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# Impact of intermittent supply on water meter accuracy

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## ABSTRACT

Supply interruptions are a common occurrence in water systems and are particularly prevalent in developing countries. During the system filling, the air that entered into the pipes when the supply was closed is expelled through any fissures including service pipes. When a meter is installed, the airflow can cause inaccuracies, over-reading, and reliability issues. This paper investigates experimentally the impact of the airflow on water meter performance during filling by means of a laboratory set-up, using pipes with diameters comparable to those of a real water system. The impact of the airflow on the accuracy and reliability of the water meters is discussed and the potential for over-reading is estimated.

**Key words:** customer meter accuracy, intermittent water supply, meter reliability, over-reading

## HIGHLIGHTS

- Supply interruptions are a common occurrence in water systems, particularly in developing countries.
- The air entering the pipes in supply interruptions is in part expelled through the customer meters causing over-reading and high rotational spin.
- Using a large experimental set-up, the paper investigates the impact of the expelled airflow on water meters.
- The estimate of over-reading and the reasons of failures are discussed.

## GRAPHICAL ABSTRACT

## INTRODUCTION

Information provided by water meters in water distribution management is relevant both for economic and hydraulic balances. For the former, the measured volumes are used to determine the customer bill while in the latter they are used to estimate leakage and non-revenue water.

It is common practice in many parts of the world to interrupt water supply when the demand exceeds the production, often leading to undesirable consequences such as pipe bursts and poor water quality (Simukonda *et al.* 2018; Taylor *et al.* 2019; Farmani *et al.* 2021). The water supply interruptions occur either by closing valves, switching off the pumps or by the natural drawdown of a tank. This action causes air to enter parts of the system which, when the supply returns, is expelled through any device or fissures, potentially including the customers' water meters. Similarly, when the supply is interrupted, air can enter pipes through the water meter (Taylor 2018).

Often the customer overcomes intermittent supply by installing storage tanks. Criminisi *et al.* (2009) have shown that, due to the inherent low flow inaccuracies over time particularly relating to the filling of tanks, water meters register less than the quantity that was delivered. The model developed by Criminisi *et al.* (2009) was implemented by Puleo *et al.* (2013) which confirmed that the cyclical emptying and filling of the tanks may cause the under-reading of the water meter. However, in the case of intermittent supply and the passage of air, this might not be the case.

The effect of the airflow through the water meters during the filling has been investigated at a laboratory scale, on small pipes. Walter *et al.* (2017) and Klingel *et al.* (2018) analysed the measurement error of single-jet (SJ) and multi-jet (MJ) water meters due to the filling of an empty pipe. The experimental set-up allowed the filling of single pipes with the same diameter of 1.95 cm and lengths ranging between 1 and 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, is mainly due to the airflow. The components due to other effects, such as air bubbles at the waterfront, unsteady flow conditions, and impact of the waterfront with the impeller, are negligible. During the tests, it was observed that dry or wet initial conditions can change the airflow velocity needed to initiate the impeller rotation because the water in the casing increases the impeller starting resistance.

As part of a wide-ranging study of the impacts of Intermittent Supply, the World Bank funded through the PPIAF programme the Department of Civil and Environmental Engineering of the University of Perugia, Italy, to undertake a research consultancy. A laboratory set-up (Ferrante *et al.* 2022) was used to investigate the impacts of pipe filling and emptying on water distribution systems. The same configuration was applied to investigate the effects of the airflow through the water meter during the pipe filling and emptying in intermittent water supply conditions. In this paper, the experimental set-up is summarised and the results of the tests are presented.

## METHODS

### Laboratory set-up

In this article, the experimental set-up consisted of a series of two polymeric pipes (Figure 1), comprising an upstream polyvinyl chloride (PVC-O) DN110 PN16 pipe and a downstream high-density polyethylene (HDPE) DN110 PN10 pipe. The same system used in Ferrante & Capponi (2017, 2018a, 2018b); Ferrante (2021) was modified to investigate the effects of filling and emptying and is described in detail in Ferrante *et al.* (2022).

The test network, composed of a series of HDPE and PVC-O pipes, with a total length of 194 m, was fed directly by the pumping system (PS), with the upstream valve PV open for the whole duration of the tests (Figure 1).

A water meter was connected to the downstream end to simulate the user connection. The most common types of water meters were used for the tests, specifically SJ and MJ water meters.

The characteristics of the water meters as defined by ISO4064-1:2017 (2017) are given in Table 1. The maximum permissible error between the minimum flow rate $Q_1$ and the transitional flow rate $Q_2$ ($\varepsilon_{1-2}$) is $\pm 5\%$ and the maximum permissible error between $Q_2$ and the overload flow rate $Q_4$ ($\varepsilon_{2-4}$) is $\pm 2\%$. By definition, $Q_4$ is the highest flow rate at which the water meter is to operate for a short period of time while the permanent flow rate $Q_3$ is the highest flow within the rated operating conditions at which the meter is to operate within the maximum permissible error. As stated by ISO4064-1:2017 (2017), water meters are supposed to measure the volume of water passing through them and so the characteristic values of discharge and errors in Table 1 do not consider airflow.

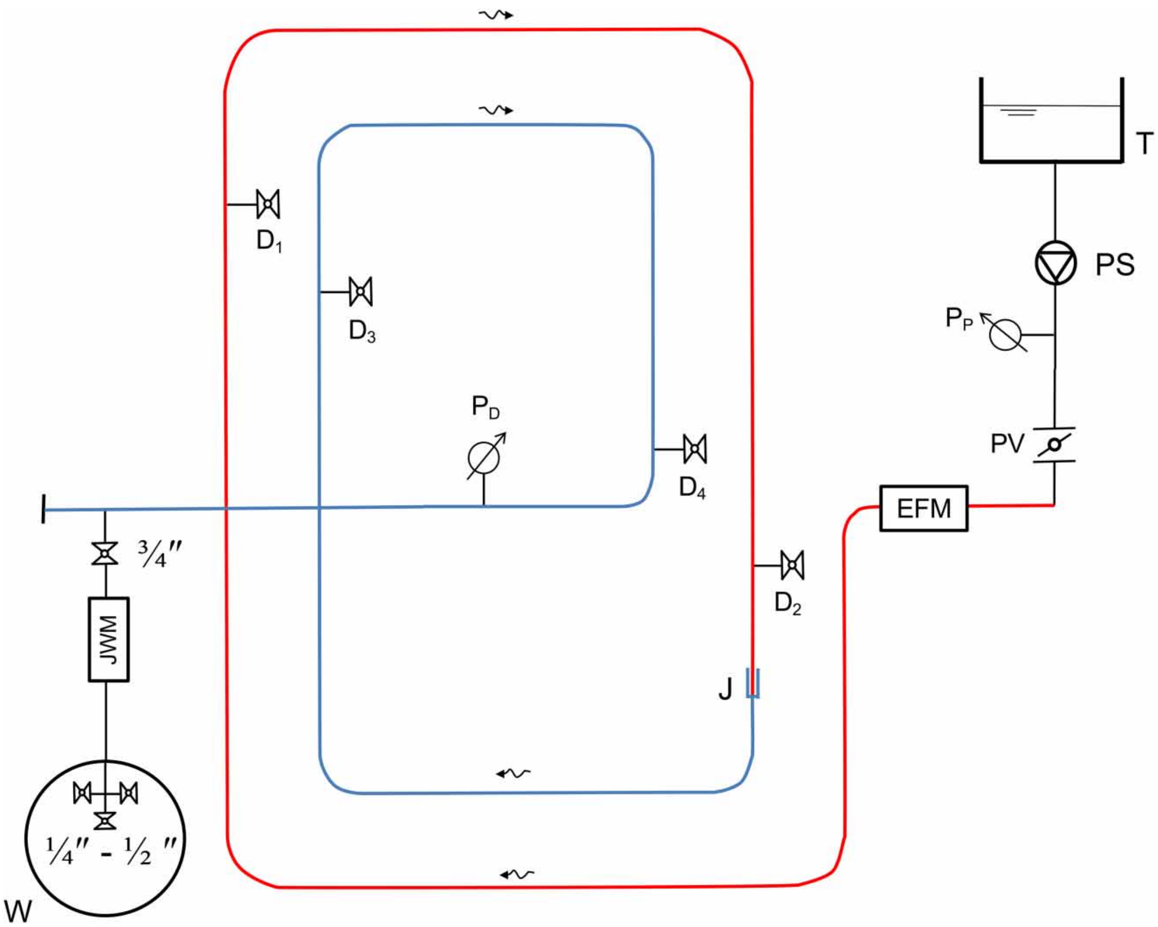


**Figure 1** | Schematic of the laboratory set-up, after Ferrante *et al.* (2022). The system is fed by the PS connected to the upstream tank T. The upstream valve PV was always open during the tests. J is the spigot junction between the upstream PVC-O pipe and the downstream HDPE pipe. $P_n$ and $D_n$ are pressure transducers and drains, respectively. The EFM is the electromagnetic flow meter. PV is a butterfly valve. The JWM is connected to the pipe by a 3/4″ ball valve. The water flowing through the JWM is collected in tank W. Three 1/4″ valves or one 1/2″ valve can be used to vary the discharge through the water meter.

The jet water meter (JWM) was connected to the end of the pipe by a 3/4″ valve, with straight steel DN20 connections longer than five diameters placed upstream and downstream, as required by good practice, to optimize the operating conditions of the meter. Downstream of the JWM and of the steel connection, the outflowing water was delivered by a DN25 HDPE pipe with a 2 m length and collected in a tank (W). Ball valves of differing diameters were installed at the downstream end of this pipe to regulate the water discharge in W. In the shown tests, one 1/4″ ball valve, one 1/2″ ball valve or three 1/4″ ball valves in parallel were used.

Two pressure transducers were used during the tests. A TRAFAG ECT 8473 absolute pressure transducer ($P_P$), with a 10-bar full scale (f.s.) and an accuracy of 0.30% f.s., was connected to the manifold downstream of the PS. A GE UNIK 5000 relative pressure transducer ($P_D$), with 6 bar f.s. and an accuracy of 0.1% f.s., was connected 2 m upstream of the pipe end.

**Table 1** | Characteristics of the water meters

| | | DN | R | $Q_{start}$ (m³/h) [(l/s)] | $Q_1$ (m³/h) [(l/s)] | $Q_2$ (m³/h) [(l/s)] | $Q_3$ (m³/h) [(l/s)] | $Q_4$ (m³/h) [(l/s)] | $\epsilon_{1-2}$ | $\epsilon_{2-4}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| SJ | Single-jet | 15 | 160 | $4–5 \times 10^{-3}$ | $15.63 \times 10^{-3}$ | $25.01 \times 10^{-3}$ | 2.5 [$6.9 \times 10^{-1}$] | 3.13 [$8.69 \times 10^{-1}$] | ±5% | ±2% |
| MJ | Multi-jet | | | [$1.1–1.4 \times 10^{-3}$] | [$4.342 \times 10^{-3}$] | [$6.947 \times 10^{-3}$] | | | | |

*Note*: $Q_{start}$ is the starting flow rate. $Q_1$ is the minimum flow rate. $Q_2$ is the transitional flow rate. $Q_3$ is the permanent flow rate. $Q_4$ is the overload flow rate. $\varepsilon_{1-2}$ is the maximum permissible error between $Q_1$ and $Q_2$ and $\varepsilon_{2-4}$ is the maximum permissible error between $Q_2$ and $Q_4$ (ISO4064-1:2017 2017).

An ISOIL Isomag 2500 electromagnetic flow meter (EFM) was used to measure the discharge in steady-state conditions, having an accuracy of 0.2% of the measured value. The flow meter can measure the mean flow velocity only when the pipe is completely filled with water.

A pulse unit comprising an electrical switch operated by a magnetic field (reed switch) was connected to one of the counter hands of the JWM, generating one pulse per litre.

The data acquisition system was based on a National Instruments Compact-DAQ NI-9188 chassis, which provided signal conditioning and analogue-to-digital conversion. For the purposes of the research activity, a graphical interface in LabView was developed to acquire synchronised data from the C-DAQ and evaluate the JWM flow rate by the pulses sent from the pulse unit.

The acquisition frequency of the data was set to 1 Hz for the EFM and 2,048 Hz for the pressure transducers. Details about the characteristics of instruments and data acquisition systems are also given in Ferrante *et al.* (2022).

### Tests

The results of six tests are shown in the following sections, obtained as the combination of two types of water meters, SJ or MJ, with three different downstream conditions, i.e. one 1/4″ valve, three 1/4″ valves in parallel or one 1/2″ valve open downstream of the water meter.

The aims of the tests were to investigate the impact of the airflow on the water meter reliability and accuracy, and on the over-reading.

All tests started in the empty pipe conditions with the switch-on of PS. The water entering the pipe from the upstream cross-section caused the propagation of a waterfront in the pipe and the consequent expulsion through the JWM and the downstream open valve(s) of the air beyond the front. The observed water-filling process is usually modelled as a rigid water column propagation because the velocity of the water varies in time but not in space.

Due to the combination of downstream valve air outflow and upstream water inflow conditions, the air pressure increased during the filling. Once the filling was complete and the waterfront reached the downstream end of the pipe, a sudden increase in the water pressure was observed at the two transducers, typical of a water hammer phenomenon. This increase can be explained by the deceleration of the flow caused by the difference between the discharge associated with the waterfront propagation at the arrival and the achievable water outflow discharge through the downstream valve.

After the complete filling of the pipe and the establishment of steady-state conditions, the PS was switched off. Drains $D_1$–$D_4$ were then opened to allow the pipe emptying and the start of the following test.

## RESULTS

Figure 2 shows the pressure head ($h$) variations in time ($t$) measured during the tests at $P_P$ (*a*, *b* and *c*) and $P_D$ (*d*, *e* and *f*), for one 1/4″ valve (*a* and *d*), three 1/4″ valves (*b* and *e*) and one 1/2″ valve (*c* and *f*) open downstream of the JWM. During the pipe filling, the transducer at $P_P$ measures the water pressure at the upstream end of the water column propagating in the pipe while the transducer at $P_D$ measures the air pressure downstream of the waterfront.

The first pressure variation at $P_P$ in Figure 2(a)–2(c) with a peak at about 10 s corresponds to the pump switch on and the beginning of the pipe filling (hollow diamond).

In the same figures, the pressure peaks after the filled diamond marker correspond to the arrival of the waterfront at the downstream end of the pipe and hence the condition of a fully filled pipe.

After the pump switched on and before the arrival of the waterfront, the pressure increase at $P_D$ corresponds to the increase of the air pressure in the pipe. In fact, the air pressure can be considered to vary in time and not in space in the whole mass of air.

As previously mentioned, the air pressure variation depends on the waterfront propagation speed, which causes a reduction of the air volume and hence the air compression, and on the dimensions of the downstream valves, which cause a reduction of the air mass in the pipe and hence a pressure decrease.

Figure 3 provides a 'dual' description of the same phenomenon as shown in Figure 2, in terms of discharges ($q$), showing both the discharge variations measured at the EFM and JWM.

Although the EFM is located close to the upstream end of the pipe, at the beginning of the pipe filling and sometimes after it, it is not able to measure the water flow probably because the pipe cross-section is not yet completely full of water, the presence of air bubbles or other disturbances. Data exceeding the scale limits in Figure 3 correspond to measurement errors.

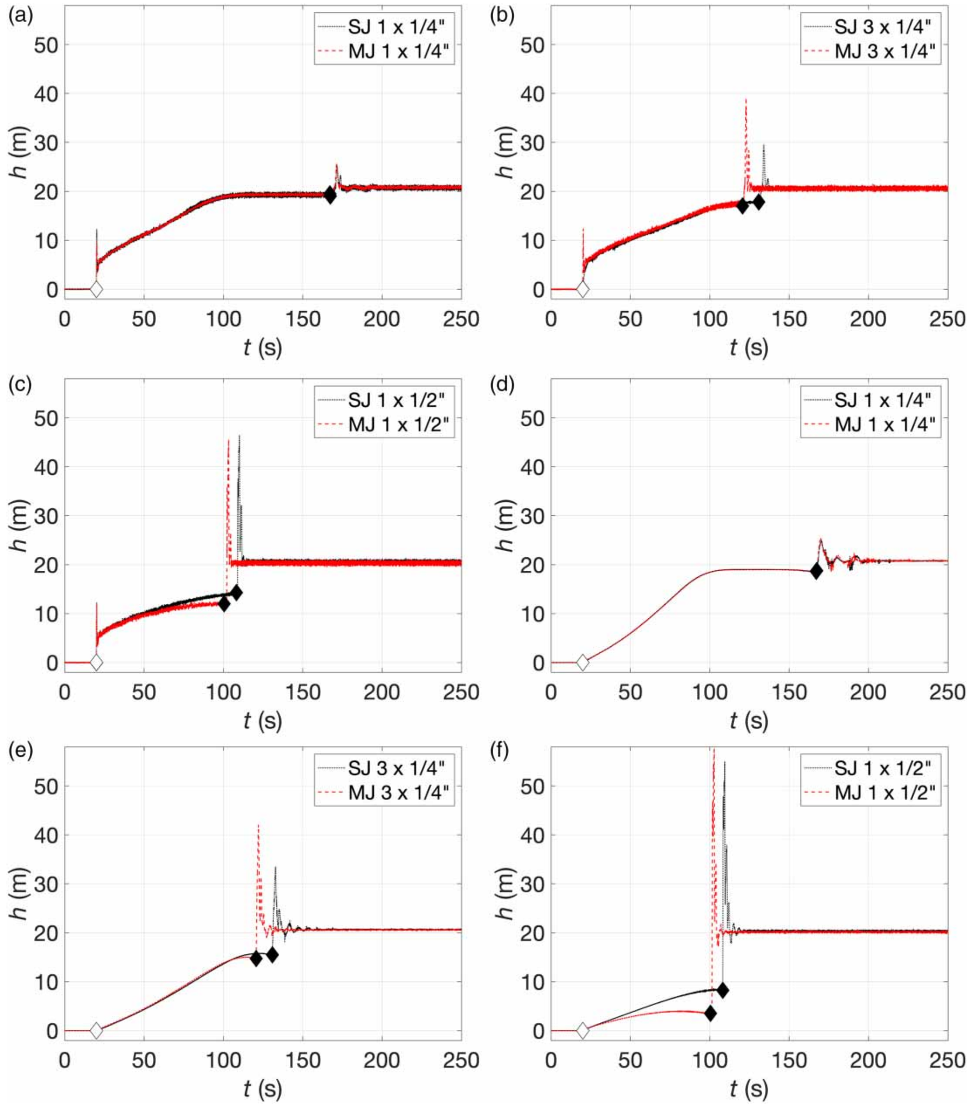


**Figure 2** | Variation in time (*t*) of the pressure head (*h*) at (*a*, *b* and *c*) $P_P$ and (*d*, *e* and *f*) $P_D$ during filling tests with (*a* and *c*) one 1/4″ valve, (*b* and *e*) three 1/4″ valves and (*c* and *f*) one 1/2″ valve, open downstream of the JWM, with SJ and MJ water meters. Hollow and filled diamonds denote the pump switch on and the arrival of the waterfront at the downstream end of the pipe, respectively.

While $P_D$ measures the air variation in time not depending on space, the EFM measures the time variation of the water rigid column discharge, which does not vary in space. The JWM measurements are linked to air discharge, although a discussion of such a relationship is given in the following sections. As a general remark, there was no evidence of a negative registration of the JWM due to the air inlet after the pump switched off. For the sake of comparison, measurements of the JWM during the tests are also shown all together in Figure 4.

Flow and water pressure at the upstream end (flow meter data in Figure 3(a)–3(c) and pressure head in Figure 2(a)–2(c), respectively) are linked by the pump characteristic curve while air and water pressures vary depending on the water column propagation and on the downstream valve opening. More detail about the pressure variations at the measurement sections during the filling is given in Ferrante *et al.* (2022). The discussion of the dependence of pressure peaks and pressure head variations with the downstream end conditions during the filling is beyond the scope of this paper.

Some differences can be seen in the pressure and discharge variations between SJ and MJ tests, especially when the three 1/4″ and one 1/2″ valves are used. As will be described later, the differences between the results of the tests with the 1/2″ downstream valve can be explained by the failure of the multi-JWM.

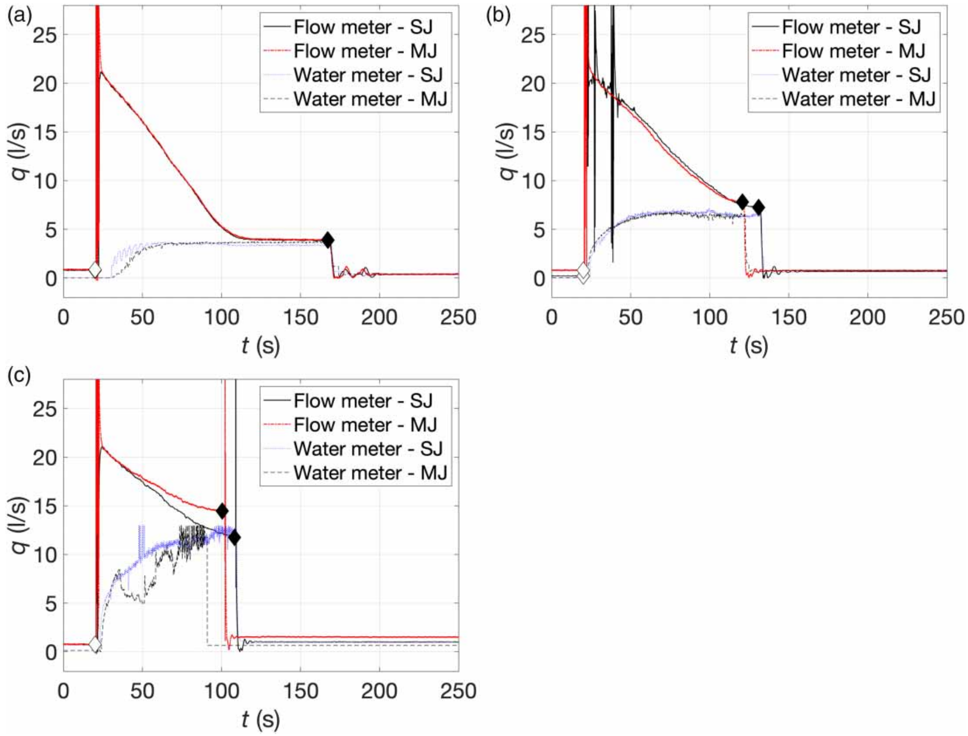


**Figure 3** | Variation in time (*t*) of the discharge (*q*) at the flow meter EFM and at the SJ and MJ water meters during filling tests with (*a*) one 1/4″ valve, (*b*) three 1/4″ valves and (*c*) one 1/2″ valve open downstream. Hollow and filled diamonds denote the pump switch on and the arrival of the waterfront at the downstream end of the pipe, respectively. Data exceeding the *q*-axis limits are due to measurement errors.

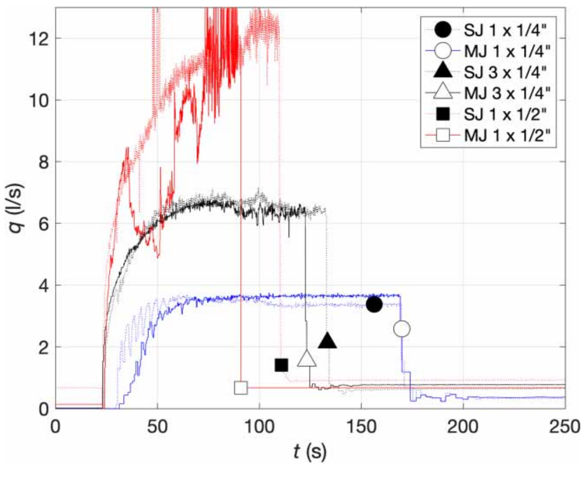


**Figure 4** | Discharge measured by the water meters during the tests with SJ or MJ water meters, for one 1/4″ valve, three 1/4″ valves or one 1/2″ valve open downstream of the water meter. Markers are used to help the line identification.

## ANALYSIS AND DISCUSSION

### The airflow through the water meters

Since the filled diamond markers in Figures 2 and 3 define the waterfront arrival at $P_D$, the JWM measurement until the marker time does not correspond to water flow but to air. The constant level of tank W confirmed that no water was collected during this period of time. On the contrary, the EFM measures the upstream water discharge that, in the rigid column propagation hypotheses, is constant along the pipe. After the transient caused by the waterfront arrival at the downstream valve, when steady-state conditions are reached, both JWM and EFM measure the water discharge.

Assuming that both air and water density were constant during the tests and that the water meter was actually able to measure the air discharge, the volume inflow measured by the EFM should be equal to the volume outflow measured by the water meter. As a consequence, the discharge measured by the JWM and EFM should be the same, which is not what the results in Figure 3 show.

Differences in measured air and water discharges cause differences in the evaluation of air and water volumes. As a matter of fact, considering the pipe lengths and inner diameters, the volume of the empty pipe is about 1.50 $m^3$. This value can be compared with the volume of the incoming water evaluated by the integral of the discharge measured by the EFM during the pipe filling in the shown tests ($V_w$) ranging between 1.37 and 1.48 $m^3$ (see Table 2). The differences between the pipe volume and the water volume entered in the pipe during the filling cannot be explained by the EFM accuracy, which could justify differences of a few litres. A possible explanation could be the unreliability of the EFM measurements at the beginning of the filling. In fact, immediately after the pump is switched on, the presence of air causes data to be missed when the water discharge reaches the highest values (see Figure 3). The missing data correspond to unaccounted-for water volumes. Another explanation could be a different amount of water in the pipe at the beginning of each test, although the time lag between two successive tests of about 1 h, with the opening of four drains along the pipe ($D_1$–$D_4$ in Figure 1), allowing the same starting conditions to be reached, which were very close to those of the empty pipe.

The outgoing air volume measured by the JWM ($V_a$) ranges between 0.445 and 0.864 $m^3$. The percentage of the air volume with respect to the water volume measured by the EFM during the same test, which provides an estimate of the empty volume at the beginning of the test, varies between 32.3 and 61.9% (Table 2).

## Water meter accuracy and airflow

The volume measured during the pipe-filling phase is due to airflow and causes over-registration. One of the objectives of the research activity was to evaluate this quantity. Hence, an issue to be addressed to relate the empty pipe air volume and the over-registration is the accuracy of the meter to measure air volume and mass. With reference to the functioning conditions during the filling, the tests show that the measured air discharge is almost always greater than the water meter overload flow rate $Q_4$, which defines the upper limit of a water meter's assured accuracy. Results in Table 2 show that the maximum value of air discharge measured during the tests ($q_{a\_max}$) ranges between 424.5 and 1,403.2% in $Q_4$.

For the same tests, it can be questioned if the valves can be considered representative of the user demand and hence of the normal functioning conditions of the water meter. To this aim, the mean values of discharges after the arrival time of the waterfront ($q_{wm}$,) evaluated in filled pipe conditions for $200 \le t \le 250$ s, are shown in Table 2. The obtained values are compared with the maximum discharge value associated by the standards to the water meter functioning conditions, i.e. $Q_3$ and $Q_4$ in Table 1:

- for tests with the 1/4″ downstream valve open, $q_{wm} \sim Q_3/2$;
- for tests with three 1/4″ downstream valves open, $q_{wm} \sim Q_3$;
- for tests with the 1/2″ downstream valve open, $q_{wm} > Q_4$.

**Table 2** | Summary of some of the results of the test

| | SJ-1/4″ | MJ-1/4″ | SJ-3 × 1/4″ | MJ-3 × 1/4″ | SJ-1/2″ | MJ-1/2″ |
|---|---|---|---|---|---|---|
| $V_w$ ($m^3$) | 1.368 | 1.485 | 1.395 | 1.377 | 1.397 | 1.395 |
| $V_a$ ($m^3$) | 0.452 | 0.655 | 0.864 | 0.445 | 0.580 | 0.558 |
| $V_a/V_w$ (%) | 33.1 | 44.1 | 61.9 | 32.3 | 41.5 | 40.0 |
| $q_{a\_max}$ (l/s) | 3.690 | 3.743 | 7.169 | 6.797 | 12.30 | 11.76 |
| $q_{a\_max}/Q_4$ (%)[a] | 424.5 | 430.5 | 824.6 | 781.7 | 1,403.2 | 1,352.6 |
| $q_{wm}$ (l/s) | 0.335 | 0.363 | 0.648 | 0.774 | 0.926 | 0.673 |

*Note*: SJ and MJ denote single-jet and multi-jet water meters, respectively. One 1/4″ valve, three 1/4″ valves or one 1/2″ valve, were used during the tests. $V_w$ is the volume of the incoming water during the filling measured by the EFM. $V_a$ is the volume of the outgoing air during the filling measured by the JWM. $q_{a\_max}$ is the maximum discharge value measured during the test by the JWM. $q_{wm}$ is the discharge measured after the pipe filling by the JWM. The characteristic values $Q_3$ and $Q_4$ of the water meters are given in Table 1.
[a]The characteristic value $Q_4$ of the water meters is given in Table 1.

These results suggest that even customer demands in the normal functioning condition range of the water meter (e.g., $q_{wm} \sim Q_3/2$) cause a rotation speed of the turbine during the filling, i.e. airflow, of more than 4 times the maximum allowed ($q_{a\_max}/Q_4 > 400\%$). In fact, the rotation speed during the pipe filling in the shown tests was as high as 14 times the rotation speed corresponding to the water flow of $Q_4$. Furthermore, during the airflow, the turbine rotates in dry conditions, which coupled with the high rotation speeds, probably contributed to the failure of five of the six water meters used in tests undertaken in the experimental research activity. This result, of operational significance to a water utility, is also demonstrated by the results of the tests with the multi-JWM and the 1/2″ downstream open valve shown in Figures 2–4 where the meter failed at around time $t = 35$ s.

Even if the meters are used in the range $Q_2 \leq q \leq Q_4$, it is questionable whether they provide the same maximum permissible error with air compared to water. In fact, water meters are calibrated for the measurement of volumes of water, i.e. a liquid with an almost constant value of density, in a given range of temperatures. During the measurement of air, the turbine rotation speed could depend on both air velocity and density, which vary in time during the filling.

It is worth noting that the discharge measured by the EFM during the filling decreases in time while the discharge of the JWM increases. As mentioned previously, the decrease of the input discharge can be explained considering that it depends on the rigid column velocity, which decreases in time due to the increase of downstream pressure and friction head losses. The increase in the airflow is caused by the increase in the air pressure inside the pipe. In the tests with one 1/4″ downstream valve (Figure 4(a)), the measured discharges converged approximately at the same value about 50 s before the water column arrived at the JWM. Only in these conditions, which are not typical of the other tests, results suggest that water meters provide a reliable estimate of the output air volumes in time, which coincide with the input water volumes.

No evident and significant differences were detected between the two types of meters tested.

## Air density variation

The continuity equation that can be used to relate the initial amount of air in the pipe with that measured by the water meters must be applied to the air mass and not to the air volume. The variations of the air pressure during the filling process are shown in *Errore. L'origine riferimento non è stata trovata* suggest that the density variation could explain some differences between the initial air volumes and mass and the air volumes measured by the water meters. Since there is an outflow of air mass through the downstream valve, the density variation during the test is not simply related to the pressure even if an adiabatic process of a perfect fluid is assumed. A model describing pressures, discharges and density variations during the filling is needed for this aim.

For the sake of completeness, in Figure 5 the pressure head variation in time measured at $P_D$ is plotted against the air discharge measured by the water meter. The data are consistent with the typical patterns of relationships used to evaluate the

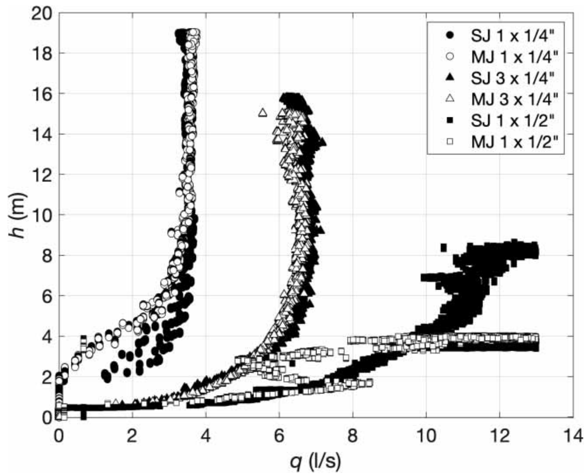


**Figure 5** | Plot of the pressure head at $P_D$ versus the discharge measured by the water meters during the tests with single- or multi-jet water meters (SJ and MJ, respectively), for one 1/4″ valve, three 1/4″ valves or one 1/2″ valve open downstream of the water meter.

airflow through an orifice (e.g., Zhou *et al.* 2020) or an air valve, with the air discharge, depending on pressures in the lower range and almost constant in the higher range of pressures (choked flow).

### Over-Reading estimation

The test results allow a rough estimate of over-reading during the pipe filling in functioning systems. In fact, the effective quantity of air measured during the filling process equated to around 0.5 $m^3$ each time the supply is interrupted. Assuming that

- the pipe diameter used in the test of 110 mm can be considered representative of a water distribution pipe in functioning systems,
- a connection density of around one property/100 m with one interruption per day,
- a mean pressure comparable to those of the tests,
- neglecting the volume of the connection to the user,

the annual over-reading could amount to as much as 90 $m^3$/year. This is likely to be an overestimate considering that there will be other outlets for the air, such as bursts and air valves. No appreciable impact was recorded of air ingress through the meter during the pipe closure which might have compensated for the over-reading.

## CONCLUSIONS

Supply interruptions are common occurrences in water systems, particularly in developing countries. This is due to the demand exceeding supply and is performed by closing the supplying valve or pumps. Customers invariably install storage tanks. An often-overlooked effect is the ingress of air when the supply is interrupted, which has to be discharged during the reopening. This air can be released through a variety of outlets, including the customer service pipes. When these are metered, it is likely that the air will have an impact on the accuracy of the registration. The present paper outlines the experimental work to evaluate the real impact of air on the measurement.

The test network of the Water Engineering Laboratory of the University of Perugia in Italy, with almost 200 m of DN110 pipes allowed the investigation of the effects of the filling of a pipe with a total volume of about 1.5 $m^3$, assessing the impact of air on the meter operation and its accuracy. The results showed the following:

- the valves downstream of the water meter used in the experiments, ranging between 1/4″ and 1/2″, as well as the water meter dimensions and the pressure close to 2 bars, can be considered representative of actual user demand conditions;
- households with installed storage tanks with open connections, to catch the supply time without manual interventions, can even have installed valves larger than those considered in the tests;
- air causes the meter to spin at around 14 times the velocity of water and around 4 times the maximum calibrated value when mean water demands are considered;
- the excessive velocity coupled with the dry state of the meter, though limited to a short time duration, can cause serious reliability issues;
- no discernible negative registration was evident due to the ingress of air at times of supply closure;
- the amount of the water meter over-registration in terms of volumes, ranging between 0.45 and 0.86 $m^3$, is significantly less than the initial air volume in the system of about 1.50 $m^3$;
- differences between air volume discharge and air mass discharge suggest that air density variation during the tests cannot be neglected;
- assuming a density of around 1 service connection per 100 m, one interruption per day would cause an over-reading equivalent to around 0.25 $m^3$/day which is probably a slight overestimate in a real network when other discharge points are also present;
- a model, which can be calibrated by the laboratory test results, is needed to improve the estimation of the over-reading in functioning systems.

In summary, the results show that the passage of air through water meters has a number of undesirable effects which ultimately will impact the customer. This relates most notably to the accuracy, over-reading and reliability of the meter. One possible solution is to use more costly meters such as electromagnetic or ultrasonic, which have no moving parts and won't read unless full of water. Alternatively, a combination check/air valve could be beneficial, even if this solution might be subject to reliability issues. Further tests and the use of a numerical model are needed in order to investigate the effects of the air density variations and the possible actions needed to mitigate the impact of intermittent supply on the water meters.

## ACKNOWLEDGEMENTS

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## DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

## CONFLICT OF INTEREST

The authors declare there is no conflict.

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