INVESTIGATION OF RESIDENTIAL WATER CONSUMPTION EVENTS BASED ON PRESSURE DATA

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ABSTRACT
Smart metering technologies are among the key contributions to the digital revolution in the water sector, primarily aimed at providing water consumption data at higher time resolution (daily or hourly) compared to the traditional meters. Although smart flow meters facilitate the gathering of water consumption data, technical limitations (e.g. battery life) may hinder their practical applications when it comes to obtaining data at very high time resolution (1 min or 1 sec, i.e. the resolution required for the characterization of water end uses). As an alternative to traditional flow-based approaches, this paper presents an innovative method for estimating water consumption events by relying only on pressure data observed at two sections of the user inlet pipe. The proposed method exploits the pressure-flowrate relationship to estimate the household water-consumption time series, while distinguishing between internal and external water-use events. The application of the proposed method to a real case study – subjected to 1-s resolution pressure monitoring for approximately a month and a half – shows method's efficacy in obtaining the time series of the flowrate entering the user and identifying water-consumption events and their characteristics.

Keywords: Pressure data; High-resolution monitoring; Water consumption

INTRODUCTION
The knowledge of users' behaviours at the level of individual end uses has gained increasing attention in the last decades. In this regard, water consumption end-use analysis can play a crucial role in the development of water-reuse strategies [1] or strategies aimed at increasing awareness about water consumption, while raising users' sensitivity toward water conservation [2]. However, it has been widely demonstrated that only data gathered at a sufficiently fine time resolution (1 min, or even better, 1 sec) allow properly investigating water consumption at the end-use level [3]. On the contrary, due to technical reasons (such as battery life) smart metered water consumption data are generally registered and collected by Water Utilities at daily or hourly time steps.

To explore alternative methods for water consumption event monitoring and analysis, Froelich et al. [4,5] proposed a method based on pressure data collection at the domestic inlet pipe. Despite its proven effectiveness, the method emerged to be poorly transferrable due to a series of limitations. First, due to the deployment of a single pressure sensor, water-consumption events of the user considered cannot be discriminated from external events (i.e. water consumption related to other users) or from pressure variations occurring in the WDN. Second, the method requires super-fine (i.e. 1 kHz) temporal resolution leading to a very large amount of data to be collected and processed, along with an intrusive phase for software calibration requiring the use of many pressure sensors.

In an attempt to overcome the limitations of the pressure-based method proposed by [4,5], [6] has recently proposed a methodology aimed at water-consumption characterization exclusively based on pressure data acquired at two sections of the user inlet pipe with a 1-s resolution. Specifically, the headloss-flowrate relation is innovatively applied in relation to these two sections and exploited to estimate the water-consumption time series of the considered user, while discriminating between internal and external events. Overall, the methodology consists of two main phases. In the first phase, pressure data are collected at two sections of the user inlet pipe and the related flowrate time series is assessed based on the headloss-flowrate relation. In the second phase, information about water consumption at the level of individual events is obtained. Taking cue from [6], an analysis of the method's efficacy in obtaining the time series of the flowrate entering the user and identifying water-consumption events and their characteristics is provided. A real residential user consisting of a single-family house was considered and subject to (*i*) the 1-s resolution monitoring of pressure data at two sections of the inlet pipe over a period of 6 weeks, and (*ii*) daily readings of the mechanical water meter, allowing the daily water volume supplied to the user to be investigated. The remaining of the work is structured in three sections. First, the methodology and the characteristics of the real case study considered to test the method are presented (*Methods*). Then, the results obtained are shown and discussed (*Results and Discussion*). Finally, the main outcomes of the study are provided (*Conclusions*).

METHODS

The proposed methodology consists of two main phases: (*i*) flowrate time series obtainment and (*ii*) water consumption event characterization. In the first phase, pressure data are collected at two sections (i.e. upstream section, U, and downstream section, D) of a user inlet pipe (e.g., the service line supplying the user or the user's plumbing system), enabling the discrimination of internal events (i.e. occurring in the user considered) from external events (i.e. due to the activity of other users) or changes in network operation. Subsequently, the headloss-flowrate relation is exploited to estimate the water-consumption time series of the considered household. From an operational standpoint, the headloss time series $\Delta H_{U,D}$ (blue line in Figure 1a) is determined by assessing the elevations of pressure sensors through direct measurement or estimate by considering the offset between signals in relation to a period with no water consumption in the household. The elevations of pressure sensors are then added to the pressure head signals monitored at sections U and D thus providing the total head H time series. Headloss time series is then evaluated and converted into flowrate by applying the headloss-flowrate relation reported in Eq. 1:

$$\Delta H_{U.D} = H_U - H_D = R_{U.D} \cdot Q^2 \quad (1)$$

being H (m) the total head, Q (m^3/s) the flowrate, and $R_{U,D}$ (s^2/m^5) the equivalent hydraulic resistance of the pipe segment between sections U and D. It is worth noting that the absence of outflow in the pipe segment between the two measurement sections is a requirement in the application of the methodology. The hydraulic resistance $R_{U,D}$ represents friction and minor losses along the service line, thus depending on pipe length, diameter, material, and layout. Its value can be assessed by (*i*) generating a series of individual water consumption events of known duration, (*ii*) reading the domestic water meter before and after each event to estimate the volume of water used and, thus, the related flowrate. Each obtained flowrate value is then (*iii*) related to the respective observed headloss along the inlet pipe, allowing system resistance $R_{U,D}$ (function of $\Delta H_{U,D}$ and Q) to be assessed through a linear-regression method. It is worth noting that the flowrate obtained by applying the headloss-flowrate relation (Eq. 1) may be affected by a level of uncertainty, mainly related to the accuracy of pressure measurements and the error in the estimation of the hydraulic resistance of the system. Considering this, the flowrate time series is preliminary processed and flowrate values lower than a defined threshold Q_{lim} are set equal to zero.

In the second phase of the methodology, information about water consumption at the level of individual events is obtained. Firstly, a filter is applied to the flowrate time series obtained in the first phase, consisting of an algorithm for signal stabilization (see black line reported in Figure 1b), event isolation, and segmentation of combined events. In greater detail, (*i*) water consumption events, defined as portions of the flowrate time series characterized by continuous and positive values, are identified (i.e. event isolation); (*ii*) a sliding window is applied to stabilize the flowrate signal making up each event (i.e. signal stabilization); (*iii*) the combined events are then segmented into a series of individual events by coupling opening and closing manoeuvres of comparable magnitude (i.e. signal segmentation). Filled areas in Figure 1b represent the result of the application of the event segmentation process to the flowrate time series (black line in Figure 1b).

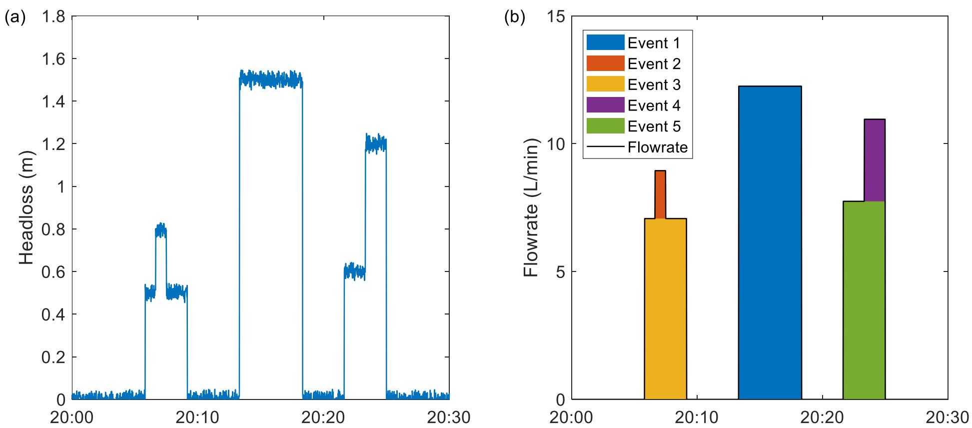

Figure 1. Main steps of the methodology: (a) obtainment of the headloss time series (blue line), (b) conversion into flowrate time series and signal stabilization (black line) and event segmentation (filled areas) over a 30-minute time window.

Subsequently to filter application, all individual events are analysed based on their features (i.e., duration, volume, flowrate, daily frequency of occurrence) and the mean value, μ , and the standard deviation, σ, are determined for each parameter. In addition, all individual events are placed in a duration-volume mesh based on their frequency of occurrence [7]. The results of these analyses can provide pivotal information for event labelling or the application of automated methods for end-use disaggregation and classification [8].

To validate the methodology, pressure data gathered in relation to a real user consisting of a single-family house with a small garden were considered. In particular, the case study consists in a household with three inhabitants supplied by a medium-size WDN located in north-eastern Italy along the Adriatic Sea. The house is provided with a 40-m long domestic plumbing system along which eleven domestic water fixtures are installed (a dishwasher, a washing machine, two showers, two toilets, and five taps). The household was subject to 1-s resolution monitoring of pressure data at two sections of the inlet pipe (with no in-between points of withdrawal) over a period of 6 weeks. In addition, daily readings of the mechanical flowmeter were performed to investigate the daily volume of water supplied to the user.

RESULTS AND DISCUSSION

The application of the proposed methodology to the residential case study considered brought to the results presented and discussed in the following. The (1-s resolution) pressure monitoring at the two sections U and D over a period of 6 weeks led to the obtainment of pressure signals which were converted in headloss time series by accounting for sensor-elevation difference. The latter was estimated in relation to a time window without water consumption in the household. Headloss time series was then converted in flowrate time series by exploiting the relation between headloss and flowrate.

On the one hand, water meter readings revealed that, on average, about 129 L/p/d (liters per person per day) were consumed in the household, while the total water consumption estimated over the 6 weeks monitoring period deviated from the observed one (i.e. that obtained from water-meter readings) on average of less than 3%, confirming the capability of the methodology of effectively providing flowrate time series starting from pressure data. On the other hand, the flowrate time series obtained in the first phase was then subject to the filtering process (i.e. event isolation, signal stabilization and signal segmentation), resulting in over 7,700 individual water consumption events, 18% of which overlapped in time. The characteristics of the above events (i.e. duration, volume, flowrate, daily frequency of occurrence) are then determined and investigated in statistical terms by providing the mean value, μ, and the standard deviation, σ, for each parameter (Table 1).

Table 1. Statistics of water event features.

Parameter	*Unit*	*Mean*	*Standard deviation*
Duration	s	30.6	45.2
Volume	L	2.4	4.7
Flowrate	L/min	4.0	2.1
Frequency	# events/person/day	51.3	22.3

To further explore water-use characteristics, all individual events were included in a duration-volume mesh as a function of (*i*) duration, (*ii*) volume and (*iii*) number of occurrences, resulting in the 3d plot of Figure 2. The latter shows that (*i*) some “fixed” events tend to repeat over time with no changes in duration and volume (e.g. events associated to volumes of 10-12 L and durations of around 45 s), and (*ii*) some others exhibit different volumes and durations, but constant flowrate (e.g. events falling on the slope corresponding to a flowrate of 17 L/min). The first ones are likely relatable to fixed-volume or automated end uses (e.g. toilet flushes, or dishwasher/washing machine withdrawals), whereas the second ones are more likely due to human-controlled end uses, depending on the way in which they are activated (e.g. taps or showers).

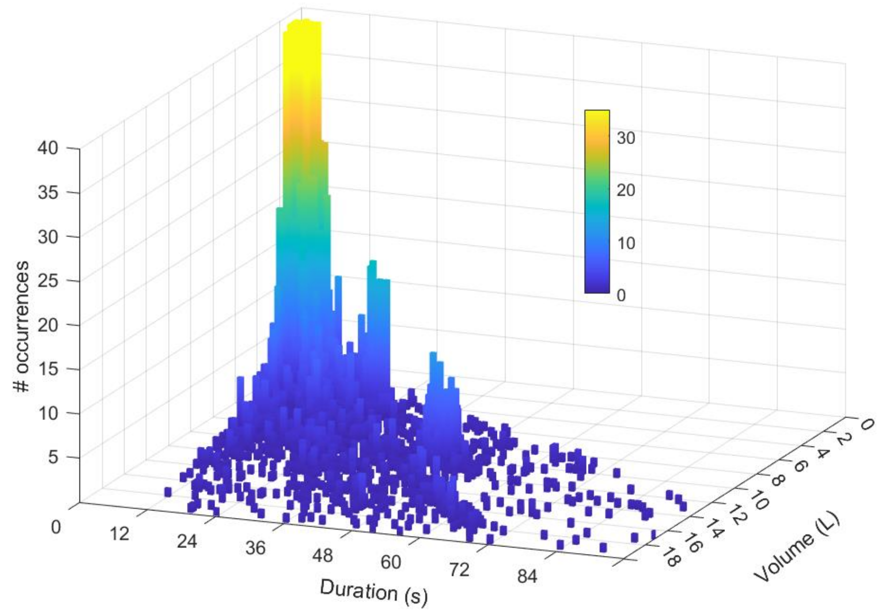

Figure 2. Duration-flowrate mesh where individual events are placed in relation to their frequency of occurrence.

CONCLUSIONS

This study investigates water consumption based on the use of pressure data gathered at two in-line sections of the user inlet pipe, exploiting the fact that differential pressure information coupled with the hydraulic resistance of the segment between the two sections can provide information about the flowrate in the pipe. The outcomes obtained in relation to a real residential case study demonstrate that pressure data acquired with a 1-s time resolution is adequate for accurately estimating the water-consumption time series and provide details about the characteristics of water consumption events. In fact, the application of the filtering process to the flowrate time series effectively led to the identification of individual water consumption events, enabling a detailed analysis of the related features. This information can be combined with additional details on end-use characteristics (e.g. those provided by reports filled in by household inhabitants), allowing the application of automated end-use disaggregation and classification methods to further explore the characteristics of water consumption at the end-use level.

Overall, the methodology was proven to provide insights into water consumption events that can support water utilities in the characterization and modelling of water consumption by exclusively relying on pressure data. Notwithstanding the promising results achieved, two main limitations affect the proposed methodology. First, the installation of at least two pressure sensors along a segment of the household inlet pipe with no in-between outflows is required to discriminate internal water uses from external consumption or changes in network operation. Second, a threshold below which flowrates are not detectable has to be fixed to account for the uncertainty related to field measurements. Future research will evaluate the inclusion of alternative approaches, e.g. techniques of cluster analysis or machine learning, to refine the process of water-event characterization. In addition, method sensitivity to hydraulic-resistance values and time resolution of pressure data will be further tested.

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