reaching 30% less energy loss at c=100% in patient Modena as compared to c=25% (Figure 6c).

At any continuity, hasty households cause more energy loss than patient ones. Under continuous supply, hasty households induce 4.4x more energy losses than their patient counterparts. For hasty households, continuous water supply is the continuity with the highest energy losses. Contrastingly, the highest energy losses for patient households occurred when continuity was 55%, corresponding to the minimum continuity required to satisfy all households' demands.

Trends in energy loss versus continuity depend strongly on the assumption about how households will withdraw water (Figure 6). For hasty intermittent networks, monotonic increases in energy loss with continuity support the hypothesis that energy loss may be one barrier to increased (or continuous) supply continuity. Similarly, the existence of a peak energy loss in patient intermittent networks suggests where continuity is below this peak, energy losses may also be a barrier to increased supply continuity. Promisingly, for patient intermittent networks, the high energy losses associated with increased supply continuity are only temporary and the energy loss under CWS may be substantially lower than its value under IWS.

3.2 Effects of leakage on Energy loss

IWS networks are often described as having a high rate of leakage and a high rate of leakage is a commonly hypothesized barrier to increased supply continuity [18]. To explore the interaction of leakage and energy loss, we varied the assumed leakage share in our intermittent models (β in Equation (4)) from 5% to 45%, while holding demand constant (thereby varying the delivered water under continuous supply).

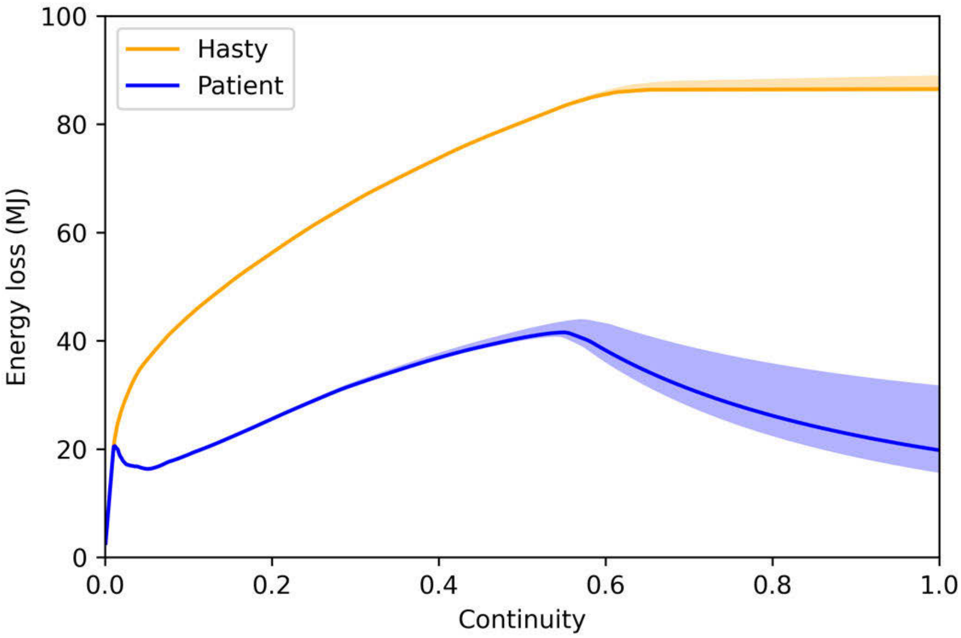


Figure 7 Energy loss vs. continuity plot in the intermittentized Modena network for hasty and patient networks under the range of leakage shares of 5% to 45% (the shaded areas) and 15% (as solid lines)

In both patient and hasty Modena networks, even a 9x increase in leakage coefficients had a much smaller effect on energy loss than changes in continuity (Figure 7). In the hasty Modena network, the 9x change in leakage coefficients changed the total energy loss by <3.6%. Conversely, leakage had a larger relative effect on energy loss in the patient Modena network (up to 103% increase) and was most notable when continuity levels were large enough to satisfy all households (>55%; Figure 7). While leakage may prevent some IWS from increasing their supply continuity, our results suggest that this barrier is not substantially compounded by leakage-induced energy losses.

4 CONCLUSION

Intermittent water supply networks persist despite their many drawbacks to utilities and households alike. This paper tested the hypothesis that energy loss might contribute to the persistence of IWS networks. To test this hypothesis, we imagined two extremes of household behaviour (hasty vs. patient) and implemented each in EPANET.

We found that network behaviour was drastically different when household withdrawals were hasty versus patient. Additional field research is needed (qualitative and/or quantitative) to help understand the rate at which consumers withdraw water from IWS and if it depends on the supply continuity. Are households in intermittent supplies predominantly hasty, patient, or something else entirely?

Our simulations of the hasty Modena network suggest that if every household behaved hastily, the energy loss would strictly increase with continuity, and energy loss could be one substantial reason why IWS are so difficult to convert to continuous water supplies. Conversely, energy loss in the patient Modena network initially increased, but once continuity was sufficient to satisfy all households, energy losses decreased with continuity. This may suggest that even where households withdraw patiently, energy losses may prove a barrier to increased continuity until continuity is long enough to satisfy all households.

At every supply continuity, energy losses were higher when households were hasty rather than patient. Where energy losses are limiting, slowing household withdrawals may prove key to achieving increased or continuous water supply. From the utility perspective, while limiting household withdrawal flows directly is not likely feasible, our results suggest that incentives and programs to reduce household withdrawal rates may prove highly beneficial.

5 APPENDIX

5.1. Household Connection Pipe Characteristics

The characteristics of the pipe connecting the storage tank to the demand node is determined based on the number, N, of hasty households represented by the node and based on the attributes of the pipe connecting a given hasty household to the network. Here, each household is assumed to have a demand of 1 m^3/day, which allows N to be calculated. Hence, the pipe characteristics are found using the equations in Table A-1.

Table A-2 Formulae to determine the connection characteristics for an artificial tank representing N households (taken from [16])

Connection Characteristic	Equivalent connection
Satisfaction consumption (m^3/day)	$\overline{Q_j} = V_s N = N$
Supply frequency ($1/day$)	$1/\mathrm{T} = 1$
Tank volume (m^3)	$V_j = V_s NT = N$
Tank height (m)	$H_j = H_i = 1$
Tank diameter (m)	$D_j = \sqrt{4V_i N}/\sqrt{\pi H_i}$
Length (m)	$L_j = 10$
Pipe friction, Hazen-Williams	$C_j = 130$
Pipe diameter (mm)	$d_j = d_i N^{0.380} = 15N^{0.380}$
Local loss coefficient	$k_j = k_j N^{-0.479} = 8N^{-0.479}$

Note: Subscript i denotes properties of an individual household, while j denotes the equivalent properties when N households are combined.

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