

Factors influencing the quality of flow measurements in drinking water systems – lessons learned

M. A. Silva^{1,2}, D. Loureiro¹, A. S. Ribeiro¹, C. Amado²

¹National Laboratory for Civil Engineering, Avenida do Brasil, 101, 1700-066 Lisbon, Portugal

²CEMAT, Instituto Superior Técnico, Avenida Rovisco Pais 1, 1049-001 Lisbon, Portugal

E-mail (corresponding author): mjsilva@lnec.pt; maria.jose.silva@tecnico.ulisboa.pt

Abstract

The flow measurement is essential for drinking water network monitoring. A better knowledge about the flow that is abstracted or pumped to drinking water systems, transferred between water utilities or monitored at the entrance of the subsystems can be achieved through the flow measurement. Nevertheless, this is a topic insufficiently studied. The accuracy can be an excellent parameter to the analysis of the uncertainty sources impact on the measurements obtained from manufacturer's catalogues, and the contributions related with installation, data acquisition, transfer, storage and processing. To understand the influence of these factors in flow data, a set of flowmeters from six water utilities was selected and surveyed in this paper. This paper aims to explore a methodology to analyse the relationship between the uncertainty in daily flow patterns and influential factors. To run the analysis, a robust coefficient of variation was computed for each hour of the workday flow pattern. The most influential factors were: the direction of the flow measurement, year of installation and practices adopted for nominal diameter selection. Although the flow profiles and the elbows are considered in the literature as factors that influence the measurement, in this set of flowmeters, no influence was verified. This exploratory analysis allowed to point out factors related to flowmeter installation that have a significant impact on the quality of the flow measurements.

1. Introduction

The flow measurement has a major role in monitoring water supply systems, providing information about the flow that is abstracted or pumped to drinking water systems, transferred between water utilities or monitoring the entrance of subsystems. In the case of water that is transferred and billed between water utilities, flow measurement becomes a crucial factor for the confidence level between the different agents and the economic sustainability of the service. When flow measurement is used for network monitoring and control of water losses, data quality is needed to ensure that results from well-known approaches (e.g., water balance, minimum night flow analysis) are trustable [1]. However, the quality of flow measurement in water supply systems is a topic insufficiently studied both nationally and internationally [2].

In Portugal, the most relevant drinking water systems were built 20-30 years ago. The population growth projections that did not occur and the firefighting requirements lead to oversize the networks and the majority of existing flowmeters. In fact, in several water utilities, a common practice is still to adopt a flowmeter diameter of the same size of the network pipe diameter,

disregarding the flow pattern and flow velocity best practices for measurement.

An informative indicator to understand the factors that affect flow measurements (usually mentioned as uncertainty sources) and their impact on results is the measurement accuracy. However, the errors indicated in catalogues only mention part of the uncertainty sources that should be taken into account (associated with the measurement equipment). The uncertainty sources related to the installation, data acquisition, transfer, storage and processing are not indicated in the catalogue. Since the measurement inaccuracy is determined by the characteristics which are not in the ideal conditions, the observation of these characteristics is necessary to the study of the factors that influence the measurement. The flow profiles are one of the factors that should be considered [3], as well as the elbows influence, in the proximity of measurement locations, able to affect measurement because of disturbance produced in the flow profiles [4,5]. The effect of different combinations of T-junctions was studied in [4]. Moreover, in [6], the existence of elbows together with the orientation of the flowmeter was considered. These characteristics in an electromagnetic flowmeter may also include, e.g., non-compliance with sizing rules, interference of

electromagnetic fields, intrinsic noise, the resolution associated to the conversion analogic to digital and data processing [7]. This list should not be adopted for non-electromagnetic flowmeters, since different factors of influence are found, e.g., in an ultrasonic or insertion flowmeters [8-10]. In any case, it is evident that the uncertainty of measurement depends on many other factors besides the equipment calibration.

In this paper, a set of flowmeters in use in Portuguese water utilities was characterised to obtain information about adopted practices, characteristics of flowmeters and installation conditions. Data were collected through a survey, in the scope of a collaborative project yield in Portugal, involving 13 water utilities (iperdas.org). Collected data included technical characteristics of the flowmeter, procedures adopted for the quality control, characteristics of recorded information, installation and installation chamber characteristics.

This paper is organised as follows. In Section 2, a description of the survey sent to the water utilities is presented, as well as the methodology used to analyse these data. Section 3 is concerned with the results obtained. Conclusions of this study and future work are presented in Section 4.

2. Methodology

The survey used to collect the information used was divided into five sections: technical characteristics of the flowmeter; quality control of data acquisition, periodic calibration and intermediate verification; characteristics of the data recorded; installation conditions; and installation chamber layout. In addition, flow data was also requested. In the next subsections, a more detailed description of the survey applied is given.

2.1. Technical characteristics of the flowmeter

Technical characteristics include the type of equipment, nominal diameter (DN) of the flowmeter, Q_3/Q_1 ratio, where Q_3 is the permanent flow and Q_1 the minimum flow [11], age, year of installation and condition (good, mean, bad). Moreover, the output mode of the data (analogic or digital) was also requested, as well as if the flowmeter is unidirectional or bidirectional.

2.2. Quality control in flowmeter acquisition, periodic calibration and intermediate verification

In this section, some questions about the flowmeters' calibration practices were surveyed. Examples are the prerequisite of a calibration certificate at the moment of the flowmeter acquisition, the existence of a calibration plan, maintenance and its execution and the periodicity of intermediate verification of parameters.

2.3. Characteristics of the data recorded

Information about the measured values that are recorded is needed, such as the type of value registered (i.e., instantaneous, mean or total value) in order to have a perception of the representativeness of the available data.

Furthermore, water utilities were asked about their control and treatment of data regarding the percentage of missing values and anomalous data.

2.4. Installation conditions

In terms of installation characteristics, the survey starts questioning how the diameter of the flowmeter is chosen, being the options the nominal diameter of the pipe or the mean velocity of flow. Different criteria are also possible to mention. The existence of established procedures to install flowmeters and requirements for technical qualification of persons responsible for installation and maintenance is also inquired. Other technical questions were made, concerning the practical conditions of installation:

- The existence of straight water pipe upstream and downstream of the flowmeter and the respective lengths;
- Levelling of the inlet and outlet pipes and the flowmeter;
- The existence of upstream and downstream valves and distances to the flowmeter;
- The existence of an upstream filter;
- The existence of electric or signal cables nearby.

Information about the water pipe where the flowmeter is installed was also collected, namely, the pipe material, its internal diameter, the pipe condition and the existence of reduction connections to the inlet pipe of the flowmeter. Characteristics related to the power supply and other characteristics specific for electromagnetic flowmeters are also relevant and, therefore, they were also part of the survey. Pulse emitter type, battery autonomy and recover capacity, protection against atmospheric discharges, ground connections of the meter and upstream and downstream connection pipes, and surrounding sources of electromagnetic radiation are some examples.

2.5. Installation chamber layout

The survey also inquired about the existence of some layout characteristics of the installation chamber, namely, access facilities, ventilation, drainage system, a system for flood detection, a system for intrusion detection, UPS/relief and switchboard.

2.6. Flow data

As mentioned previously, flow data recorded was requested. This allows studying the flow velocity and the volume measured in each flow velocity range. The flow time series was also analysed to characterise the flow range. These analyses are of great importance in order to

evaluate the suitability of the flowmeter and to reduce the effect of measurement errors and their uncertainties.

Firstly, a similar period of the flow data was selected from all the flowmeters and the time interval was uniformised. Secondly, flowmeters installed upstream of storage tanks were separated from the analysis because they have patterns that are guided by emptying/filling storage tanks rules. The remaining flowmeters, that are installed in distribution networks, were divided into groups according to the definition of the daily pattern: flow data with a regular daily pattern during the selected period, flow data with irregular patterns, and flow data with an intermediate behaviour. Lastly, in each group, the answers to the survey were analysed to understand if there is a connection between the factors under study and the uncertainty in the daily flow patterns. In order to measure this uncertainty, a robust version of the coefficient of variation of the flow was computed for each hour and flowmeter. Let be $\mathbf{X}_t = \{X_{1t}, X_{2t}, \dots, X_{nt}\}$, where X_{it} represents the value of the flow time series at time t of the working day i ($i = 1, \dots, n; t = 0, \dots, 23$). The Robust Coefficient of Variation (RCV) is defined as:

$$RCV(t) = \frac{MAD(\mathbf{X}_t)}{|\text{Median}(\mathbf{X}_t)|} \quad (1)$$

where MAD is the Median Absolute Deviation, i.e. $MAD(\mathbf{X}_t) = \text{Median}(|X_{it} - \text{Median}(\mathbf{X}_t)|)$.

3. Results

Data from 25 flowmeters from six water utilities were analysed, 88% of which were electromagnetic flowmeters. The variability of DN is significant, with values in a range from 40 mm to 600 mm. However, the most typical DN was of 200 mm. The average age of the flowmeters was approximately equal to 10 years, though the average number of years they are installed is lower than ten years. The condition was indicated as good in 72% of the flowmeters and as average in 12%. The status of the remaining 12% is not known. Relative to the flow direction, 40% of these flowmeters were bidirectional. In metrological terms, the ratio Q_3/Q_1 varied significantly, between 25 and 1 000, although this information is only available for 44% of flowmeters.

In terms of quality control applied to flowmeter acquisition, periodic calibration and intermediate verification, the number of answers was scarce. A calibration certificate at the moment of flowmeter' acquisition was required to 92% flowmeters of the 48% for which this information was available. Nevertheless, calibration plan, maintenance and intermediate verification only exist for 70% of the 40% flowmeters having this information available, with an interval of one or five years.

Regarding the type of measured value recorded, all 52% of flowmeters with answers make records of the total value, being that the only data recorded in only 23% of these flowmeters. The remaining 77% flowmeters also make records of the instantaneous value. Furthermore, the results showed that less than 20% of the water utilities control the flow data received (e.g., data synchronisation, control of the percentage of non-received and anomalous data), although 50% did not answer. This control is considered as critical to ensure data redundancy and to detect problems due to faults in the equipment or the communication systems. Furthermore, it is crucial to ensure that the data history is the most complete as possible (i.e., without missing values).

In terms of flowmeter selection and its installation, there is no information about the criteria used to select 32% flowmeters. In the other 68% of meters, the diameter of 65% was selected based on the diameter of the main. In addition to this criterion, only 18 % of flowmeters were selected also taking into account the consumption history. Only 24% of the flowmeters were selected taking into account the mean flow velocity expected. Not considering the flow conditions increases measurement errors and related uncertainties. Moreover, procedures for the flowmeter installation are not usual, such as requirements for technical qualification of the person responsible by the installation. Only one water utility indicated they have these procedures and requirements.

Considering the 76% of answers about the existence of straight water pipe upstream and downstream of the flowmeter, only 11% (respectively, 5%) of flowmeters do not have a straight water pipe upstream (respectively, downstream). This 5% of meters that do not have a straight water pipe downstream also do not have it upstream. The average length of the upstream straight water pipe is 1,16 m, while the average length of the downstream is 0,84 m. Considering the recommendations in [12], the length of the upstream straight water pipe should be at least five times the DN and the length of the downstream should be at least two times the DN. In practice, only 60% of the flowmeters have an upstream straight pipe of enough length, while 93% have a downstream straight pipe with the adequate length. Regarding the levelling of the inlet and outlet pipes and the flowmeter, all the water utilities that answered this question said that they are levelled. Moreover, almost all or even all water utilities pointed out that there are neither an upstream filter of the meter nor electric or signal cables nearby. Contrariwise, a metering valve upstream or downstream exists in 94% of the installations with answers with a median distance between it and the flowmeter of 1 m.

Regarding the material of network pipes, Figure 1 shows the percentages of types of water pipes material used. The

most typical is the cast iron, followed by the asbestos cement and the steel. The status of water pipe inside was indicated as good in almost all the flowmeters with an answer.

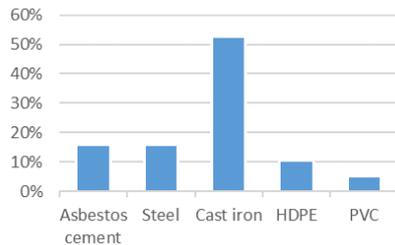


Figure 1: Material of water pipes (HDPE: High-density polyethylene; PVC: Polyvinyl chloride).

Questions about the characteristics related to the electric supply and specific for electromagnetic flowmeters were left blank for most of the cases.

For the analysis of the flow data, a screening was performed to select only the flowmeters with more than three weeks of data. This condition resulted in the selection of only 21 flowmeters, since the other four do not have at least three weeks of data. There is a significant number of flowmeters where the flow velocities are very low (below 0,25 m/s), generating large errors and uncertainties. In 38% of the flowmeters, the volume measured below 0,25 m/s was higher than 40%. Moreover, in 71% of the meters, the volume measured below 0,50 m/s was higher than 40%.

Since the flow data have different time interval steps and the biggest is 60 minutes (Table 1), the time step of all flow time series was uniformised for 60 minutes, allowing to perform a direct comparison of time series. Furthermore, the flow data have different time intervals, as can be seen in Table 1, and data can be available for three years or only for one month. Even when it is available for only one month, it can be different for different flowmeters. Thus, a selection of the time interval to be used in the analysis should be made, trying to harmonise as much as possible the data used. For data with only one month, all the data was considered, regardless of the month in question. For data with more months, June (of 2015, if possible) was the month selected, since it is one of the months more frequent. For flowmeters 17 and 18 and once June was not available, September was selected. The choice of September was made due to its similarity in terms of users' occupation and weather with June, in Portugal. Besides this, these two flowmeters were separated from the general analysis as they were associated with storage tank filling. Their behaviour is very different and cannot be compared with flow data measured in the middle of the network. Figure 2 shows a month of flow data from meter 17, associated FLOMEKO 2019, Lisbon, Portugal

with a storage tank filling. It is possible to observe that, in almost all month, the flow is equal to zero or a maximum closer to 200 m³/h. Although flowmeter 18 is also associated with a storage tank filling, its records show different behaviour. In this case, the flow does not frequently achieve the zero and the maximum values, varying in the middle results. This means that flowmeters associated with storage tanks filling should be analysed separately, due to the different parametrisations of the tanks.

Table 1: Basic characterisation of flow data from each flowmeter (time interval, time step and percentages of missing and null values).

| Flow meter | Time interval | Time step (minutes) | Percentage of missing values | Percentage of null values |
|------------|---------------------|---------------------|------------------------------|---------------------------|
| 1 | 01/01/15 – 27/10/16 | 60 | 0,1% | 2,4% |
| 2 | 01/01/15 – 27/10/16 | 60 | 0,1% | 0,0% |
| 3 | 01/01/15 – 27/10/16 | 60 | 0,1% | 0,0% |
| 4 | 02/07/13 – 30/06/16 | 15 | 0,8% | 0,0(7)% |
| 5 | 02/07/13 – 30/06/16 | 15 | 0,0(6)% | 0,0(2)% |
| 6 | 02/07/13 – 30/06/16 | 15 | 3,7% | 0,0% |
| 7 | 01/01/15 – 31/12/15 | 15 | 0,0(2)% | 0,0% |
| 8 | 01/01/15 – 01/01/16 | 15 | 0,2% | 0,0% |
| 9 | 01/01/15 – 31/12/15 | 15 | 1,2% | 0,0% |
| 10 | 01/01/15 – 31/12/15 | 15 | 0,4% | 0,0% |
| 11 | 17/05/17 – 28/06/17 | 15 | 0,0% | 0,7% |
| 12 | 17/05/17 – 28/06/17 | 15 | 0,0% | 0,1% |
| 13 | 17/05/17 – 28/06/17 | 15 | 0,0% | 0,1% |
| 14 | 16/05/17 – 30/06/17 | 15 | 0,0% | 0,9% |
| 15 | 17/05/17 – 28/06/17 | 15 | 0,0% | 0,0% |
| 16 | 17/05/17 – 28/06/17 | 15 | 0,0% | 2,2% |
| 17 | 01/09/16 – 20/11/16 | 30 | 0,0% | 26,0% |
| 18 | 01/09/16 – 20/11/16 | 30 | 0,0% | 1,7% |
| 19 | 02/11/16 – 28/11/16 | 15 | 0,0% | 0,0(4)% |
| 20 | 01/11/16 – 29/11/16 | 15 | 9,1% | 0,6% |
| 21 | 01/08/16 – 31/08/16 | 15 | 0,0% | 71,6% |

The remaining 19 flowmeters are placed in the network and their behaviour should reproduce the water consumption of the associated network sector. Since there is a daily and weekly seasonality in the water consumption, all working days of the month under analysis were represented in the same graph to allow the

vision of the variation along the month. Weekends were not considered due to the small representativeness. Three groups of flowmeters were identified: the first one is constituted by eight flowmeters with a defined daily pattern (although the pattern can be different from meter to meter); the second one by five flowmeters with a daily pattern more or less defined, but with higher variation; and the last one constituted by six flowmeters with an irregular daily pattern. Figure 3 presents three examples of flowmeters, one from each of the groups, showing the differences between them. Although the flowmeter 1 has outliers, it presents a defined daily pattern with low variation and, consequently, it was included in the first group. The example of a flowmeter that was included in the second group is the 13th meter. A pattern is possible to identify with low values of consumption until 6/7 a.m., followed by an increase of values. Another increase of values occurs at 8/9 p.m. Although this flowmeter has a daily pattern, the variation in each time instant is more significant than in the flowmeter 1. Thus, it was considered in another group. The last group is constituted by flowmeters as the 19th, presented in Figure 3. In this case, there is no daily pattern.

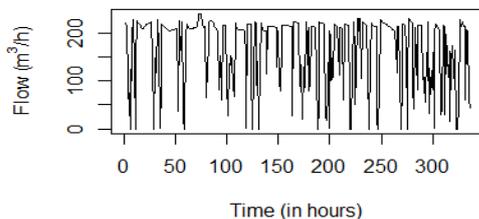


Figure 2: Example of flow data from a storage tank filling of one month.

For the analysis of the factors that influence the uncertainty, the RCV series of the working days was used together with the groups' division. Therefore, the factors that allow a good distinction between the groups are the factors that are influencing the uncertainty of these flowmeters. Flowmeter 21 was excluded from the analysis due to the observation of a high number of zeros that unable the computation of the RCV.

Figure 4 shows the RCV for each flow time series divided by the three groups (three plots) according to the direction of the flowmeter (bidirectional - red or unidirectional - green). A distinction is visible: the flowmeters with less variation are predominantly bidirectional, while the flowmeters with higher variation are predominantly unidirectional.

The same analysis was repeated for each question that was made in the survey. A relation was not obtained for almost all the factors. Although the flowmeters with higher variation were installed predominantly in 2016, it is believed that this relation is not general and is due to

the data used. The sample of flowmeters installed in older years may not be representative, while the number of flowmeters installed in 2016 is high. The practices used to select the meter DN also showed a relationship with the flow data variation. Meters with higher variation have DN's chosen based only on the pipe network DN, while flowmeters with lower variation have DN's chosen based on the mean velocity. Although the flow profiles and the elbows are considered as two factors that influence the measurement quality, in this study, no clear relation between them and the flow data was possible to establish.

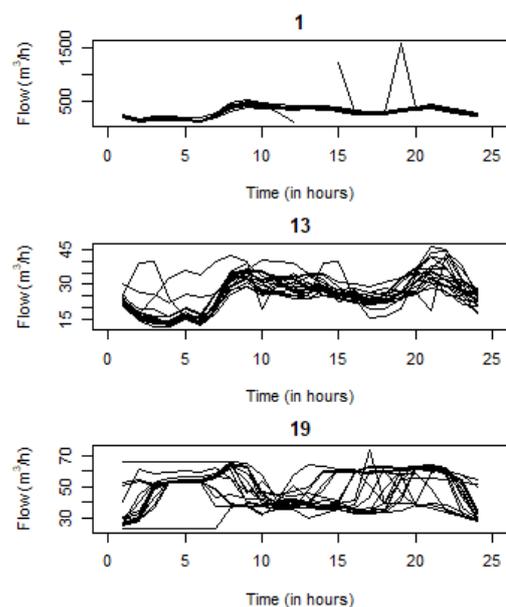


Figure 3: Examples flowmeters from each group (1 – defined daily pattern, 13 – defined daily pattern with more variation, 19 – irregular daily pattern).

4. Conclusion

This paper aimed to explore a methodology to analyse the relationship between the uncertainty in daily flow patterns and influential factors. With this purpose, a set of flowmeters was studied in the context of a national project yield in Portugal. Each water utility answered a survey about the flowmeters selected, in terms of the technical characteristics of the flowmeter, the quality control, the data recorded, the installation characteristics and the flow data.

For an accurate comparison between the flowmeters, the flow data was normalised for a time interval step of one hour and one month was selected. When possible, the month selected was June. Two flowmeters were separated from the analysis, because they are placed before a storage tank and, therefore, the flow data reflects its filling. On the other side, the flowmeters placed in the middle of the network have daily and weekly seasonality. Thus, only the working days were considered, and the

flowmeters were divided into groups according to the definition of their daily patterns. Then, the RCV was computed for each hour of a day for each flowmeter. The analysis of the factors that influence the flow measurement quality was based on the analysis of the RCV. Three factors were identified as influence factors of the measurement quality: the direction of the flow in the flowmeter (unidirectional or bidirectional); the installation year; and the characteristics used to select the flowmeter' DN.

This exploratory analysis allows for understanding the practical impact on the quality of the flow measurements of some factors associated with the installation of flowmeters. The low rate of answers limited a more in-depth analysis. Furthermore, these results indicate that there is still a long way to go when it comes to flow measurement quality. In the future, a more in-depth study of each flowmeter will be done, through the modelling of the daily patterns. Then, the uncertainty in each time instant could be computed. Moreover, in the future, the effect of the time step in the uncertainty can also be analysed using the flow data with small time steps.

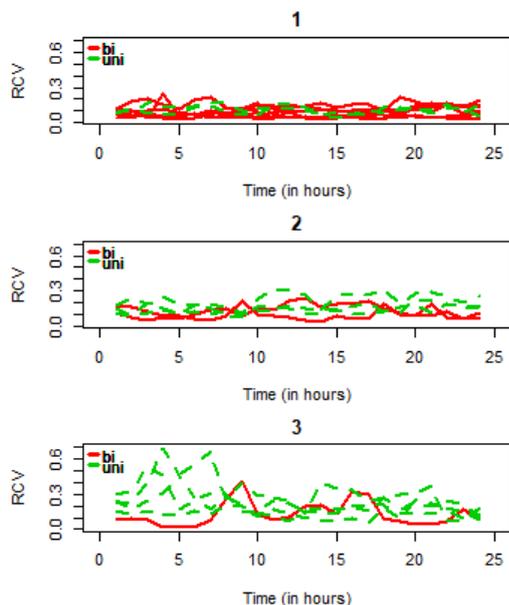


Figure 4: Robust coefficient of variation (RCV) for the three groups according to the flowmeter direction (legend, bi: bidirectional; uni: unidirectional).

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