Water Resources Management (2023) 37:3921–3933
https://doi.org/10.1007/s11269-023-03532-x

Addressing Water Meter Inaccuracies Caused By Intermittent Water Supply: A Laboratory Investigation of Remedial Measures

Marco Ferrante[1] · **Dewi Rogers**[2] · **Josses Mugabi**[3] · **Francesco Casinini**[1]

Received: 25 January 2023 / Accepted: 1 May 2023 / Published online: 18 May 2023

Abstract
The interruption of supply in water distribution systems is a common management practice particularly prevalent in developing countries. Upon reopening, the air is expelled through user service pipes, which causes over-reading and seriously impacts the water meter reliability. This paper aims to assess by laboratory tests the effects of air flow on water meter performance by laboratory tests, using a set-up with diameters comparable to those of real water systems. The improvements introduced by applying unmeasured-flow reducer and air valves at different locations are also tested. The relevance of the results of the laboratory activity for practical applications is discussed, both for reducing the over-reading and improving the reliability of the water meters.

Keywords Intermittent water supply · Water distribution · Water meter · Unmeasured-flow reducer valve · Air valve

1 Introduction

Many residents in urban areas, especially in low- and middle-income countries, receive water through water distribution systems operated intermittently. Several authors have estimated that globally up to one billion people receive intermittent water service (e.g.,

---

✉ Marco Ferrante
marco.ferrante@unipg.it

Dewi Rogers
dewisrl2001@gmail.com

Josses Mugabi
jmugabi@worldbank.org

Francesco Casinini
francesco.casinini@studenti.unipg.it

[1] Department of Civil and Environmental Engineering, University of Perugia, Via G. Duranti, 93, Perugia 06125, EU, Italy

[2] DEWI s.r.l., Via dei Ceraioli 15, Colombella, Perugia 06134, EU, Italy

[3] World Bank Group, 10 Marina Blvd, Singapore, Singapore

Charalambous and Laspidou 2017; Kumpel et al. 2017; Taylor et al. 2019). Intermittently operating a water service impacts the water quality, distribution equity, and structural integrity of the pipes (e.g., Agathokleous and Christodoulou 2016; Gullotta et al. 2021; Simukonda et al. 2018; Kumpelet al. 2015).

The transition from continuous (twenty-four hours per day and seven days per week) to intermittent water supply (IWS) and vice versa is governed by the balance between water availability, leakage, and customer demands (Taylor et al. 2019; Kumpel et al. 2017; Fan et al. 2014). In such circumstances, water demand measurement is challenging (Kumpel et al. 2017) due to the reduced reliability of water meters.

Installing customer tanks to balance demand and supply patterns may cause under-registration of the water meters (Al-Washali et al. 2020; Criminisi et al. 2009; De Marchis et al. 2010). Criminisi et al. (2009) showed that water meters tend to under-read due to the inherent low flow inaccuracies over time, particularly concerning the filling of tanks. Puleo et al. (2013) also confirmed that the cyclical emptying and filling of the tanks might cause the under-reading of the water meter.

In addition, air flowing through the meters during the filling can cause over-reading and failures. Klingel et al. (2018) and Walter et al. (2017) present a systematic laboratory analysis of the measurement error of single- and multi-jet water meters due to filling an empty pipe. The experimental set-up involved a single pipe with a diameter of 1.95 cm and lengths varying from 1 to 25 m, with a maximum volume of 7.72 l. The authors concluded that the measurement error, defined as the difference between the registered volume and the actual volume of water through the water meter, was only related to the volume and pressure of the air in the pipe and not to the water front impact with the impeller or unsteady flow conditions. Preliminary results from other laboratory tests with a more realistic set-up with greater length and diameter show over-reading and reliability issues relating to water meters operating with air (Ferrante et al. 2022; Ferrante et al. 2022). The same issue is also reported by Taylor (2018).

In this paper, we report the results of laboratory tests to assess the potential benefit of applying devices such as unmeasured-flow reducer (UFR) and air release (AR) valves to mitigate the effects of meter over-reading and reduce the risk of failure. Specifically, we investigate the impact of UFR and AR on multi-jet water meters, installed alone and in combination, and considering the AR valve location. Finally, we draw conclusions and practical implications for managing IWS systems.

The original and significant contributions of the paper are the laboratory test results using a realistic set-up with multi-jet water meter, UFR, and AR valves. The findings of the study have practical relevance for the management of IWS systems.

2 Materials and Methods

The set-up at the Water Engineering Laboratory of the University of Perugia, Italy, was modified specifically to investigate the mitigation of the effects of pipe filling with different strategies.

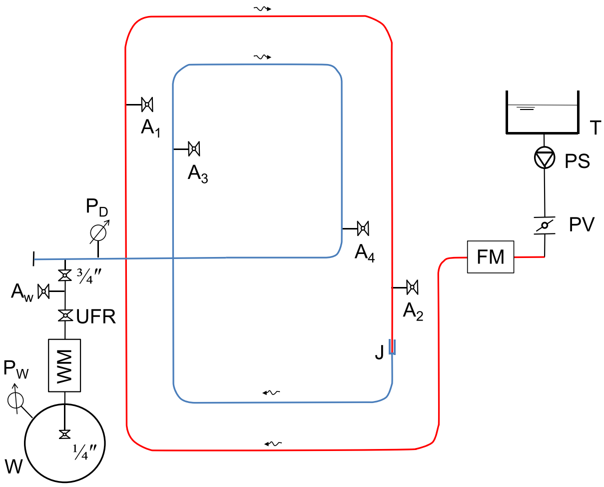


Fig. 1 The schematic of the laboratory set-up. J was the spigot junction between the upstream PVC-O pipe and the downstream HDPE pipe. P_D and P_W were pressure transducers. FM was the flow meter. The pumping system PS was used to feed the system from the recirculating tank T. The upstream valve PV was kept open during the tests. Air release valves were connected at $A_{1\text{-}4}$ and A_W. UFR was the unmeasured-flow reducer valve. The water meter, WM, was connected upstream by a 3/4" ball valve to the pipe and downstream to the tank W

2.1 The Experimental Set-up

The experimental set-up used consisted of a series of two polymeric pipes (see Fig. 1), i.e., an upstream Oriented Polyvinyl Chloride (PVC-O) DN110 PN16 pipe with length $L_O = 99.18$ m and a downstream High-Density Polyethylene (HDPE) DN110 PN10 pipe with length $L_E = 92.79$ m. The characterization of the rheological behaviour of the pipe materials and the response in terms of pressure time histories during transients in pressurized pipe conditions are reported in (Ferrante 2021; Ferrante and Capponi 2018; Ferrante and Capponi 2017). Further details of the experimental set-up are in (Ferrante et al. 2022).

The system was supplied directly by a pumping system PS, and the filling was obtained by having the pump switched on and the upstream valve PV open. Four 1" connections, A_1 to A_4, were also located along the pipe for air release valves.

A water meter, WM, was connected to the end of the pipe by a valve to simulate the user connection. Straight steel DN20 connections with a length greater than five diameters were placed upstream and downstream, as required by good practice, to optimize the operating conditions of the water meter. A connection for air release valves upstream of the water meter, A_W, was also used. A DN25 HDPE pipe delivered the discharge from the water meter with a 2 m length to a tank (W). Ball valves of differing diameters were installed at the downstream end of this pipe to regulate the water flow in W. In the illustrated tests, one ¼" ball valve was used. A pressure transducer, P_W, was also connected to W to measure the water level.

2.2 Instruments and Data Acquisition

The pressure variations in time shown in this paper have been acquired at P_D (see Fig. 1) by a UNIK 5000 relative pressure transducer manufactured by GE (U.S.A.), with 6B full scale (f.s.) and accuracy of 0.10 nother UNIK500 transducer with 150 mB f.s. was connected at P_W.

An electromagnetic flow meter, FM, manufactured by ISOIL (Italy), was used to measure the discharge variation with time at an accuracy of 0.2% of the measured value. FM measured the absolute value of the flow (i.e., with positive values also associated with reversing flow) only when the pipe was full of water.

A DN16 R160 multi-jet water meter was used in the tests, although volumetric rotary piston and single-jet water meters have also been tested. Rotary piston water meters failed without providing reliable results. Single- and multi-jet water meters with the same metrological characteristics were shown to have almost identical behaviour (Ferrante et al. 2022).

The water meter data complied with ISO4064-1 (2017). The maximum permissible error, ϵ_{1-2}, between the minimum flow rate $Q_1 = 15.63*10^{-3}$ m^3/h and the transitional flow rate $Q_2 = 25.01*10^{-3}$ m^3/h is +/-5% and the maximum permissible error, ϵ_{2-4}, between Q_2 and the overload flow rate $Q_4 = 3.13$ m^3/h, is +/- 2%. By definition, Q_4 is the highest flow rate at which the water meter is designed to operate for short periods. The permanent flow rate $Q_3 = 2.50$ m^3/h is the highest flow within the rated operating conditions at which the meter is intended to operate within the maximum permissible error. As defined by ISO4064-1 (2017), water meters are intended to measure the volume of water passing through them, so the characteristic values of discharge and errors do not relate to air flow.

The data acquisition system was based on a Compact-DAQ NI-9188 chassis manufactured by National Instruments (U.S.A) with eight input/output module slots, which provided signal conditioning and analog-to-digital conversion. The acquisition frequency of the data was 1 Hz for the flow meter and 2048 Hz for the pressure transducers. A pulse unit comprising an electrical switch operated by a magnetic field (reed switch) was connected to one of the counter hands of the water meters, generating one pulse per liter. A digital module with eight digital input/output channels (DIO) counted the pulses from the reed contacts of the flow meters. A discharge of Δt^{-1} l/s was then associated with each interval between two pulses of duration Δt seconds.

The distances of instruments and air valve connections from the upstream end of the pipe are given in Table 1.

3 Results

In the tests, the pipe was filled from an empty pipe condition by switching on the pump. Once the pipe was full, the system was allowed to reach steady-state conditions. Then, the pump was switched off to begin the pipe emptying phase, and the drains were opened to allow complete emptying. After about one hour from the beginning of each test, the system was ready to begin the subsequent one.

The effects of different valve types and location on the water meter during the filling have been investigated.

3.1 The Effects of the Unmeasured-Flow Reducer Valve

Unmeasured-Flow Reducer or UFR valves are typically used to reduce the unaccounted-for water in low flow conditions. The device relies on the basic principle that a flow is only allowed when the upstream pressure exceeds the downstream pressure for a given value. In

Table 1 Distance of instruments and air valve connections from the upstream end of the pipe

-	P_V	FM	A_1	A_2	A_3	A_4	P_D	A_W
x(m)	0	0.70	44.52	94.07	134.78	182.01	191.27	193.37

this way, by differential pressure control, small demands lower than the minimum measurable discharge Q_1 of the water meter are not permitted.

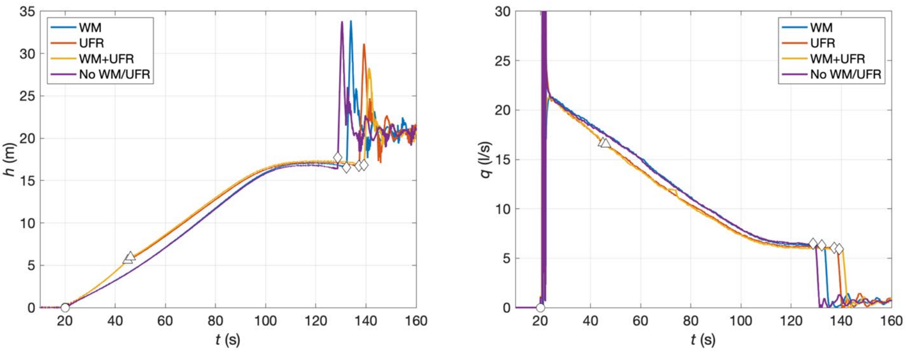
UFR valves in intermittent water supply systems can be helpful for many reasons, including reducing under-registration caused by user tanks. In this paper, the objective was to see whether they would reduce the over-reading and risk of failures due to air flow during the pipe filling when coupled to an air release valve.

The pressure head variations in time, or pressure signals, $h(t)$, acquired at $\mathrm{P_D}$ during tests with and without a UFR valve, are shown in Fig. 2a. From the pump switch-on (circle markers) to the arrival of the water front (diamond markers) the transducer measured the air pressure. The water front arrival at the downstream end caused an increase in the pressure head and a water hammer phenomenon (Ferrante et al. 2022).

Pressure signals acquired during the tests with and without the water meter (WM and No WM/UFR in the figure legend, respectively) are similar, confirming that the presence of a water meter does not significantly modify the flow conditions. Further confirmation is given by the similarity between the pressure signals acquired with a UFR valve with and without a water meter (WM+UFR and UFR, respectively). On the contrary, the UFR valve affects the air pressure variation, delaying the water front arrival at the downstream end (diamond markers in Fig. 2a) and decreasing the downstream maximum pressure values. The same behaviour is also confirmed by the discharge signals $q(t)$, acquired during the same tests by FM and shown in Fig. 2b. The measurements above the plot limit correspond to errors and can be explained by a no-completely full pipe condition.

The UFR valve is closed at the switch-on of the pump (circle markers) because the atmospheric pressure is the same upstream and downstream of the valve. During the pipe filling, the upstream air pressure increases while the downstream atmospheric pressure does not change. When the pressure difference reaches the set point, the valve opens. The UFR opening time, denoted in the figures by triangles, can be detected by a typical variation in the pressure signals. The setting value of the UFR used in the tests is around 6 m.

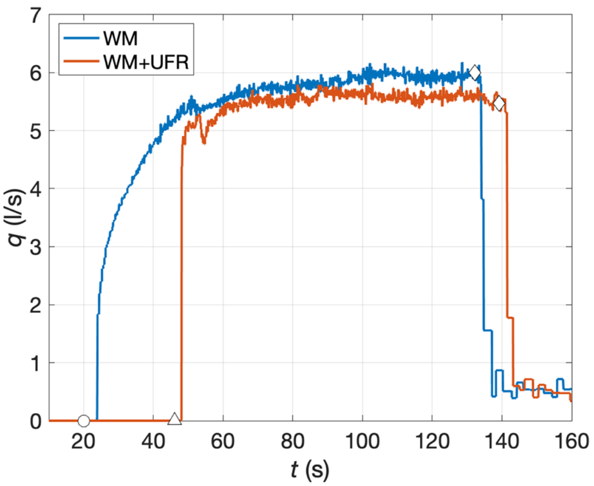
As highlighted in Fig. 3, where the results of the same tests as Fig. 2 are shown, the UFR modifies the water meter reading during the filling. The UFR activates about 26.1



(a) (b)

Fig. 2 Variation in time during a test of **a** pressure head at the pressure transducer $\mathrm{P_D}$ and **b** discharge at the flow meter FM. The circle and diamond markers indicate the pump switch-on and the arrival of the water front at $\mathrm{P_D}$, respectively. The triangle markers indicate the opening of the UFR valve

Fig. 3 Discharge measured by the water meter during the pipe filling when a UFR is installed (WM+UFR) or not installed (WM). The circle and diamond markers indicate the pump switch-on and the arrival of the water front at P_D, respectively. The triangles inndicate the opening of the UFR valve



s after the pump is switched on, preventing the air flow through the water meter for a longer duration. As a result, the total volume measured by the water meter during the air flow, V_{WM}, is reduced to 0.501 m^3 when the UFR valve is installed, compared to the 0.587m^3 measured without the UFR valve. This volume can be compared with the total air volume in the pipe in the initial conditions, V_A= 1.518 m^3 and the volume measured by the flowmeter FM during the same tests, V_{FM} ≈1.4 m^3. Differences between these values can be explained by the fact that the water meters are not designed nor calibrated for the air volume measurements and that FM cannot measure the discharge if the measurement section is not filled with water.

3.2 The Effects of the Air Release Valve

In water supply systems (mainly transmission mains), air valves are traditionally designed and installed at the point of maximum elevation for two reasons: the expulsion of the air during the system filling and normal functioning conditions, and the air inflow during the emptying. Water distribution systems are not designed for intermittent supply, although they are often operated in such situations, and air release (AR) valves are rarely installed. To understand how air valves could positively affect the water meter air flow during the filling, D040 1" air release valves manufactured by A.R.I. (Israel), were used in a series of tests. AR valves were connected to the upper part of the pipe upstream of the water meter (A_W in Fig. 1) and at other locations along the pipe (A_W and A_1 to A_4).

Figure 4 shows the pressure signals acquired during tests with the water meter (WM in the figure legend) and with the air valve installed at different locations (WM+A_n). The presence of an AR valve increases air outflow, reducing air pressure during the filling. Comparing the test results defines two limiting conditions: one with a water meter without air valves (WM, the same test used as a reference in Fig. 2) and another with an AR valve installed immediately upstream of the water meter (WM+A_W). Air valves installed at intermediate locations induce the same pattern defined by the test with the air valve at A_W before the arrival of the water front. At the water front arrival, they close, causing an air pressure increase toward the same pressure value of the no AR valve test.

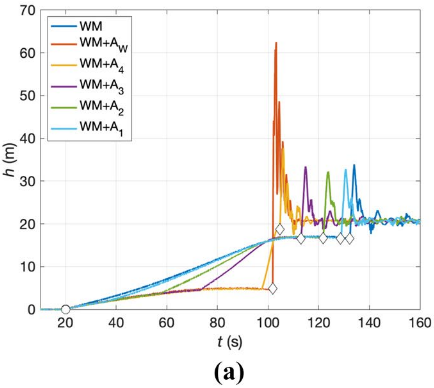


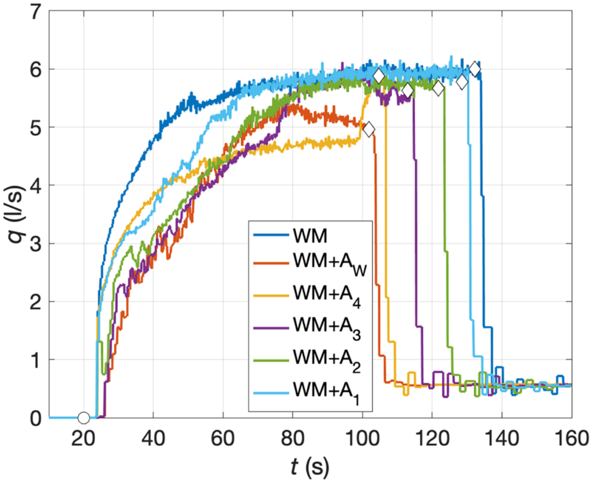
Fig. 4 Variation in time during a test of **a** pressure head at the pressure transducer P_D and **b** discharge at the flow meter FM. The circle and diamond markers indicate the pump switch-on and the arrival of the water front at P_D, respectively

Interestingly, the air valve located close to the water meter, i.e., at A_W, yields the greatest over-pressure value. In contrast, the one on the distribution pipe closest to the upstream valve, i.e., at A_1, has the lowest. A thorough investigation of the dependence of pressure peaks on the downstream end conditions is beyond the scope of this paper.

The description of the same tests in terms of discharges is given in Fig. 4. The same limiting conditions of the pressure signals define the discharge variations when air valves are located at different locations. The discharge signals before the arrival of the water front at the air valve are almost coincident.

Figure 5 shows the effects of air valves on the discharge measured by the water meter during the same tests of Fig. 4. The arrival of the water front and the following switch from air to water flow (diamond markers) varies regularly from the no air valve test to the test with the air valve at A_W, with an air flow duration decreasing with the air valve distance from the water meter. The total volume measured by the water meter during the air flow, V_{WM}, given by the area under the evaluated discharge in the time

Fig. 5 Discharge measured by the water meter during the pipe filling. The circle and diamond markers indicate the pump switch-on and the arrival of the water front at P_D, respectively



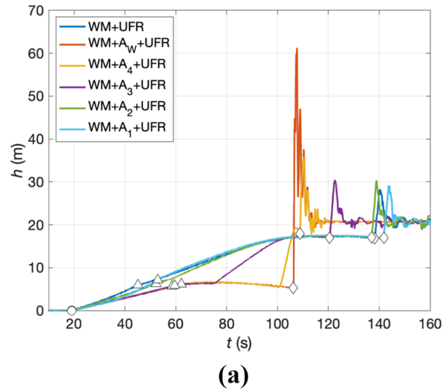


Fig. 6 Variation in time during a test of **a** pressure head at the pressure transducer P_D and **b** discharge at the flow meter FM. The circle and diamond markers indicate the pump switch-on and the arrival of the water front at P_D, respectively. The triangle markers indicate the opening of the UFR valve

interval between the pump switch-on (circle markers) and the water front arrival (diamond markers), decreases from 0.587 (WM) to 0.535 (WM+A_1), 0.454 (WM+A_2), 0.385 (WM+A_3), 0.345 (WM+A_4), and 0.310 m^3 (WM+A_W), i.e., with the distance of the air valve from the upstream end of the pipe.

3.3 Combined effects of UFR and AR valves

Figures 3 and 5 show that UFR and AR valves reduce the total volume measured by the water meter during the filling. We performed further tests to investigate the combined effects of UFR and AR valves, installing the UFR downstream of A_W and upstream of the water meter (as for the test of Fig. 2) and the air valves at the exact locations as the tests in Fig. 4.

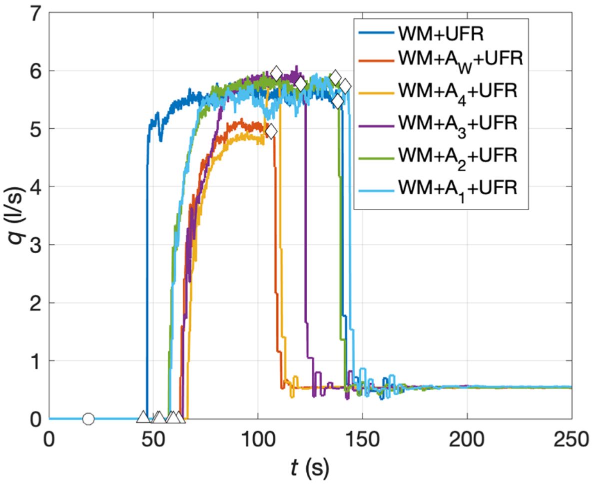


Fig. 7 Discharge measured by the water meter during the pipe filling. The circle and diamond markers indicate the pump switch-on and the arrival of the water front at P_D, respectively. The triangle markers indicate the opening of the UFR valve

The results shown in Fig. 6 are similar to those of Fig. 4 with only minor variations in the pressure and discharge signals caused by the UFR. The triangle markers denote the UFR valve openings at air pressure values between 5.6 and 7.1 m.

The effects of the UFR on the discharge measured by the water meter, shown in Fig. 7, are more evident than those shown in Fig. 5. In the shown tests, the total volume measured by the water meter during the air flow, V_{WM}, decreases from 0.501 (WM+UFR) to 0.440 (WM+A_1), 0.426 (WM+A_2), 0.290 (WM+A_3), 0.193 (WM+A_4), and 0.190 m^3 (WM+A_W). The main differences are in the starting time of the water meter measurements (triangle markers) and the water front arrival time, as discussed in the following.

4 Discussion

UFR and AR valves individually reduce the volumes measured by the water meter during the air flow.

Figure 3 shows the main effect of the UFR, which consists of a delay in the start of the water meter measurement of the air flow during the pipe filling. Since UFR avoids the air flow through the water meter until the pressure differential set value is reached, in the tests where it is installed, the air pressure increases more during the filling (Fig. 2a) than in tests where it is not installed. Consequently, the water front arrival at the downstream end of the pipe is also delayed (diamond markers in Fig. 3).

The capability of water meters to measure air volume and mass is questionable. For example, it is expected that the total amount of air measured during the pipe filling when UFR is installed or not is the same, even if the outflow is only allowed through the water meter. The results of the tests show that the delay in the water meter measurement beginning and the delay in the water front arrival are not compensated and that the measured air volume decreases from 0.587 to 0.501 m^3 when the UFR is installed.

The AR valves increase the air outflow during the filling, reducing the total air volume measured by the water meter. Figure 8 shows the values of the volumes measured during the air flow for air valves installed at different locations (hollow circles). The volumes V'_{WM}

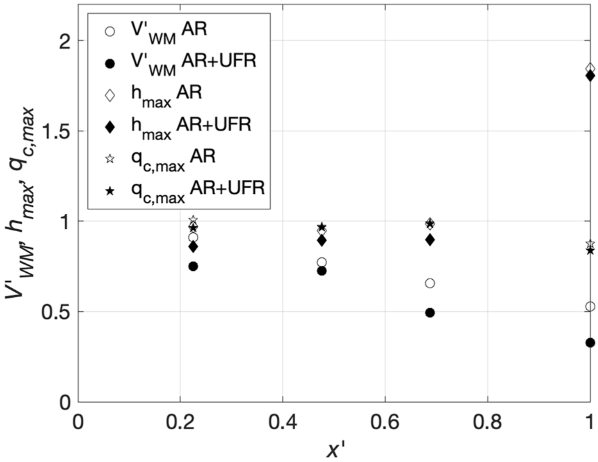


Fig. 8 Variation of normalized air volume, V'_{WM}, pressure maxima, p_{max}, and discharge maxima at the water meter, $q_{c,max}$, for tests with an AR valve at a different location along the pipe. Tests with air valve (hollow markers, AR) and with air valve and UFR (filled markers, AR+UFR) are considered. The distance from the upstream section, x', is normalized to the total length of the pipe

are normalized with the volume measured in the test with no AR valves installed. The AR valve location is also expressed as the ratio of the distance from the upstream valve to the total pipe length, x'.

The air valve location does not significantly affect the measured maximum discharge, which is the major suspect of water meter failures. The ratio of the maximum value measured during tests with air valves at different locations to the maximum value measured when no valves were installed ($q_{c,max}$, hollow stars in Fig. 8) is close to 1.

The main effect of an air valve is on the maximum pressure measured at P_D, at least when the AR valve is close to the downstream end of the pipe. The ratio of the maximum pressure measured during tests with AR valves installed at different locations to the maximum pressure measured during the tests with no AR valves, h_{max}, is close to one for most of the distances (diamond markers in Fig. 8). Still, it reaches a value greater than 1.8 when the valve is installed immediately upstream of the water meter.

When the UFR valve is installed with an AR valve, it significantly modifies the start and the duration of the air flow through the water meter. In Fig. 9, hollow circles denote the pump switch-on, almost coinciding with the air flow beginning, t_0, when the UFR is not installed. The same figure shows the UFR opening times (filled triangles) and the water front arrival times (t_w, diamonds) for AR valves at a different location along the pipe. Filled and hollow diamonds denote tests with and without UFR, respectively. When the UFR was installed, the air flow began at times denoted by filled triangles and stopped at the time marked by filled diamonds. In the tests where the UFR was not installed, the air flow duration is defined by the distance between hollow circles and hollow diamonds. The comparison of hollow and filled markers confirms the results of Fig. 3, that the UFR effect is to delay both the start and end of the air flow but with a reduction of the total air flow measurement duration. This result is also confirmed by the variation of V_{WM} with the location of the AR valve along the pipe when the UFR is installed (filled circles in Fig. 8). The UFR does not significantly affect the pressure and the maximum discharge measured by the water meter (filled diamonds and stars, respectively).

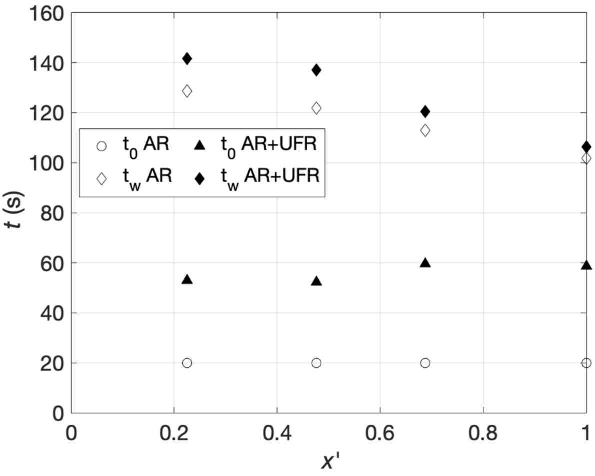


Fig. 9 Times corresponding to the beginning of the air flow through the water meter (circle and triangle markers, t_0), and the water front arrival time (diamond markers, t_w), for tests with an air valve at a different location along the pipe. Tests with air valve (hollow markers, AV) and with air valve and UFR (filled markers, AV+UFR) are considered. The distance from the upstream section, x', is expressed as the ratio to the total length of the pipe

5 Conclusions

As part of a wide-ranging study of the impacts of intermittent supply funded by the World Bank through the PPIAF programme, a series of tests were undertaken in the Water Engineering Laboratory of the University of Perugia to investigate the effects of the air flow on the water meters during the pipe filling and remedies.

Preliminary tests and previously published papers pointed out that over-reading and possible failure are the main two effects of the air flow through the water meters during the pipe filling. The system set-up was configured to reproduce the permanent flow rate of the water meter (ISO4064-1 2017) and similar to those installed on user connections. In such conditions, the water meter over-read by about 0.6 m^3 and reached a rotation speed in dry conditions close to seven times the overload flow rate (ISO4064-1 2017).

Considering the pipe's total volume of about 1.5 m^3, the result suggests that, neglecting leaks and other possible air outflows in similar conditions, about 40% of the air contained in the system could be billed by water meters connected to user connections.

The high rotation speed in dry conditions was one of the reasons for the failure of many water meters used during the testing. Some low-cost single-jet water meters failed after only a few seconds, with the same metrological characteristics as the used one. Other water meters, based on different measurement principles and with improved quality for water measurements, such as those with rotary pistons, failed in the same functioning conditions of the shown tests.

A possible solution is to use UFR and air valves. The effect of both was assessed singularly and in combination and compared.

UFR valves are mainly used in continuous supply conditions to reduce the under-reading in low flow conditions by preventing the discharge when pressure differences are lower than a given set value. In this study, they were used to avoid air flow during the filling. The UFR valve used had a setting around 6.5 m of water, which fulfilled the purpose of delaying the start of the air flow. Even on its own, the UFR reduced the over-reading, although the same air mass was evacuated through the water meter. The maximum rotation speed of the water meter was not affected by the UFR, which could not reduce the failure risk due to the high rotation speed in dry conditions.

Air valves are needed to manage air extraction. This effect is highlighted in Fig. 7, with results of tests with air valves producing consistently lower discharge values in time compared to the test without air valves and with water front arrival times increasing with the air valve distance from the upstream end of the pipe.

The air valve location plays an important role. Air valves keep evacuating air until the water front reaches them, and they close to avoid the water outflow. The larger the air valve distance from the upstream end, the better it works and the more air outflows. Unfortunately, the use of air valves close to the water meter also results in an increase in the maximum overpressure after the arrival time. This effect can be explained considering that the air valve acts parallel to the water meter and the downstream valve simulating the user demand. In certain circumstances, and the test conditions are in one of these, larger valves can reduce the air cushion effect and increase the velocity of the water column impacting the valve. Furthermore, air valves, instead of other valves, do not allow the water outflow and ultimately stop the water flow. For this reason, the water hammer phenomenon can seriously affect the pipe and the system.

Air valve size and location design is a trade-off between over-reading and overpressure. Since overpressure determination can be complicated, it requires numerical models. The models could also assist in the optimal over-reading reduction. The results presented here could help in developing such models.

The results suggest that the most effective remedy can be achieved by combining UFR and air valves. The reduced flow the UFR generates allows the air valve to work more efficiently. In general, the measured volume during the air flow can be reduced by increasing the starting time, reducing the measured discharge curve, and anticipating the air flow ending. Acting along these three different directions, the area under the measured discharge curve can be significantly reduced (see Fig. 8). In the test conditions, the combined effect was to reduce the over-reading because of air by 68%.

The length and diameter of the pipe, the functioning conditions, and the simulated user connections can be considered realistic and representative of a water distribution system. Further research activities are needed to verify the findings of this investigation in a more complex laboratory system, with more than one water meter installed, and in the field. Some parameters, such as the number and the size of air valves and the setting of the UFR opening pressure, could be relevant not only for the effects on the water meters but also for reducing the overpressure and increasing the equity between users during the filling, delaying the user connection activation when higher pressure values are reached in the system. The reliability of valves at the user connection level, compared to the district level, should also be investigated, particularly in networks with significant sedimentation.

Acknowledgements The active support of Claudio Del Principe for the laboratory activities is gratefully acknowledged.

Author Contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by M. Ferrante. The first draft of the manuscript was written by M. Ferrante and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding Open access funding provided by Università degli Studi di Perugia within the CRUI-CARE Agreement. This work was supported by the World Bank Group contract number 7199396 “An Investigation of Technological Solutions to Mitigate the Impact of Intermittent Water Supply”.

Declarations

Conflicts of Interest The authors declare they have no financial interests to disclose.

References

Agathokleous A, Christodoulou S (2016) Vulnerability of urban water distribution networks under intermittent water supply operations. Water Resour Manag 30(13):4731–4750. https://doi.org/10.1007/s11269-016-1450-3

Al-Washali T, Mahardani M, Sharma S, Arregui F, Kennedy M (2020) Impact of float-valves on water meter performance under intermittent and continuous supply conditions. Resources, Conservation and Recycling 163.https://doi.org/10.1016/j.resconrec.2020.105091

Charalambous B, Laspidou C (2017) Dealing with the complex interrelation of intermittent supply and water losses. Scientific and Technical Report Series, IWA publishing

Criminisi A, Fontanazza CM, Freni G, Loggia GL (2009) Evaluation of the apparent losses caused by water meter under-registration in intermittent water supply. Water Sci Technol 60(9):2373–82. https://doi.org/10.2166/wst.2009.423

De Marchis M, Fontanazza CM, Freni G, La Loggia G, Napoli E, Notaro V (2010) A model of the filling process of an intermittent distribution network. Urban Water J 7(6):321–333. https://doi.org/10.1080/1573062x.2010.519776

Fan L, Liu G, Wang F, Ritsema CJ, Geissen V (2014) Domestic water consumption under intermittent and continuous modes of water supply. Water Resour Manage 28(3):853–865. https://doi.org/10.1007/s11269-014-0520-7

Ferrante M (2021) Transients in a series of two polymeric pipes of different materials. J Hydraul Res IAHR 7(6):1–10. https://doi.org/10.1080/00221686.2020.1844811

Ferrante M, Capponi C (2017) Experimental characterization of PVC-O pipes for transient modeling. J Water Supply Res Technol AQUA 66(8):606–620. https://doi.org/10.2166/aqua.2017.060

Ferrante M, Capponi C (2018) Comparison of viscoelastic models with a different number of parameters for transient simulations. J Hydroinf 20(1):1–17. https://doi.org/10.2166/hydro.2017.116

Ferrante M, Rogers D, Casinini F, Mugabi J (2022) A laboratory set-up for the analysis of intermittent water supply: First results. Water 14(6):936. https://doi.org/10.3390/w14060936

Ferrante M, Rogers D, Mugabi J, Casinini F (2022) Impact of intermittent supply on water meter accuracy. J Water Supply Res Technol AQUA 71(11):1241–1250. https://doi.org/10.2166/aqua.2022.091

Gullotta A, Campisano A, Creaco E et al (2021) A simplified methodology for optimal location and setting of valves to improve equity in intermittent water distribution systems. Water Resour Manag 35(13):4477–4494. https://doi.org/10.1007/s11269-021-02962-9

ISO4064-1 (2017) Water meters for cold potable water and hot water - Part 1: Metrological and Technical Requirements

Klingel P, Mastaller M, Walter D (2018) Accuracy of single-jet and multi-jet water meters under the influence of the filling process in intermittently operated pipe networks. Water Supply 18(2):679–687. https://doi.org/10.2166/ws.2017.149

Kumpel E, Woelfle-Erskine C, Ray I, Nelson KL (2017) Measuring household consumption and waste in unmetered, intermittent piped water systems. Water Resour Res 53(1):302–315. https://doi.org/10.1002/2016WR019702

Puleo V, Notaro V, La Loggia G, Freni G, Fontanazza CM, De Marchis M (2013) A mathematical model to evaluate apparent losses due to meter under-registration in intermittent water distribution networks. Water Supply 13(4):914–923. https://doi.org/10.2166/ws.2013.076

Simukonda K, Farmani R, Butler D (2018) Intermittent water supply systems: causal factors, problems and solution options. Urban Water J 00(00):1–13. https://doi.org/10.1080/1573062X.2018.1483522

Taylor DDJ (2018) Tools for managing intermittent water supplies. Thesis

Taylor DDJ, Slocum AH, Whittle AJ (2019) Demand satisfaction as a framework for understanding intermittent water supply systems. Water Resour Res 55(7):5217–5237. https://doi.org/10.1029/2018WR024124

Walter D, Mastaller M, Klingel P (2017) Accuracy of single-jet water meters during filling of the pipe network in intermittent water supply. Urban Water Journal 14(10):991–998. https://doi.org/10.1080/1573062x.2017.1301505