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Influence of Various Accessories Upstream Large Water Meters

Iñigo Albaina[1] · Iñigo Bidaguren[1] · Urko Izquierdo[1] · G. A. Esteban[1]

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Abstract
The focus of this study is on large flow meters, for which there is limited information due to their large size, making testing and research challenging. This research was conducted to quantify the effects of various accessories located upstream of these meters. Even a small percentage of variation in error can correspond to a significant volume of water. Accurate meters are crucial in many applications that involve large volumes of water as precise flow measurements are necessary for smooth and efficient processes while avoiding costly errors and downtime. Inaccurate large water meters can have far-reaching implications, such as overbilling or underbilling and production inefficiencies, which result in wasted resources and energy. Furthermore, inaccurate flow measurements can lead to environmental consequences as industries must comply with strict regulations regarding wastewater discharge limits. Uncertainty about the economic impact of an accessory installed upstream of a medium-sized water meter leads many water utilities to oversize the meter chambers to mitigate potential negative errors. In this study, six types of elements were tested upstream of ten brand-new water meters from six different manufacturers, constructed using four different metering technologies: single-jet, Woltmann, electromagnetic, and ultrasonic. Each meter unit was tested at five flow rates, ranging from the minimum to overload. The tests were conducted with accessories set in different orientations and distances upstream of the water meters under study. The research shows that the accessories used can cause significant deviations in measuring errors compared to the regular errors found under undisturbed working conditions.

Keywords Large water meter · Single-jet · Woltmann · Electromagnetic · Ultrasonic · Flow measurement

✉ Iñigo Albaina
i.albaina@ehu.eus

Iñigo Bidaguren
i.bidaguren@ehu.eus

Urko Izquierdo
urko.izquierdo@ehu.eus

G. A. Esteban
gustavo.esteban@ehu.eus

[1] Escuela Ingeniería Bilbao, Rafael Moreno Pitxitxi nº 3, 48013 Bilbao, Biscay, Spain

1 Introduction

Water is vital for human survival, and managing it is crucial for sustainable development. As the world's population grows, the demand for water is increasing, straining its availability. Accurate measurement of water usage is essential for effective management. Water meters are indispensable tools for measuring and monitoring water consumption, especially in large-scale applications like industry, commercial buildings, municipalities, and irrigation systems. Large water meters accurately measure and manage high-volume water flow, ensuring efficient and sustainable water resource usage.

Large water meters, despite their importance, have been relatively neglected in academic literature compared to their smaller counterparts. This research gap is notable due to the distinct challenges involved in accurately and reliably measuring large volumes of water, including pressure loss, flow velocity, and the impact of impurities on meter accuracy.

Water losses can be categorized into two main types: physical losses (real) and commercial losses (apparent) (Lambert 2003). Physical losses occur due to leaks in distribution mains, storage tanks, and service connections (Lambert et al. 1999; Arregui et al. 2018). On the other hand, apparent losses result from unauthorized consumption (Lambert and Taylor 2010; Mutikanga et al. 2011), data handling errors (Rizzo 2006; Canto Ríos et al. 2014), and meter inaccuracies (Arregui et al. 2005; Fontanazza et al. 2015; Pacheco et al. 2020). Among these factors, meter inaccuracies play a significant role in apparent losses and are influenced by various factors (Arregui et al. 2005) such as the inherent accuracy of the meter device, consumption profile (Fanner and Thornton 2005; Criminisi et al. 2009; Richards et al. 2010), intermittent supply (Ferrante et al. 2023), blockage by particles, device aging (Arregui et al. 2005; du Plessis and Hoffman 2015), and installation (Burke and Hannah 2010; Albaina et al. 2020). To mitigate metering errors, optimal replacement programs (Van Der Linden 1998; Yazdandoost and Izadi 2018) and in situ testing (Johnson 1999; Seidel and Blumer 1999) are highly recommended.

The influence of installation effects on the calibration of flow meters is a classic problem identified from decades that is studied both experimentally and computationally (Holm et al. 1995; Mickan et al. 1996). The flow distortion is particularly influencing on, but not exclusive of, ultrasonic flow meters (Carlander and Delsing 2000; Kumar et al. 2020), and flow correction factors are investigated to reduce inaccuracies coming from flow asymmetry (Mousavi et al. 2020; Gryshanova et al. 2023). The specific configuration of piping and accessories affecting in a different way the accuracy of each particular water meter is a technological issue that is still worth defining in detail.

While guidelines for installing water meters with different technologies can be found in (Bowen et al. 1991; American Water Works Association (AWWA) 2012; Baker 2016), and specifically for large meters in (American Water Works Association (AWWA) 2011), most accuracy research focuses on domestic meters with nominal diameters ranging from DN13 to DN40 (Neilsen et al. 2011; Ethem Karadirek 2020). This paper will address the accuracy of large water meters, which, despite being fewer in number, account for a significant portion of registered water volumes in supply systems (Jeffcoate and Pond 1989; Van Der Linden 1998; Jackson 2007; Johnson 2007; Roberts and Monks 2015). In many supply systems, a mere five to ten percent of these large meters can contribute to 40 to 50 percent of the total billing (Seidel and Blumer 1999).

This paper investigates errors in large water meter readings caused by upstream flow distortion effects resulting from installation conditions. Various tests were conducted using common elements found in these installations, such as clap valves, Y-filters, convergent and divergent cones, double clap valves, and double elbows. Multiple water meters from different manufacturers and using different technologies (single-jet, Woltmann, electromagnetic, and ultrasonic) were tested to assess their accuracy and the associated effects of over- and under-registration. This research contributes to optimizing water management and ensuring sustainable use of this critical resource.

The novelty of this paper lies in addressing the scarcity of information regarding large water meters used in water process controls and industries. The study provides valuable insights into the significance of accurate measurements in these meters for applications with high water volume usage. It explores the impact of upstream accessories on meter accuracy, considering the challenges posed by the large size of the meters and the limited available data. By focusing on this specific aspect, the research fills a gap in the understanding of industrial flow meters and their behaviour in real-world conditions. The findings contribute to the field of process control engineering by highlighting the importance of precise measurements for achieving efficiency, profitability, and sustainability in various sectors.

2 Materials and Methods

2.1 Test Bench and Testing Procedure/Protocol

The accuracy tests of the meters were conducted using a fully automated gravimetric test bench designed for testing and calibrating water meters and flowmeters of various sizes, ranging from DN13 to DN150. This facility operates as an Authorized Metrological Verification Body for the Spanish Government and holds certification from the "Entidad Nacional de Acreditación (ENAC)"—the agency appointed by the Spanish government to serve as the National Accreditation Body in accordance with European Regulation (EC) No. 765/2008 (Regulation (EC) No 765/2008 of the European Parliament and of the Council).

The testing procedure used during the laboratory tests met all the requirements defined in (ISO 4064-2:2014b). The complete layout of the test bench, while further information on the test bench's key features, additional details, and testing protocol steps can be found in (Albaina 2016; Albaina et al. 2020, 2023).

2.2 Meter Sample Description

This research primarily focuses on testing technologies commonly used for measuring water consumption in large customers. However, each measuring technology is distinct and has specific requirements and sensitivities to flow profile distortions. Furthermore, the relationship between flow rate, velocity distribution, and the sensing element's performance is complex, resulting in non-linear effects on measuring errors caused by flow distortions. Consequently, the impact of valves, pipe fittings, or other elements installed upstream of a meter cannot be quantified in advance and can only be evaluated qualitatively. All the meters tested were at least classified as T30, which ranges from 0.1 to 30 °C. More detailed information about the characteristics of each meter can be found in (Albaina 2016; Albaina et al. 2020). Our facility also operates within that temperature range, so we are not capable of obtaining experimental data beyond that range, which we consider to be the most common in water utilities.

2.3 Accessories Used to Produce Flow Profile Distortions

Six types of accessories were used to induce flow disturbances in the study: Clap Valve, Convergent and Divergent Cone, Y-filter, Double Elbow, and Double Clap Valve. The Clap Valve tests focused on its normal operating position. The Convergent and Divergent Cone tests explored situations with variations in diameter between the supply pipe and the meter. The Y-filter tests considered the degree of clogging, with tests conducted using both "clean" and "clogged" filters. The Double Elbow tests involved placing two 90º elbows consecutively, both in vertical and horizontal positions. Similarly, for the Double Clap Valve, tests were conducted in both vertical and horizontal positions to evaluate the different effects on the measuring elements.

2.4 Flow Rates Tested

The study obtained the measuring error for each water meter at five different flow rates. The selection of these flow rates aimed to provide a better representation of the actual performance of water meters in the field. Often, the flow rates of water consumption do not align with the normalized flow rates that define the meter's metrological class. Additionally, the lower end of the range for meters with the best metrological class has closely spaced minimum and transition flow rates, leaving a significant portion of the range without measuring error information. Consequently, the chosen flow rates for each meter size were not based on standardized values but focused on covering as much of the measuring range as possible. This approach increased redundancy and facilitated the identification of potential inconsistencies in the results. Detailed information on the test flow rates for each meter type can be found in (Albaina 2016; Albaina et al. 2020).

2.5 Uncertainity of the Tests

The overall uncertainty of the tests considered the reading resolution of each meter's totalized volume, the characteristics of the testing equipment, and the reference weighing tank used for each flow rate and meter type. The uncertainty is particularly high at low flow rates due to the relationship between the reading resolution of flow meters, which can be as high as one liter for the WEH65, and the total volume of the gravimetric tank (TNK3) used for those flow rates. The uncertainty calculations followed the recommendations provided in (EURAMET 2015, 2018; ISO 4064-1:2014a; ISO 4185:1980; ISO 5168:2005). Detailed information about the uncertainty for each meter and flow rate can be found in (Albaina 2016).

2.6 Test Program Description

The objective of this study was to assess how large water meters respond to flow disturbances caused by upstream accessories. The evaluation considered various flow rates within the meter's measuring range and took into account its specific metrological class.

The test program was designed based on the hypothesis that the proximity of an accessory to the meter would increase the disturbance reaching the meter and consequently affect its measuring error. It was assumed that if a directly connected accessory did not cause significant disturbance, installing a straight section of pipe between the valve and the meter would have a minimal impact on the meter's error.

Each meter underwent an initial test where the accessory was connected directly to the meter (0D upstream). The results of this test were compared to the meter's reference error curve, which was established under ideal conditions with more than 10 diameters of straight pipe upstream. If the error curves showed no significant differences, the test for that specific situation was concluded.

The decision to continue or terminate the tests depended on the level of uncertainty associated with each test and the maximum allowable change in error. Generally, if the variation from the reference error curve was within ± 5% between flow rates Qa and Qb (the interval with the highest uncertainty), and within ± 2% for the remaining flow rates (often coinciding with the meter's class limits), it was considered that no significant differences existed, and the test could be stopped.

In cases where significant differences were observed, a new test was conducted with an additional three-diameter-length straight pipe section (3D) placed between the meter and the accessory. The same criteria were used to determine whether to continue or terminate the test under the new working conditions. Straight pipe sections of lengths 0D, 3D, 5D, and 10D were considered, assuming that distances longer than 10D would sufficiently mitigate any flow disturbance. It should be noted that most of the meters tested in this study were classified as U0-D0 meters in terms of their sensitivity to flow disturbances.

3 Results

The researchers used box-whisker plots, which helped identify the interquartile interval, mean, median, and extreme values, to visualize the variability and potential bias in the measurement errors of various metering technologies at different flow rates. They found that the impact of an upstream distortion on meter performance is not solely determined by the technology or type of upstream accessory. Instead, there can be significant variation in the effect among meters of the same technology when exposed to the same flow profile distortion.

The study conducted in a controlled laboratory environment measured errors in different metering technologies at various flow rates. The results can only be analysed qualitatively due to significant variations in behaviour between different disturbances and meter technologies. The study emphasizes the importance of meter technology and construction, as they directly impact meter accuracy. Even meters of the same technology can exhibit different behaviours owing to their unique designs.

Therefore, it is not appropriate to generalize conclusions about the effect of a particular flow distortion to other meter brands within the same technology. Each meter brand may respond differently, so individual characteristics must be considered when assessing accuracy.

3.1 Reference Error of the Meters Under Examination

The individual reference error curve of the meters, representing the percentage error when no flow distortion is present, can be found in (Bowen et al. 1991). These results are included in a consolidated box-whisker plot in each figure for comparison. The data series is labelled as "Error (%)" and is depicted in red colour.

3.2 Measuring Errors Caused by a Clap Valve

This section focuses on the performance of different water meter types with an upstream clap valve. The study examines various clap valve settings and distances from the tested meter. It's observed that the clap valve causes minor flow distortions, primarily leading to under-counting for class B water meters. Figure 1 (top left) shows an overall under-registration effect, more pronounced at lower flow rates than higher ones, with an estimated average under-registration of 8%. Though seemingly insignificant, for meters with a diameter greater than 50, this leads to a substantial volume of unquantified water in cubic meters (m^3).

Figure 1 (top right) summarizes test results for water meters with different lengths of upstream straight pipe. Surprisingly, little difference is observed between 0D, 3D, and 5D, mainly due to consistent under-registration even at 10D for the same water meter. The behaviour varies significantly among different meter technologies (Fig. 1, bottom left). Some single-jet meters show slight under-registration, while certain Woltmann meters exhibit more pronounced under-registration. However, it is concluded that the observed differences are not solely due to the technology used but also depend on the specific construction characteristics of the meter.

The next section individually analyses the meters in the presence of a clap valve. Overall, all single-jet meters show a slight under-registration compared to the reference curve, especially at low flows. However, these differences fall within acceptable limits and are not considered significant. The CES65 meter displays some under-registration, which improves when a straight section of 3D is introduced, bringing it within the acceptable range. On the other hand, the WDW65 meter exhibits under-registration even with a 10-diameter straight section, and there is an anomalous point with a 10% over-registration at the minimum flow. Additionally, the second flow of the ESS100 meter shows an error close to -5%, likely due to its electronics (refer to Fig. 1, bottom right).

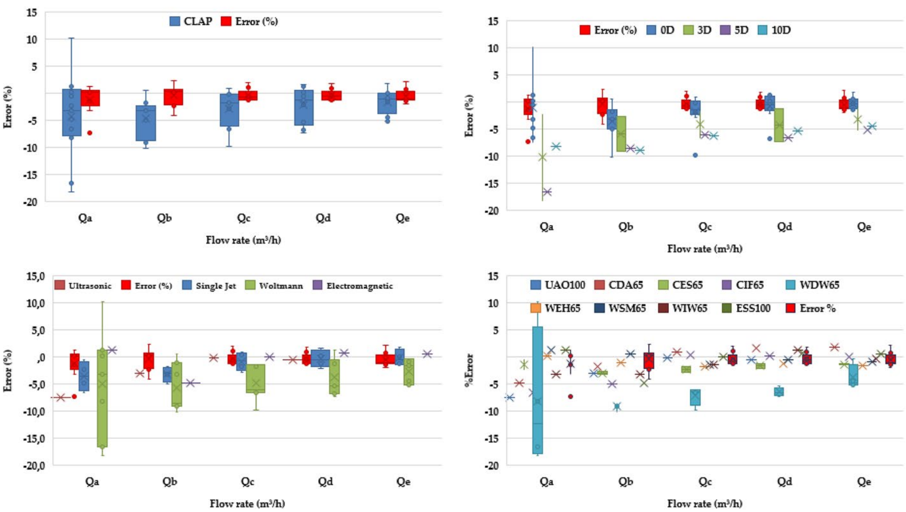

Fig. 1 Clap valve. Top-left: Overall View. Top-right: Diameters of straight pipe upstream. Bottom-left: Different technologies of water meters. Bottom-right: Individual test results for each flow meter

3.3 Measuring Errors Caused by a Y-filter

Figure 2 (top left) summarizes Y-filter test results, displaying potential situations where curves fall outside the allowed range, resulting in both over and under-registration, with variations up to ± 15%. The distinction between clean and clogged filters is minimal, with only two over-registration points at small flows observed in one of the meters (Fig. 2, top right). However, there is no over-registration with the clean filter.

Lengthening the upstream straight section of pipe shows improvements in the curves for all tested meters. However, for some models, the improvements are minimal, requiring up to 10 diameters to shift the under-registration from -10% to -5% (Fig. 2, middle left).

Figure 2 (middle right) shows that single-jet meters are minimally affected by the filter, displaying slight under-registration. Woltmann meters mainly experience under-registration, but some over-registration also appears. Ultrasonic meters show a slight under-registration, even with the clean filter. However, these small differences, particularly at low flows, might be attributed to the uncertainty in the meter reading. Electromagnetic meters display minor variations in both directions without a clear trend.

Among the specific meters, CDA65 shows slight under-registration within acceptable limits, with no significant change between tests conducted at 0D and 3D. WDW65 is most

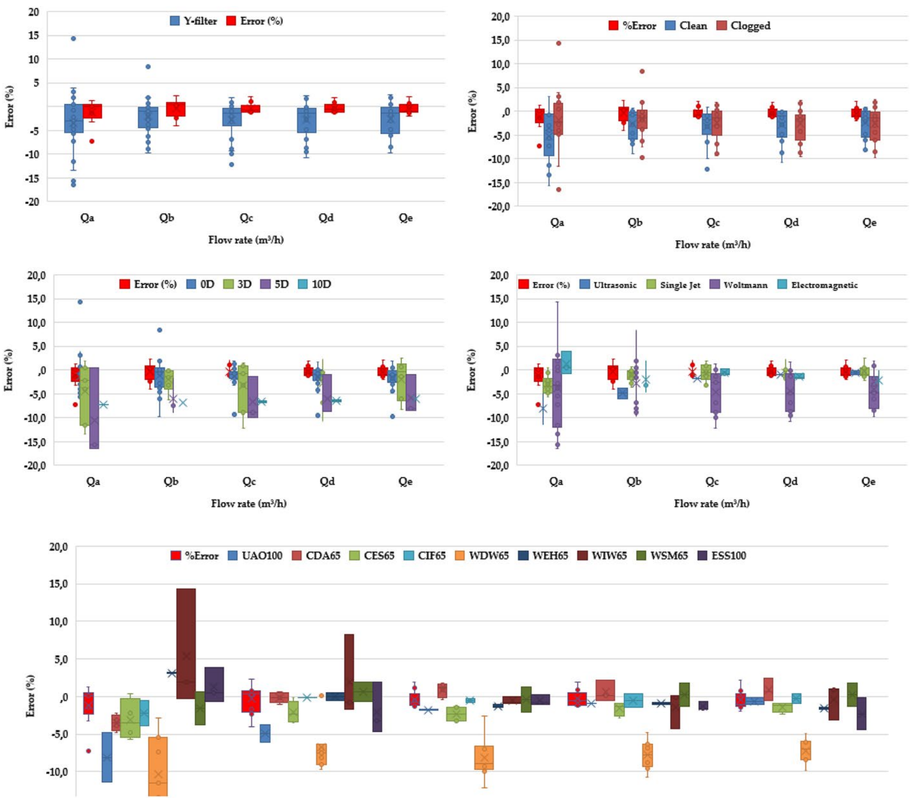

Fig. 2 Y-filter. Top-left: Overall View. Top-right: Clean and Clogged arrangement. Middle-left: Diameters of straight pipe upstream. Middle -right: Different technologies of water meters. Bottom: Individual test results for each flow meter

affected, exhibiting consistent under-registration with both the clean and clogged filters. Notably, there is no significant improvement until a straight length of 10D is introduced upstream. CES65 experiences slight under-registration with no clear improvement relationship as the straight section of pipe upstream is increased. WEH65, CIF65, WSM65, and UAO100 are not affected by either situation tested. In WIW65, an over-registration is observed at small flows, significantly improving the curve when a straight length of 3D is introduced upstream (see Fig. 2, bottom).

3.4 Measuring Errors Caused by a Convergent Cone

Based on the meter group results, it is concluded that, except for one meter, the others are not significantly affected by the arrangement placed immediately upstream of the meter (Fig. 3, top left and right). Regarding technology, it is observed that a convergent cone does not affect Woltmann-type meters. However, one specific Woltmann meter is affected, while the other two are not. This suggests that the observed effect is likely due to the specific construction characteristics rather than the operating technology itself (Fig. 3, bottom left).

The WDW65 meter is the only one influenced by the placement of the convergent cone, causing an under-counting of up to 12% compared to the actual volume. However, when a straight section of 3 diameters of pipe is introduced upstream of the meter, an improvement is observed, leading to a curve similar to the reference curve (Fig. 3, bottom right).

3.5 Measuring Errors Caused by a Divergent Cone

Similar to the previous case of the convergent cone, this arrangement only affects the WDW65 meter, but in the opposite direction, resulting in an overcount of approximately 5% (Fig. 4, top left and right). However, when a straight section of 3 pipe diameters is

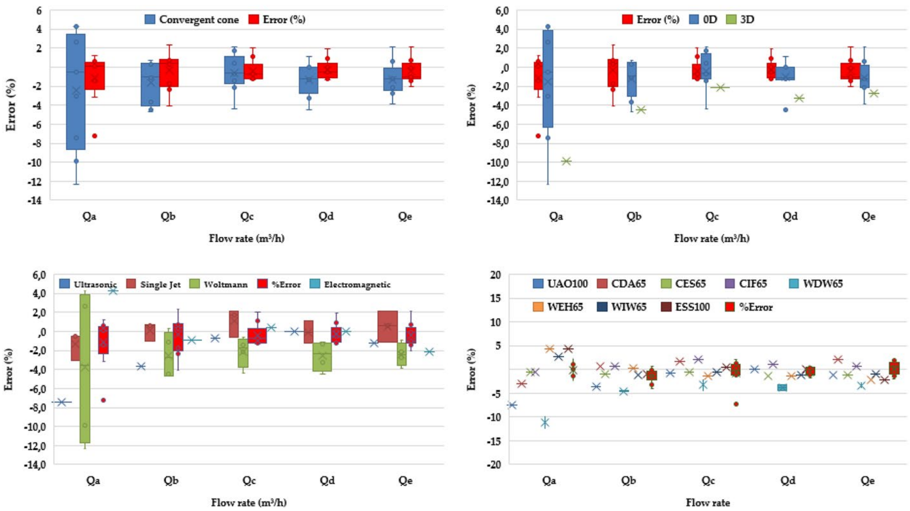

Fig. 3 Convergent cone. Top-left: Overall View. Top-right: Diameters of straight pipe upstream. Bottom-left: Different technologies of water meters. Bottom-right: Individual test results for each flow meter

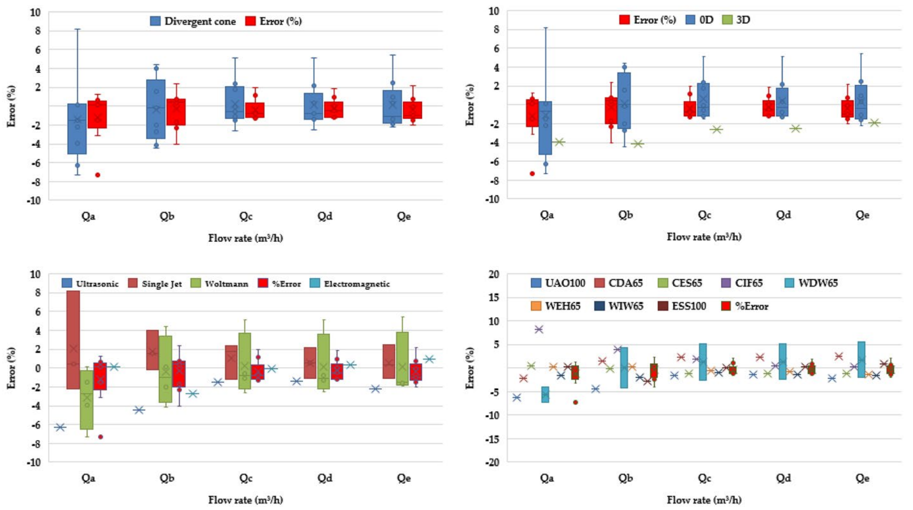

Fig. 4 Divergent cone. Top-left: Overall View. Top-right: Diameters of straight pipe upstream. Bottom-left: Different technologies of water meters. Bottom-right: Individual test results for each flow meter

added between the meter and the accessory, a significant improvement is observed, leading to a curve similar to the one obtained without any disturbing element.

Regarding technology, the same conclusion is drawn as in the previous case, as the Woltmann-type meters are not affected except for one specific meter. This suggests that the effect is likely due to the construction characteristics of that particular meter rather than the operating technology (Fig. 4, bottom right).

The discrepancies in the points at minimum flow for the Woltmann-type meters, compared to their reference curves, are more likely attributed to the higher uncertainty in the reading of these points. The only meter that shows an impact is the WDW65 with an overcount of approximately 5% (Fig. 4, bottom left).

3.6 Measuring Errors Caused by a Double Elbow

Upon observing the results of the water meter tests, it can be concluded that, except for a few meters, the majority are not significantly affected by the arrangement placed immediately upstream. Additionally, there are no notable differences between the vertical and horizontal arrangements on a global scale, although individual differences are analysed further.

As straight sections of pipe are added between the meter and the accessory, there is an overall improvement in the error curves that fall outside the control range. However, this improvement is not substantial for one of the technologies (Fig. 5, top and middle left).

Neither of the double elbow arrangements affects the single-jet meters or the Woltmann-type meters, except for one specific meter. This suggests that the observed effect is likely due to the construction characteristics of that particular meter rather than the operating technology (Fig. 5, middle right).

The WDW65 meter is affected by the placement of a double elbow, resulting in an undercount of up to 12% compared to the actual volume. Both horizontal and vertical arrangements show practically the same curves, with the vertical arrangement performing slightly better. Only when a straight section of 5 pipe diameters is added does the curve fall

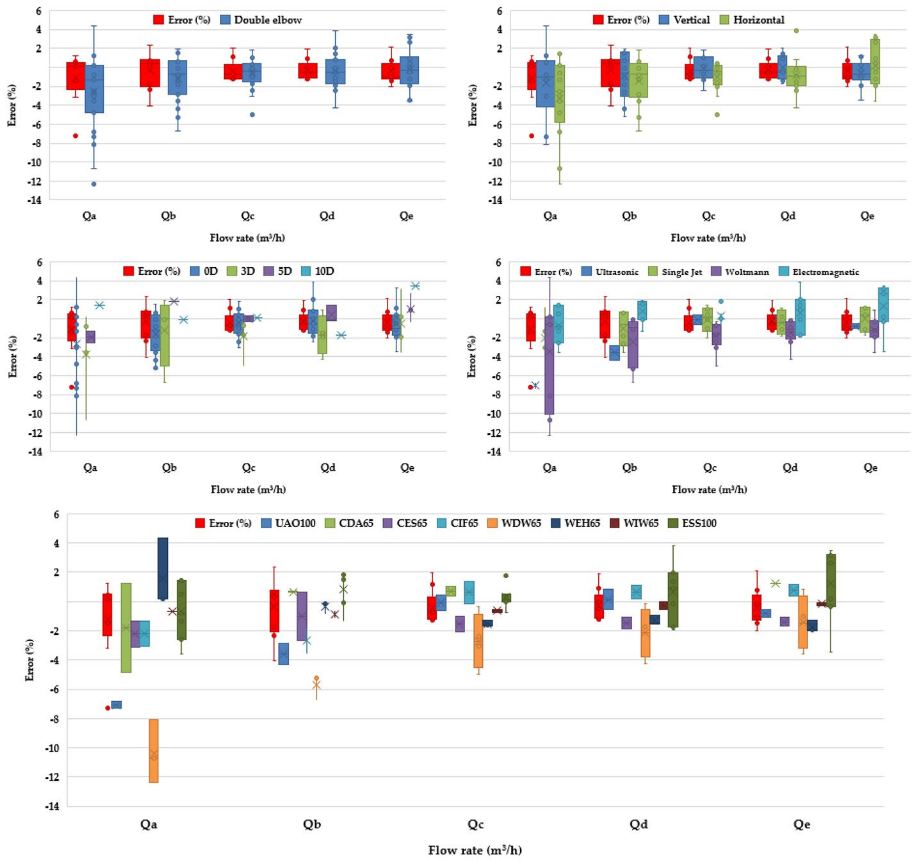

Fig. 5 Double elbow. Top-left: Overall View. Top-right: Horizontal and Vertical arrangement. Middle-left: Diameters of straight pipe upstream. Middle -right: Different technologies of water meters. Bottom: Individual test results for each flow meter

within the control range. Interestingly, the curve performs better at 0D than at 3D, indicating that the low reproducibility of the WDW65 meter may have a significant influence. The ESS100 meter is also affected, but with deviations that do not exceed 4% in absolute value.

When comparing the horizontal and vertical arrangements, the horizontal arrangement shows a worse trend compared to the vertical one when straight sections of pipe are placed between the double elbow and the meter. In the vertical arrangement, the anomaly in the maximum flow point of the ESS100 meter is corrected with straight sections of 3 diameters and above. However, in the horizontal arrangement, the point outside the range for the same meter persists even with a straight section of 10 diameters upstream (Fig. 5, bottom).

3.7 Measuring Errors Caused by a Double Clap Valve

Overall, the analysis reveals that this type of accessory has a significant impact on both overcounting and undercounting, particularly at small flow rates. There are no notable differences between the horizontal and vertical arrangements of the accessory.

Regarding the straight sections of pipe necessary to mitigate the effects of the accessory, several meters require 5 to 10 pipe diameters to recover the profile of the reference curve (Fig. 6, top and middle left).

Both Woltmann and single-jet meters are affected in terms of meter technology. The variation in the curve is more pronounced for Woltmann meters compared to single-jet meters, particularly at low flow rates. For single-jet meters, the accessory arrangement leads to overcounting in the horizontal position and undercounting in the vertical position at low flow rates (Fig. 6, middle right).

Based on Fig. 6 (bottom), the following conclusions can be drawn:

- CDA65: Overcounting in small flow for the horizontal position and undercounting for the vertical position.
- WDW65: No significant variation between horizontal and vertical positions; overcounting at the minimum flow and undercounting for the rest. Improves with the introduction of straight sections of pipe, resulting in undercounting.
- CES65: Undercounting only in small flow for the vertical position.

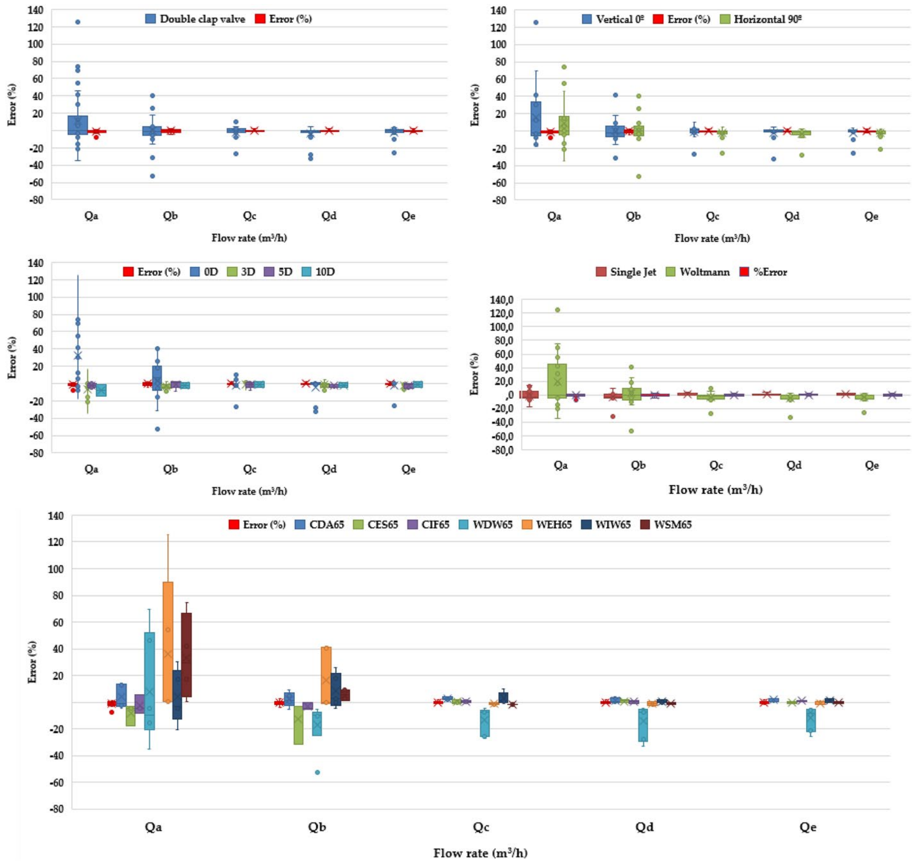

Fig. 6 Double clap. Top-left: Overall View. Top-right: Horizontal and Vertical arrangement. Middle-left: Diameters of straight pipe upstream. Middle -right: Different technologies of water meters. Bottom: Individual test results for each flow meter

– WEH65: Overcounting in small flow for both positions.
– CIF65: Overcounting in small flow for the horizontal position and undercounting for the vertical position.
– WSM65: Overcounting in small flow for both positions.

3.8 Summary

Table 1 summarizes the main conclusions of the study on the influence of disturbances on meter errors. The table provides a rough indication of how much the error of a meter may deviate under different disturbances. The figures in the table are qualitative measures, as the actual influence can vary depending on flow conditions, meter design, and severity of

Table 1 Accessories placed upstream different water meter technologies

Accessory	Technology	Config	0D	3D	5D
Clap valve	Single-Jet		✓		
	Woltmann		✓		
	Ultrasonic		✓		
	Electromagnetic		✓		
Y-filter	Single-Jet	clean	✓		
		clogged	✓		
	Woltmann	clean	✓		
		clogged	✓		
	Ultrasonic	clean	✓		
		clogged	✓		
	Electromagnetic	clean	✓		
		clogged		-6%	✓
Convergent cone	Single-Jet		✓		
	Woltmann		✓		
	Ultrasonic		✓		
	Electromagnetic		✓		
Divergent cone	Single-Jet		✓		
	Woltmann		✓		
	Ultrasonic		✓		
	Electromagnetic		✓		
Double elbow	Single-Jet	V 0°	✓		
		H 90°	✓		
	Woltmann	V 0°	✓		
		H 90°	✓		
	Ultrasonic	V 0°	✓		
		H 90°	✓		
	Electromagnetic	V 0°	-4%	✓	
		H 90°	+3%	✓	
Double Clap valve	Single-Jet	V 0°	±30%	✓	
		H 90°	±14%	✓	
	Woltmann	V 0°	±70%	±20%	✓
		H 90°	±70%	±20%	✓

the disturbance. Blank spaces indicate no expected influence, while a checkmark indicates that a particular disturbance did not significantly affect meter errors in the tests.

4 Conclusions

Based on the test results and considering the previous hypotheses, the following conclusions can be drawn:

- For nominal diameters 65–100 mm, the length of straight pipe upstream of meters plays a significant role in reducing the impact of flow disturbances. The required length depends on meter technology.
- Measuring technologies differ in their sensitivity to flow disturbances. Even within the same technology, variations in design can significantly affect the meter's error under upstream flow distortion.
- Clap valves and convergent/divergent cones do not affect any of the tested meter technologies. Single-jet meters are affected by double clap valves, while Woltmann meters are affected by double flap check valves. Regarding filters, based on the testing criteria and hypotheses used, the Woltmann technology is not affected, but when a meter with its original filter was tested, the error curve rose 15% above the actual value. This suggests that a certain level of filter clogging may lead to incorrect readings and a proportional increase in error. Both horizontal and vertical double elbows and dirty filters affect electromagnetic meters, but the deviation from the error curve is minimal in the latter cases.
- The objective of this work is to analyse how flow disturbances caused by different fittings impact the readings of various types of meters. In this analysis, it is important to consider the reproducibility of the tested meters, which refers to their ability to consistently produce the same result for a given situation. The reproducibility is influenced by factors such as the technology and construction quality of the meters.

In the case of the WDW65 meter, it has been observed during multiple tests that its behaviour does not align with expectations or with other meters of the same technology. Although the results indicate that the WDW65 meter is affected by almost all the fittings, the deviations observed are believed to be a result of its inherent lack of reproducibility, rather than solely due to flow disturbances.

With this understanding, a corrected table has been prepared, omitting adverse results that were observed only at small flows, typically at the minimum flow rate.

- Although most U0 meters are insensitive to flow disturbances, several were affected by upstream accessories. This highlights the importance of considering installation conditions when using U0 meters.

Based on the data, it is beneficial for both customers and water utilities to carefully inspect the installation conditions of medium and large water meters. Incorrect installations can result in measuring errors that impact both parties financially. Customers may receive higher bills than their actual consumption, which can be particularly damaging when the water utility has high tariff rates. On the utility side, this study demonstrates that under certain conditions, meters can significantly under-register.

This work is limited to approved cold water meters for operation in accordance with ISO 4064-2:2018. The use of other types of fluids or temperature ranges exceeding 30 °C is beyond the scope of this work.

Once the problem addressed in this work is identified, a recommended solution involves the installation of a sufficiently long straight section of pipe between the fitting and the meter.

However, limited space often makes this solution challenging and costly. Therefore, finding an alternative solution is important. One possibility is to explore the impact of placing these fittings downstream, which could optimize the available space. We are currently working in this direction.

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Availability of Data and Materials The data that support the results of this study are available from the corresponding author, Iñigo Albaina, upon reasonable request.

Declarations

Ethical Approval Not applicable.

Consent to Participate All authors consented to participate.

Consent to Publish All authors consented to publish.

Competing Interests The authors have no relevant financial or non-financial interests to disclose.

References

Albaina I (2016) Análisis de la incidencia de las condiciones de instalación sobre el error de medición de los contadores de agua no-domésticos y su repercusión económica. PhD Thesis, Universidad del País Vasco/Euskal Herriko Unibertsitatea

Albaina I, Arregui FJ, Bidaguren-Alday C, Bidaguren I (2020) Influence of butterfly and gate valves upstream large water meters. Water (Switzerland) 12. https://doi.org/10.3390/W12092563

Albaina I, Esteban GA, Bidaguren I, Izquierdo U (2023) New switching gate diverter valve for large flow measurement systems. Flow Meas Instrum 93:102425. https://doi.org/10.1016/j.flowmeasinst.2023.102425

American Water Works Association (AWWA) (2012) Water Meters-Selection, Installation, Testing, and Maintenance. AWWA Manual M6
American Water Works Association (AWWA) (2011) Flowmeters in Water Supply, 2nd Ed. (M33)
Arregui FJ, Cabrera E, García-Serra J (2005) Key factors affecting water meter accuracy. In: Proc. Leakage. pp 1–10
Arregui FJ, Cobacho R, Soriano J, Jimenez-Redal R (2018) Calculation proposal for the economic level of apparent losses (ELAL) in a water supply system. Water (Switzerland) 10. https://doi.org/10.3390/w10121809
Baker RC (2016) Flow measurement handbook: Industrial designs, operating principles, performance, and applications. Cambridge University Press
Bowen PT, Harp JF, Entwistle JM Jr, Shoeleh M (1991) Evaluating residential water meter performance. AwwaRF and AWWA, Denver
Burke L, Hannah C (2010) Improve Accuracy With Proper Water Meter Installation. Opflow 36:18–21. https://doi.org/10.1002/j.1551-8701.2010.tb02351.x
Canto Ríos J, Santos-Tellez RU, Hansen Rodríguez P et al (2014) Methodology for the identification of apparent losses in water distribution networks. Procedia Eng 70:238–247. https://doi.org/10.1016/j.proeng.2014.02.027
Carlander C, Delsing J (2000) Installation effects on an ultrasonic flow meter with implications for self diagnostics. Flow Meas Instrum 11:109–122. https://doi.org/10.1016/S0955-5986(00)00005-4
Criminisi A, Fontanazza CM, Freni G, La Loggia G (2009) Evaluation of the apparent losses caused by water meter under-registration in intermittent water supply. Water Sci Technol 60:2373–2382. https://doi.org/10.2166/wst.2009.423
du Plessis JA, Hoffman JJ (2015) Domestic Water Meter Accuracy Water Soc III(1):197–208. https://doi.org/10.2495/ws150171
Ethem Karadirek I (2020) An experimental analysis on accuracy of customer water meters under various flow rates and water pressures. J Water Supply Res Technol - AQUA 69:18–27. https://doi.org/10.2166/aqua.2019.031
EURAMET (2015) Guidelines on the calibration of non-automatic weighing instruments, 4th edn. EURAMET cg-18
EURAMET (2018) Guidelines on the determination of uncertainty in gravimetric, vol calibration, 3rd edn. EURAMET cg-19
Fanner P, Thornton J (2005) The importance of real loss component analysis for determining the correct intervention strategy. In: Proceedings of the IWA Specialised Conference "Leakage 2005." pp 1–11
Ferrante M, Rogers D, Mugabi J, Casinini F (2023) Addressing water meter inaccuracies caused by intermittent water supply: A laboratory investigation of remedial measures. Water Resour Manag. https://doi.org/10.1007/s11269-023-03532-x
Fontanazza CM, Notaro V, Puleo V, Freni G (2015) The apparent losses due to metering errors: a proactive approach to predict losses and schedule maintenance. Urban Water J 12:229–239. https://doi.org/10.1080/1573062X.2014.882363
Gryshanova I, Rak A, Korobko I (2023) The investigation of the correction factor for ultrasonic flow meters. Measurement 219:113326. https://doi.org/10.1016/j.measurement.2023.113326
Holm M, Stang J, Delsing J (1995) Simulation of flow meter calibration factors for various installation effects. Measurement 15:235–244. https://doi.org/10.1016/0263-2241(95)00007-8
ISO 4064-1:2014 Water meters for cold potable water and hot water - Part 1: Metrological and technical requirements. ISO, Geneva, Switzerland
ISO 4064-2:2014 Water meters for cold potable water and hot water - Part 2: Test methods. ISO, Geneva, Switzerland
ISO 4185:1980 Measurement of liquid flow in closed conduits — Weighing method. ISO, Geneva, Switzerland
ISO 5168:2005 Measurement of fluid flow — Procedures for the evaluation of uncertainties. ISO, Geneva, Switzerland
Jackson J (2007) Why smart managers should insist on - And maximize revenue from - Large meter testing. J Am Water Work Assoc 99:30–35. https://doi.org/10.1002/j.1551-8833.2007.tb07865.x
Jeffcoate P, Pond R (1989) Large water meters: guidelines for selection, testing, and maintenance. World Bank Technical Paper (ISSN 0253-7494; no. 111; ISBN 0-8213-1375-4)
Johnson EH (1999) In situ calibration of large water meters. Water SA 25:123–135
Johnson EH (2007) Estimating uncertainty of flow measurement for the in-situ calibration of large water meters. Australas J Water Resour 11:41–52. https://doi.org/10.1080/13241583.2007.11465310

Kumar K, Komble S, Thorat S et al (2020) Validation of installation effects of an ultrasonic flow meter on butterfly valve using numerical analysis. Mater Today Proc 46:6692–6699. https://doi.org/10.1016/j.matpr.2021.04.164

Lambert A (2003) Assessing non-revenue water and its components: A practical approach. Water 21 c:50–51

Lambert A, Taylor R (2010) Water loss guidelines. Water New Zealand. The New Zealand Water & Wastes Association. Wairoa Aotearoa

Lambert AO, Brown TG, Takizawa M, Weimer D (1999) A review of performance indicators for real losses from water supply systems. J Water Supply Res Technol - AQUA 48:227–237. https://doi.org/10.2166/aqua.1999.0025

Mickan B, Wendt G, Kramer R, Dopheide D (1996) Systematic investigation of pipe flows and installation effects using laser Doppler anemometry - Part II. The effect of disturbed flow profiles on turbine gas meters - A describing empirical model. Flow Meas Instrum 7:151–160. https://doi.org/10.1016/S0955-5986(97)00010-1

Mousavi SF, Hashemabadi SH, Jamali J (2020) Calculation of geometric flow profile correction factor for ultrasonic flow meter using semi-3D simulation technique. Ultrasonics 106:106165. https://doi.org/10.1016/j.ultras.2020.106165

Mutikanga HE, Sharma SK, Vairavamoorthy K (2011) Assessment of apparent losses in urban water systems. Water Environ J 25:327–335. https://doi.org/10.1111/j.1747-6593.2010.00225.x

Neilsen MA, Barfuss SL, Johnson MC (2011) Off-the-shelf accuracies of residential water meters. J Am Water Works Assoc 103:48–55. https://doi.org/10.1002/j.1551-8833.2011.tb11531.x

Pacheco VMF, Valdés RE, Gil EB et al (2020) Techno-economic analysis of residential water meters: A practical example. Water Resour Manag 34:2471–2484. https://doi.org/10.1007/s11269-020-02564-x

Richards GL, Johnson MC, Barfuss SL (2010) Apparent losses caused by water meter inaccuracies at ultralow flows. J Am Water Works Assoc 102:123–132. https://doi.org/10.1002/j.1551-8833.2010.tb10115.x

Rizzo A (2006) Apparent water loss control: theory and application. Water Conference in Ferrara (Italy) in May 2006 Conf, pp 1–9

Roberts SE, Monks IR (2015) Fault detection of non-residential water meters. Proc - 21st Int Congr Model Simulation, MODSIM 2015 2228–2233. https://doi.org/10.36334/modsim.2015.l7.roberts

Seidel HF, Blumer D (1999) Testing meters in place saves time, money. Opflow 25:12–13. https://doi.org/10.1002/j.1551-8701.1999.tb02216.x

Van Der Linden MJ (1998) Implementing a large-meter replacement program: A comprehensive large-meter replacement program can help utilities avoid revenue losses caused by malfunctioning meters and increase reliability of service to customers. J Am Water Work Assoc 90:50–56. https://doi.org/10.1002/j.1551-8833.1998.tb08484.x

Yazdandoost F, Izadi A (2018) An asset management approach to optimize water meter replacement. Environ Model Softw 104:270–281. https://doi.org/10.1016/j.envsoft.2018.03.015