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Investigation of pressure transients induced on a real water service line by user's activity

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ABSTRACT

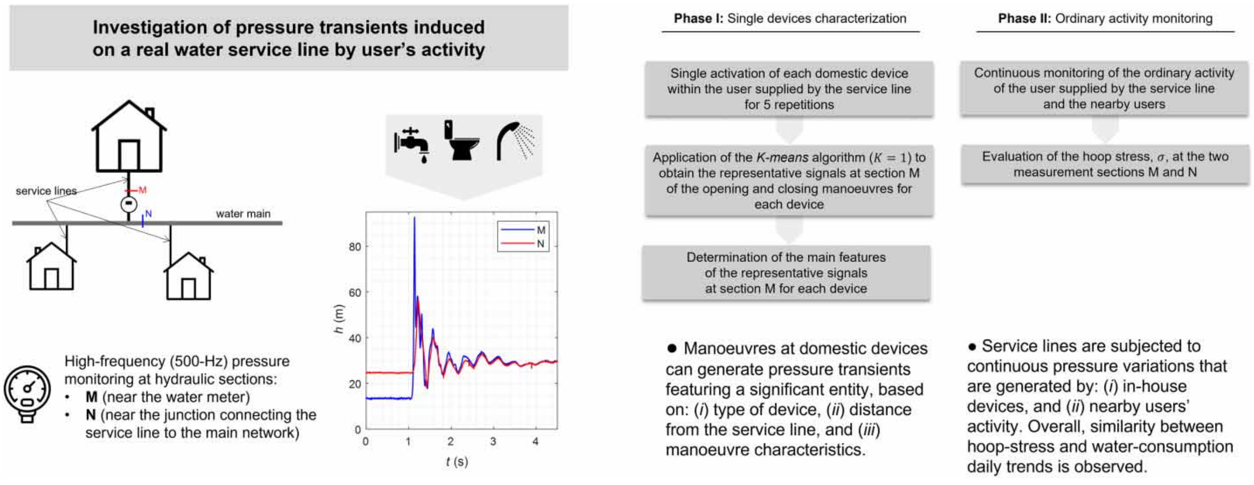
Recent studies point out that water distribution networks can be affected by long- and short-term pressure oscillations due to the users' activity. However, these transients, generated at the household level, before reaching the water distribution network pass through, and thus affect, the water service line and can contribute to its deterioration. Despite the role of user-induced transients in stressing service lines, few studies in the literature explored the topic, exclusively by means of laboratory tests. The current study is aimed at exploring the effects of user's activity on a real service line starting from the field monitoring of pressure data at 500-Hz temporal resolution. Pressure signals are collected both when activating single water devices of the user supplied by the service line and during the ordinary use of domestic devices. The analyses of the acquired data highlight that the domestic service line is subjected to significant pressure variations (which can reach extreme values of −15 and +65 m) based on the device type and distance between the device and the service line and that the use of these devices can continuously stress the water service line.

Key words: plumbing system, transient analysis, unsteady flow, water demand, water service line

HIGHLIGHTS

- Analysis of user-induced pressure variations on a real water service line supplying a domestic user.
- Characterization of single manoeuvres executed at domestic devices within the user based on a high-frequency pressure monitoring.
- Continuous high-frequency pressure monitoring aimed at studying the effect of the ordinary activity of both the user supplied by the service line and the nearby users.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Water supply systems are designed to provide drinking water to users, a matter of paramount importance to human health and economic development (Duan *et al.* 2020). Supply systems include water distribution networks (WDNs) and minor systems with the latter, that represent the final stage of water supply, including the service lines and domestic plumbing. Service lines are small-diameter pipelines – from fractions of an inch to a few inches – of small length – from a few metres to tens of metres – that connect the domestic private plumbing to the main pipe of the WDN; accordingly, a water meter is installed just downstream of the junction for billing purposes.

WDNs are typically designed and managed with respect to steady-state conditions under the assumption that the transient events are unconditionally very slow (Marsili *et al.* 2021). Instead, they are subjected to pressure transients and, in this context, McInnis & Karney (1995), Haghighi (2015) and Marsili *et al.* (2022) provide some examples of unsteady modelling of real and complex WDNs. In this regard, recent studies explore the mid- and long-term impacts of pressure transients on pipe stress and deterioration in WDNs as a possible reason for the failure of these systems (Wang *et al.* 2014; Rezaei *et al.* 2015; Starczewska *et al.* 2015; Rathnayaka *et al.* 2016; Rezaei & Stoianov 2017; Mazumder *et al.* 2019; Jara-Arriagada & Stoianov 2021).

In providing an extensive review of computational and numerical methods for modelling transients in pipe systems, Ghidaoui (2005) points out that water hammer occurs regularly in the WDNs whenever flow conditions are changed rapidly as the results of planned operations such as pumps start and shutdown (Meniconi *et al.* 2015; Huang *et al.* 2020a), automatic self-adjustment of pressure reducing valves or variable speed pumps (Meniconi *et al.* 2017; Ferrarese & Malavasi 2022), or unplanned events, such as accidental valve closure or pipe rupturing (Ramos *et al.* 2009). However, transients in WDNs may also be due to the users' activity and thus generated at the domestic devices activated by the users (i.e., water fixtures – or *end uses* – such as toilets, taps, showers, washing machines, etc.). In fact, these transients produce smaller, but more continuous, pressure changes. In Marsili *et al.* (2021, 2022), e.g., it is shown that long- and short-period oscillations overlap in such transients. The long-period oscillations (with a period larger than 1 min) are characterized by dominant frequencies linked to the geometric and mechanical properties of the network, whereas the latter oscillations (with a period shorter than 1 s and the entity varying over space and time) are due to users' activity.

These oscillations are generated at the domestic devices activated by the users and propagate in the domestic private plumbing. In any case, pressure waves go through the service line and reach the main pipes of the WDN after interacting with the network junction. Accordingly, the transient behaviour of pressurized pipe systems influenced by manoeuvres executed at the peripheral branches depends on their flow conditions and geometric characteristics (Meniconi *et al.* 2021, 2022a, 2022b; Marsili *et al.* 2023). Anyway, the service line is the first element, in most cases managed by the water utilities, to be stressed by pressure waves generated by users' activity before they reach the main WDN.

Field experience reveals that water service lines are among the most vulnerable elements of the water supply systems and are often affected by leaks, in many cases undetected for long periods (AwwaRF 2007; Resenterra *et al.* 2008; Thorton *et al.* 2008; Lee & Meehan 2017). The failure of water service lines may result not only in water leakage and waste of energy (Colombo & Karney 2002, 2003), but also water quality issues due to the intrusion of untreated or contaminated water with a consequent health risk (Karim *et al.* 2003; LeChevallier *et al.* 2003; Byod *et al.* 2004; Gullick *et al.* 2004; Tamminen *et al.* 2008; Aisopou *et al.* 2011; Jones *et al.* 2014; Huang *et al.* 2020b). Therefore, because of the high failure rate of the service lines, the analysis of the effects of the users' activity is of interest for assuring their integrity, reliability, and durability. However, only a few studies in the literature have explored the dynamic behaviour of the service lines to date, and they present exclusively the results of laboratory tests (Lee *et al.* 2012; Lee 2015). Specifically, Lee *et al.* (2012) describe the design and realization of a testbed aimed at replicating the pressure range that affects a service line when manoeuvres are carried out inside the household (i.e., in the domestic plumbing) or outside (i.e., in the WDN). On the one hand, the paper shows that negative pressure conditions generated externally to the user may result in extremely low-pressure values (as low as about -1 bar), which is sufficient for the intrusion of microbial or chemical contaminants in service lines or the creation of cavitation bubbles, with the consequent erosion of the inner part of pipelines. On the other hand, it is reported that pressure transients generated by the user can stress the service line and the sections of the domestic plumbing, which is likely to produce fatigue failures.

In a more recent paper, Lee (2015) carried out laboratory tests on a T-junction connecting a service line with a WDN; during tests, pressure monitoring is executed at three hydraulic sections near the junction. The monitoring confirms that the presence of a leakage near the junction mitigates the transient pressure peaks due to internal or external users' activity (Capponi *et al.* 2020).

To the authors' best knowledge, the current literature lacks of studies aimed at analysing the user-induced pressure variations in service lines, while highlighting the effects that users' activity can have on service lines and the main pipes of the WDN. In this context, the scope of this paper is to characterize the pressure transients due to users' activity on a real water service line and to quantify the stress to which it is subjected. This objective is pursued through the high-resolution monitoring of the pressure in two sections of a real service line: (*i*) near the water meter, and (*ii*) at the junction connecting the service line to the main WDN, respectively. A series of single manoeuvres are executed internally at the user supplied by the line to evaluate the pressure variations generated by the activation of single devices. In addition, the continuous monitoring of a period of ordinary users' activity is conducted to characterize the pressure stress to which the service line is subjected in its standard functioning.

Section 2 describes the case selected for pressure monitoring, along with the main features of the measurement campaign, and the methodology applied to analyse pressure field data. The results of the analyses conducted on the pressure signals collected in the field are then reported and discussed along with study implications and future research directions (section 3). Lastly, some comments about the effects of users' activity on the transient behaviour of the service line are provided (section 4).

2. MATERIALS AND METHODS

2.1. Case study

The minor system considered in the study is part of the WDN supplying Lido di Spina, a seaside resort along the Adriatic coast located in the municipality of Comacchio, in the Emilia-Romagna region (northern Italy). This seaside resort is characterized by seasonal population fluctuations; due to tourism, the population strongly reduces during the winter period and increases in the summer. Specifically, the total resident population in the municipality of Comacchio is about 23,000 inhabitants, whereas, at the height of the tourist season, it is typically about 3.5 times larger. Moreover, the majority of tourist facilities in the area are holiday homes (82.5% of the total number of sleeping accommodations), whereas the capacity of camping sites and hotels is much smaller (15.0 and 2.5%, respectively) (Mazzoni *et al.* 2022).

The service line considered in this paper is connected to a portion of the WDN that supplies a mainly residential area through a DN175 asbestos cement pipeline. This pipeline is also the starting point of a DN60 asbestos cement pipe from which two DN32 polyethylene branches supply 7 and 10 service lines, respectively (Figure 1). These service lines are DN20 polyethylene pipes with a length of 2–5 m.

A measurement campaign was conducted with specific reference to one of the aforementioned users, i.e., user U1, and the respective domestic plumbing system and service line. In greater detail, user U1 is a single-family two-storey house including a small front yard and a small backyard. Figure 1 shows the layout of the cold-water plumbing system of user U1 connected to the main WDN through a 4-m long service line with a mechanical water meter.

User U1's domestic plumbing is composed of DN20 polyethylene pipelines with a total length of about 40 m. Domestic devices are indicated with a black circle in Figure 1. Each device is labelled with an alphanumeric code in which the letter indicates the type of end use (F for toilet flushers, T for taps, and S for showers). In greater detail, devices T1 and T7 are taps including a ball valve; devices T2, T3, T4, and S1 are taps and a shower with mixer valves; devices T5 and T6 are taps with knobs. Moreover, the two toilets of the household (devices F1 and F2) have single-flush tanks.

Two sets of field measurements are considered: the first one carried out in the winter of 2020 (hereinafter, winter) and the latter in the summer of 2021 (hereinafter, summer), that is, during the low and high tourist season, respectively. The first set of measurements is aimed at analysing the selected service line with almost no external disturbances and, in fact, it was performed in a winter period characterized by a low number of active users in the WDN. On the contrary, the second set of measurements is aimed at evaluating the effect of the ordinary activity of the user supplied by the service line and the nearby users around the household. Accordingly, it was performed in a summer period characterized by a high number of active users in the WDN.

Furthermore, two sections are considered for monitoring purposes: section M, near the mechanical water meter, and section N, near the junction connecting the service line of user U1 with the main WDN (Figure 1). On the one hand, sections M and N were chosen because they are easily accessible to operators in the field. On the other hand, in accordance with the

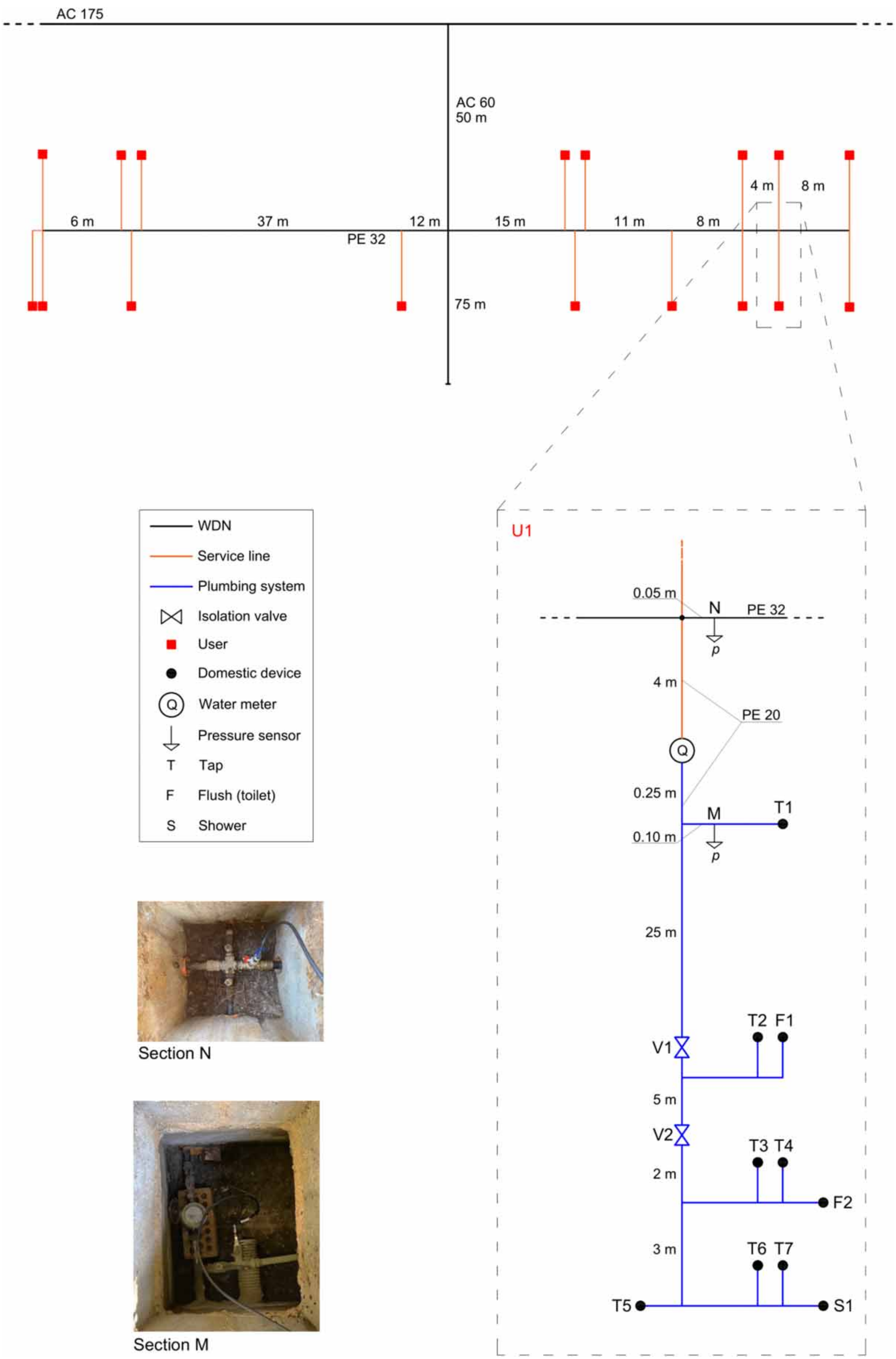


Figure 1 | Layout (not in scale) of the considered portion of the main WDN and the minor system including a service line and a domestic plumbing system, i.e., user U1. Sections M (near the water meter) and N (near the junction connecting the user to the main WDN) are also indicated in the layout.

scope of this study, section M was considered because it is representative of the pressure variations to which the service line is subjected, while section N is representative of the pressure transients entering the main WDN after interacting with the connection to the service line.

From an operational standpoint, the simultaneous monitoring of pressure at sections M and N was conducted with an acquisition frequency $f_a = 500$ Hz, using two TRAFAG® pressure sensors with a measuring range of 0–10 bar and 0–25 bar and transmitting an output signal in the 4–20 mA and 0–10 V potential range, respectively. Analog potential signals were converted into digital signals through a series of National Instrument® modules, while the overall data acquisition process was carried out by means of LabVIEW® software.

Unlike pressure data, flow data were not known in detail. This is because the inlet of the system was equipped only with a mechanical water meter (providing a cumulative volume) during the monitoring. However, discharge values – estimated based on the data provided by the volumetric flow meter – were between 0.05 and 0.40 L/s, which is in line with those of typical end uses of water (Blokker *et al.* 2010). These correspond to velocities ranging from 0.3 to 1.2 m/s, considering a diameter of 20 mm.

2.2. Methods

In the following, the field measurements executed in the two different periods (i.e., winter and summer) and the analysis of the obtained data, structured in two phases, are described (Figure 2). In greater detail, the first phase of analysis is focused on data acquired during the winter period and is aimed at the detailed characterization of the pressure variations induced by single manoeuvres executed at in-house domestic devices. In the second phase of the analysis, the results of the continuous summer monitoring are considered and interpreted in light of the results that emerged from the first phase of the analysis, to characterize the effects of the ordinary users' activity, in relation to both the user supplied by the service line and the nearby users.

During the first period of measurements (i.e., winter period), quick opening and closing manoeuvres at user U1 devices were executed. Precisely, five opening and closing manoeuvres, with the aim of evaluating the repeatability of the test on each device, were carried out. In order to make the pressure stable in the system, a sufficiently long time interval (i.e., about 10 s) was maintained between two successive manoeuvres. Moreover, taps were activated through quick manual manoeuvres, with the only exception of device T1, which was subjected to both manual and automatic manoeuvres (i.e., through the use of an irrigation-timing device). With specific reference to toilets F1 and F2, opening manoeuvres included flushing, whereas closing manoeuvres included triggering of the float valve due to tank filling. The time series of pressure data measured at section M, h_M, due to the five (manual) opening and closing manoeuvres of device T1 is

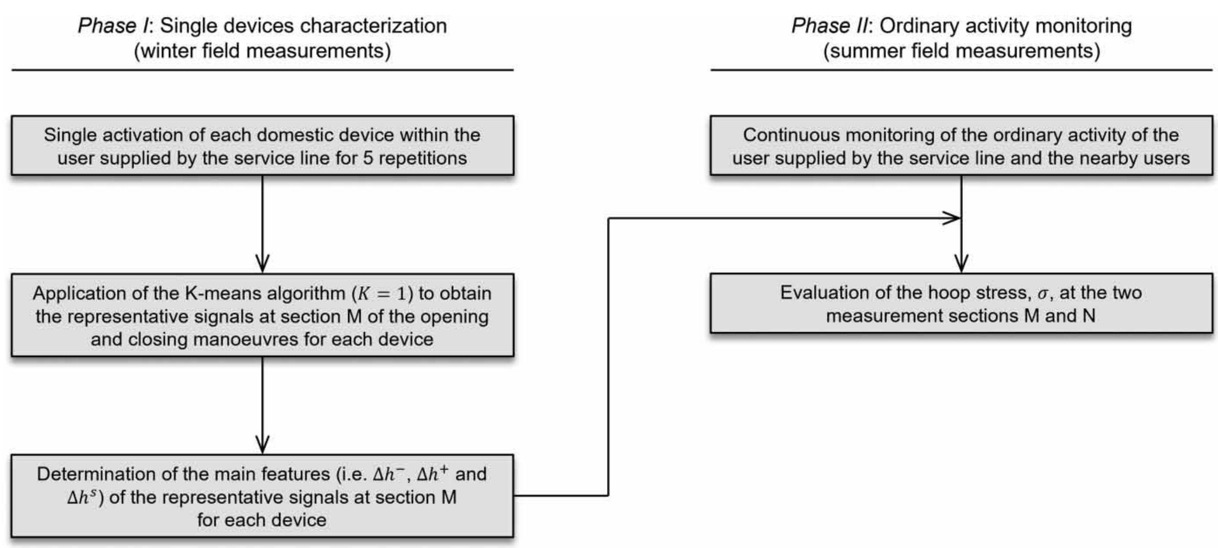


Figure 2 | Schematic representation of the analyses conducted on the pressure data observed in the field.

shown, by way of example, in Figure 3. The figure confirms that each opening/closure manoeuvre occurs when the pressure in the system is stable, i.e., a sufficiently long time after the previous manoeuvre.

To characterize the effects of the transient induced by activating each domestic device, the following approach is used (see also Figure 2). First, the pressure signals collected during the five opening manoeuvres are compared for each device. With this aim, the K-means algorithm (Lloyd 1982) is applied to the five pressure signals to obtain a pressure signal that is representative of the manoeuvres carried out at the considered device. Specifically, the K-means algorithm is applied (by imposing a partition class number $K = 1$) to obtain the centroid of the manoeuvres by minimizing the squared Euclidean distance of the signals. The same is done when considering the pressure signals acquired during the corresponding five closing manoeuvres. The results of the application of the K-means algorithm for the characterization of the manual manoeuvres carried out at device T1 are reported, as an example, in Figure 4, whereas the representative pressure signals of other domestic devices are reported in Appendix A (Figures A1–A11). In these figures, signals related to individual manoeuvres are represented with grey lines, whereas the centroid obtained by applying the K-means algorithm is represented with a thick black line.

To characterize the representative pressure signal of each domestic device, the maximum absolute pressure variation during the opening, Δh^{-}, and the closing manoeuvres, Δh^{+}, and the difference between the stabilized pressure before and after the opening manoeuvre, Δh^{s}, are considered (Figure 4). Precisely, Δh^{+} and Δh^{-} are representative of the extreme pressure variations experienced by the pipelines, whereas Δh^{s} is related to the head loss in the service line. In fact, considering, for example, the manoeuvre of device T1 (Figure 4), it can be observed that, given a static network pressure head of about 30 m, after an opening manoeuvre pressure tends to stabilize in a couple of seconds, then remaining at a value of 14 m. This pressure drop is due to the head losses in the service line when the device is active. Similarly, during a closing manoeuvre, the pressure head tends to increase from about 14 m to the static network pressure head of about 30 m in a few seconds. It is worth noting that, because only one device at a time was activated (in turn), Δh^{s} is a function of the discharge supplied by that device: the larger the discharge, the larger Δh^{s}.

To evaluate the effects of users' ordinary activity in relation to both the user supplied by the service line and the nearby users, a further monitoring was carried out during the summer period (Figure 2). Indeed, the measurements carried out in

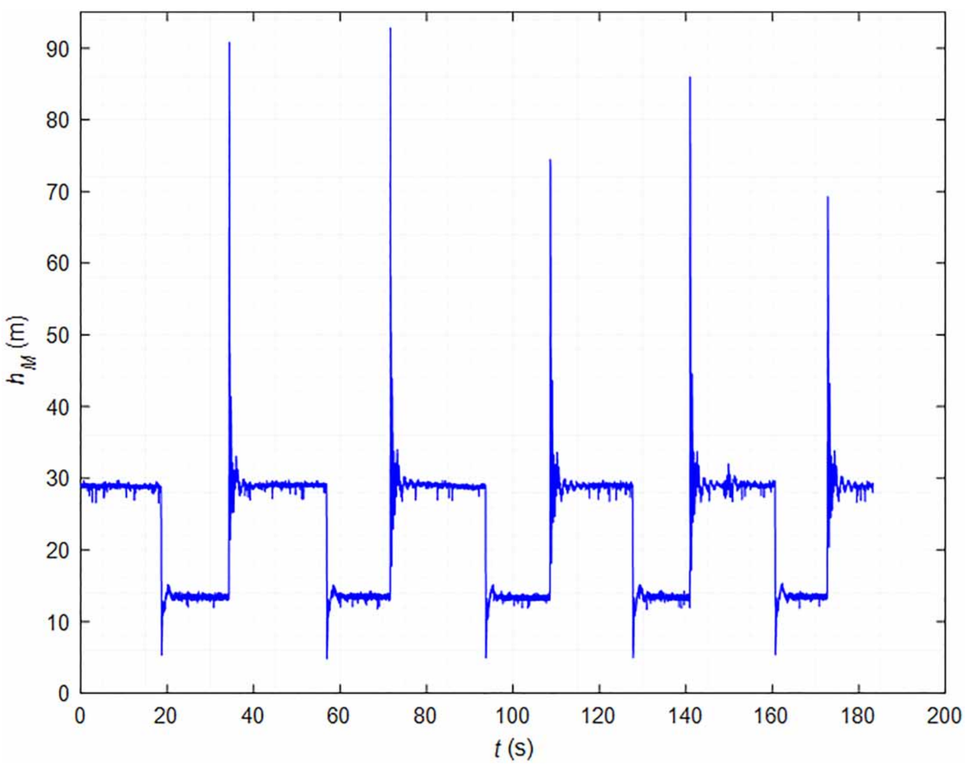


Figure 3 | Pressure signal measured at section M, h_M (m), due to five opening and closing manoeuvres (manually) executed at device T1 of user U1.

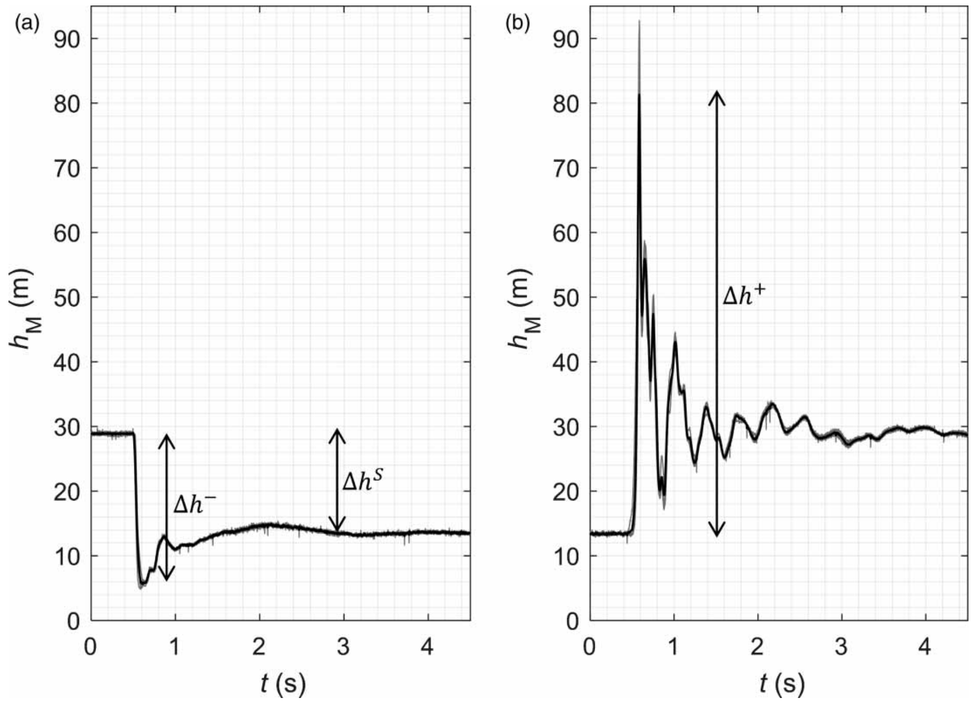


Figure 4 | Pressure signals of five manual opening (a) and closing (b) manoeuvres (grey lines) and representative pressure signal (black line) for device T1 of user U1. The maximum absolute pressure variations occurring during opening (Δh^-) and closure (Δh^+) of the device are also indicated, along with the difference between the stabilized pressure before and after the opening manoeuvre (Δh^S).

the winter period were necessary in order to correctly interpret the results of the summer pressure monitoring characterized by the continuous overlapping of pressure waves generated by the users' activity. Specifically, the high-frequency pressure signal was monitored continuously for about 6 days to grasp the effects – in terms of pressure fluctuations and pressure stress in pipes – of the ordinary activity of the user supplied by the service line considered and the nearby users. From an operational standpoint, the Barlow's equation (Adams *et al.* 2018) is considered for evaluating the hoop stress, σ, and thus to point out the pressure stress in the pipes in the long period:

$$\sigma = \frac{\sum_{i=1}^{n} |h(t_{i+1}) - h(t_i)| D\gamma}{2e} \tag{1}$$

where D [L] and e [L] are the internal diameter and thickness of the pipe, respectively, γ [ML^{-2} T^{-2}] is the liquid specific weight, and n is the number of pressure data acquired in a given time window and making up pressure signal h [L]. In particular, the hoop stress on the service line is evaluated assuming $D = 20$ mm and $e = 2$ mm for section M, and $D = 32$ mm and $e = 3$ mm for section N.

3. ANALYSIS AND DISCUSSION OF RESULTS

The results of high-resolution pressure monitoring are firstly discussed in relation to the winter period, i.e., by considering the effects of the individual manoeuvres at devices of user U1 in terms of pressure variations measured at the domestic service lines (i.e., section M) and at the connection with the main WDN (i.e., section N). Results in terms of pressure variations at sections M and N over the summer monitoring period are then presented.

With reference to the tests carried out during the winter period, at section M, it is worth noting that the pressure signals generated by the set of five opening (and closing) manoeuvres of each device are generally quite similar, especially in the case of devices including ball or mixer valves (i.e., T1, T2, T3, T4, T7, and S1). As an example, Figure 4 compares the pressure signals obtained by the five manual opening (a) and closing (b) manoeuvres (reported with grey lines) at device T1, which show to be almost indistinguishable. This implies that the signal obtained through the application of the K-means algorithm can effectively be considered representative of the opening (and closing) of the considered device. Conversely, as far as devices with knobs (i.e., T5 and T6, Figures A6–A7) are regarded, the initial phase of individual manoeuvres is slightly different from case to case. This is because manoeuvres on knob taps are typically slower, and then more dependent on how they are carried out.

The main characteristics of the representative pressure signal of each domestic device are reported in Table 1 together with the distance of each device from the service line, d_M.

Overall, it can be observed that the effects of users' activity on the domestic service line (i.e., at section M) are rather different when different devices and manoeuvres are considered. In fact, manual closing manoeuvres at device T1 generate a quite large maximum absolute pressure variation (Δh^+ around 70 m), which is greater than the maximum absolute pressure variation Δh^- due to opening manoeuvres of the same device (i.e., about 25 m).

The pressure signal of the automatic manoeuvres executed at device T1 by means of an irrigation-timing device (the representative signals of which are reported in Appendix A) is similar to those resulting from manual opening and closing manoeuvres on the same device but with slightly smaller extreme pressure variations. This difference is mainly due to the additional, localized head loss given by the installation of the irrigation-timing device, resulting in a smaller flow rate. This is also confirmed by the decrease in Δh^s values, i.e., about 15 m in the case of the tap without the irrigation-timing device (manual manoeuvre) and 8 m in the case of the tap with the irrigation-timing device (automatic manoeuvre). In fact, according to the Allievi–Joukowsky equation, the smaller flow rate (and, consequently, the smaller mean velocity) induced by the installation of the irrigation-timing device leads to maximum pressure variations that are smaller than those observed without this device.

With regard to the other devices of user U1, it can be observed that the entity of the maximum pressure variations is typically smaller (i.e., between 3 and 12 m) for both the closure and opening manoeuvres. Moreover, even if two devices of the same type (e.g., mixer-valve taps) are considered, the induced pressure transient may be considerably different as a consequence of the different distance from the service line. As an example, if devices T2 and T3 are considered (both including a mixer valve and therefore expected to produce similar localized head losses), the pressure regimes due to manoeuvres at device T2 are almost three times larger than the ones induced at device T3. This is because the distance between the service line and the former device is about 23 m, whereas the distance from the latter device is about 30 m. In fact, longer distances are typically related to larger head losses: this results in a reduction of the discharge provided by device T3 and, therefore, in Δh^s values related to T3 opening. This implies smaller pressure variations observed at section M in face of a manoeuvre at device T3. However, longer distances between the service line and the device do not always result in smaller flow rates, and thus smaller pressure variations. In fact, different pressure variations may also be due to different localized head losses produced by devices. For example, as far as manoeuvres at devices T4 and S1 are concerned, it can be observed

Table 1 | Characteristics of the representative pressure signals for opening and closing manoeuvres at the devices of the user U1 (defined with respect to section M)

Device	Δh^+ (m)	Δh^- (m)	Δh^s (m)	d_M (m)
T1	67.9	23.1	15.6	1
T1 + irrigation-timing device	45.5	16.0	8.1	1
T2	11.3	7.4	0.9	23
F1	5.2	6.1	1.0	23
T3	3.9	3.1	0.4	30
T4	3.9	4.7	0.7	30
F2	3.2	5.2	0.8	30
T5	2.8	4.4	0.5	33
T6	3.4	5.6	2.1	38
T7	4.7	7.8	2.3	38
S1	4.8	7.1	1.8	38

that, although device T4 is closer to the service line (i.e., 30 m) than device S1 (i.e., 38 m), the flow rate of device T4 is smaller and thus device T4 is characterized by a smaller Δh^s-value. As a result, the observed pressure variations are smaller when manoeuvres are executed at device T4 with respect to those at device S1.

The effects of the manoeuvre on pressure variations can be observed by comparing, for example, devices T4 (mixer tap) and T5 (knob tap). The manoeuvres executed at device T5 give rise to smaller pressure variations. This difference is likely to be due to the type of device. In fact, manoeuvres on the knob tap are typically slower than manoeuvres on the mixer tap and therefore lower pressure variations are generated by knob-tap activation. Similar considerations apply also to devices T6 (knob tap) and T7 (tap with a ball valve), the distance of which from the service line is the same. In this case, the pressure variations induced by manoeuvres at device T6 are smaller than those induced by manoeuvres at device T7 because of the longer times generally required to activate a knob.

To point out also the impact on the main WDN of the pressure transients generated within the plumbing system and propagating through the service line, the pressure signals measured at section N in proximity to the junction connecting the service line to the main WDN, h_N, is then considered. For the sake of brevity, only the pressure signals simultaneously observed at section M (blue line) and N (red line) during a closing and opening manoeuvre (manually) executed at devices T1 and F1 are shown in Figure 5.

Considering the pressure signals due to manoeuvres executed at T1 (Figures 5(a) and 5(b)), it can be observed that the pressure variations due to the opening manoeuvres are slightly larger in section M than in section N when the device is

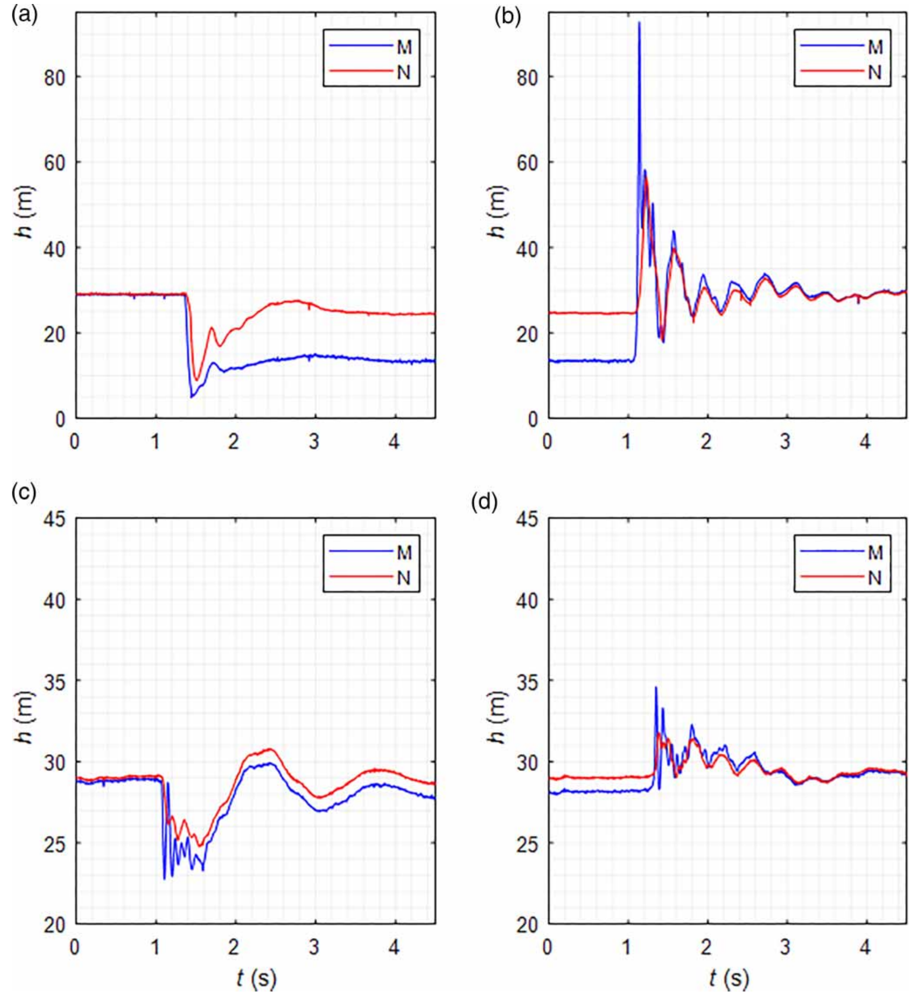


Figure 5 | Pressure signals observed at sections M (h_M, blue line) and N (h_N, red line) due to opening (a,c) and closing (b,d) manoeuvres manually executed at devices T1 and F1 of user U1.

activated (about 25 vs. 20 m). A few seconds after the manoeuvre, pressure in sections M and N stabilizes on different values (14 vs. 25 m) because of the head losses produced in the service line. In addition, when the device is closed, the pressure wave Δh_M (75 m) propagates along the service line up to the junction connecting to the main water distribution system. However, only a part is transmitted to the adjacent pipelines and is thus registered at section N. This is due to the transmission and reflection mechanisms that affect the interaction of the pressure wave with the junction and are related to the system geometry and materials making up the system (Pan *et al.* 2022).

More in general, the effects in terms of the maximum absolute pressure variations Δh^- and Δh^+ on the WDN (i.e., at section N) are summarized in Table 2. Such values reveal that, during closing manoeuvres, Δh^+ measured at section N is – on average – about 3 m but it can reach values up to 29.5 m. Moreover, Δh^- is – on average – equal to about 4.5 m, but extreme values of about 19.8 m are observed, as well. Such average values are in line with the ones resulting from the monitoring of an actual WDN, as reported by Marsili *et al.* (2021).

The outcomes of the first phase of analysis – focused on pressure variations induced by single-device activations – provide useful information for the interpretation of the results of the pressure monitoring conducted in the summer period, during which the continuous overlapping of pressure waves generated by the ordinary users' activity occurs.

Considering field data observed during the summer monitoring, the pressure signals acquired at sections M and N during a daytime and a night-time window of 1 h (i.e., from 13:00 to 14:00, 28 July 2021, and from 03:00 to 04:00, 28 July 2021) are reported as an example in Figures 6(a) and 6(b), respectively. With reference to the daytime period (Figure 6(a)), it is worth noting that the household was inhabited only in the second half of the time window considered (i.e., from 13:30 to 14:00). In this latter period, the in-house activity is clearly recognizable in the pressure signal acquired both at M and N in the form of some opening and closing manoeuvres interspersed with a drop pressure at M – with an entity Δh^s – corresponding to in-house water use. As confirmed by the homeowner, these pressure variations are related to the activation of in-house taps and are characterized by Δh^-, Δh^+ and Δh^s of some metres, in line with the results obtained in the first phase of analysis.

Even though the house was uninhabited in the first period of the considered time window (i.e., from 13:00 to 13:30) – and thus in-house activity did not generate pressure variations – the effects of external manoeuvres could be clearly detected. In fact, despite homeowners' absence, frequent positive and negative pressure peaks, equally affecting sections N and M, were observed. This clearly demonstrates that the considered service line is affected not only by pressure oscillations generated by the manoeuvres of devices within the supplied house (i.e., by the activity of the user) but also by pressure oscillations generated by manoeuvres of devices at the nearby houses (i.e., by the activity of the neighbours). In other words, not only pressure oscillations generated within the considered house affect and pass through the service line reaching the WDN, but also pressure oscillations generated in the nearby houses reach the service line of the considered house. In greater detail, considering only the pressure signal at section M, i.e., considering the service line of the user U1, and recalling that during the first half of the considered time window (i.e., from 13:00 to 13:30) the house was uninhabited, the hoop stress values evaluated

Table 2 | Characteristics of the representative pressure signals for opening and closing manoeuvres at the devices of the user U1 (defined with reference to the hydraulic section N)

Device	Δh^+ (m)	Δh^- (m)	d_N (m)
T1	29.5	19.8	5
T1 + irrigation-timing device	22.2	13.4	5
T2	2.7	4.6	27
F1	2.3	4.4	27
T3	2.4	2.7	34
T4	2.7	3.5	34
F2	2.4	3.9	34
T5	2.2	3.2	37
T6	2.3	4.3	42
T7	5.8	3.4	42
S1	3.8	7.5	42

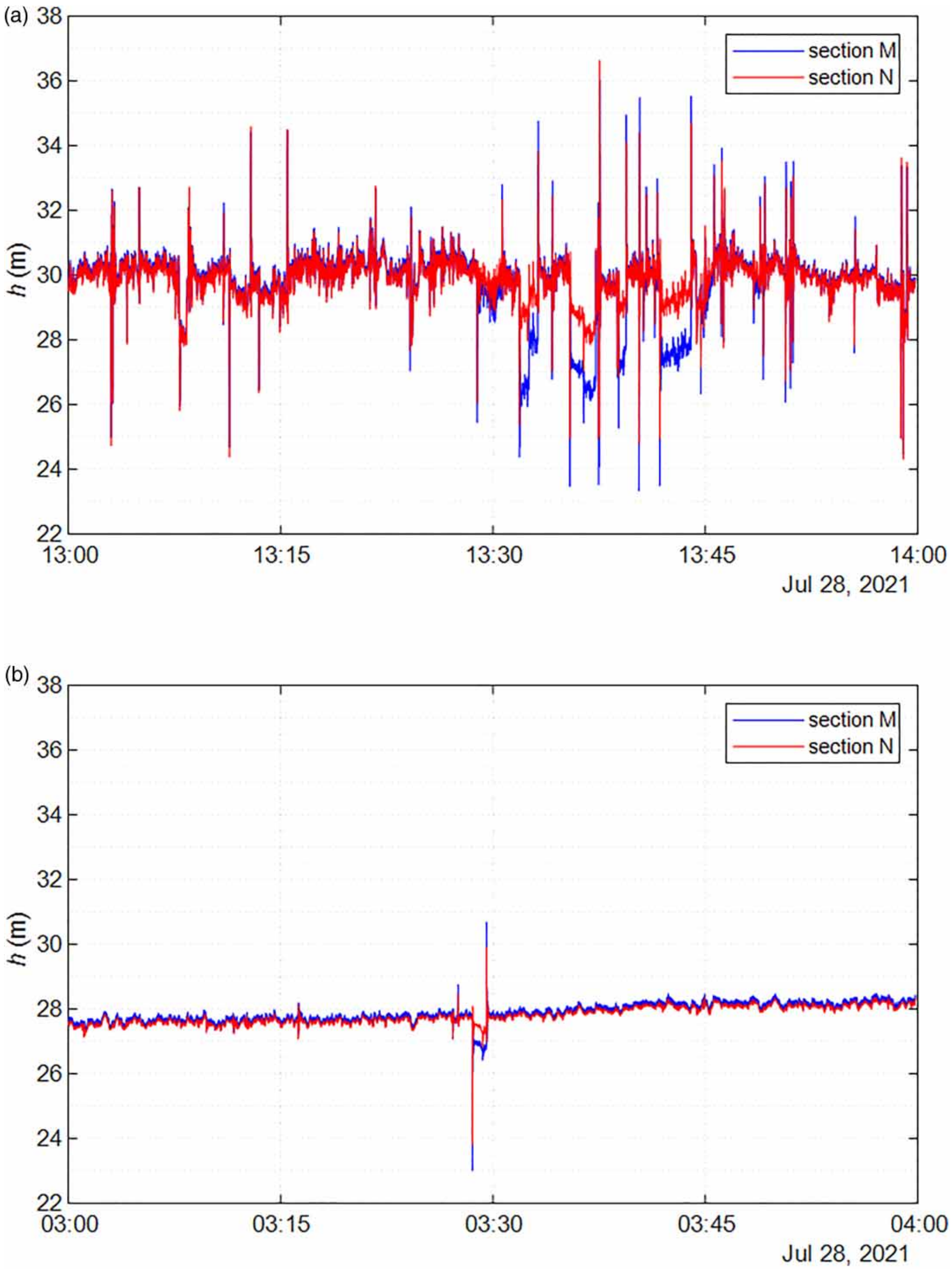


Figure 6 | Pressure signal monitored at section M during a 1-h time window during (a) the daytime (from 13:00 to 14:00, 28 July 2021) and (b) the night-time (from 03:00 to 04:00, 28 July 2021) in the summer period.

considering the first and second half of the period are very similar, with a slight increase (i.e., 10%) in the second half. This indicates that the stress affecting the service line of the considered house is in large part due to the manoeuvres executed within nearby houses.

Considering the night-time period (Figure 6(b)), both pressure signals show smaller fluctuations and only a few pressure spikes related to single manoeuvres carried out at in-house domestic devices. Hoop stress evaluated during the night-time period presents values about 2.5 times smaller than those observed during the daytime period, accordingly with the drop in users' activity during the night-time hours.

In light of the above, it can be noted that opening and closing manoeuvres related to water consumption produce pressure variations in the service line which are characterized by higher magnitude and frequency during the daytime as opposed to the night-time. This outcome is in line with those presented in the study by Marsili *et al.* (2021). Moreover, as far as the current case study is concerned, it emerges that the activity of external users produces the majority of pressure variations affecting the considered service line.

The evaluation of the average hoop stress defined by Equation (1) at sections M and N with a 1-h time step on the overall summer monitoring period of 6 days points out the relation between pressure variations generated in the network and users' activity (Figure 7). In fact, the obtained trend of the hoop stress is similar to that of the net inflow of the area considered, which is in turn in line with the typical pattern of residential water consumption. In greater detail, it emphasizes during the hours typically affected by the highest consumption (i.e., early morning, noon, and evening) whereas it reduces at night-time (Mazzoni *et al.* 2023). This further demonstrates the significant correlation between the observed pressure variations and users' activity. Such a relationship should not be neglected given that the hoop stress could lead to service line failure due to fatigue. However, this aspect is worthy of further in-depth analyses in future studies.

3.1. Recommendations, implications and future directions

In this section, operational recommendations and technical limitations emerging from the work are provided, along with a discussion of the study practical implications and future research directions.

With reference to the requirements for the measuring equipment and the limitations that arose during the measurements, some considerations and recommendations are of interest. In fact, a number of issues arise, with main regard to the placement and installation operations of pressure sensors. Specifically:

- Measurement sections have to be accessible to operators and this is not always guaranteed. In addition, connection elements along the pipes have to be envisaged in order to allow sensors' installation. In particular, considering the measurements section in the proximity of the water meter on the plumbing side, the placement of the connection element, if not already present, can be easily placed given that a ball valve is generally already installed for the isolation of the private plumbing

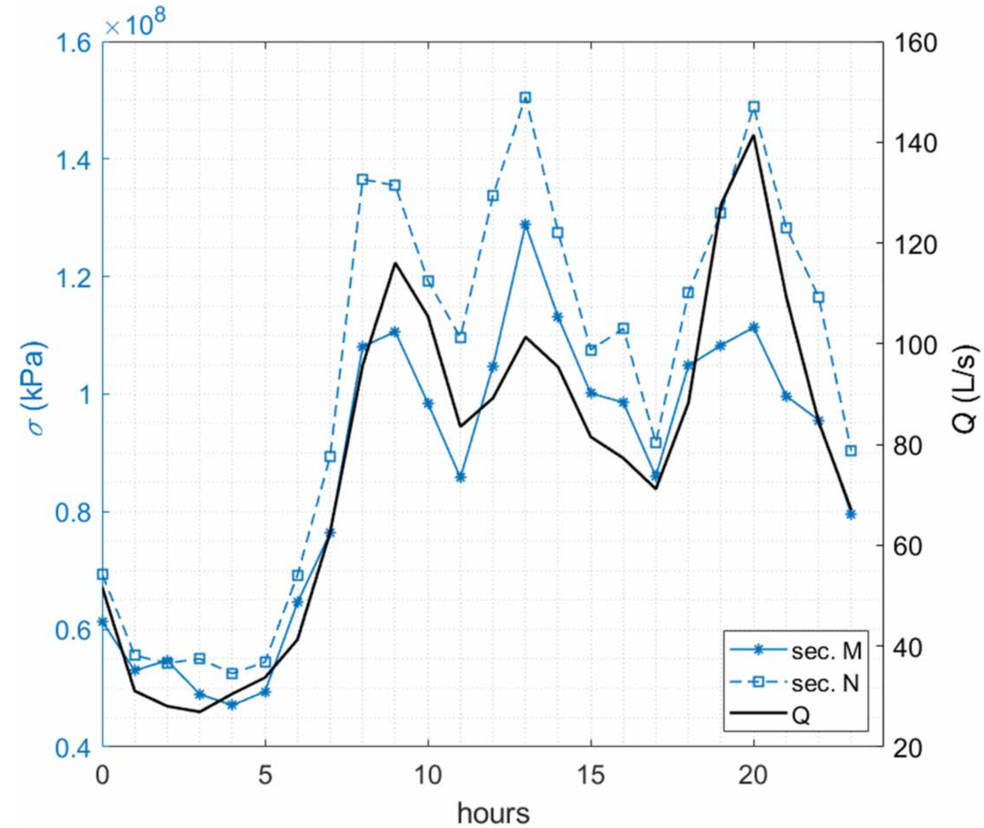


Figure 7 | Hourly average hoop stress σ at sections M and N evaluated with a 1-h time step during the 6 summer days of monitoring (i.e., from 00:00, 23 July 2021 to 00:00, 30 July 2021).

system. This valve can thus be temporally closed to isolate the plumbing system during the installation of the connection element where the transducer is placed. Concerning the measurement section in the proximity of the junction of the service line with the network, network side, the operations are generally more complex given that it is necessary to isolate the portion of the network to place the connection element allowing for the installation of the transducer. This operation entails the authorization and the support of the water utility (Pinto *et al.* 2015).

- In the case of pressure sensors needing wiring, they have to be connected with a cable of a sufficient length (typically metres or tens of metres), depending on each pressure transducer's location and its distance from the power supply (if needed) and the acquisition system. In the current case, cables of 20 m were sufficient. In addition, cables connecting measurement sections outside private property have to be properly settled, possibly providing for the underground passage inside the lining pipe (if present).
- Concerning the monitoring time step, a high-frequency acquisition of pressure data ($>10^2$–10^3 Hz) has to be guaranteed given the small lengths and the high wave speeds typically characterizing minor systems. Moreover, a synchronized acquisition of pressure data is necessary if it is planned to install more than one sensor.

The practical implications of the study are manifold. High-frequency monitoring of the pressure of a real water service line has shown to be useful to characterize the pressure oscillation and thus the consequent cyclic loading condition affecting this element in its standard functioning. As shown for this case study, user-induced pressure variations can be significant. But, if on the one hand, transients due to users' activity cannot be avoided, the consequent overlapping of the pressure wave is related to generally manageable aspects such as network topology and materials. In addition, the inclusion of passive remedies (e.g., air vessels, air valves, viscoelastic pipeline segments, etc.) can be evaluated.

Concerning future directions, the developments of the study will be addressed in two main directions: (*i*) the experimental study of the interaction mechanisms (i.e., transmission and reflection) at the connection junction between the water service line and the main network and (*ii*) the definition of fast methods aimed to effectively reproduce pressure variations in a minor system in the face of the activation of in-house domestic devices. Both objectives are aimed at providing additional operational indications to the known 'good practice' for the design of minor system (e.g., VDI 6006:2017-11) that can guide the technicians in the design and realization of these systems.

4. CONCLUSIONS

The analyses proposed in this study were executed with the aim of characterizing the effects of transients on a real water service line. Transients were generated by a series of single manoeuvres at an individual user over a period of ordinary activity. The analysis of pressure signals collected with a high-frequency acquisition ($f_a = 500$ Hz) at two sections of the system points out that the pressure variations generated at domestic devices considerably affect the service lines. The related significant and continuous stress depends on the characteristics and the location of the device considered along with the type of manoeuvre. In particular, the following aspects are worthy of remark:

- pressure stress generated by in-house devices is generally more evident on the service line as opposed to the WDN, given the interaction mechanism of pressure waves with the junction that connects the service line and the main network. In the current study, pressure variations observed in proximity to the connection between the WDN and domestic service line (i.e., section N) were about ± 5 m. Conversely, the service line itself (i.e., section M) experienced much larger pressure variations, with extreme values of – 15 and +65 m. More in general, wave transmission and reflection are related to the diameter and the wave speed of the pipes converging in the junction. In this regard, the larger the WDN pipe diameter, the larger the decrease of the hoop stress in the network due to in-house activity, and thus the increase of such stress at the service line;
- the summer monitoring campaign confirms that the service line can be continuously affected by pressure variations that are more important during the daytime, whereas they reduce at night-time. These pressure variations are generated not only by in-house devices (i.e., internally at the user supplied by the service line) but also, and mainly, externally to the user. In this respect, the flow meter has a negligible effect on the pressure propagation and pressure waves produced by external users easily enter the service line, subjecting the latter to significant and frequent pressure changes. Moreover, with reference to a long-term period evaluation, a service line supplying a not very active user may still be subjected to high-pressure stress due to the activity of neighbour users. Conversely, the service line of a very active user but surrounded by a limited number of neighbour users may be subject to a lower-pressure stress state.

Based on field measurements, the results of the analysis indicate that the effects of transients induced by the activation of domestic devices on a real service line are not negligible in terms of pressure stress on pipes. Accordingly, they lay a basis for further studies aimed at investigating the role of user-induced transients in contributing to the long-term deterioration process of the pipelines, and specifically service lines.

AUTHORS' CONTRIBUTIONS

V. M., S. A., S. M. conceptualized the whole article; V. M. rendered supported in data curation; V. M., F. M., S. A., F. M., C. C., and S. M. rendered supported in formal analysis; B. B. and M. F. conducted funding acquisition; V. M., S. A., F. M., F. M., C. C., and S. M. developed the methodology; S. A., S. M., B. B., M. F. administered the project; S. A., B. B., and M. F. brought the resources; V. M. and S. M. rendered support in software development; S. A., S. M., B. B., and M. F. supervised the work; V. M., F. M., S. A., F. M., C. C., S. M., S. A., B. B., and M. F. wrote the review and edited the article. All authors have read and agreed to the submitted version of the manuscript.

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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