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Review of hydraulic modelling approaches for intermittent water supply systems

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ABSTRACT

Intermittent water supply (IWS) is widely used around the world, and with the increase in population and predicted future water scarcity, IWS applications seem to continue. While most of the existing studies on water supply concentrate on continuous water supply (CWS), the research focused on the IWS is now becoming mainstream. Hydraulic modelling is an effective tool for the process of planning, design, rehabilitation, and operation of water distribution systems. It helps significantly in engineers' decision-making processes. The necessity of modelling IWS systems arises from the complexity and variety of problems caused by intermittency. This paper offers a review of the state-of-the-art IWS modelling and identifies the key strengths and limitations of the available approaches, and points at potential research directions. Currently, neither computer software nor a practically used approach is available for modelling IWS. For a rigorous simulation of IWS, system characteristics first need to be understood, i.e., the user behaviour under pressure-deficient conditions, water losses, and filling and emptying processes. Each of them requires further attention and improvement. Additionally, the necessity of real data from IWSs is stressed. Accurate modelling will lead to the development of improved measures for the problems caused by intermittency.

Key words: EPANET, EPA-SWMM, hydraulic modelling, intermittent water supply, macroscopic model, pressure-dependent analysis

HIGHLIGHTS

- Reviews are provided in intermittent water supply (IWS) hydraulic modelling approaches and pressure-driven analysis methods conducted to address pressure-deficient conditions.
- The distinctive characteristics of IWS are highlighted as well as its adverse impacts, principally inequitable supply.
- Challenges of modelling IWS are identified.
- Each case study is unique, and uncertainties prevail around the practices of the IWS system.

NOMENCLATURE

Full form of abbreviations

ADEV	Average deviation of the sum of each DN supply ratio from the ASR
ASR	Average supply ratio
CV	Check valve
CWS	Continuous water supply
DDA	Demand-dependent analysis
DN	Demand node
ECT	Elastic column theory
EOA	Equivalent orifice area
FCV	Flow control valve
GIS	Geographic information system
IWS	Intermittent water supply
MOC	Method of characteristics
NHFR	Nodal head-flow relationship

PDA	Pressure-driven analysis
PDD	Pressure-dependent demand
PRV	Pressure reduction valve
RCT	Rigid column theory
RSV	Reservoir
UC	Uniformity coefficient
WDN	Water distribution network
WDS	Water distribution system

1. INTRODUCTION

Intermittent water supply (IWS) is a term frequently used to define an unreliable piped urban water supply service that does not provide water to consumers every day of the week or 24 h a day (Charalambous & Laspidou 2017; Simukonda *et al.* 2018). Although IWS is considered the most accessible and cheapest short-term solution for meeting the increasing demand for water, poor governance and poor system management in the long term are the leading causes of perpetuating its intermittent nature (Charalambous 2012; Simukonda *et al.* 2018). More detailed information on the causes, consequences, and solutions of IWS can be found in the literature (Klingel 2012; Galaitsi *et al.* 2016; Simukonda *et al.* 2018).

IWS is commonly used in developing countries where water scarcity and other limiting factors are issues and/or will be an issue in the near future (Abu-Madi & Trifunovic 2013; Kumpel *et al.* 2017). Half of the water distribution systems in Asia, and two-thirds in Latin America, Africa, and the Middle East (Vairavamoorthy & Elango 2002; Vairavamoorthy *et al.* 2007; Klingel & Nestmann 2013) are operated intermittently. It has also been practised in some parts of Europe, mainly during dry seasons or periods of water scarcity (De Marchis *et al.* 2010). Around 1,313 million people are currently subjected to IWS, representing 18% of the world's population (7,301 million), 38% (2,774 million) have continuous water supply (CWS), and the rest (44%) lack a piped system altogether (Charalambous & Laspidou 2017). Different operational characteristics of IWS are applied in different areas; for instance, in 2009, the average supply time was 5.2 h in India and 8.5 h in Jordan (Danilenko *et al.* 2014). More detailed information can be found in Kumpel & Nelson (2016) and Charalambous & Laspidou (2017), in which the data for the operation of IWS systems around the world are synthesised. Galaitsi *et al.* (2016) specify the type of intermittency by proposing three definitions: (1) *Predictable* in which the supply schedule is known by consumers, and the amount of water received by each one of them is enough to cover their needs similarly to CWS systems. (2) *Irregular* where the supply schedule is unknown, but sufficient water can be collected by the user similar to the predictable type of intermittency. (3) *Unreliable* in which the water supply schedule is unknown and the amount of water mostly insufficient.

Intermittent supply results in water quality problems (Kumpel & Nelson 2016), pipe bursts, significant water losses (Mutikanga 2012; Erickson 2016), inequitable distribution (De Marchis *et al.* 2010; Chandapillai *et al.* 2012; Ameyaw *et al.* 2013), meter malfunctioning (Arregui *et al.* 2006; Criminisi *et al.* 2009; Mutikanga *et al.* 2011; Mutikanga 2012; Arregui *et al.* 2013; De Marchis *et al.* 2013; Fontanazza Chiara *et al.* 2015) along with coping cost for consumers, utilities, and the society (Vairavamoorthy *et al.* 2007; Ameyaw 2011). Negative consequences occur due to the unique characteristics of the system, such as supply interruptions which will be discussed later in this paper.

Understanding the system behaviour through hydraulic model simulations is crucial to proposing solutions for the aforementioned problems. In the absence of suitable software for IWS hydraulic modelling, researchers have explored different approaches. This paper aims to scrutinise the existing literature regarding hydraulic modelling and its application to IWS case studies and identify key gaps in knowledge about IWS systems. The implications of this paper are believed to pave the way for future studies in the context of IWS hydraulic modelling and, consequently, its improvement.

The paper consists of five sections: the second section, after the introduction, explains the approach adopted to do this review. The third section summarises and critically analyses the studies on hydraulic modelling methods of IWS developed and applied so far. It starts with clarifying the unique characteristics of IWS, followed by presenting the studies implemented in EPANET, mathematical models for simulation of the filling process and household tanks, macroscopic models, and methods applied in EPA-SWMM. The fourth section presents the issue of inequity in water distribution in IWS and how it has been addressed by different researchers. The final section presents the conclusions, key gaps in the body of knowledge, and recommendations for future research.

2. REVIEW METHODOLOGY

This review covers studies on IWS which take into account the hydraulic modelling aspect of such water supply systems. The first studies conducted on the topic date back to the late 1980s and early 1990s (e.g., Reddy & Elango 1989; Chandapillai 1991; Vairavamoorthy 1994), while interest and publications in the area of research have increased significantly lately. Web of Science, Google Scholar, SCOPUS, and ScienceDirect are the databases used. The journal papers retrieved from the databases were selected using the following search keywords: IWS, pressure-driven (dependent) analysis, hydraulic modelling, filling process, water distribution networks, water supply networks, and any combinations of these. There are a large number of publications presenting different pressure-driven analysis (PDA) methods with a wide range of purposes and applications (i.e., leakage, IWS, reliability analysis, design, and real-time control of water distribution networks (WDNs)). While many of these could be potentially used for modelling the pressurised state of IWS, only the ones that have already been used in IWS hydraulic modelling are referenced. Another key part of this paper refers to the filling process, which is a core element of IWS and a relatively new area of research interest.

The collected publications were analysed and discussed based on the following key aspects:

§ In terms of model building procedure:
- o The level of detail considered in the hydraulic model and how well it corresponds to reality.
- o The assumptions and simplifications in the methodology.
- o Efficiency in terms of computational cost and accuracy of the results (model errors) obtained in the context of the scale of the problem and network size.
- o Challenges faced in each case study and how they were addressed in hydraulic modelling.
- o Parameters and calibration, in order to acknowledge the unique characteristics of each case study and discuss their impact on results.

§ In terms of research objectives: the purpose of hydraulic model development and their applications, and the areas that the hydraulic models are developed and applied (e.g., improvement of supply equity, IWS to CWS conversion, leakage, etc.)

3. HYDRAULIC MODELLING OF IWS SYSTEMS

This section discusses the hydraulic modelling of IWS, which serves as a basis for the paper, beginning with a description of the characteristics of the IWS system itself.

3.1. IWS system characteristics

IWS systems need to be hydraulically analysed considering their unique nature, and this makes the modelling complex:

Parameters for the hydraulic analysis of IWS (Batish 2003):

1. *Water supply from the source*: Water is released from the source intermittently.
2. *Network charging process*: Since the water is distributed to the system at specified intervals, filling and emptying of the pipes occur periodically in the system (De Marchis *et al.* 2010). Dual-phase flow emerges (i.e., free-surface flow and pressurised flow) during filling/emptying.
3. *Household tanks*: During periods of disruption in water supply, some consumers store water in household tanks located either on their roofs or underground. It is common for consumers to store as much water as possible in their tanks when supply resumes while continuing to consume water for their everyday needs.

Contrary to CWS, in many IWS systems, pressures are often insufficient to satisfy consumers' demands at all or a number of demand nodes especially during peak demand hours. In such cases, outflows at demand nodes are dependent on pressure and the most appropriate approach is PDA. In PDA, pressure is considered explicitly in the system of hydraulic equations, and it is directly linked with demand. PDA methods achieve this by incorporating a nodal head-flow relationship (NHFR) in the system of hydraulic equations. Several NHFRs have been proposed in the literature with the distinguishing factor being the existence of an upper boundary for outflow in their equations. Equations with an upper boundary (Bhave 1981; Germanopoulos 1985; Wagner *et al.* 1988; Chandapillai 1991; Fujiwara & Ganesharajah 1993; Tanyimboh Tiku *et al.* 2001; Tanyimboh & Templeman 2010) are suitable for modelling demands with controlled outlets (e.g., taps or tanks with flow control mechanisms or float valves). On the other hand, equations without an upper boundary (Reddy & Elango 1989, orifice equation) are suitable for modelling demands without a control mechanism (e.g., uncontrolled outlets or overflowing tanks).

Upper and lower boundaries ($H_{\min}$, H_{req}) in NHFRs designate the pressure head above which pressure-dependent outflow occurs and the pressure head above which full demand is supplied, respectively. Consequently, actual consumption at demand nodes (taps or tanks) differs from the original demand. The actual flow delivered at each demand node (DN) is based on the amount of water released from the source, the pressure availability, and user behaviour (Batish 2003; Ingeduld *et al.* 2006; De Marchis *et al.* 2010). Thus, under such conditions, it is difficult to predict the user water consumption.

Shirzad *et al.* (2013) investigated various pressure–discharge relationships with experimental work. Different size faucets with different opening status were explored. Results showed that the orifice equation and Wagner *et al.*'s (1988) equation without the upper threshold for which full demand is delivered showed better agreement with the experimental data. Tanyimboh & Templeman's (2010) equation showed good agreement with collected results after the calibration of parameters α and β. Walski *et al.* (2017) performed an experimental study in a laboratory set-up trying various pipe layouts and orifice openings. Results showed that the observed pressure and flow outputs agreed well with the orifice equation model. In further experimental work of Walski *et al.* (2018), the impact of having outlets at different elevations at a DN was investigated. Results showed that the elevation differences of outlets can have a significant impact on outflows. The proposed equation that describes the exponent takes into account the number of orifices at the DN, the range of orifice elevations, and the elevation below the node of the lowest orifice.

Experimental studies in laboratories could contribute to improved understanding and give insights into system behaviour under pressure-deficient conditions and complex consumer behaviour. A major advantage of laboratory studies is the flexibility and simplicity of arrangements as well as the ease of simulating different scenarios in a time-efficient manner compared to real case studies. Full control of the system and reasonably accurate data acquisition are important characteristics that could lead to the validation of current concepts as well as new findings. An obvious disadvantage of laboratory case studies is their small scale, although with current knowledge being limited modelling of more simple cases seems reasonable.

It is a common practice in CWS models that demand points and their corresponding consumption are aggregated at the model's DNs. Major assumptions about elevations and connectivity to the main WDN are made. Such simplifications could be reasonable in the case of sufficient pressure that guarantees CWS. However, the results of the above NHFR experimental studies suggest that in a range of low pressures, elevation differences in outlets can significantly affect outflow (Walski *et al.* 2018). Also, other parameters that increase the complexity of the relationship between flow at a node and pressure are the variable human behaviour of the person opening the faucet, the difference in elevations of the faucet and the model node, and the complexity of piping between them.

Challenges for building an IWS model: Data acquisition is one of the most significant challenges in building the model. Building a decent quality model depends on representing all elements of the system as realistically as possible. While in most CWS cases, design and maintenance interventions are well documented, in some IWS cases, the position, connectivity, and status of hydraulic elements are unknown and need to be mapped before building the model. Finally, model building is exacerbated by the lack of publicly available software suitable for IWS simulation.

Challenges for calibration and validation of the methods: The availability of measurement data is a fundamental issue in the analysis of IWS as it is imperative for calibration and validation as well as model building. After building an accurate model of the WDN, it is equally essential to calibrate and validate its correspondence to the real system based on pressure and flow-field measurements.

Issues resulting from the operational management of IWSs:

§ In the event of repeated opening and closing of valves, there can be pressure fluctuations leading to pipe failures. Other than pressure fluctuations, dynamic phenomena like transient flows are generated contributing in pipe and fittings' wear. Consequently, an increase in leakage occurs in such systems (Klingel 2012; Dighade *et al.* 2014; Charalambous & Laspidou 2017).

§ There is an increase in apparent losses caused by meters under registration in two ways: first, meter aging, and second, due to the low-flow rate induced by float valves in households (Criminisi *et al.* 2009; Mutikanga *et al.* 2011).

§ Illegal connections are triggered by a lack of water availability, poor management by the utility, breakdown of recording consumer registration, corruption and mismanagement, lack of household connections, and inappropriate tariffs (Butler & Memon 2006; Vermersch *et al.* 2016). It is estimated that 50% of water losses are due to private and illegal connections (Galaitsi *et al.* 2016).

Vairavamoorthy (1994) categorised IWS systems based on water availability as starved and non-starved systems. 'Starved' defines systems where supplied water is not enough for consumers to fill their household tank. The term 'non-starved' describes systems where sufficient water can be collected to fill household tanks during supply duration. Similarly, Taylor *et al.* (2019) defined IWS as satisfied and unsatisfied based on the amount of water a single consumer can get. If a consumer can get as much water as they demand, they are called 'satisfied'; if not, they are called 'unsatisfied.' A network can also consist of satisfied and unsatisfied users. These classifications are crucial for the analysis and assessment of IWS. Both classifications have similar meanings and are appropriate for representing IWS.

To date, there is no available software for the simulation of the hydraulic behaviour of IWS. In the absence of suitable software for modelling, researchers have proposed different methods to analyse the system. Most studies focus on the pressure dependency of nodal outflow and use different PDA methods mainly through EPANET (Section 3.2). However, some researchers use EPA-SWMM that was originally developed to model free-surface flow in drainage systems. The use of EPA-SWMM for IWS modelling involves manipulating the available hydraulic elements (nodes, conduits, etc.) to behave according to hydraulic elements in a clean WDN (Section 3.4). Other researchers developed new mathematical models that include the filling process (Lieb 2016) and the existence of household tanks (Criminisi *et al.* 2009) (Section 3.3.). An overview of IWS hydraulic modelling approaches is shown in Figure 1.

3.2. Modelling IWS in pressurised state (EPANET)

This section presents and discusses studies that have proposed and applied various pressure-dependent demand (PDD) hydraulic models that implement NHFRs in real case studies. All the following studies focus on modelling the fully pressurised state of the WDN while the filling and emptying processes are not considered. The main focus is to include intrinsic elements of an IWS system, such as low pressures at DNs and the consumers' household storage tanks. In most cases, the aforementioned PDA methods (Section 3.1.) are used to take into account the effect of low pressures on the actual demand outflows.

3.2.1. Controlled outlets

Trifunović & Abu-Madi (1999) tested and compared two different approaches for modelling demands in IWS systems where consumers use household storage tanks. The first approach uses a pressure threshold at which the specified demand is satisfied and below which the outflow is pressure-dependent. Different pressure thresholds were tested (6, 12, and 36 m) in a case study, and results showed instability in the pressure profiles at DNs as well as negative pressures. In the second approach, the individual household roof storage tanks were clustered and represented by one large but shallow tank (depth of 1–2 m) in the network model. A check valve (CV) and a flow control valve (FCV) were also added between the original DN and the artificial tank to prevent backflow to the system and limit outflow at DNs to the required demand, respectively. The second approach that includes the introduction of tanks is more realistic than the first approach, which produces profound changes in pressure and even negative pressures.

Similar to the work of Trifunović & Abu-Madi (1999), Macke & Batterman (2001), and Ameyaw (2011), individual household storage tanks were aggregated into larger-sized tanks in the model. In Macke & Batterman (2001), the size of the

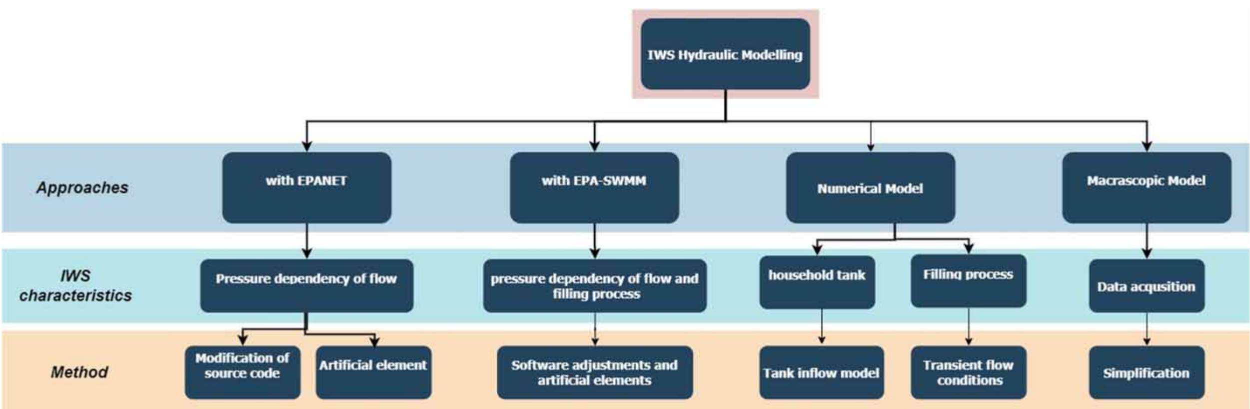

Figure 1 | IWS hydraulic analysis methods.

equivalent model tanks and the diameter of the pipes connecting the tanks to the network were subject to calibration using field data. The equivalent tank depth is 1 m for all tanks, and a CV is introduced between the original DN and the tank. A set of artificial elements was also used in order to model pressure-dependent leakage. A 2-m long pipe leading to a tank of a very big size is connected to all leakage nodes. Calibration of the model was conducted on multiple factors, including the diameter of artificial leakage pipes, instead of the usual calibration, which considers only pipe roughness.

Ingeduld *et al.* (2006) incorporated Wagner *et al.*'s (1988) NHFR and considered household storage roof tanks in their hydraulic model. The assignment of tanks to network junctions is done in a semi-automated way using available geographic information system (GIS) data and consumer questionnaires (e.g., for the physical properties of the tanks and their connection to the network). Leakage is taken into account as a percentage of the total supplied volume. In Puleo (2014), household tanks' fill rate is modelled with Wagner *et al.*'s (1988) equation and depends on the level of the tank's floater level. $H_{\min}$ is considered equal to the tank elevation and H_{req} is assumed to be equal to +10 m after considering the head losses in the consumer connection pipe.

A summary of the studies mentioned in this section can be found in Table 1.

Table 1 | IWS studies using EPANET for hydraulic modelling considering controlled outlets

	Hydraulic model					
Authors	**PDD model**	**Leakage model**	**Private tanks**	**Study objective**	**Details of objective**	**Case study**
Trifunović & Abu-Madi (1999)	Tanks or NHFR	–	–	Demand modelling of the IWS system with private storage tanks	Individual household RSVs are modelled either as PDD nodes, or as shallow tanks of large surface area	Tulkarm, Palestine
Macke & Batterman (2001)	Tanks	Artificial pipe tank arrangement		Calibration, simulation, and water loss reduction in IWS	Individual household tanks are aggregated at nodes and are represented by large tanks in which size and connecting pipe diameter are calibrated with field data	Al Koura, Jordan
Ingeduld *et al.* (2006)	Wagner *et al.* (1988)	Distributed across network pipes as % of demand	Tanks	PDA of IWS	Provide a PDA tool to help in network rehabilitation, planning, and conversion to CWS	Shillong, India and Dhaka, Bangladesh
Ameyaw (2011)	Tanks	–	–	Macroscopic hydraulic simulation of IWS with the use of tanks and equity improvement interventions during design	Installation of system tanks is considered in order to improve the equity of water distribution. Optimisation of tank size based on the maximisation of equity and the minimisation of cost	Four nodes in series network (Gupta & Bhave 1996)
Puleo (2014)	Wagner *et al.* (1988) combined with orifice equation	–	–	Real-time optimal control of IWS	Novel hydraulic model for IWS with household tanks and optimal valve operation	Palermo, Italy
Ilaya-Ayza *et al.* (2017)	Emitter (modified EPANET2 Pathirana (2010))	–	–	Multi-criteria optimisation of supply schedules in IWS	Criteria for optimisation are to: maintain pressures across the network close to a reference pressure, reduce inconvenience for consumers, modify the shorter supply schedules, and ease sector operation	Oruro, Bolivia

3.2.2. Uncontrolled outlets

Batish (2003) and Chandapillai *et al.* (2012) investigated the design of IWS systems aiming to provide equitable distribution of water resources to consumers. Batish's (2003) demand model is based on attaching at each DN a reservoir (RSV) with an elevation of the required total head. The author notes that modelling demands with tanks would be more realistic (as in Trifunović & Abu-Madi (1999) and Macke & Batterman (2001)). However, this approach would require much more detailed information about the individual household storage tank sizes and their connection to the network. Chandapillai *et al.* (2012) consider pressure dependency of the delivered demand through the NHFR proposed by Reddy & Elango (1989) and Chandapillai (1991). This was incorporated into the EPANET model by adding an emitter at each DN, which substitutes the assigned demand.

Fontanazza *et al.* (2007) considered that consumers use household storage tanks with pumps to collect as much water as possible during the supply period. The pump ensures the outflow of water in the storage tank even when the nodal pressure is less than the minimum required ($H_{\min}$) for having an outflow at the node. Reddy & Elango's (1989) NHFR is used to model the pressure dependency of outflow in household tanks. Due to the presence of the pump, there is no minimum required pressure to have outflow at the storage tanks ($H_{\min} = 0$). It is also considered that there is no H_{req} for which the demand is satisfied. The total nodal outflow is limited only by the tank size which is defined according to the nodal daily demand. The pump characteristics are chosen, so that it can fill the storage tank in 4 or 5 h.

In Mohapatra *et al.* (2014), artificial RSVs are assigned at each DN with an elevation equal to the ground level plus the required pressure head. Outflow to the artificial RSV in this case is not restricted by setting an upper boundary of required pressure that satisfies the full demand. Each artificial RSV in the model is connected to the main network with a pipe of diameter and length equivalent to that of the pipes leading to consumer ends. The length and roughness coefficient for the equivalent pipe is that of the dominant pipe and its diameter is determined appropriately as in Walski *et al.* (2003). This pipe is also set to act as a CV to prevent backflow from the RSV to the main distribution network. Leakage is also taken into account in the model as discharge through emitters with a coefficient of 0.6. The emitter coefficient is calibrated with leakage data that assume equal distribution of the total leakage flow rate across leakage points.

Gottipati & Nanduri (2014) used Tanyimboh Tiku *et al.*'s (2001) NHFR but without an upper threshold for outflow. The methodology for equity assessment and the hydraulic model were applied in the real case study used in Kansal *et al.* (1995), as well as two sample networks, one with a grid layout and one with a radial layout. In Ilaya-Ayza *et al.*'s (2017) supply schedule optimisation study, hydraulic simulations are performed using the EPANET 2 version as modified by Pathirana (2010). High peak flows cause reduction of pressure and flow at the most remote or elevated points relative to the source.

Table 2 summarises the studies mentioned above. These studies use a wide variety of hydraulic modelling techniques depending on each specific case study. In cases where consumers were considered to leave their taps open throughout the supply period (uncontrolled outlets), no specific demand was attributed at DNs. Uncontrolled outlets are taken into account by using either PDD equations without head pressure upper limit for which demand is fully satisfied (H_{req}) or artificial RSVs at DNs which maintain a constant elevation and do not fill. In other cases, consumers' behaviour is considered by specifying nodal demands or assigning finite volume tanks at DNs. Modelling nodal demands with tanks is realistic in cases where consumers use storage tanks. This can be considered a volume-dependent demand, and the tank's filling rate is pressure-dependent. In cases where consumers use tanks that overflow, the approach of no upper limit in outflow would be more realistic.

3.3. Numerical, empirical, and macroscopic models

Some researchers have developed complex mathematical models considering the unsteady filling process and the existence of the household tanks to represent the hydraulic behaviour of the system more accurately. Others have proposed more simplistic approaches (i.e., macroscopic models) while addressing the challenge of getting detailed data from real IWS systems. These are presented under the following subsections.

3.3.1. Integration of periodic filling and emptying process in the hydraulic analysis of IWS

With the intermittency of water supply, periodic network filling and emptying of the piped network occurs in IWS, which then leads to the development of transient flow phenomena with highly varying velocity and head (i.e., from pressurised to partial-flow regime and *vice versa*). Such behaviour points to the necessity of integration of continuity and momentum equations (Ingeduld *et al.* 2006).

Table 2 | IWS studies using EPANET and considering uncontrolled outlets for hydraulic modelling

	Hydraulic model					
Authors	**PDD model**	**Leakage model**	**Private tanks**	**Study objective**	**Details of objective**	**Case study**
Batish (2003)	RSVs	–	–	Design of IWS systems	RSVs are used to model demands. Different positions for FCV installation are investigated in order to improve the equity of water distribution	Pinjore, Haryana, India
Fontanazza *et al.* (2007)	Reddy & Elango (1989) (emitter)	–	Pump and RSV	Analysis of IWS and assessment of water distribution equity	Investigate the equity of water distribution in the case where consumers use private pumps to store water in household tanks	Palermo, Italy
Chandapillai *et al.* (2012)	Reddy & Elango (1989) (emitter)	Distributed across network pipes as % of demand	Tanks	Design of IWS systems for the equitable distribution of water	Optimisation of the different pipe diameters based on the maximisation of equity and the minimisation of cost	Two-loop sample network
Mohapatra *et al.* (2014)	RSVs	Emitter	–	Network assessment in IWS and CWS	Model IWS with uncontrolled outlets at consumers' end with RSVs at DNs	Nagpur, India
Gottipati & Nanduri (2014)	Wagner *et al.* (1988)	–	–	Assessment of equity in water distribution and optimal design of IWS systems	Assess the impact of source elevation, variation of demands at DNs, and changes in pipe diameters in equity	Kansal *et al.*'s (1995) case study

IWS systems may be more accurately modelled if the network charging and emptying processes are also included in the analysis. By doing so, the moment each consumption node starts receiving water will be taken into account. This crucially impacts the unfair distribution of water among consumers.

Water network charging (i.e., hydraulic filling of pipes) has been modelled either using the Rigid Column Theory (RCT) or Elastic Column Theory (ECT) (Walski *et al.* 2003; Bhave & Gupta 2006; Zhou *et al.* 2011). While in RCT, it is assumed that the water is incompressible and the pipes are rigid; in ECT, the elasticity of the pipes and the compressibility of the fluid are considered as it assumed to be the result of momentum variations (Walski *et al.* 2003; Bhave & Gupta 2006).

RCT has limited applications in analysing instantaneous flow changes as it is unable to interpret the behaviour of pressure wave generation. Transient flows are only controlled by inertia and the friction that is applicable to surge conditions (i.e., in the case of slow and minor head changes, the compressibility of the flow and pipe deformation can be neglected) (Walski *et al.* 2003; Bhave & Gupta 2006). Considerations of pipe elasticity and flow compressibility in ECT produce wave propagation characterised by the elasticity of the liquid and the pipeline (Walski *et al.* 2003; Bhave & Gupta 2006).

The boundaries of the system (e.g., tanks and dead ends) play a crucial role as well as equations that describe the transient flow, as they also impact the behaviour of the transient conditions (Walski *et al.* 2003).

To consider the unsteady filling process, Liou & Hunt (1996) developed a numerical model which is based on the RCT. The model was verified with a laboratory test. However, De Marchis *et al.* (2010) claim that the model is not suitable for complex WDNs due to the fluid incompressibility assumption. They proposed a model using the method of characteristics (MOC) to solve the partial differential equations of momentum and continuity for weakly compressible liquids and applied to the city of Palermo to calibrate and validate it. They combined the tank inflow emitter law of Criminisi *et al.* (2009) and the filling process equation based on the assumption that the water column cannot be fragmented and the air pressure internal to the network is equivalent to the atmospheric pressure and created a mathematical model. The average node head discharge parameter settings are inspired by Criminisi *et al.*'s (2009) field study. Their results seem promising in terms of evaluating the strategies for intermittent WDN management, particularly addressing the inequitable supply problem. De Marchis *et al.* (2011) then used this numerical model to analyse the inequitable distribution of water under different water availability situations. However, from Mohan & Abhijith's (2020) point of view, this model has limited application to small diameter pipes because they assume that the water column front is perpendicular to the pipe axis and the flow depth is always equal to the pipe diameter.

Additionally, their model is not made available, and its validation has been done with data of a single time step. Freni *et al.* (2014) used this hydraulic model in their proposal of using pressure reduction valves (PRVs) for improving water supply equity. Other numerical models employing the transient flow conditions are developed by Nyende-Byakika *et al.* (2012) and Nyende-Byakika *et al.* (2013).

Lieb (2016) developed a mathematical model to capture the bi-dimensional behaviour of the filling's front as a mathematician using the Preissman slot model. This model ensures a smooth transition between the empty and the pressurised pipes, and at the same time, it incorporates time-dependent boundary conditions. To reduce the risk associated with infrastructure damage, optimisation that improves the system operations is proposed. However, the available computer simulations are computationally expensive due to the complexity of such models.

Experimental works were also carried out (Walter *et al.* 2017; Weston *et al.* 2022) using one pipe connected to an RSV. Walter *et al.* (2017) investigated the metering errors caused by air resulting from pipeline filling. Weston *et al.* (2022) explored the effects of some hydraulic parameters (initial/final pressure, initial/final flow rate, valve operation speed, and leakage percentage) on the filling and emptying of pipes. They observed the negative pressures and over-pressurisation of the system, which can be associated with the water quality. Walter *et al.* (2017) observed that 93% of the air volume in the pipe is measured by the meters due to the filling process of an empty service connection.

Mohan & Abhijith (2020) proposed an improved PDA hydraulic model that considers partial-flow regimes inside the piping system of the network. Integration of partial flow in the hydraulic model is a novel feature in IWS hydraulic modelling. Partial flows in pipes are common either during the filling process or at later stages of supply. Their study focuses on highly intermittent WDNs, and thus, the head–outflow relationship considers outflows through uncontrolled outlets as in Reddy & Elango (1989). The model was tested on the real case study of the WDN of North zone 10 of Madurai, Tamil Nadu, India, which consists of 30 DNs and 30 pipes in a branched configuration. The model is useful for both pressurised and pressure-deficient conditions, and the outcomes can be fruitful for the analysis of water quality variations (Mohan & Abhijith 2020).

The studies mentioned in this section are shown in a summary form in Table 3.

The steady-state analysis is sufficient to analyse hydraulic systems that undergo slow changes in velocity and pressure. A transient analysis is required when changes in flow and pressure occur rapidly within a short period of time. Transient flow conditions were developed in IWS during the network filling process. Rapid filling problems are two-phase phenomena, and it is necessary to implement multi-phase modelling (Vasconcelos & Wright 2005). However, multi-phase modelling is more complex, and the computed results would have more uncertainty. An accurate theoretical simulation of every physical phenomena that can occur in an actual hydraulic system is nearly impossible. Therefore, all modelling of transients involves some approximation and simplification of the real problem (Walski *et al.* 2003).

The transient phenomenon should be considered not only in the analysis process but also in the design process. The operating speed of the valves and the size of the pipes should be chosen, so that the detrimental effects of transients can be avoided.

3.3.2. Macroscopic models

Taylor *et al.* (2019) approached the modelling aspects of IWS from a unique perspective proposing a parsimonious model addressing the difficulty in detailed data acquisition from such networks. The model aims at understanding the operation and persistence of IWS by indicating the relationships among consumer demand satisfaction, source water availability, consumer demand, and leakage. Aggregated behaviour of a system is considered in this macroscopic model. Hence, the entire system is represented based on user behaviour, and a single leakage with a mathematical equation based on the volume of water supplied to the network was taken as equal to the sum of the volume received by consumers and the leakage volume:

A single satisfied and unsatisfied consumer: $$V_R = \begin{cases} V_D & \text{:Satisfied} \\ K_D\, th^{\emptyset} & \text{:Unsatisfied} \end{cases} \quad (1)$$

Aggregated consumer: $$V_R = V_D \min\left(1, \frac{th^{\emptyset}}{\gamma_S}\right) \quad (2)$$

Table 3 | Numerical and empirical studies for filling and emptying process of IWS

Authors	Category	Used model: Theory and solution method	Used model: Filling process 1D	Used model: Filling process 2D	Study objective	Methodology	Application/case study	Conclusion
Liou & Hunt (1996)	Unsteady filling process	RCT		–	To consider the unsteady filling process	A numerical model was developed, and it was verified with a laboratory experiment	A pipeline connected to a RSV	The proposed model can be applied to the networks; in case, there is no air intrusion: high-flow velocity or small diameter of pipes
De Marchis *et al.* (2010)	IWS filling process	Both water and pipeline characteristics are considered by using the MOC		–	To simulate the IWS filling process where users have household tanks	A mathematical model was developed for the simulation of the filling process that takes place in IWS	One of the supply networks in Palermo/ Italy	The occurrence of inequality due to household tanks was confirmed with the model applied to a real case study. The developed model can be useful for further analysis of IWS
Nyende-Byakika *et al.* (2012)	Pipe filling process	Different solution methods are applied for different flow conditions		–	To perceive flow transition from free-surface flow to pressurise flow takes place filling of IWS	Equations derived from Saint Venant's principle considering spatial and temporal changes in flow and pressure characteristics	–	The proposed algorithm helps understanding of low-flow conditions by calculating the pressure and flow at a particular time
Nyende-Byakika *et al.* (2013)	IWS system analysis	MOC		–	To develop models for IWS, particularly free-surface flow conditions, namely low pressure open channel flow (LPOCF)	Three approaches were suggested addressing IWS: demand-dependent analysis (DDA), PDA and modelling the pipe filling and pressurisation	WDN of Kampala/ Uganda	The framework suggested for IWS will be useful for operational considerations
Freni *et al.* (2014)	IWS filling process	MOC		–	To develop a dynamic model that accounts for the filling process and the existence of PRVs	The model of De Marchis *et al.* (2011) (network filling process) and the dynamic approach of Prescott & Ulanicki (2008) (PRV model) were combined	One of the WDS of Palermo in Sicily	The importance of PRV usage to improve equity was demonstrated
Lieb (2016)	IWS filling process	Preissman slot model		–	To capture the two-dimensional behaviour of transient flow during the network filling process	A numerical model was developed to enable the transition from empty to pressurised pipes, and then optimisation was used to enhance IWS	Alameda/ Arraij´an/ Panama	The work could be the starting point for building modelling and optimisation tools for IWS

Walter *et al.* (2017)	Experimental pipe filling process	Experiment	–	–	To measure the error in a single jet water metre caused by air during the filling process	Experiments were conducted for dry and wet metre case	A pipe connected to a water tank	While measurement error only depends on air volume in the dry metre case, additionally it depends on pipe pressure in the wet case
Weston *et al.* (2022)	Experimental pipe filling process	Experiment	–	–	To perceive the effects of some hydraulic parameters on the duration of the filling and emptying process	Inequitable distribution was tested under different scenarios	A single pipe connected to a RSV	Negative pressures were observed during the filling process
Mohan & Abhijith (2020)	Partial-flow regimes in IWS	PDA-PF model developed			To introduce a methodology accounting for partial-flow regimes in IWS	The PDA-PF model was proposed. Starved network conditions were elucidated by including uncontrolled outlets in the model. Simulation results from EPANET were compared with PDA analysis	Madurai city, India	The duration of the partial-flow conditions was found to make up a quarter of the total duration

where V_R (m^3/day) and V_D (m^3/day) are the daily volume of water received and demanded by consumers, respectively. K_D (m^3/day) is pipe and topography constant, t is duty cycle (fraction of time a system is pressurised), φ is the pressure exponent of consumer demand, $h \equiv H/H_t$, (H) supply pressure, (H_t) targeted supply pressure, and γ_S is the minimum th^{φ} required to satisfy consumers.

Leakage rate of a single leak: $$Q_L = C_d A [2gH]^{\alpha} \left(\frac{86,400\ S}{1\ \text{day}} \right) \tag{3}$$

Daily leakage volume for the network: $$V_L = tQ_L = K_L A t H^{\alpha} \tag{4}$$

Model equation: $$V_P = V_D \min\left(1, \frac{th^{\emptyset}}{\gamma_S}\right) + V_{LC}\alpha th^{\alpha} \tag{5}$$

Q_L (m^3/day) is the leakage flow rate of a single leak, A is the orifice's cross-sectional area, C_d accounts for the orifice's shape, α accounts for the flow rate's pressure dependency, V_L (m^3/day) and V_{LC} (m^3/day) is the daily volume of leaked water and targeted leaked water, V_P (m^3/day) is the daily volume input to a network, and $\alpha \equiv A/A_t$, A_t is the equivalent orifice area (EOA) required to achieve a project or system's targets.

The model is calibrated using four reference CWS networks that are simulated as IWS using the method of Macke & Batterman (2001). The model indicates that there is an optimum point between satisfied demand and unsatisfied demand which might be the justification for the existence of IWS. On one hand, the model is extremely useful for the improvement of IWS, such as conversion purpose (from IWS to CWS), and it can be applied to different IWSs. On the other hand, this macroscopic model has some limitations to represent IWS systems. Lack of network topology and spatial variation of pressure affect other system parameters dependent on pressure such as the uniqueness of individual consumers, the gradual transition from unsatisfied to satisfied, or the pipe filling process (Taylor *et al.* 2019).

Similarly, in 2018, a simplified model was proposed by Taylor *et al.* (2018) to explore strategies for the improvement of water quality in IWS. The model equations relate supply duration, supply pressure, and leakage rate. They represented leakage with Equation (4), in which the EOA was used to quantify water quality. They concluded that longer supply duration might improve water quality but only during the flushing phase. In the subsequent steady state, it creates an adverse effect.

3.4. Modelling of IWS with EPA-SWMM

EPA-SWMM has been preferred for hydraulic analysis of IWS by some researchers, as it is capable of simulating the transition from the free surface to pressurised flow.

The usage of EPA-SWMM started with a masters thesis written by Segura (2006) targeting the conversion of IWS to CWS. The idea of developing his method in EPA-SWMM was to represent the pressure dependency of flow related to the existence of household tanks. For this reason, a storage tank is connected to the node with an outlet at each junction, in which the pressure dependency of flow is assigned. The method also includes outflow from storage with a normal daily water consumption curve assigned as negative inflow to the storage nodes. The application of this method to the case study in Villavicencio in Colombia showed that the inequitable distribution is exacerbated by the usage of bigger tank size.

Similarly, Cabrera-Bejar & Tzatchkov (2009) included household tanks in their method but simulated supply schedules of IWS by introducing an inflow pattern to the source node. Kabaasha (2012), Shrestha & Buchberger (2012), and Dubasik (2017) developed methods in EPA-SWMM to simulate IWS behaviour with slightly different node configurations and adjustments of settings in the software. Whereas Kabaasha (2012) and Dubasik (2017) preferred to dismiss the inclusion of household tanks in node configuration by assuming that users always leave their taps open, Shrestha & Buchberger (2012) included a pump in the node configuration as well as household tanks. That way, the inflow at each node is dependent on the available nodal pressure and the pump capacity. Kabaasha (2012) implemented his assumption to the node configuration by connecting an outfall to each DN via an outlet. Thus, the inflow will only depend on the available pressure at the node, and it is implemented by introducing an NHFR at each outlet.

The ability of EPA-SWMM in representing the behaviour of the filling process was evaluated by validating the results with a field experiment in a WDN in Sicily (Italy) by Campisano *et al.* (2019a). Their method is the same as the method developed by Kabaasha's (2012) PDA approach, except that they introduced different head-flow relationship equations to the outlet.

Meanwhile Kabaasha (2012) used an exponential relationship, and Campisano *et al.* (2019a) used Wagner's equation (Wagner *et al.* 1988). They concluded that EPA-SWMM is reliable in simulating the filling process of IWS.

With the aim of considering household tanks in the modelling, Campisano *et al.* (2019b) developed a method including storage elements connected to the nodes. They used the hyperbolic law of the emitter developed by De Marchis *et al.* (2015) to predict the flow rate based on available pressure entering household tanks controlled by float valves:

$$\begin{cases} Q = Q_{\max} = C_v a_v \sqrt{2g[(h - z_t) - SL]} & \text{if} \quad H \leq H_{\min} \\ Q = Q_{\max} \tanh\left(m \dfrac{H_{\max} - H}{H_{\max} - H_{\min}}\right) \tanh\left(n \dfrac{H_{\max} - H}{H_{\max} - H_{\min}}\right) & \text{if} \quad H_{\min} < H < H_{\max} \\ Q = 0 & \text{if} \quad H \geq H_{\max} \end{cases} \tag{6}$$

where Q (m^3/s) is inflow to tank; $Q_{\max}$ (m^3/s) is the value of inflow 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 gravity acceleration; h (m) is nodal pressure head in the network; z_t (m) is float valve elevation; S is the energy line slope; L (m) is the length of pipe connection between the network node and tank; m and n are non-dimensional coefficients; H (m) is tank water level; and $H_{\max}$ (m) and $H_{\min}$ (m) are, respectively, tank water levels corresponding to full closure and full opening of the float valve.

This method (Campisano *et al.* 2019b) was employed for the improvement of equity by Gullotta *et al.* (2021).

Since EPA-SWMM requires at least an outfall to drain water from the system (Rossman 2017), methods do not have outfalls connected to the junction nodes placed an outfall somewhere in the network. Table 4 summarises the methods applied in EPA-SWMM for modelling IWS. All the methods use the dynamic wave routing method, which allows the simulation of pressurised flow by solving the St Venant equations (Rossman 2017).

Overall, the hydraulic analysis of IWS with EPA-SWMM served different purposes: simulation of the network filling process (Cabrera-Bejar & Tzatchkov 2009; Campisano *et al.* 2019a); more accurate consideration of household tank (Campisano *et al.* 2019b); hydraulic modelling of IWS with EPA-SWMM with the comparison of the EPANET-PDA approach (Kabaasha 2012); better management of coping strategies of users by having information on the time of getting water (Segura 2006); improvement of equitable supply (Dubasik 2017); and the provision of a reliable continuous supply (Shrestha & Buchberger 2012).

Methodologies were developed for specific case studies, and hence, settings are made accordingly. Each of the methods mentioned above approximates the IWS behaviour and is useful in terms of proposing solutions caused by intermittencies such as inequitable supply and the convergence of the system to CWS. However, they have challenges with detailed data acquisition. Furthermore, since EPA-SWMM requires substantial modification incapable of simulating the water distribution system (WDS), and the complexity of the underlying equations pose some errors in the model results (e.g., the existence of flooding the junctions, the appearance of a flow routing error, and increase in run time caused by embedded additional elements). The suitability of the settings in terms of the working principles of EPA-SWMM is crucial for both the accuracy and the stability of the results. Furthermore, most of the studies did not validate the results against the field data as data acquisition is one of the main challenges faced.

3.5. Observations

The different hydraulic models for IWS systems presented in this section can be addressed based on the level of detail they are emulating. Macroscopic models attempt to provide a system representation on the highest scale by aggregating the major components of water input and output such as volumes of water supply from source(s), demands, and leakage. Furthermore, more detailed models (e.g., EPANET) represent hydraulic elements in greater detail (e.g., specific demand points and household tanks) while taking into account pressure dependency of demands and household tank filling. Some models (e.g., EPA-SWMM and numerical models) are even able to simulate processes such as the filling process or partial flow in pipes.

Each of the above models can be useful for decision-makers for different purposes and uses. Their suitability can depend on data availability, uncertainty of the physical and operational status of elements in the real WDN being modelled (pipe diameters, valve statuses, leakage levels and location, etc.), and the desired level of accuracy or scale. It should be stressed that IWS shows increased complexity compared to CWS and poses different challenges in the modelling process. Current studies are still investigating different methodologies for modelling and analysis of such systems.

Table 4 | IWS studies using EPA-SWMM for hydraulic modelling

Authors	Hydraulic model: Artificial elements	Hydraulic model: NHFR	Hydraulic model: Private tanks	Hydraulic model: Filling process	Study objective	Details of objective	Case study	Supply schedule
Segura (2006)	Outlets and tanks	Applied based on field measurements	Tank	1D	Conversion from IWS to CWS	To learn the time water delivered to each consumer, so that they can plan the water usage. In this way, large storage usage can be prevented	Villavicencio, Colombia	7 days
Cabrera-Bejar & Tzatchkov (2009)	Tanks	–	Tank	1D	Modelling initial network charging	A schedule of IWS is introduced to the network	Guadalajara/ Mexico	3 days – the first 5 h a day
Kabaasha (2012)	Outlets and outfalls	Linear relationship	–	1D	Modelling unsteady-flow regimes in WDS	Various networks are used for both demand-driven and pressure-driven analysis; results are compared with EPANET 2.0	Real-life and synthetic networks	24-h simulation with the first 3 h and the last 6 h supply for unsteady-flow simulation
Shrestha & Buchberger (2012)	Pump tank outlet outfall	–	Tank	1D	IWS conversion to continuous with satellite water tanks	Modelling of existing IWS and proposed WDS with satellite tanks	Kathmandu/ Nepal	Duration of simulation: 14 days water supplied every 2.5 h for alternate days in a week. The intermittent inflow of 2.6 litres per second (lps) is introduced at the source node
Dubasik (2017)	–	–	–	1D	The transition from IWS to CWS and the improvement of equitable supply	A real case study designed for CWS is used. CWS operation is modelled with EPANET 2.0 with DDA. IWS operation is modelled with EPA-SWMM	Espavé/Panamá	Some scenarios are applied
Campisano *et al.* (2019a)	Outlets and outfalls	Wagner *et al.* (1988)	–	1D	The ability of EPA-SWMM for simulating the filling process	The filling process validated with field data	Ragalna/Sicily/ Italy	The duration of the simulation is 4 h with 4 h supply duration
Campisano *et al.* (2019b)	Outlets, tanks, and outfalls	Hyperbolic law of the emitter	Tank	1D	Consideration of household tanks in modelling of IWS with EPA-SWMM	Flow entering the tank is modelled with an equation from De Marchis *et al.* (2015)	–	–
Gullotta *et al.* (2021)	Outlets, tanks, and outfalls	Hyperbolic law of the emitter	Tank	1D	Improvement of equity in IWS with users has household tanks	A novel methodology based on optimisation is developed to improve equitable supply	Northern Italy	14 days simulation. The amount of water continuously released from the supply RSV was assumed equal to 70% of the total daily demand

In particular, the challenges in the modelling are:

1. The complexity of the flow during the filling and emptying process.
2. Calibration and validation of the parameters required to model household tank inflow.
3. The detailed data required to build a hydraulic model.
4. The uncertainties with regard to consumers' behaviour (e.g., pipe size and connectivity at the consumer's end, the existence of household tank and/or private pump, demand pattern, etc.).
5. The practical application of macroscopic models without looking into the detail of the system behaviour.

Section 3 presented the studies addressing the challenges and the peculiarity of IWS which were mentioned in Section 3.1. It is clear from the above discussion that intermittency in the water supply affects the WDS's behaviour as well as consumers' behaviour. The following section (Section 4) discusses the issue of inequity in water distribution among consumers as a result of IWS, the current measures of equity, and the existing methodologies for equity improvement. It is important to note the critical role of IWS hydraulic models in the process of decision-making with regard to equity improvement interventions.

4. WATER DISTRIBUTION EQUITY

PDA is suitable for modelling the fully pressurised state of IWS as it provides a more realistic calculation of pressures and flows in IWS where pressures are usually insufficient to satisfy full demand. This way, DNs appear to have different levels of demand satisfaction and the inequity in the distribution of water is observed. The issue of inequity is evident in most of the demonstrated IWS hydraulic modelling case studies and it has been addressed in several other publications that do not use explicit hydraulic modelling. Current measures of supply equity as well as proposed interventions from the literature are discussed in the following subsections.

4.1. Measures of supply equity

Different measures of equity/inequity have been proposed. Two performance indices are used in Fontanazza *et al.* (2007) to evaluate the equity of water distribution: (i) the supply ratio (SR) between the water volume supplied to the consumers in a service cycle (V_{sup}) and the consumers' demand (V_{dem}): V_{sup}/V_{dem} and (ii) the ratio between the water flow discharged to the user during a service day in intermittent (Q_{int}) and continuous distribution conditions (Q_{cont}): Q_{int}/Q_{cont}.

Ameyaw (2011) used a measure called deviation of equity and is defined as:

$$D_E = \text{Min} \sum_{i=1}^{n} |(\%Q_{av} - \%Q_s)| \tag{7}$$

where N is the number of consumer nodes in the WDN. Q_s (%) is the SR of each DN as a percentage (actual volume supplied to the amount required), and Q_{av} (%) is the average ratio of water delivered to all DNs in the network as a percentage.

Chandapillai *et al.* (2012) measured how inequitable the distribution of an available quantity of water focusing on the minimum SR observed in the network is. The drivers of the optimisation procedure are the minimisation of cost and the increase of SR of the most disadvantaged/deficient DN and the respective index is shown in the equation subsequently:

$$\text{Inequity} = 1 - \text{Min}\left\{\frac{V_{sup}}{V_{dem}}\right\}_j \tag{8}$$

where V_{sup} is the volume of water supplied during the service cycle, V_{dem} is the volume of demand during the service cycle, and j is the DNs' number.

Authors note that optimisation of pipe diameter with these objectives could result in a network with very small diameter pipes which might not satisfy required flow rates. Hence, a minimum head requirement is also incorporated as a constraint: the minimum head surplus of the network DNs ($H_{avl} - H_{min}$) should be greater than zero.

Gottipati & Nanduri (2014) proposed a new equity assessment index, namely uniformity coefficient (UC), which considers the deviation of each node's SR from all nodes' average supply ratio (ASR). The deviation of the SR of the node from the ASR is computed at each node, and the mean of these deviations is defined as the average deviation of the sum of each DN supply ratio from the ASR (ADEV). UC is defined as:

$$UC = 1 - \left(\frac{ADEV}{ASR}\right) \tag{9}$$

Different scenarios were considered in the analysis of a real case study to assess the impact of the source elevation, the variation of demands at certain nodes, and changes in pipe diameters in the UC. Two sample networks are used to assess the impact of the location of the source RSV and the effect of the layout of the network in the UC.

In Vairavamoorthy (1994), the overall objective was to distribute the limited quantity of water of an IWS as fairly and equally as possible. Considering water-starved systems (Section 3.1) where pressure dictates the quantity of water collected by the consumers, the objective for the improvement of equity was set as minimisation of pressure diversity at the minimum cost. Ilaya-Ayza *et al.* (2017) followed a similar pressure-oriented approach for optimising operational scheduling, which aims to maintain pressures in the network close to some reference pressure.

Overall, either the volume SR or pressure uniformity is the core element of the current equity indices used in the hydraulic modelling of IWS during its fully pressurised state. The use of a pressure equity measure could be justified in cases where there is high uncertainty about demands or if it is known that consumers' behaviour resembles more closely flow through uncontrolled outlets. In this case, care should be taken that aggregated DNs do not have large elevation differences as this is going to affect the accuracy of results. For example, lower elevation aggregated nodes would, in reality, have higher available head pressures and thus larger supply ratios, and *vice versa*. A major shortcoming of the above hydraulic models that use the volume SR indices to measure equity is that they do not consider the filling process during which a large volume of water is delivered in an inequitable manner (e.g., nodes closer to the source start receiving water several minutes or hours before the furthest ones). New equity measures should be defined alongside improved models that address the above shortcomings. Again, the appropriate equity measure might differ according to each individual case study or hydraulic model used and such a choice should be well justified.

4.2. Equity improvement interventions

Various types of network interventions have been proposed in order to achieve a more equitable distribution of water. Vairavamoorthy (1994) and Batish (2003) considered the use of FCVs at specific pipes to constrain flow at sections that receive more water and increase flow at sections with low-flow rates. In Vairavamoorthy (1994), the problem was formulated with two aims/stages: first determine the optimum locations for the FCVs and secondly define the optimum valve settings for each. Gullotta *et al.* (2021) examined the installation of gate valves and valves of different levels of closure for improving equity. The pipes on which the valves are installed as well as the valves' level of closure were used as the decision variables in the optimisation problem. NSGA-II was used for the optimisation and the objective was the maximisation of UC (as defined in Gottipati & Nanduri (2014)) with the constraint of not reducing the SR at demand nodes that initially had an SR value of >0.70.

Chandapillai *et al.* (2012) considered the design phase of an IWS and the diameters of all pipes were used as the decision variables. Ameyaw (2011) and Gottipati & Nanduri (2014) considered the possibility of installing elevated storage tanks in the network for equity improvement. In Ameyaw (2011), a multi-objective optimisation algorithm is used to generate solutions with regard to the number and size of the elevated storage tanks. The objectives of the optimisation are maximisation of equity (deviation of equity, see the above subsection) of distribution among consumers and minimisation of cost.

In terms of operational scheduling, Ilaya-Ayza *et al.* (2017) considered different supply schedules for each subnetwork of a WDN in order to improve the conditions and quality of service for the consumers. The main goals of the multi-criteria optimisation process are to maintain pressures across the network close to a reference pressure, reduce inconvenience for consumers, modify the shorter supply schedules, and ease sector operation. Supply sessions are split into different supply blocks and are optimised for which subnetworks are supplied during each supply block.

Overall, the use of hydraulic elements of different attributes such as different types of valves with various settings, service tanks, and gate valves has been studied. All the above have proved to be efficient in improving water distribution equity across WDNs even if the applicability of such methodologies in large and complex networks is questionable. The vast search space for different solutions in terms of topology and setting (e.g., for valve closure) complicates the process of finding an optimal solution and increases the computational cost significantly. More research in the field of cost-efficient interventions and operational management of hydraulic elements is required for the improvement of water supply service, equity in distribution, water quality, and leakage reduction.

5. CONCLUSIONS AND RECOMMENDATIONS

Access to clean potable water should be ensured for all people even if, under current IWS practices, this necessity is not guaranteed in terms of quantity or quality. IWS is considered as a measure to cope with the inability of the system or lack of resources to provide CWS. In many cases, though, it has been established as the norm, and the water supply conditions seem to further deteriorate under the IWS regime. IWS should be avoided whenever possible, but in cases where it cannot, comprehensive design principles are needed. In cases where IWS is established, new management approaches are needed in order to improve the quality of service and push forward for converting the operation of the system to CWS. Interventions in the physical components or operational management of the system can provide significant improvement. The hydraulic modelling aspect is critical for working on the above. Understanding of conceptual behaviour (ranging from individual user behaviour to the entire system) of the system is at the heart of this issue.

In this study, first, fundamental WDN pressure-driven hydraulic analysis methods were covered to establish a foundation for the main subject of this paper. After that, a wide range of approaches to hydraulic analysis methods of IWS were covered. From the examined literature, it can be highlighted that the choice of hydraulic model is done for each case individually taking into account the specific case characteristics (i.e., availability of water, user behaviour, existence of household tanks, and pumps). It is established from observation in IWS that low pressures are dominant in the network. Hence, the pressure-dependent hydraulic model is required to be used for IWS. An important aspect that is usually neglected is the network filling process. EPANET is not able to simulate the filling process, but EPA-SWMM is capable of doing it. However, the software is for the urban drainage system, and tools need to be adjusted to represent a WDN. There are also other attempts for a more accurate simulation of the filling process, but they are in the early stage of commercial application.

With regard to the available simulation software reviewed above, the EPANET-based ones have the advantage of being able to implement network elements and features related to water supply systems, while EPA-SWMM lacks some of these features (e.g., different types of pumps and valves, or water quality modelling).

While all the above models are insightful for better understanding the behaviour of IWS systems, more robust and complete models are needed in order to support decision-making in system operation and intervention planning. The knowledge gap still does exist and there is a need for developing more appropriate tools and methodologies that holistically address the unique system characteristics of the water distribution systems in developing countries. A realistic model should be able to simulate partial flow during the filling and emptying processes or in the cases of air intrusion in the pipeline system due to low pressure.

To conclude, the hydraulic modelling of IWS systems is still an area under research. The current literature indicates that the models developed so far are not holistic in a way that they can be applied to real IWS. Further research should address the following key gaps in knowledge:

§ The behaviour of water users under pressure-deficient conditions needs to be analysed and understood better with the aim of improving the characterisation and estimation of water consumption in IWS systems. This is vital for improving the existing IWS hydraulic models and tools as water consumption is the driving force of these systems.

§ Water losses, either from leaks or unauthorised connections, are a huge issue in IWS systems and are critical components of the modelling of IWS systems. It is well known that background losses increase after the establishment of IWS and these continue to increase since network components deteriorate rapidly. Macroscopic models like the one introduced by Taylor *et al.* (2019) can be beneficial for getting insight into the system's behaviour. Improved understanding and characterisation of water losses in IWS systems are critical for the hydraulic modelling of these systems.

§ The water filling process of an IWS system remains under research. Hydraulic models of IWS systems that consider the filling in and emptying out processes in addition to the pressurised state of the IWS need to be developed.

§ There is a need to establish procedures and systems for a more systematic collection of wide-ranging data in real IWS systems, so that hydraulic models of these systems could be more accurately built and calibrated. Information about IWS system topology and existing physical components is critical for its hydraulic modelling but often not available. Critical information is also often missing for the operation, maintenance, and performance of these systems. Collecting all this data will lead to better models with more accurate predictions and a clearer view of how equitable the water distribution is in reality.

Furthermore, once the above issues are addressed and improved hydraulic models of IWS systems are created, these could be used to improve the planning and operation of these systems by addressing a wide range of relevant issues such as improved equity of water supply via better scheduling and/or system configuration changes (including the creation of district-metered-areas), reduction of water losses, and improved water quality. Accordingly, a new hydraulic analysis method based on EPA-SWMM will be proposed in the subsequent study.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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