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Key Points:

- Standard terminologies were recommended for the classification of IWS on the basis of their characteristics
- Two methods for hydraulic analysis were proposed: i) for unsatisfied IWS; and ii) for satisfied and partially satisfied IWS.
- Comparing each of the proposed methods to the state-of-the-art methods demonstrated their advantages.

Abstract

For the analysis of water distribution systems, hydraulic simulation is of great importance; however, there are no suitable and holistic simulation tools for Intermittent Water Supply (IWS), so researchers are forced to utilise EPA-SWMM software, which needs some modifications to make it suitable for IWS analysis. This study focuses on providing a generic IWS analysis method in EPA-SWMM. Firstly, IWSs were classified according to coping strategies (e.g., household tank installation) customer satisfaction, supply schedule and duration to provide a unified terminology to the body of knowledge and assist in predicting the systems' behaviour, which should be reflected in the modelling process. Then EPA-SWMM based modelling approaches were compared paying attention to the case studies applied and two improved hydraulic modelling approaches have been proposed depending on the customer satisfaction of the network (namely i) unsatisfied IWS, ii) satisfied and partially satisfied IWS). Ultimately, customer satisfaction is the key, as the IWS systems are driven by user water consumption behaviours that are based on the demand-supply relationship. The application of the proposed methods to two different case studies and comparison with the state-of-the-art methods demonstrated their capability, compatibility with EPA-SWMM operating principles, and the ability to simulate the IWS system behaviour in a more realistic manner. In addition, the proposed methods are generic, unlike the available ones, which, in most cases, are only applicable to the specific case study.

1. Introduction

Water distribution systems where water is provided to the customer on an intermittent basis (i.e., not continuously) are called intermittent water supply systems (IWS) and are widely used around the world, especially where water is scarce. In perspective, 32% of the world's population, corresponding to more than one billion people, is affected by pipe water intermittency (Charalambous & Laspidou, 2017). The operational characteristics, timing of water delivery to the system, supply duration, and regularity of such systems vary depending on water availability in different areas (Danilenko et al., 2014; Kumpel & Nelson, 2016). For example, the average duration of water supply is 5.2 hours in India, and 8.5 hours in Jordan (Danilenko et al., 2014).

Consumers deal with interruptions in water supply by placing domestic tanks either on the roof or on the floor of their buildings (Arregui et al., 2006; Criminisi et al., 2009). The presence of domestic tanks has a massive impact on the characteristics of the system behaviour. When water is released into the system, the pipe network fills up and reaches the end-users. Typically, customers who are close to the source and at a low elevation (advantaged customers) are the first to receive the supply. Once supply resumes, the advantaged customers fill their tanks at a higher flow rate than their daily average, depending on the available pressure at the nodes. Therefore, high pressure loss occurs in pipes, which delays the entire network filling. Consequently, consumers located far from the source or at higher elevations receive water with lower flow rates and delays occur leading to the inequitable distribution of water among users (De Marchis et al., 2011; Vairavamoorthy et al., 2007). IWS differs from Continuous Water Supply (CWS) in terms of water availability, operation, customer satisfaction and coping strategies (e.g., household tank installation). Therefore, IWS's simulation requires the inclusion of: pressure dependency of the nodal outflow (i.e. actual water consumption is different from the demand (Batish, 2003; Ingeduld et al., 2006)); household tanks and network filling and emptying process.

Considering the many problems arising from intermittent operation of a network (e.g. water quality issues, the inequitable distribution of water), it becomes clear how imperative it is to have a suitable modelling approach to be able to detect the issues and create solutions to such networks. Researchers attempt to use the traditional software for Water Distribution Systems (WDSs), EPANET 2.0 (Rossman, 2000) to simulate IWS with several approaches. These include:

- placements of artificial elements in the network (Ameyaw, 2011; Battermann & Macke, 2001; Mohapatra et al., 2014);
- EPANET 2.0 source code adjustments (Ingeduld et al., 2006), the usage of the emitter devices (De Marchis et al., 2011; Tanyimboh & Templeman, 2010); and
- an iterative procedure of nodal outflow correction considering the pressure dependency of the flow (Chandapillai, 1991; Gottipati & Nanduri, 2014).

However, EPANET 2.0 is not able to simulate the transient flows that occur during the network filling process. Mohan and Abhijith (2020) developed PDA-PF model, which accounts for pressure dependency of flow and partial flow characteristics inside the piping system of the network for highly intermittent systems. Building on this, Meyer and Ahadzadeh (2021) argued that the authors' model has limited ability for wide application (i.e. multiple sources and loops, flow reversals). Additionally, this PDA-PF model was neither calibrated nor validated with field data (Mohan & Abhijith, 2020).

Some other researchers have worked on complex hydraulic models utilising the network filling process (De Marchis et al., 2010; Lieb, 2016; Liou & Hunt, 1996). However, they are limited in their ability to simulate the complete IWS behaviour, are complex to implement and require high computational effort.

EPA-SWMM (Rossman, 2015) software has been seen as a suitable tool for simulation of IWS, although it was developed to analyse urban drainage systems. The software can simulate both free-surface and pressurised conditions (Rossman, 2015). Segura (2006) was the first researcher who used EPA-SWMM. After that, the use of EPA-SWMM was recommended by Cabrera-Bejar & Tzatchkov (2009) and followed by other practices of the software in IWS simulation with different approaches (Campisano et al., 2019a, 2019b; Dubasik, 2017; Kabaasha, 2012). However, it should be noted that only Campisano et al. (2019a) validated their approach on the ability of EPA-SWMM representing the behaviour of the network filling process; achieved using a field experiment conducted in a Water Distribution Network (WDN) in Sicily (Italy). However, they used Wagner et al.'s (1988) equation to implement the pressure dependency of the flow rate. This equation has a threshold flow rate equal to the average flow rate (demand) corresponding to the required pressure in the system. Above the required pressure, the flow rate remains the same (equivalent to the demand). In IWS systems, high flow rates occur when supply resumes, which would be neglected by this equation.

Also, IWS network characteristics might differ from one another. Most of the existing modelling approaches were developed using the features of a specific case study applied, with the tools in EPA-SWMM being adjusted accordingly. There is a consensus on the definition of IWS among the researchers but not on the classification of its practices around the world. Thus, there is no generic IWS modelling approach that can be applied on all types of case studies or networks. The present work aims to:

1. Recommend standard terminologies for the classification of IWS based on their characteristics.

2. Propose two different methods for hydraulic analysis with EPA-SWMM based on demand satisfaction: i) for *unsatisfied IWS*; and ii) for *satisfied and partially satisfied IWS*, employing high flow rate occurrence in IWS and capturing system behaviour.

3. Evaluate each of the proposed methods using two different case studies by comparing them with the state-of-the-art methods

2. Classification of IWS

IWS systems are well defined, and knowledge of such systems has been gaining with the growth of studies on the practical application of such systems around the world. Yet, there is a lack of a broad classification of IWS systems and a unified terminology. Some researchers have defined IWS based on user satisfaction and supply schedule. Vairavamoorthy (1994) grouped IWS networks into two categories based on water availability, defined as starved and non-starved networks. The term "starved" is used to describe systems where consumers are unable to collect sufficient quantities of water to fill available household storage. The term "non-starved" is used to describe those systems where consumers are able to collect significant quantities of water to fill available household storage. Taylor et al. (2019) used the term "satisfied IWS" to describe networks where all customers get sufficient water to meet their demand, and "unsatisfied IWS" in which all the users receive less water than their needs. Galaitsi et al. (2016) proposed three definitions concerning customer disruption:

1. "Predictable intermittency", where supply characteristics are known and regular.
1. "Irregular intermittency" where user receives water at unknown intervals within a very short time.
2. "Unreliable intermittency", where the supply is irregular with insufficient quantity.

We should note that predictable and irregular intermittency may resemble Continuous Water Supply (CWS) if there is sufficient water storage.

Mokssit et al. (2018) also referred to "unreliable", "regular", and "predictable" intermittency with similar meanings but only considering the regularity of service, still helping to validate its relevance. In some cases, IWS is practised because of temporary events such as droughts and maintenance (Solgi et al., 2015; Wagner et al., 1988). Simukonda et al. (2018a) called these practices "partial intermittency" because, in most cases, not the entire system is affected by intermittency.

In general, as observed from prior studies, in some cases the researchers used different terms for the same meaning, and in other cases, they used the same terminology but referred to slightly different meanings. In addition, there is a lack of terminology for the duration of IWS practised and consideration of users' coping strategies. In this paper, we classify the IWS systems into four different categories based on: the duration of water supply; coping strategies; supply schedule; and user satisfaction (Figure 1).

Figure 1. IWS Classification

- According to the duration that IWS is practised: In some cases, IWS could be seen as a temporal solution to the depletion of water resulting from long term drought (Charalambous & Laspidou, 2017; Simukonda et al., 2018b). For example, after four years of drought in Cyprus, IWS was applied (approximately 12 hours of supply every two days) for two years starting from 2008 to conserve national water reserves despite its negative consequences (Christodoulou & Agathokleous, 2012). These IWSs are referred as "***short-term IWS***" in this paper. In other cases, IWS is a standard method of operation in many countries in Asia, Africa, and

Latin America (particularly low- and middle-income countries). These types of practices are referred to as "***long-term IWS***".

- According to the coping strategies: Users explore various ways to deal with water intermittency, such as having household tanks and pump connections (Charalambous & Laspidou, 2017). This is imperative to be considered in the hydraulic analysis, and to this end, IWSs are distinguished as "***without household tanks***", "***with household tanks",*** and "***with household tanks and pumps***" in this paper.
- According to the supply schedule: The customer needs to have information regarding the duration of pump activity and the water supply schedule, as sometimes, they may need to wake up at night to open the valve of the household tank (Galaitsi et al., 2016). The terms "***predictable IWS***" and "***irregular IWS***" are suggested in this paper depending on the supply schedule and duration information. IWS is predictable when the supply schedule is known, and transversely is irregular when the supply schedule is unknown.
- According to customer satisfaction: "***satisfied IWS"*** means that all the users in a network can get enough water that they demand during limited supply time. However, in "***unsatisfied IWS***", the users do not get enough water that they demand, primarily when there is a very short supply duration. In most cases, an IWS fits somewhere in between systems, whereby some users get enough water to meet their needs whilst others do not (Taylor et al., 2019); for this system the term "***partially satisfied IWS***" is used in this paper.

3. EPA-SWMM based IWS modelling approaches

EPA-SWMM based IWS methods are divided into "methods without household tanks" and "methods with household tanks", based on the node configurations of the methods. Moving forwards, a detailed description of these methods, their parameter settings and their applications are provided. Furthermore, they are thoroughly analysed in the results section, with the accuracy of the methods being evaluated by comparing the results of each method.

3.1. Methods without household tanks

There are three different approaches (Campisano et al., 2019a; Dubasik, 2017; Kabaasha, 2012) available for IWS modelling without embedding the storage elements in the node configuration. Kabaasha (2012) addressed the failure of pumps resulting from electricity outrages and supply rationing. He used two different approaches, termed as demand-driven (DDA), and pressure-driven analysis (PDA) in EPA-SWMM 5.0. Please note that DDA will not be explained and applied in this study as IWS requires PDA. Kabaasha (2012) applied the hydrodynamic model to water distribution networks with real-world complexity and compared the results with EPANET_EMITTER (Pathirana, 2010) enabling him to consider the pressure dependency of the flow. The networks ranging from simple to complex, gravity-fed or pumped, and single or multiple sources were used to run different experiments. Dubasik (2017) studied the water distribution system of Espave in Panama, which is operated intermittently due to water scarcity during dry seasons. He modelled the system under both IWS and CWS conditions. CWS of the Espave water system was modelled with EPANET 2.0 using demand-driven analysis, and IWS operation was modelled with EPA-SWMM 5.1 to simulate transient, pressure-driven conditions in the system. They run the model under different scenarios constructed concerning the demand-supply relationship based on the flowrate data from the Espave water supply. Campisano et al. (2019a) conducted a study on simulating the network filling process in IWS. They validated model results with data from a real case study in the municipality of Ragalna in Italy. The case study is explained in Section 5.1 and used to compare the methods without tanks.

The methods without household tanks (Campisano et al., 2019a; Dubasik, 2017; Kabaasha, 2012) assume that users consume as much water as possible during the supply time. Figure 2 shows demand node configuration in EPA-SWMM for Kabaasha (2012) and Campisano et al. (2019a), and the features of methods without household tanks (Campisano et al., 2019a; Dubasik, 2017; Kabaasha, 2012) are explained below with EPA-SWMM terms:

- Flow received by the users at each demand node was modelled using an outfall element connected to each junction with an outlet element, and the invert elevation of the outfall was set the same as that of the junction to which it is connected (Campisano et al., 2019a; Kabaasha, 2012). Dubasik (2017) used only the junction node to represent the demand node. He placed an outfall to the system, which is not connected to any node. The maximum water elevation in the source is used to set the elevation of the outfall.

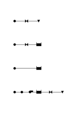


Figure 2. Demand node configuration

- Different pressure dependency of flow equations was considered with a rating curve embedded in the outlet links of each demand node (i.e. Kabaasha (2012) used Equation 1 corresponding to Figure S1 in Supporting Information S1, Campisano et al. (2019a) used Wagner et al.'s (1988) equation, (Equation 2)).

$$Q_{\text{user}} = \begin{cases} 0 & P < 0 \\ SP^{\gamma} & 0 < P < P_{\text{req}} \\ Q_{\text{req}} & P > P_{\text{req}} \end{cases} \quad (1)$$

where Q_{user} [l/s] is the actual demand, Q_{req} [l/s] customer demand, P [m] is the nodal pressure, P_{req} [m] is the required pressure, S is the proportionality constant and   is the power of the pressure.

$$Q_{\text{user}} = \begin{cases} 0 & P < P_{\text{min}} \\ Q_{\text{req}} \left(\frac{P - P_{\text{min}}}{P_{\text{req}} - P_{\text{min}}} \right)^{\beta} & P_{\text{min}} < P < P_{\text{req}} \\ \text{Q}_{\text{req}} & P > P_{\text{req}} \end{cases} \quad (2)$$

where Q_{user} [l/s] is the actual demand, Q_{req} [l/s] required nodal demand, P [m] is actual nodal pressure, P_{min} [m] is the minimum pressure required to receive flow by the node, P_{req} [m] is the pressure required to satisfy demand and   is a calibration parameter typically ranging from 0.5 to 1.

- While Kabaasha (2012) did not consider the demand pattern by keeping the nodal demand at a fixed value, Campisano et al. (2019a) and Dubasik (2017) introduced demand patterns in different ways. They assigned it via control rules by assigning coefficients to the rating curves (Campisano et al., 2019a). Demand was assigned to each junction node as a negative inflow, and the pattern was created by multipliers of the base inflow for each node (Dubasik, 2017). Dubasik (2017) assumed that demand is equal to supply during the system's operational period. Junction nodes in EPA-SWMM physically can represent the confluence of natural surface channels, manholes in a sewer system, or pipe connection fittings (Rossman, 2017). For this reason, a considerable volume of water can be held (Rossman, 2017). To prevent the storage of the water in junctions (i.e. to be employed as junction node in a water distribution system), a negligible value of the surface area was assigned under the dynamic wave options (Campisano et al., 2019a; Dubasik, 2017; Kabaasha, 2012).

- A junction node can be in the surcharged condition in EPA-SWMM if the connected pipes are full or if the water level in the junction exceeds the crown of the highest connected conduit. Users can assign this maximum allowable head (H_{max}) to the junctions. It includes the maximum free water surface elevation that can exist and surcharge depth. As an example, for a fitting, it would be the top of the highest pipe. When the head computed at a node exceeds H_{max}, the nodes become flooded, and this flow is then lost from the system (Rossman, 2017). If the junction is required to represent pipe fittings not allowing any water to escape, then its maximum depth should be zero, and its surcharge depth should be set at a high value. In doing so, the junction is allowed to remain in a pressurised state causing no flooding (Gironás et al., 2009). In this regard, Kabaasha (2012) chose a maximum of 500 m as H_{max}, Dubasik (2017) used the inner diameter of the pipe at each junction. Where over one pipe is connected to a junction, the largest inner diameter was used. Dubasik (2017) chose the surcharge depth such that it will be higher than the hydraulic grade line. Campisano et al. (2019a) assigned an exceedingly high surcharge depth to the junctions.

- Tanks with a constant water level were modelled with the storage element in EPA-SWMM by assigning a very large bottom area such that the water level variations can be neglected (Campisano et al., 2019a; Kabaasha, 2012). In a different approach, Dubasik (2017) included the source and the tank in the model based on the characteristics of the case study. He assigned an inflow to the tank to represent the flow from the source to the tank.

- Kabaasha (2012) used the “hot-start” file to ease the numerical instabilities in the results. EPA-SWMM has an additional feature that generates this binary file which contains the results of previously run analyses. Initial conditions of a subsequent run can be defined by using the hot start file (Rossman, 2015).

3.2. Methods with household tanks

Some methods include the household tanks, which amplified the complexity of the model. These methods were used for various purposes and applied to different case studies worldwide where intermittency is practised. Segura (2006) considered water-quality problems and conversion of intermittent water supply to a continuous system. First, the study showed that EPA-SWMM could simulate pressurised conditions properly by applying a simple case study and comparing the results with EPANET (Segura, 2006). Then the method was applied to a case study in Villavicencio in Colombia (Segura, 2006). Cabrera-Bejar and Tzatchkov (2009) modelled the initial filling process of IWS. They also suggested the usage of EPA-SWMM only for modelling filling process and after that usage of EPANET for simulating pressurised state. They used a small network from Guadalajara, Mexico, with three days duration and 5 hours of water supply per day. Shrestha and Buchberger (2012) demonstrated the effectiveness of the satellite tank usage in the provision of a more reliable continuous water supply to Kathmandu, Nepal. Satellite tanks are elevated structures used to provide required water to downstream by maintaining a sufficient head (Shrestha & Buchberger, 2012). The study addressed the usage of pumps and storage tanks as coping strategies for the intermittency of the water. Both of which are used by approximately half of the households in Kathmandu. To model both existing and the proposed IWS, EPA-SWMM was chosen. Campisano et al. (2019b) developed a method to capture household tanks in the model by inclusion of storage elements connected to the junctions. This method was then used by Gullotta et al. (2021a) and Gullotta et al. (2021b) for inspection of improvement of equitable supply.

The methods with household tanks (Cabrera-Bejar & Tzatchkov, 2009; Campisano et al., 2019a; Segura, 2006; Shrestha & Buchberger, 2012) were developed in line with the assumption of the existence of free-flowing outlets. Meaning that customers leave their tap open, filling their tanks during supply hours. Accordingly, water received by end-users depends on available pressure and the supply duration of the limited water. Shrestha and Buchberger (2012) considered the pump capacity besides to the pressure and supply duration. Figure 3 shows the demand node configuration of the methods with household tanks and the features of these methods are explained below with EPA-SWMM terms:

- Storage elements were connected to the junction nodes with conduits (Cabrera-Bejar & Tzatchkov, 2009), with outlets (Campisano et al., 2019b; Segura, 2006) and with pumps (Type 3 pumps in EPA-SWMM) (Shrestha & Buchberger, 2012), as it is illustrated in Figure 3. They were employed corresponding to a group of private tanks connected to a node. The capacity of the tanks was calculated based on different assumptions. Segura (2006) assumed an average of 8 cubic metres per household. Real dimensions were used by Cabrera-Bejar and Tzatchkov (2009). Shrestha and Buchberger (2002) chose a dimension of 3.5 cubic metres. Campisano et al. (2019b) defined the household tank size based on the assumption that a four-person household has a 1 m^3 tank.

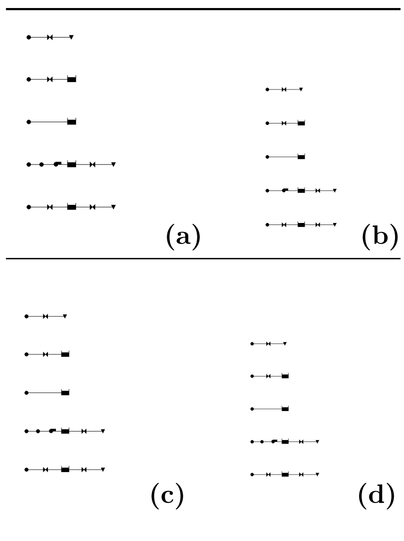


Figure 3. Demand node configurations of each method (a) Segura (2006), (b) Shrestha and Buchberger (2012), (c) Cabrera-Bejar and Tzatchkov (2009), (d) Campisano et al. (2019b)

- Segura (2006) and Campisano et al. (2019b) assigned the pressure dependency of the flow to the outlets using Equation 3 and Equation 4, respectively:

$$Q_{\text{user}} = 0.05.\ h^{0.5} \quad (3)$$

where Q_{user} [l/s] is the actual demand, h [m] is nodal pressure. The equation is created based on field measurements.

$$Q = \begin{cases} Q_{\max} = C_v \bullet a_v \bullet \sqrt{2 \bullet g \bullet [(h - z_t) - S \bullet L]} & if\ H < H_{\min} \\ Q_{\max} \bullet \tanh\left(m \bullet \frac{H_{\max} - H}{H_{\max} - H_{\min}}\right) \bullet \tanh\left(n \bullet \frac{H_{\max} - H}{H_{\max} - H_{\min}}\right) & \text{if } H_{\min} < H < H_{\max} \\ 0 & if\ H > H_{\max} \end{cases}$$

(4)

where Q [m^3/s] accounts for storage tank inflow of user; Q_{max} [m^3/s] is the maximum inflow that occurs when the float valve is fully open; C_v [-] is the float valve emitter coefficient; a_v [m^2] is the valve inflow area; g [m/s^2] is the acceleration due to gravity. C_v and a_v are dependent on the floater position, that is, on the water level in the tank. Z_t [m] is the float valve elevation; h [m] is the nodal pressure head in the network; S [-] is the slope of the energy grade line; L [m] is the pipe length between the network node and the tank; m and n are coefficients which have to be determined experimentally; H [m] is the tank water level, and H_{min} [m] and H_{max} [m] are water levels in the tank which corresponds to the float valve when it is fully open and fully closed respectively.

Equation 4, the hyperbolic law of the emitter, developed by De Marchis et al. (2015), was used to predict the flow rate based on pressure entering household tanks controlled by float valves. The progressive closure of the orifice by the floating valve (for values of H, between H_{min} and H_{max}) was obtained through the use of control rules in EPA-SWMM. Achieved by prescribing reduction coefficients to Q_{max} with a granularity of 2 mm (Campisano et al., 2019b).

- While Segura (2006) and Campisano et al. (2019b) assigned control rules to outlets to stop the water when the tank is full (i.e. tank depth is 1 m), Cabrera-Bejar and Tzatchkov (2009) did not consider the closure of the household tank valve in their approach.
- Segura (2006) and Cabrera-Bejar and Tzatchkov (2009) defined a daily demand pattern as a negative inflow curve to the properties of each storage to consider water usage from the tanks (Figure 3a, Figure 3c). Whereas Shrestha and Buchberger (2012) and Campisano et al. (2019b), managed this by assigning daily demand patterns to another outlet link - via connecting the storage node to the outfall node (Figure 3b, Figure 3d).
- At least one outfall is necessary for dynamic wave flow routing to represent the discharge of the water. For this reason, Segura (2006) and Cabrera-Bejar and Tzatchkov (2009) placed an outfall in the model. Cabrera-Bejar and Tzatchkov (2009) connected this outfall to a random junction of the network with a fictitious pipe with a diameter of 0.001m in order not to affect simulation results.
- High surcharge depths were assigned to the junction nodes to prevent flooding during pressurised conditions (Cabrera-Bejar & Tzatchkov, 2009; Campisano et al., 2019b; Segura, 2006; Shrestha & Buchberger, 2012).
- The source was represented with the storage node element in EPA-SWMM. The settings were defined based on the case study applied. A very large bottom area was assigned to simulate constant water level (Segura, 2006); the actual dimensions of the source were used with the supply schedule introduced with an inflow pattern (Cabrera-Bejar & Tzatchkov, 2009; Shrestha & Buchberger 2012; Gullotta et al. 2021a).

4. Recommended methods for different types of IWS

All the mentioned methods are useful, but they are not generic. Essentially, methods need to be compatible with the working principles of EPA-SWMM so that errors and instabilities are reduced.

The classification of IWS systems helps to predict all systems' behaviour, which should be reflected in the modelling process. It will then be easier to compare the case studies and recommend generic solutions (Galaitsi et al., 2016). This study proposes two main generic hydraulic modelling methods based on user satisfaction. These are namely, "*unsatisfied IWS*", "*satisfied and partially satisfied IWS*". Furthermore, all types of IWS explained in Section 2 were considered. In particular, user demand satisfaction and household tanks were envisaged in the development of the proposed methods.

4.1. Unsatisfied IWS

Some developing countries have a very low duration of water supply, such as India where it averages only 5.2 hours per day (Danilenko et al., 2014). People cannot access enough water to meet their needs, and for this reason, consumers leave their taps open to collect as much water as possible during supply hours. Accordingly, the nodal outflow is the maximum amount of water that can be taken from the node, which is related to the uncontrolled type of water usage. This idea has led to the development of the nodal head flow relationship (NHFR) equation having no upper limit on flow rate. Reddy and Elango (1989) started it with the suggestion of a methodology for water-starved networks operating intermittently. Their method assumes that the nodal outflows wholly depend on pressure. Subsequently, the equation of Reddy and Elango (1989) was incorporated in the modelling procedure by Vairavamoorthy (1994) for the application of a pressure deficient network in Madras, India and by Mohan and Abhijith (2020) for the application of a highly intermittent system (i.e. very short duration of supply) in a municipality of India.

In other respects, Wagner et al.'s (1988) equation has been commonly used in various ways in the studies concerning pressure deficient conditions in Water Distribution Network (WDN) (Mahmoud et al., 2017; Muranho et al., 2014; Paez et al., 2018). The equation represents a controlled type of outlet with a reference pressure (i.e. required pressure (P_{req}) is the service pressure), above which the flow rate is assumed to be constant and equal to the demand (Q_{req}). First, reference pressure plays a significant role in the amount of water delivered to each node. Flow rate decreases when the reference pressure increases and vice versa (Wu et al., 2009). For this reason, it is essential to define P_{req} more realistically based on the field measurements for each case study (Ackley et al., 2001). Second, the upper limit prevents the variability of demand from being considered, as the maximum demand could be greater or less than the design flow rate (Q_{req}) (Giustolisi et al., 2008). Under the conditions of the higher peak factor in IWS, the equation of Wagner et al. (1988) is limited in its ability to represent the pressure-flow relationship.

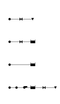
Figure S2 in Supporting Information S1 illustrates the aforementioned nodal head flow relationships. Both Reddy and Elango's (1989) equation and Wagner et al.'s (1988) equation are derived from the orifice equation. While Wagner et al. (1988) suggested a parabolic relationship between P_{min} (minimum pressure needed for nodal outflow) and P_{req}, Reddy and Elango (1989) recommended nodal outflow is wholly dependent on pressure and continues to increase even when the pressure is bigger than P_{req}.

The studies explained in Section 3.1, i.e. for methods without household tanks, used either upper limit in NHFR equation (Campisano et al. 2019a; Kabaasha, 2012) or did not use any equation to assign pressure dependency of the flow (Dubasik, 2017). The pressure dependency of the flow equation with an upper limit in flow rate (controlled-type demand representation) employs only WDNs with sufficiently long supply duration (Mohan & Abhijith, 2020). In this study, Reddy and Elango's (1989) equation is seen to be suitable for *unsatisfied IWS* to simulate uncontrolled-type demand as given below:

$Q = K.(P - P_{\min})^{0.5}$ (5)

where: Q [l/s] is flow rate; P [m] is the required pressure head at which nodal outflow is equal to estimated demand which is gained from EPANET extended period simulation results for each node; P_{min} [m] is the minimum pressure; K is constant which depends on outlet features (i.e., it is calculated by using pressure and demand values for each node. Pressure values are gained from EPANET simulation results).

Figure 4 shows the demand node configuration of our proposed method for *unsatisfied IWS*. Flow received by the users at each demand node is modelled using artificial elements outlet links and outfall nodes. Equation 5 is embedded in the outlet link to assign pressure dependency of flow.



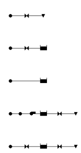
Other model settings are the same as those of Campisano et al. (2019a) (i.e. demand pattern and source representation, the features of the junction node).

However, this approach does not give realistic results for satisfied or partially satisfied IWS. The reason is that nodal discharge will not necessarily follow the increase in the nodal head as the consumers require a limited total amount of water at a time (Tabesh, 1998). Controlled type demands are required for satisfied and partially satisfied networks with longer water supply periods.

4.2. Satisfied and partially satisfied IWS

Sometimes, there is a reasonable supply duration which makes some customers to be satisfied and some unsatisfied. Here, the water consumption behaviour is more complex, and we should consider the effects of household tanks in the hydraulic simulation. Such tanks will be filled based on the pressure, and once the users get enough water and fill their tanks, they will then tend to close their valves.

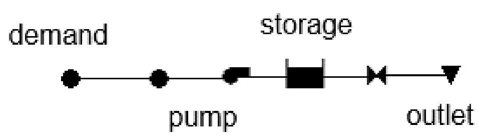
The methods considering this behaviour in EPA-SWMM were gathered and explained under the methods with household tanks section, i.e. Section 3.2. Each of them provides insight and is useful but has limitations to use the tools in EPA-SWMM. These will be thoroughly discussed in the result section (Section 6.2).



In this sense, for *satisfied and partially satisfied* IWS, the household tanks and the users' water consumption from the tank are added to the node configuration which is shown in Figure 5.

Our proposed method employs the household tanks to fill at a pressure-dependent rate and user's water consumption from the tank. Control rules are used to set the status of the dummy pipes to closed so that the inflow stops when the tank is full. An outlet is used to introduce the water consumption from the tank. As long as there is water inside the tank, the user will satisfy their needs as if they are not impacted by intermittency.

For those IWS where customers have pumps in addition to the household tanks, pumps must be included in the modelling approach. Pumps can be embedded in the node configuration, as was advised by Shrestha and Buchberger (2012). Here, as stated in their paper, the flow rate entering the household will depend on the pump's pressure and capacity. This type of pump is represented in EPA-SWMM with Type 3 pumps (Shrestha & Buchberger, 2012). The node configuration is shown in Figure 6 below.



Other settings are also applied to the proposed methods in line with the EPA-SWMM user manual:

- Network junctions should have an extremely high surcharge depth during the pressurised conditions to prevent the occurrence of the overflow
- In EPA-SWMM, junction nodes represent manholes; for this reason, the minimum nodal surface area should be assigned a tiny value (i.e., 0.0001).

5. Application

Two different case studies and different assumptions were used for the comparison: The first case study was used for methods without household tanks (including the proposed method for *unsatisfied* IWS). The second case study was chosen to apply methods with tanks (as well as the proposed method for *satisfied and partially satisfied* IWS).

EPA-SWMM solves the St Venant equations (i.e., a pair of partial differential equations of conservation of mass and momentum) to represent hydraulics of unsteady non-uniform flow. These equations can be solved using either the dynamic wave analysis or the kinematic wave analysis option in EPA-SWMM. Since dynamic wave analysis solves the complete form of St Venant equations, it provides the most accurate results (Rossman, 2017). Therefore, the dynamic wave routing option was chosen for all the methods. The network is assumed to be empty before the simulation starts. The pipes were represented in the model as force main elements in EPA-SWMM.

5.1. Case study 1

The case study is acquired from Campisano et al. (2019a). The network supplies water to a district of the municipality of Ragalna in south-eastern Sicily, in Italy. The gravity-fed network is supplied with a constant head (2.8 m) tank. A tank with a constant water level was modelled using the storage node tool for which large values for the bottom area are assumed, thus neglecting the water level variations during the network filling phase for all the methods.

The layout is shown in Figure S3 in Supporting Information S1, and the network data and nodal demands are available in Campisano et al. (2019a). They estimated requested demand values based on flow measurements from an ultrasonic flowmeter installed at the source outlet (Campisano et al., 2019a). They also conducted a field study and collected pressure data within a time step of 5 minutes from two pressure gauges, which were near nodes 13 and 46 (Figure S3 in Supporting Information S1). The field data was extracted from the figure shown in their paper using the web-based tool "WebPlotDigitizer" (Version 4.5; Rohatgi, 2021). The network was empty at the beginning of the simulation, which lasted for 4 hours.

To allow for a fair comparison h_{min}, h_{req} and values were chosen as those selected by Campisano et al. (2019a); 5m, 30m, 0.5, respectively. In addition, the pipes were discretised so that the maximum length of each pipe is at most 100m in order to obtain more accurate results. The routing time step was set 10 seconds accordingly.

5.2. Case study 2

The Case Study 2 data, which were acquired from Gullotta et al. (2021a), belongs to a water distribution network in northern Italy (Farina et al., 2014). The network built in EPA-SWMM comprises 26 junction nodes, one storage node representing the source and 32 conduits (pipes), as shown in Figure S4 in Supporting Information S1. Water is provided to 30,000 inhabitants from the source. The storage has an elevation of 35 m above sea level with a total head of 40 m. The network is quite flat, and hence junction nodes are assumed to have zero elevation. All the pipes have the same manning coefficient of 0.01 s/m$^{1/3}$, which is a typical value for PVC pipes.

The network pipe characteristics information (length, diameter) and daily nodal demand can be gained from Gullotta et al. (2021a). Hourly multipliers of the average demand are shown in Figure S5 in Supporting Information S1. The model is run for 24 hours with a reporting step of 5 minutes and a simulation time step of 10 seconds. All pipes and tanks were empty at the beginning of the simulation. Capacity and the locations of the storage tanks are defined such that they account for a group of existing household tanks. The capacity of 1 m^3 was assumed to be sufficient for a four people household and the tanks were located 1 m below the ground (Gullotta et al., 2021a).The source is represented by storage elements with their real dimensions. The supply schedule is introduced with an inflow pattern (35.34 l/s considering the water shortages, which is, 70% of demand − 24 h supply/day) (Gullotta et al., 2021a).

6. Results and Discussion

6.1. Methods without household tanks

Results of the three methods (i.e. Campisano et al. (2019a), Dubasik (2017) and Kabaasha (2012)) were compared with the field data extracted from the study of Campisano et al. (2019a). The proposed method for unsatisfied networks was also included in the comparison. Figure 7 shows the pressure values (5-minute intervals) of each method during a 4-hour simulation, and the pressure values of field data in nodes 13 and 46, respectively.

(a) (b)

Figure 7. Comparison of field pressure values with simulation results of each method (a) Node 13 (b) Node 46

Statistical parameters were used for a closer inspection of the results. Descriptive statistics and the correlation of the results are shown in Table S1 and Table S2 in Supporting Information S1 for nodes 13 and 46, respectively. Based on the statistical metrics and Figure 7, Campisano et al. (2019a), Kabaasha (2012), and the proposed method for *unsatisfied* IWS are remarkably similar to field data. Their differences can be attributed to the pressure–flow relationship assigned. The pressure values of Dubasik (2017) were better matched with field data in Node 13 and least matched with the data in Node 46 compared to other studies. An explanation for this might be that he assigned demand values as negative inflow to each node. When the pressure is sufficient, the results matched better. Node 13 is closer to the source than Node 46 and is at a lower elevation (Figure S3 in Supporting Information S1). For this reason, while pressure is sufficient in Node 13, Node 46 has pressure deficiency.

The goodness of fit between the methods and the field data was quantified by the Root Mean Squared Error (RMSE) value for each pair (Table 1). When both

Node 13 and Node 46 are considered, the proposed method and Campisano et al. (2019a) were better match with the field data.

Table 1 Root mean square error for each method

	Campisano et al. (2019a)	Kabaasha (2012)	Dubasik (2017)	Proposed method for unsatisfied IWS
Node 46				
Node 13				

6.2.Methods with household tanks

The results were evaluated and were compared to each other from different aspects. Figure S6 in Supporting Information S1 shows the flow rate values in pipes and the pressures at nodes at the end of the simulation (i.e. at time point 23:55). Some tanks have different water levels, and some pipes have different flow rates based on the results presented in Figure S6 in Supporting Information S1. These variations can be attributed to the node configuration, which defines the time and the amount of water delivered to each node. In this context, three key parameters must be considered: i) the pressure–flow relationship equation, ii) the size of the tank at each household and iii) the water consumption from the tank. These parameters are important for an accurate prediction of the actual amount of water delivered to each node. Segura (2006) and Campisano et al. (2019b) and proposed method for *satisfied and partially satisfied* IWS introduced the pressure–flow relationship equation to the outlets at each node. These equations are in the form of emitter equation and different emitter coefficients were assigned to each node. However, Cabrera-Bejar and Tzatchkov (2009) do not consider any equation. The induced pressure dependency of flow affects the flow rate in pipes and the duration of household tanks filling accordingly (Figure S6 a,b,c,d in Supporting Information S1).

The dimensions of the household tanks are taken as the same for each method, which is important for the time each user gets the water. In IWS, users who live near the source get water first, fill their tanks, and then water distributes to the other nodes depending on their location and the elevation. This pattern can be seen from Figure S6 a,b,c,d in Supporting Information S1. There are differences between the flow rate in pipes and the level of water in the tank based on the distance from the source as well as the magnitude of the emitter coefficient at each node. However, even though control rules are assigned to prevent water from entering the tank after its filled, in the method of Campisano et al. (2019b) and Segura (2006), water is still coming with a very low flow rate.

Another aspect related to the control rules is that once the pipe connecting node to the household tank is closed, it was assumed to remain shut throughout the simulation. However, users continue to consume water from the tank. For these reasons, when the water level reaches the maximum, the decrease in water level is expected. Figure 8 shows the changes in water level in storage nodes 18 and 20 throughout the simulation for each method. As there is no pressure dependency of flow equation assigned to the outlets in Cabrera-Bejar and Tzatchkov (2009)' method, the tanks fill rapidly. In the other methods including that which is proposed for *satisfied and partially satisfied* IWS, the tanks are filled according to the emitter coefficients assigned to each node.

After the tanks are filled, the decrease in the water level can be observed in both nodes for the proposed method and the method of Segura (2006). However, we cannot see this pattern in the method of Campisano et al. (2019b), as the tanks are yet to be filled. Since, Cabrera-Bejar and Tzatchkov (2009) did not take into account the closure of the household tank float valve in their method, water level remains constant after reaching its maximum.

(a) (b)

Figure 8. Household tank water level throughout the simulation (a) storage for Node 18 (b) storage for Node 20

Overall, Figure 8 shows that the proposed method better reflects the filling and emptying process of the household tank than the other methods. In both Node 18 and Node 20, there is an increase in the water level in the tank based on the pressure. When the water level reaches its maximum, the valve is closed and therefore the water level is lowered based of consumption. Table S3 from Supporting Information S1 shows the total system input volume for 24 hours duration of supply. From the table, the employment of each method results with slightly different system input volume. This can be attributed to the household tank fill rate and, consequently, the valves' closure connected to the tanks.

For the comparison purpose, all the methods assume that users consume water from the tank as if they are not affected by water scarcity. Therefore, the demand pattern is used to simulate water consumption from the tank using different settings in EPA-SWMM. While Segura (2006) and Cabrera-Bejar and Tzatchkov (2009) used "direct negative inflow", Campisano et al. (2019b) and proposed method assign water consumption via an "outlet" tool. A negative inflow assignment creates continuity errors regarding whether there is water inside the tank; water is assumed to be consumed from it. Moreover, water should physically leave the system, which is possible with the outfall element. Otherwise, once each node reaches the assigned surcharge depth, flooding occurs. Table S4 from Supporting Information S1 shows the percentage of the continuity error, flooded nodes and the computational time of each method (using Windows 10, Intel(R) Core(TM) i7-8700K CPU @ 3.70GHz 3.70 GHz computer with 32.0GB of RAM). As shown in Table S4 from Supporting Information S1, Segura (2006) and Cabrera-Bejar and Tzatchkov (2009) have high continuity errors. This is because in their method, they have only one outfall in the system. Whereas in other methods, including the proposed method, each node has an outfall in which water leaves. The node configuration of the proposed method for satisfied and partially satisfied IWS (Figure 5) is more straightforward and seems to be more aligned with EPA-SWMM's operating principles, resulting in reduced computational time and continuity errors.

In summary, as the number of additional elements and the control rules increases, so does the computational time (Table S4 from Supporting Information S1). With a larger network, the computational time and the errors will likely be much higher. The configurations should be made as simple as possible considering the actual intended usage of the software (i.e. EPA-SWMM is a rainfall-runoff simulation model (Rossman, 2015). The advantage of the recommended method is that it is simplified and gives comparable results.

7. Limitations

While the general concept of the node configuration seems appropriate for IWS, the storage components make the model much more complicated, and field data is required to validate whether the configurations affect the model accuracy. In addition, emitter coefficients assigned to outlets need to be verified experimentally or through field research to simulate the pressure dependency of the flow accurately. Because emitter coefficients are system specific and are affected by various factors, including system pressure, elevations of the nodes, shape, and dimensions of the orifice (De Marchis et al. 2015; Walski et al. 2018). It even becomes more challenging to define emitter coefficients when the demand points are aggregated to the demand nodes in the model. A more comprehensive method of determining emitter coefficients would be very beneficial. It gets more challenging when the demand points are aggregated to the demand nodes in the model. It would be beneficial if a more thorough method could be suggested to determine emitter coefficients.

8. Conclusions

Based on a specific case study, IWS systems may differ in terms of operational characteristics and network elements. To make a generic modelling method, these aspects should be considered. For this reason, this study suggested IWS hydraulic analysis methods in EPA-SWMM based on user satisfaction. The methods were recommended considering all types of intermittencies in practice and the quantitative comparison of the currently used methods in EPA-SWMM. Methods in the literature were developed for specific case studies, and assumptions were made based on the aim of the study. Comparing the methods in this situation was challenging. However, the comparison was made based on the appropriateness of setting up EPA-SWMM to have the desired impact as well as the accuracy of the results. Recommended methods were also included in the comparison.

The proposed methods appear to be more appropriate, compared to the available methods in the literature. The proposed method for *unsatisfied* IWS addresses the appropriateness of the uncontrolled type of demand for water-starved networks. Recommended methods for *satisfied and partially satisfied* IWS employ the customer water consumption behaviour with the coping strategies at the household level (i.e. household tanks and pumps). However, it is important to keep in mind that the adjustments of the tools in EPA-SWMM should be made very carefully so that continuity and instability errors can be avoided. While the proposed method for *unsatisfied* IWS was verified with the field data, the proposed method for *satisfied and partially satisfied* IWS only compared with other available methods. It needs to be verified with field data.

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Open Research

Datasets for this research are included in these papers (and their supplementary information files): Campisano, A., Gullotta, A., & Modica, C. (2019a). Using EPA-SWMM to simulate intermittent water distribution systems. *Urban Water Journal*, *15*(10), 925–933. https://doi.org/10.1080/1573062X.2019.1597379

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