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# Evaluation of the measurement performance of water meters depending on water quality

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## ABSTRACT

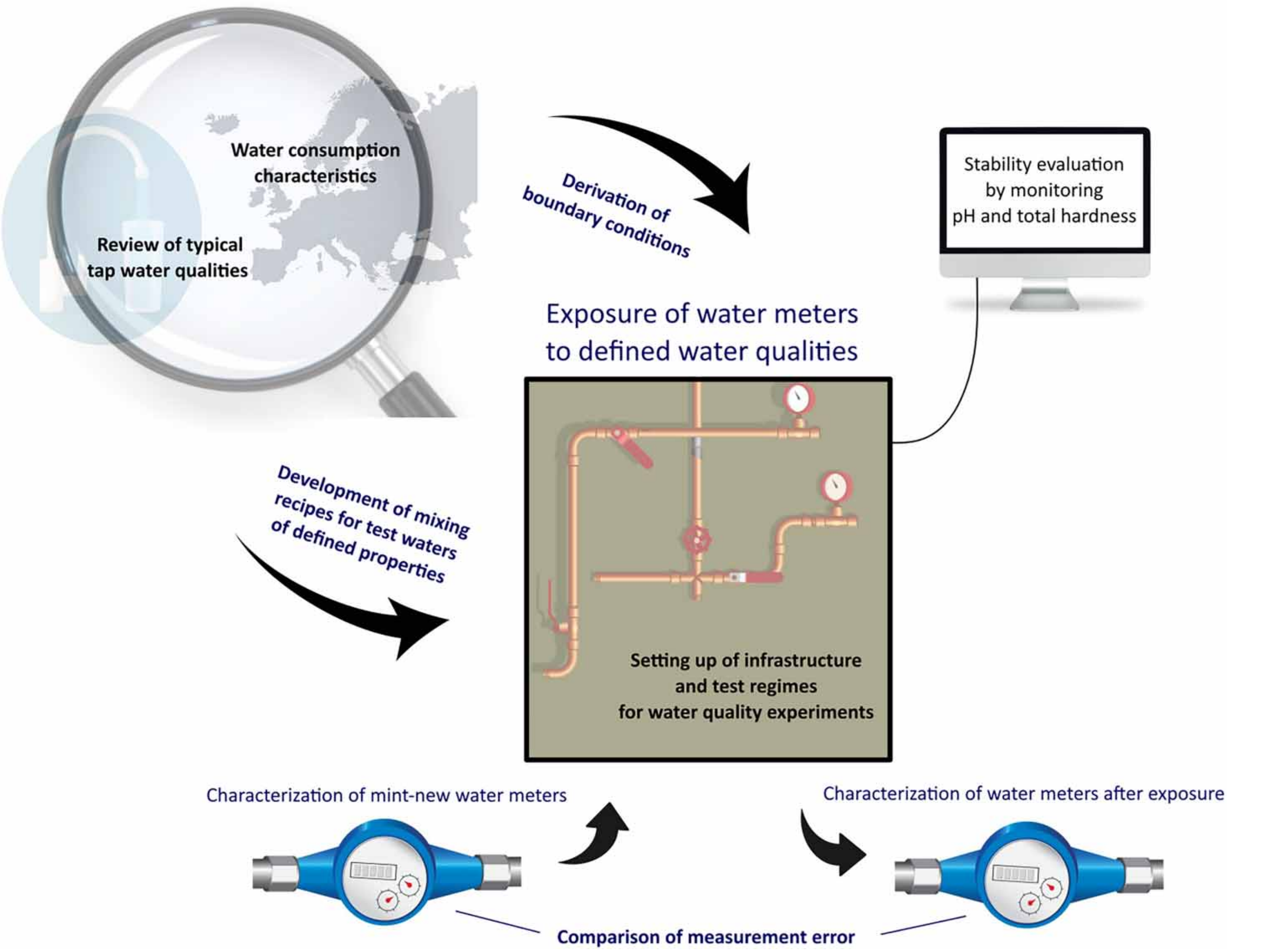
Water meters of different types and sizes are used to monitor and bill the water supply. Although the water is of drinking water quality, its chemo-physical properties often adversely affect the measuring behaviour of a meter after a while. There is thus the risk that they no longer meet legal requirements and may no longer be used. In this paper a test regime with a focus on pH, total hardness and particle load is presented which allows water meters to be tested closer to their operating conditions prior to placing them on the market. The regime goes beyond the conventional continuous durability test as described in OIML R49:2013(E) and ISO 4064:2014. The feasibility and reliability of the test regime has been demonstrated through implementation at different facilities. In the study, the measurement performance of water meters of various types and from different manufacturers was also investigated. A heterogeneous spread of measurement errors was found for both, water meters in mint conditions and those which were exposed to a defined water quality. Furthermore, compared to the conventional continuous durability test, the test regime developed in the study generally leads to stronger changes in the measurement error of the water meters.

**Key words:** cold water meters, test regime, water meter accuracy, water quality

## HIGHLIGHTS

- Test derived to assess performance of water meters closer to their operating conditions.
- Mixing recipes for test waters of different quality developed to ensure comparability.
- Error curves of the water meters depend on the combination of meter type and manufacturer.
- Trend to less effects on electronic water meters.
- Comparison carried out to tests with tap water tendency to larger water quality-related effects in the error curves.

## GRAPHICAL ABSTRACT




## INTRODUCTION

The quality of the water that passes through a household water meter in the course of its operation can have a significant influence on its measurement accuracy and thus on its service life. In the last decades, various efforts have been made to gain a better understanding of this influence. To give some examples with a view on Europe, in the 1980s a comprehensive survey of the performance of household water meters depending on operational conditions and water quality led to a shortening of the validity of verification in Germany from eight to six years (Schulz 1985). Studies in 2005 (Hutter *et al.* 2005) and 2016 (Wendt *et al.* 2017) showed a noticeable effect of sediments and water quality on multi-jet water meters. Arregui *et al.* (2005) investigated among others the effect of fatigue, depositions and water consumption patterns on the measurement accuracy on domestic and industrial water meters of different types. They found distinct sensitivities to influencing factors for different water meter types. However, they could also illustrate the effects different realizations of water meters experience. In Denmark, actual meter installations are currently under scrutiny regarding their effect on the accuracy of metering. This is done by taking a set of actual installations (2352 water meters) and testing the most common types in the laboratory. Anglian Water aimed at the development of a meter maintenance and replacement strategy analysing devices that had been exposed to varying conditions, such as hard and soft water or areas where maintenance work may have led to particles getting into the water meters, for example (Elster 2007). Recently, in Austria a country wide campaign was undertaken to gather data on water quality, installation properties and water meters. In this campaign 719 water meters were evaluated (55% impellor, 18% ultrasonic, 27% piston) and the waters these meters were exposed to analysed (Milota 2019). No clear evidence on meter performance depending on the water quality was found. Cichoń & Królikowska (2020) investigated the impact the deposition of solid particles has on water meter performance. As part of a research cooperation, data collected by the utility Hamburg Wasser from around 14,000 water meters in a large-scale test were evaluated from various points of view. The data of the large-scale test included the operating time, the installation status, the installation location, the type, the manufacturer and the measurement deviation of the investigated water meters (exclusively impellors) for specified flow rates (Kroner *et al.* 2019). Similar to the result of the Austrian campaign, no correlation between the measurement deviation of the water meters and, in this case, geographical location, operating time or total recorded volume could be proven. In contrast to this, Arregui *et al.* (2018) were able to show a correlation between the size of the measurement deviation and age, respectively, of the total recorded volume of the water meters for two types of single-jet water meters from a water utility in Spain. In addition, a significant difference in the performance of both types of water meters was found, even though they were constructed similarly, had been working under comparable operating conditions and had been exposed to water of the same quality.

In documents with a normative character such as OIML R 49:2013(E) or ISO 4064:2014, two types of durability tests are described for water meters with a permanent flow rate $Q_3 \leq 16\ m^3/h$. The discontinuous test is to be performed for 100,000 on-off cycles, each part having a duration of 15 s and a test flow rate of $Q_3$. The continuous test consists of exposing the water meter to an overload flow rate of $Q_4$ over a period of 100 h. Both test types do not reflect the actual operating conditions of a water meter.

Against this background and the fact that the measurement accuracy of water meters is of considerable importance for billing as well as for the control of the supply network or leakage detection, it would be helpful to have laboratory tests available to test water meters for water quality related impacts in order to be able to identify eventual problems as promptly as possible. To realize this, a validated test regime is needed that reflects the actual operating conditions but is still practicable in terms of time. For Europe, a proposal for such a test regime has been developed within the EMPIR Joint Research Project (JRP) 17IND13 'Metrology for real-world domestic water metering' (Metrowamet).

## METHODOLOGY

### Determination of test parameters

For the development of a test procedure to enable a systematic investigation of the influence of water quality on the measurement performance of water meters, various input information is required. Firstly, it must be known what kind of flow rates and flow rate changes the water meter typically experiences over a certain period of time. On the other hand, it must be known what water quality range such a meter is typically exposed to and what parameter values, in turn, represent significant deviations from this.

Schumann *et al.* (2020) showed that consumption behaviour in Central Europe and partly beyond is fairly similar in its characteristics, which is why it is to be expected that the typical total consumption is also similar. Since the focus of the study was on domestic water meters, meters of a size $Q_3 = 2.5\ m^3/h$ were considered. For these meters a total throughput of 189 $m^3$ in six years (calibration period in Germany) is a common consumption amount (Wendt *et al.* 2017). This value was used in the development of the test regime and it determines the duration of the experiments for a given flow rate or flow rate profile.

With regard to the flow rates and flow rate changes to which a water meter is exposed during its operating time, two different approaches can be considered. On the one hand, the dominating flow rate can be taken as the continuous constant load. This approach is similar to the one used in ISO 4064:2014 and OIML R 49:2013(E). On the other hand, a typical consumption profile can be derived from time-resolved consumption data and this can be used as the basis for a time-dependent load by repeating it continuously. Both approaches have been pursued in the development of the test regime.

Based on Schumann *et al.* (2020) it was possible to determine the typical flow rate range seen by a household water meter. According to this study, a greater proportion of flows occurs between 0.75 and 0.8 $m^3/h$. A typical flow profile reflecting real-world water consumption in a larger part of Europe is shown in Figure 1(a). This profile contains various characteristics of water consumption encountered in European households (Schumann *et al.* 2020) The profile was derived from European consumption data. It was generated manually based on boundary conditions for the tests and considering practical and control aspects. The purpose of using two different test regimes was to find out whether there is a difference in the experimental results when a static or a dynamic flow regime is used.

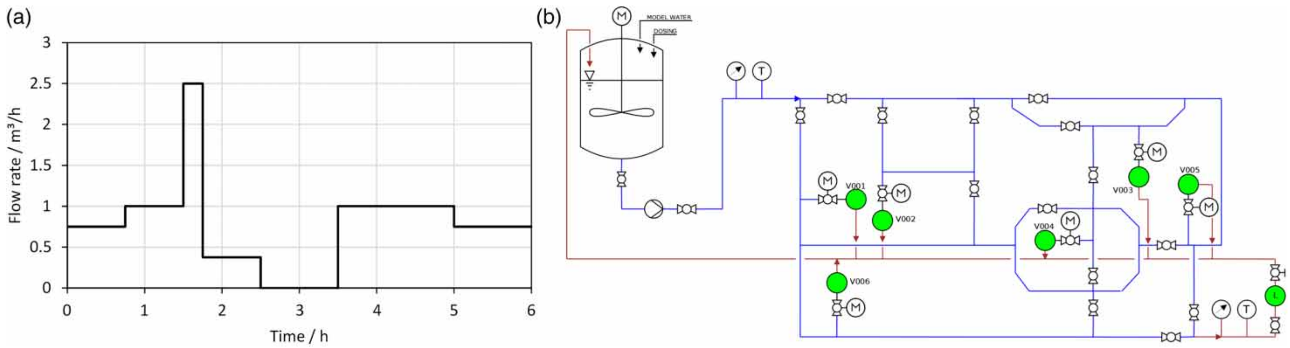



**Figure 1** | (a) Test profile used in the development of the test regime regarding the influence of water quality on the measurement performance of water meters. The profile contains typical features of water consumption in European households. The profile was repeatedly run in the small-scale model networks until a total throughput of 189 $m^3$ was reached, (b) hydraulic scheme of the small-scale model network set up at PTB.

The study focused on physical properties of the water and their effect on water meter performance, this means pH, total hardness and particle load. To determine the range of values for the first two parameters, the results of the survey about the inorganic chemical quality of European tap-water (Banks *et al.* 2015) were used. It was decided to select the 25%-, 50%- and 75%-quantiles for the pH and hardness values given in the test regime to be developed as this would cover the water quality range typically encountered in Europe. This yielded the following total hardness and pH values:

Total hardness: 1 and 3 mmol/L

pH: 6.5, 7.7 and 9.5.

A literature study was conducted to derive a particle load encountered by water meters that is as close to reality as possible in terms of particle size and concentration. However, the number of publications with usable information for Europe is limited. The publications by Gauthier *et al.* (1999), Barbeau *et al.* (2005) and Vreeburg *et al.* (2008) provide orientation. In the end it was agreed to use concentrations of 2.8, 6.2 and 20 mg/L and two ranges of grain sizes of 0–63 and 60–300 μm. Quartz sand was used in the study to keep the focus on wear-related effects.

## Set-up of experiments

The essential purpose of the study was to develop a test regime that makes it possible to evaluate the measurement performance of water meters depending on the chemo-physical properties of water on a sound metrological basis. In addition to the definition of parameters, it was also necessary to determine how the metrological implementation should take place and which parameters ought to be monitored during the experiments. In order to guarantee a comparability of the measurement results, it had to be ensured that identical and reproducible test waters with stable properties were available. For this purpose, mixing recipes were developed by the DVGW-Technologiezentrum Wasser (TZW) in the frame of the Metrowamet project for various test waters starting with a base test water as reference. Details about the composition of the test waters are given in Tables 1 and 2.

The general experiment procedure consisted of three parts: Before exposing the water meters to any test water the measurement error associated with their mint condition was determined at six fixed predefined flow rates on test rigs for water meter testing (measurement uncertainties: U ($k$=2)=0.1 … 0.3%). These measurements were used as baseline measurements. Depending on the partner, the measurement regime was standing start-stop or flying start-stop. The comparability of the test rigs was demonstrated within EURAMET project 1507.

For exposing the water meters to a defined test water either conventional test rigs for stress tests or small-scale model networks were used at the partners. A constant flow rate of 0.75–0.8 $m^3$/h was used with test rigs deployed for water meter testing at the Czech Metrology Institute (CMI), FORCE Technology (FORCE), Research Institutes of Sweden (RISE) and Tubitak Ume (TUBITAK). The Physikalisch-Technische Bundesanstalt (PTB) and TZW each set up a small-scale model network on which the flow profile shown in Figure 1 was continuously run.

In Figure 1(b) the hydraulic scheme of PTB's model network is shown exemplarily. A storage tank with a capacity of about 100 L (resp. 200 L at TZW) is filled with water of a defined quality. A stirrer is used to ensure that the water properties remain uniform throughout the entire volume. With a built-in pump the water is circulated through the model network. Dynamic

**Table 1** | Mixing recipes for test waters with total hardness values of 1, 2 and 3 mmol/L

| **Base test water*** | | Water: highly purified water | | | | |
|---|---|---|---|---|---|---|
| =stock solution | | | | | | |
| **Substance name** | **Substance formula** | **Stock solution (SL)** g/L | **Ion** | **Ion concentration in SL** g/L | **SL dosing** ml(SL)/L(TW) | **Test water ion concentration (TW)** mg/L |
| **Calcium chloride dihydrate** | $CaCl_2 \times 2\ H_2O$ | 86.9 | $Cl^-$<br>$Ca^{2+}$ | 41.9<br>23.7 | 0.5 | 21.0<br>11.8 |
| **Magnesium sulfate heptahydrate** | $MgSO_4 \times 7\ H_2O$ | 77.9 | $SO_4^{2-}$<br>$Mg^{2+}$ | 30.4<br>7.7 | 2 | 60.7<br>15.4 |
| **Sodium bicarbonate** | $NaHCO_3$ | 67.2 | $HCO_3^-$<br>$Na^+$ | 48.8<br>18.4 | 2.5 | 122.0<br>46.0 |
| **2** | **mmol/L total hardness** | | | | | |
| **Calcium chloride dihydrate** | $CaCl_2 \times 2\ H_2O$ | 86.9 | $Cl^-$<br>$Ca^{2+}$ | 41.9<br>23.7 | 1.064 | 44.6<br>25.2 |
| **Magnesium sulfate heptahydrate** | $MgSO_4 \times 7\ H_2O$ | 77.9 | $SO_4^{2-}$<br>$Mg^{2+}$ | 30.4<br>7.7 | 4.256 | 129.3<br>32.7 |
| **Sodium bicarbonate** | $NaHCO_3$ | 67.2 | $HCO_3^-$<br>$Na^+$ | 48.8<br>18.4 | 2.5 | 122.0<br>46.0 |
| **3** | **mmol/L total hardness** | | | | | |
| **Calcium chloride dihydrate** | $CaCl_2 \times 2\ H_2O$ | 86.9 | $Cl^-$<br>$Ca^{2+}$ | 41.9<br>23.7 | 1.632 | 68.4<br>38.7 |
| **Magnesium sulfate heptahydrate** | $MgSO_4 \times 7\ H_2O$ | 77.9 | $SO_4^{2-}$<br>$Mg^{2+}$ | 30.4<br>7.7 | 6.526 | 198.2<br>50.1 |
| **Sodium bicarbonate** | $NaHCO_3$ | 67.2 | $HCO_3^-$<br>$Na^+$ | 48.8<br>18.4 | 2.5 | 122.0<br>46.0 |

*The same test water as the one for 1 mmol/L total hardness experiment.

flow profiles are realized via valves and a connected control unit in which the profiles are programmed. At the inlet of the model network a flow meter is installed to monitor the volume flow. To monitor the measuring conditions, a pressure sensor and a temperature sensor are installed on the inlet and outlet side. The system is connected to a cooling circuit so that a predefined temperature stability is guaranteed. All relevant operation data is typically recorded in 1 min sampling intervals. Up to six water meters can be tested simultaneously.

The exposure duration of 10–14 days per experiment was based on when a total volume of 189 $m^3$ was reached, which depended on the realized test regime. A test protocol was developed in which all essential information and measurement results for the experiments were to be entered. During all measurements, flow rate, pressure, temperature, pH and total hardness of the test water were monitored. The latter two were measured at time intervals between 0.5 and 3 days typically using hand-held devices (pH: typical resolution: 0.01; accuracy: $\pm$0.02; hardness: typical resolution: 0.02 mmol/L, accuracy: $\pm$5%. For pH measurements hand-held devices such as pHenomenal® MU 6100 L from VWR Collection, OHOUS ST3100M, WTW pH 540 GLP were used, for total hardness, e.g. photometer HI97735C Hanna Instruments, Sutest/Pro Water Hardness Test Kit, Vodarenska akciova společnost, a.s./L1249. RISE logged pH and total hardness (and sampling temperature) every 2 minutes by an online measuring system (OFS Online Fluid Sensoric GmbH, pH sensor of type 130, ion-sensitive hardness sensor (Ca/Mg selective) with polymer membrane of type 630). FORCE, RISE and TZW also carried out laboratory measurements of the test waters regarding pH and total hardness hardness (potentiometric measuring method, complexometric titration method according to DIN 38406-3).

**Table 2** | Mixing recipes for test waters with pH values of 6.5, 7.7 and 9.5

| Substance name | Substance formula | Stock solution (SL) g/L | Ion | Ion concentration in SL g/L | SL dosing ml(SL)/L(TW) | Test water ion concentration (TW) mg/L |
|---|---|---|---|---|---|---|
| 6.5 | pH | | | | | |
| Calcium chloride dihydrate | $CaCl_2 \times 2\ H_2O$ | 86.9 | $Cl^-$<br>$Ca^{2+}$ | 41.9<br>23.7 | 0.5 | 21.0<br>11.8 |
| Magnesium sulfate heptahydrate | $MgSO_4 \times\ 7\ H_2O$ | 77.9 | $SO_4^{2-}$<br>$Mg^{2+}$ | 30.4<br>7.7 | 2 | 60.7<br>15.4 |
| Sodium bicarbonate | $NaHCO_3$ | 67.2 | $HCO_3^-$<br>$Na^+$ | 48.8<br>18.4 | 2.5 | 122.0<br>46.0 |
| Di-Sodium hydrogen phosphate dihydrate | $Na_2HPO_4 \times\ 2\ H_2O$ | – | – | – | – | 1,370.0 |
| Potassium dihydrogen phosphate | $KH_2PO_4$ | – | – | – | – | 3,340.0 |
| 7.7 | pH | | | | | |
| Calcium chloride dihydrate | $CaCl_2 \times 2\ H_2O$ | 86.9 | $Cl^-$<br>$Ca^{2+}$ | 41.9<br>23.7 | 0.5 | 21.0<br>11.8 |
| Magnesium sulfate heptahydrate | $MgSO_4 \times 7\ H_2O$ | 77.9 | $SO_4^{2-}$<br>$Mg^{2+}$ | 30.4<br>7.7 | 2 | 60.7<br>15.4 |
| Sodium bicarbonate | $NaHCO_3$ | 67.2 | $HCO_3^-$<br>$Na^+$ | 48.8<br>18.4 | 2.5 | 122.0<br>46.0 |
| Di-Sodium hydrogen phosphate dihydrate | $Na_2HPO_4 \times 2\ H_2O$ | – | – | – | – | 1,443.0 |
| Potassium dihydrogen phosphate | $KH_2PO_4$ | – | – | – | – | 258.0 |
| 9.5 | pH | | | | | |
| Calcium chloride dihydrate | $CaCl_2 \times 2\ H_2O$ | 86.9 | $Cl^-$<br>$Ca^{2+}$ | 41.9<br>23.7 | 0.5 | 21.0<br>11.8 |
| Magnesium sulfate heptahydrate | $MgSO_4 \times 7\ H_2O$ | 77.9 | $SO_4^{2-}$<br>$Mg^{2+}$ | 30.4<br>7.7 | 2 | 60.7<br>15.4 |
| Sodium bicarbonate | $NaHCO_3$ | 67.2 | $HCO_3^-$<br>$Na^+$ | 48.8<br>18.4 | 2,5 | 122.0<br>46.0 |
| Sodium hydroxide | NaOH | 80 (=2 M) | – | – | 0.17 | – |

After each experiment, the measurement error of the meters was determined once again at the test points used in the baseline measurements. All verification measurements were repeated 3–5 times.

The involvement of altogether six parties in total in the study made it possible to divide up the various experiments and to pursue and compare different approaches. It also provided insights into how representative the measurement errors are that occur after the water meters have been exposed to a certain test water. A total of 187 water meters with a size of $Q_3$=2.5 $m^3/h$ covering five different types commonly used in households in Europe from nine different companies were investigated (Table 3). All water meter types were exposed to test waters in horizontal position. Some of the single-jet and multi-jet meters were also exposed to test waters in the vertical position.

At a second stage the experiments wwere extended in order to verify measurement results and also to gain insight into how critical the experiment duration is for the measurement result. For this purpose, the trial period was extended once again by the same amount of time after the water meters had been checked for their measuring performance after the regular period had passed. The hardness tests were extended to include measurements at a greatly increased hardness value of 6.6 mmol/L. Also, using a combination of increased total hardness and particles (6 mmol/L and particles with a concentration of 20 mg/L, grain size 50% fine/50% coarse) it was exemplarily investigated whether a combination of effects has a greater impact on the measurement errors than the individual influences. Here, too, the experiment duration was doubled again after an

**Table 3** | Overview of water meters ($Q_3$=2.5 $m^3$/h) used in the study

| Company | Single- jet R80 | Single-jet R160 | Multi-jet R100 | Multi-jet R160 | Piston R160 | Magnetic-inductive R160 | Ultrasonic R100 | Ultrasonic R160 | Ultrasonic R250 | Ultrasonic R400 |
|---|---|---|---|---|---|---|---|---|---|---|
| A | 11 | | | | | | | | | |
| B | 4 | | 4 | | 4 | | | 4 | | 12 |
| C | | 18 | | 18 | | | | | 18 | |
| D | | | | 3 | | | | | | |
| E | | | | 19 | | | | | | |
| F | | | | 18 | | | | | | |
| G | | | | | 3 | | | | | |
| H | | | | 3 | 13 | 14 | | | | |
| I | | | | | | | 18 | | 3 | |

intermediate measurement of the water meters. To round off the work a comparison was made between the results of the continuous stress test according to OIML R 49:2013(E) and ISO 4064:2014 and the results after exposing the water meters to a defined test water.

## RESULTS AND DISCUSSION

### General assessment of the test regime

The mixing recipes for the base test water and the different test waters have proven themselves. The waters could be mixed without any problems. The stability of their properties which was already assessed during the recipe development could be confirmed again during the various experiments. Figures 2 and 3 show examples of the stability of the test waters. Within the measurement uncertainties, measured parameter values and target values match very well.

A significant result of the tests is that it is apparently not relevant whether the water meters are tested with a constant or a variable flow. Meter-specific effects have a much stronger impact than a reliable statement could be made on this.

### Measurement performance of water meters in mint condition

In order to be able to make a reliable statement on the extent to which water quality affects the measurement performance of water meters, there needs to be an understanding into what differences in measurement performance already occur with water meters in mint condition. In addition to being used as a reference to later determine changes in the measurement deviations depending on the water quality, these base measurements were summarized and evaluated with regard to the variability in the measurement deviation depending on the meter type. The results of these baseline measurements are summarized in Figure 4. The average measurement errors range between 0.01 and 3.5% in absolute values. From the standard deviations shown it becomes clear that there is partly quite a spread in the measurement errors of individual meter type-manufacturer combinations. The majority of the water meters in mint condition meet the requirements regarding the maximum permissible error (MPE) of $\pm 2$ and $\pm 5\%$ with the transitional flow rate as divider prescribed in the relevant normative documents, however not all. Figure 4 also illustrates that there is no system regarding the sign of the measurement error depending on the water meter type and the flow rate. It cannot be established that for a particular meter type the measurement error for flow rates below a certain value is basically negative or positive or vice versa. In general, the measurement errors of the meters also change their sign, so that there are no one-sided measurement errors, and no party is favoured or disadvantaged. Some general things stand out:

- The measurement deviations for a meter type and manufacturer partly vary considerably as can be seen from the standard deviations.
- For the most part, water meters based on an electronic measuring principle show smaller measurement deviations. However, there are obvious exceptions, e.g. piston-based meters can have similar measurement deviations in a comparable order of magnitude as ultrasonic or magnetic-inductive meters. An ultrasonic meter (manufacturer B, R160) can have larger measurement deviations than mechanical water meters.

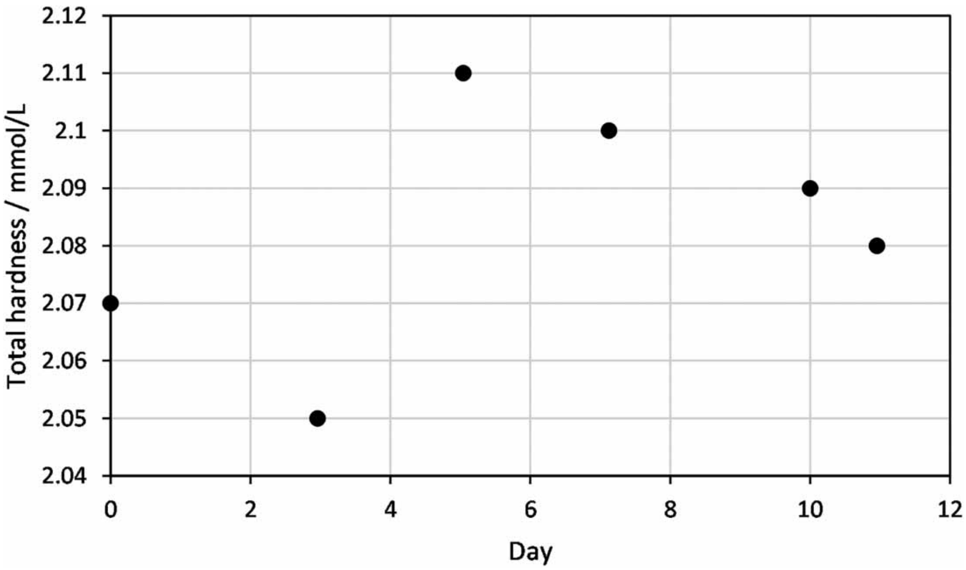



**Figure 2** | Verification of the stability of the total hardness value of the test water used in the 2 mmol/L experiment at FORCE. The hardness was determined by subtracting at t < 72 h water from the test system and then measuring it in a laboratory.

- The largest measurement deviations do not necessarily occur at small flow rates at or below a few tenths $m^3/h$.
- A water meter type from one manufacturer with different R-ratios does not necessarily have the same measurement deviations at the same flow rates as can be seen for company B. However, for the meters of company I this could not be detected.

Figure 5 shows exemplarily the individual results for the multi-jet and ultrasonic water meters. With multi-jet meters, the error curves of the individual meters are often simply shifted parallel. In the case of manufacturer C one water meter completely fails the normative requirements. A spread of $\pm 2\%$ between the error curves seems to be common. Not surprisingly due to the measuring principle, larger measurement errors and greater variability occur at small flow rates around 0.015 $m^3/h$. The picture is fairly similar for the ultrasonic meters. The spread of the error curves appears to be narrower when not taking the errors at flow rates around 0.015 $m^3/h$ into account. It is noticeable that in the case of manufacturer I the error curves are more or less evenly distributed between $\pm 1\%$, while for manufacturer B the measurement errors of ultrasonic meters with R400 are located in a band between 0.5 and $-1.5\%$ for flow rates above 0.015 $m^3/h$ and vary between $-0.5$ and 3.5% in the low flow rate range. It is interesting to note that water meters with R160 and R400 from the same manufacturer B show slightly different error curves regarding level and course. This is not the case with manufacturer I. Here, ultrasonic meters with R100 and R250 have very similar error curves, which is why they were shown together in one diagram. This underlines that a generalisation of the results should be avoided in many cases.

The quintessence of the investigations is that no generally valid statements can be made about the measurement performance of water meters, but at least the combination of meter type plus manufacturer must be considered. From the outset, there is a range of variation in the measurement deviations of 1% or more per flow point (without taking into account the standard deviations of the individual measurement points or the measurement uncertainty inherent in the test rig), which must be taken into account when assessing whether a water quality affects the meter performance.

### Evaluation of measurement errors of water meters depending on water quality

In the evaluation, both the changes in the measurement errors in absolute terms and in relation to the baseline measurement of the individual water meters were considered. Figure 6 shows examples of the analysis. As already observed for the baseline measurements, the results for the influence of the water quality on the measurement performance of the water meters are also extremely heterogeneous:

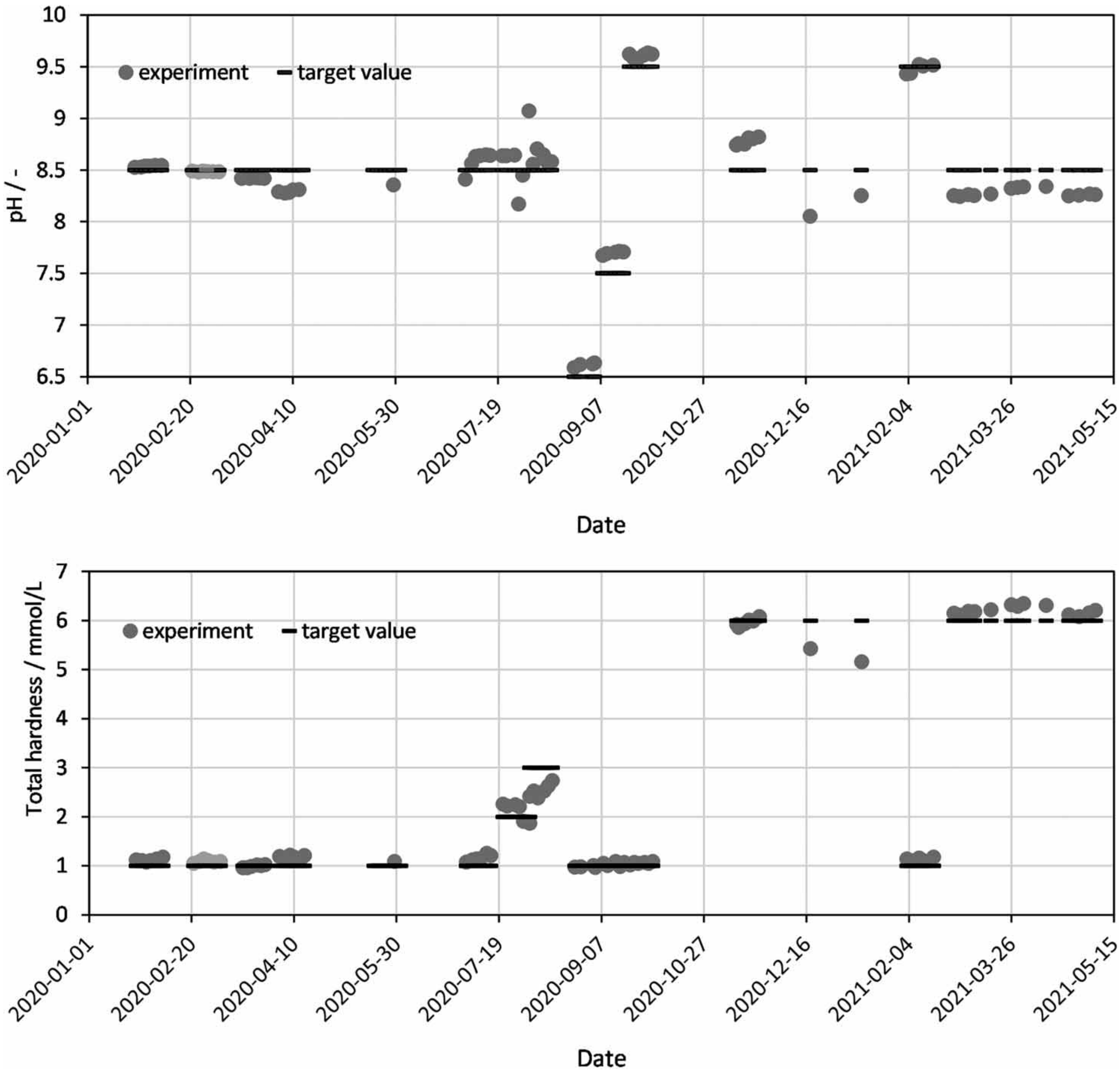



**Figure 3** | Stability of pH and total hardness during the various water quality experiments performed at PTB. In summer 2020 the place where the pH and hardness measurements were made (≠ location of the small-scale model network) got temporarily quite warm which resulted directly in the scattering of the parameters.

- Impairments of the water due to hardness, pH value or particle load can cause measurement errors in water meter performances. In many cases, the changes in the measurement errors are in the range of up to 1%, commonly well below.
- There is no consistent change in the measurement errors compared to the baseline measurement, i.e. no systematically increasing or decreasing errors.
- The largest effects do not necessarily occur at the lowest flow rates or the poorer water quality. Several examples were found where maximum effects occurred at pH 7.7 and flow rates were between 0.8 and 1.8 $m^3$/h.
- Compared to the results of the continuous stress test according to OIML R 49:2013(E), the water quality-related changes in the measurement errors tend to be at least of a similar order of magnitude, frequently significantly larger (up to a factor of 10).
- Water meters with an electronic measuring principle tend to have less of an effect related to water quality than meters with a mechanical measuring principle. However, this has not yet been reliably proven on the basis of the meters considered so far as there are exceptions.

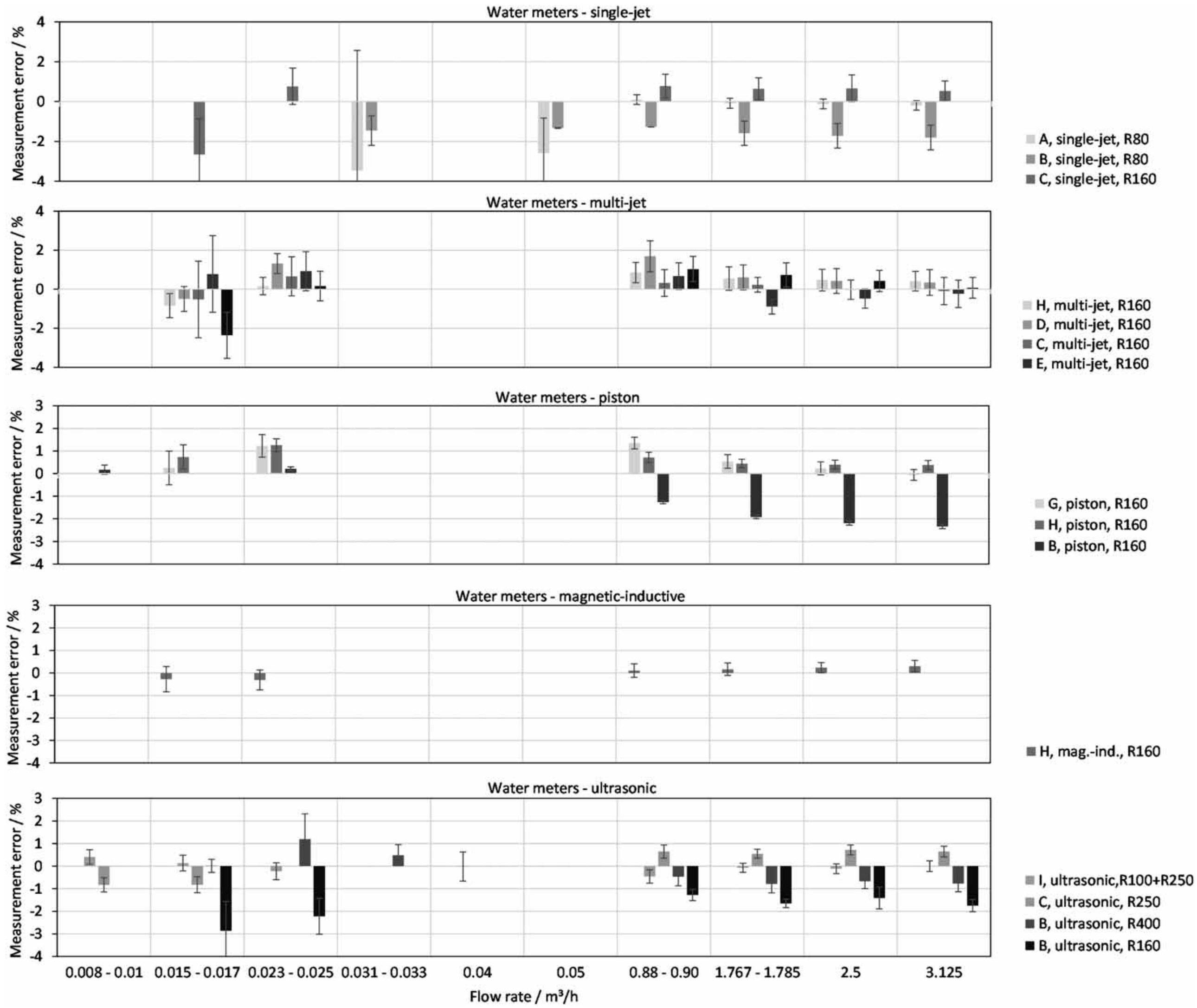



**Figure 4** | Average values of measurement errors of the investigated 187 water meters of different types in mint condition and associated standard deviations; The letter stands for the individual manufacturer. Flow ranges are shown on the x-axis, as some measurements were taken at slightly different flow rates. Each cell corresponds to a flow range. Please note standard deviation bars were partly cut off in the top diagram.

- In the examples where single-jet and multi-jet water meters were installed vertically and horizontally, the vertically installed meter had the greater effects.
- The combination of a high hardness value and particles did not lead to significantly different measurement errors than those of the individual effects.
- The extension of the experiment time by about another 2 weeks at a hardness value of 6 mmol/L and thus a doubling of the load showed a slightly greater effect in comparison. However, a comparable experiment with a water quality of 6 mmol/L plus particles did not lead to an increase in the measurement error after extending the experiment duration by another 2 weeks.

The variability in the effects is illustrated by the examples shown in Figures 7 and 8. If the water quality has an impact, it is in the sense that the meter often measures less volume compared to the as-new condition, which is in line with expectations. Wear and increased friction may lead to reduced smoothness in mechanical devices, which means that these devices then capture less volume. Electronic meters may be affected by abrasion or deposits. For test waters with a pH value of 7.7,

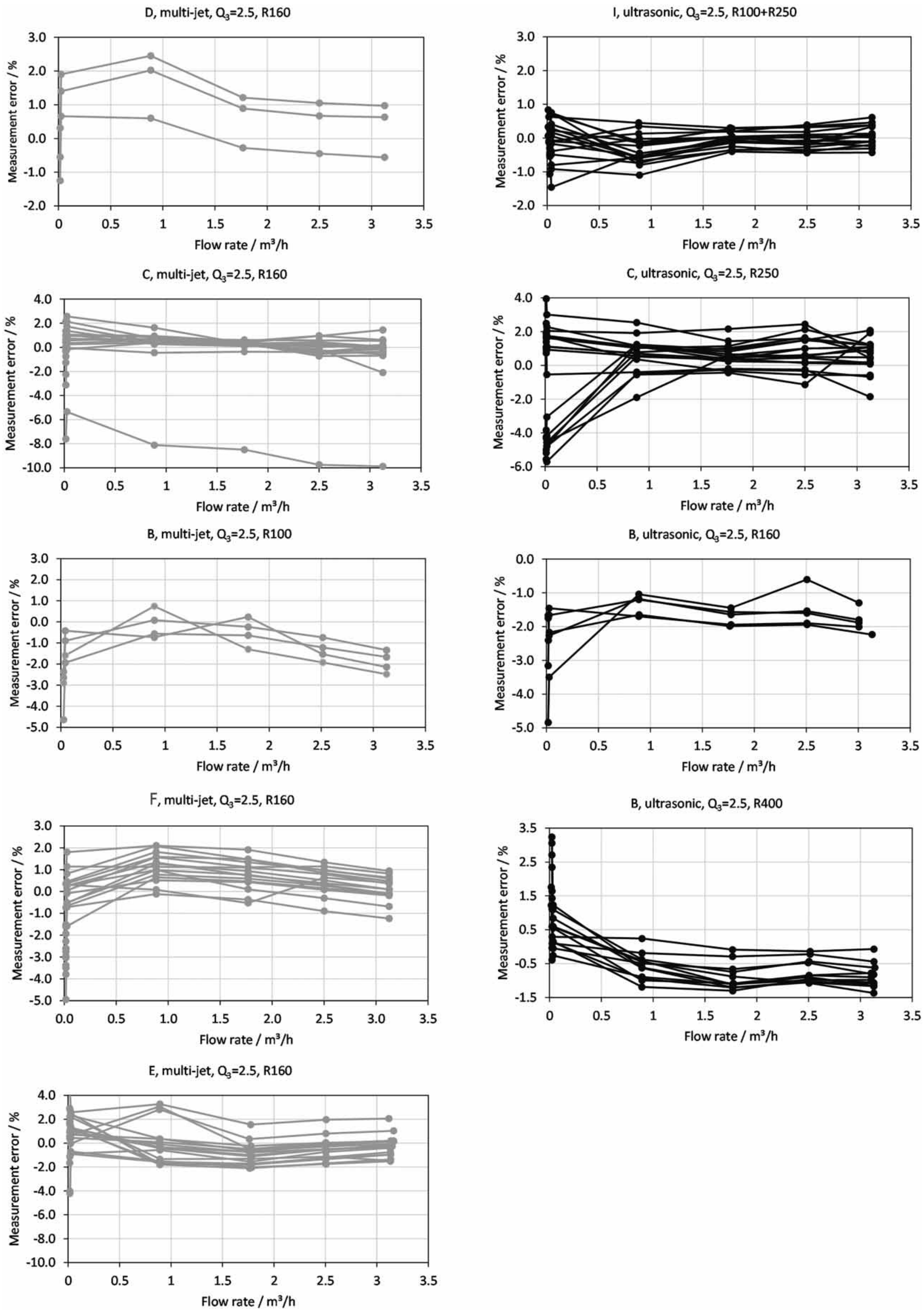



**Figure 5** | Measurement errors of multi-jet (left) and ultrasonic (right) water meters in mint condition from different manufacturers; note the different y-axis scaling.

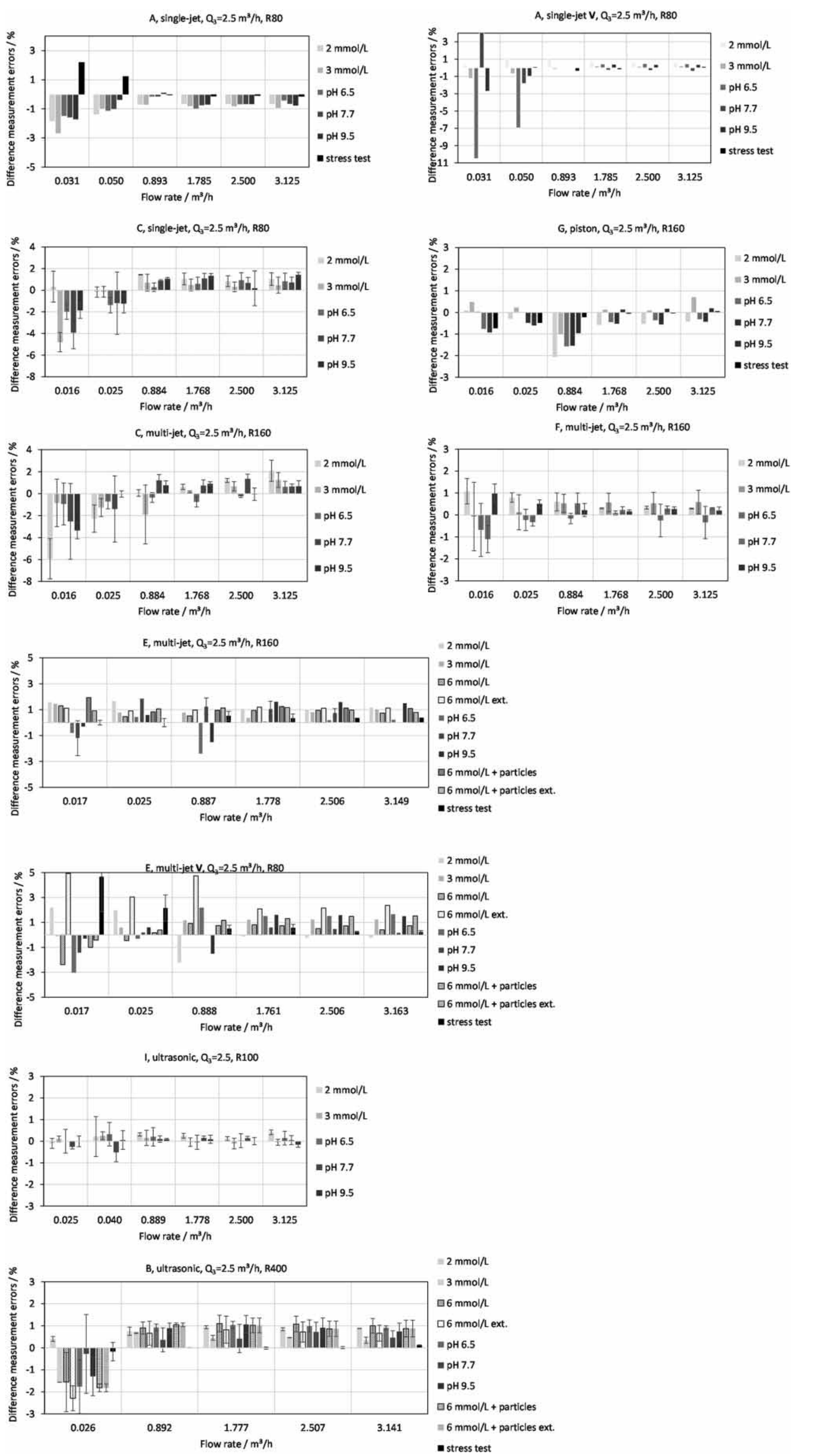



**Figure 6** | Difference between the measurement errors obtained at the end of a water quality experiment and the ones for the baseline measurement. Where standard deviations are included, the average of the results of several water meters is shown. Note the partially different scaling. Water meters installed in a vertical position are marked by a 'V'.

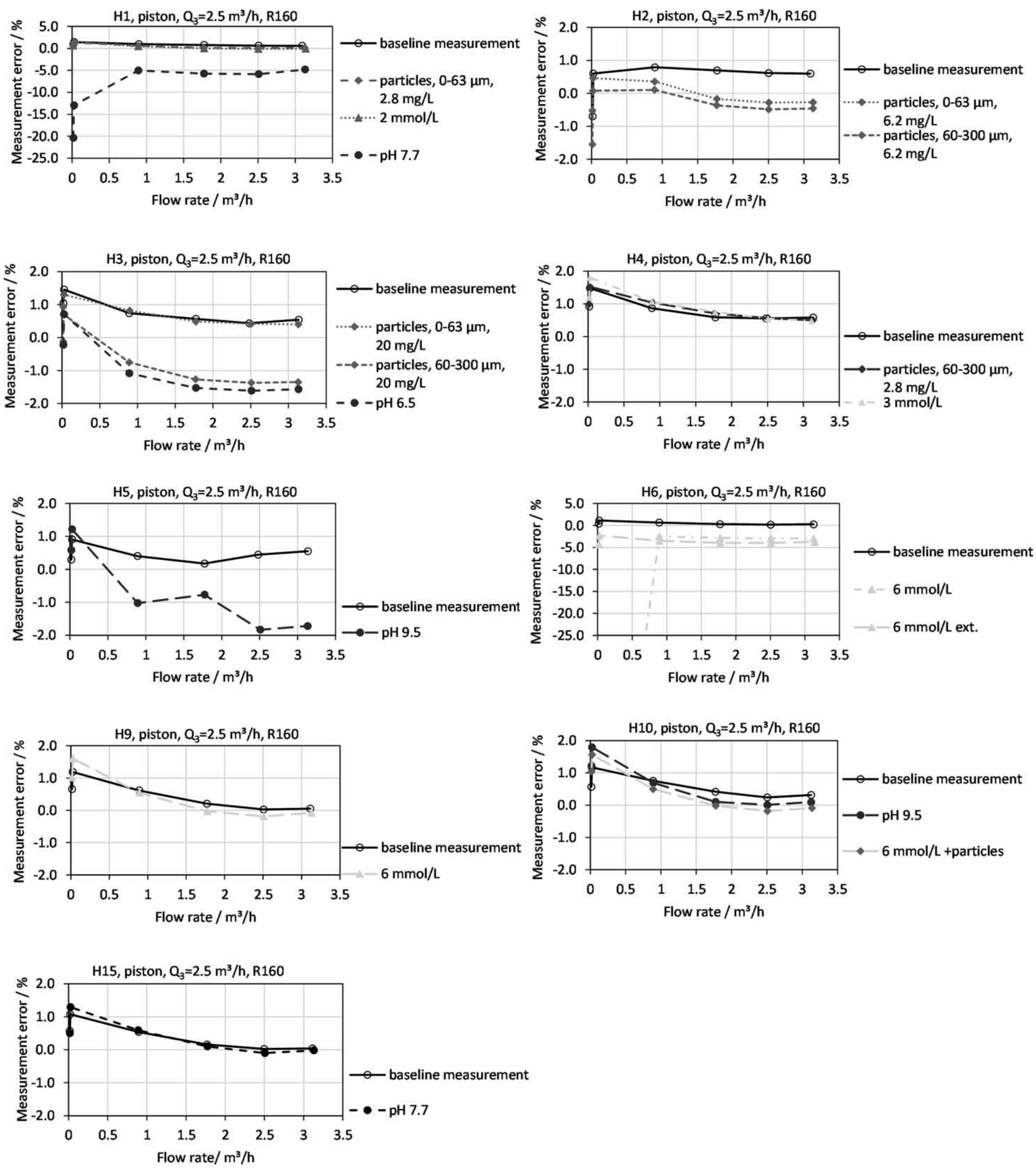



**Figure 7** | Measurement errors obtained for eight piston water meters of manufacturer H for mint condition and after exposing them to different water qualities. Note the partially different y-axis scaling.

respectively, a hardness value of 6.6 mmol/L and a significant deterioration of the measurement deviation of about 5% could be observed in some cases (e.g. H1 and H6 in Figure 7). In the case of the 6 mmol/L this deviation could be confirmed when the experiment was extended. However, the experiments were repeated and no significant differences between the measurement errors of this meter type and manufacturer in mint condition and exposed condition were found in these cases (H9, H15

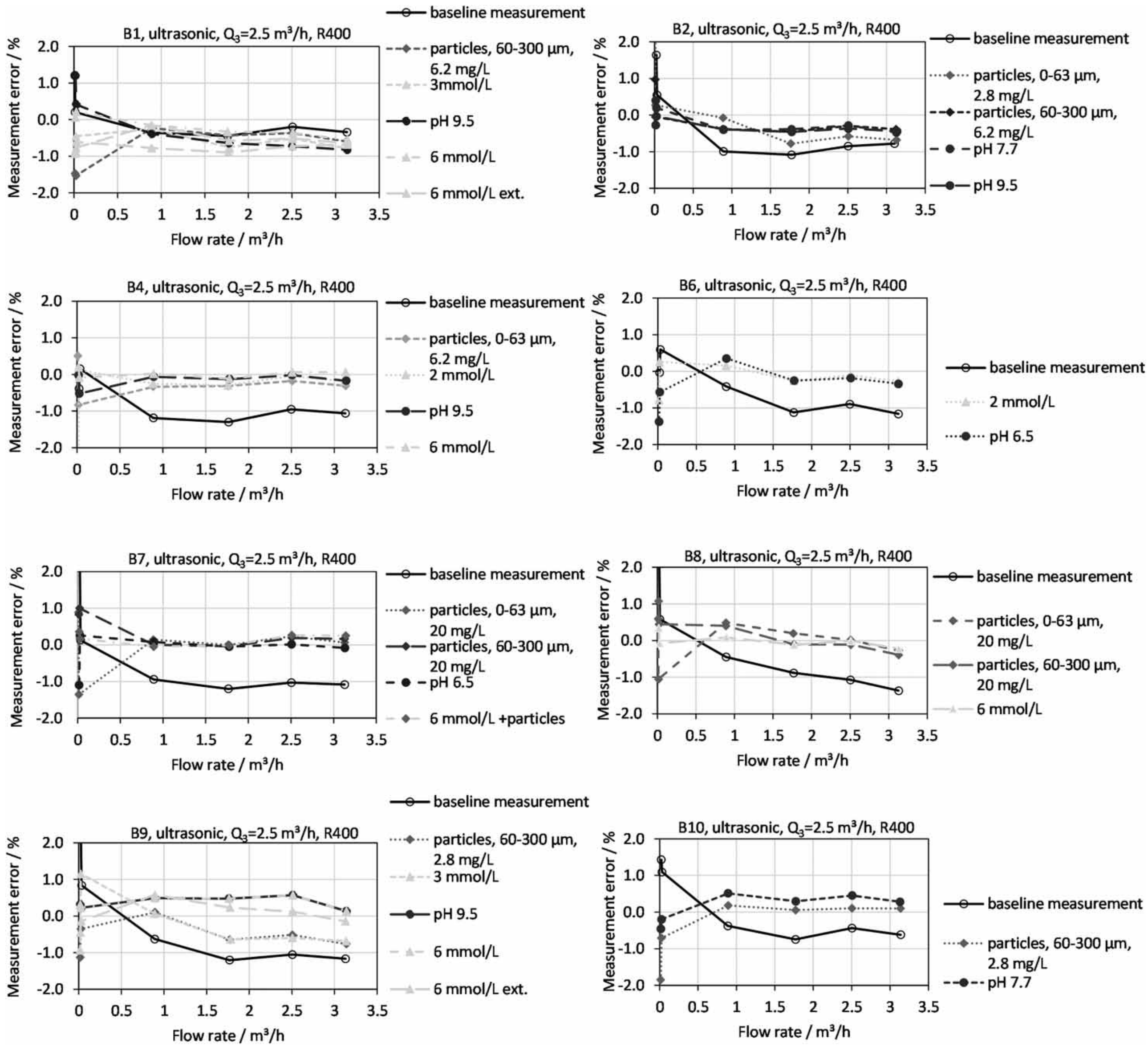



**Figure 8** | Measurement errors obtained for eight ultrasonic water meters of manufacturer B for mint condition and after exposing them to different water qualities.

in Figure 7). Something similar was found for a test water with a pH value of 9.5 (H5 and H10 in Figure 7). In one case a difference of about 2.5% was obtained and in the other one a change of 0.2% for flow rates above 0.5 $m^3/h$. This suggests that meter-specific effects play a significant role such as different batches. The fact that the particle load has a noticeable effect above a certain size and concentration (examples H2 and H3 in Figure 8) is, as explained above, not surprising for devices based on an oscillating piston. However, the measurement errors are still within the MPE.

The results obtained for the ultrasonic water meters (R400) of manufacturer B (Figures 6 and 8) give a more homogeneous picture. Larger changes in the measurement errors occur for these water meters at flow rates below 0.03 $m^3/h$. It is noticeable that for seven out of eight water meters of this type and batch, the measurement error for new devices is around −1% at flow rates above 0.5 $m^3/h$. Regardless of the water quality to which the meters are exposed, the measurement error of these meters at flow rates above 0.5 $m^3/h$ shifts upwards after the experiments by about 1%. Below 0.5 $m^3/h$ the measurement deviation shifts significantly downwards by about 2%, sometimes even more.

Examples of results obtained for various water meters from conventional stress tests are included in Figure 6 (last column in the column sets per flow rate). In almost all cases, the sign of the changes resulting from conventional stress test and new test regimes is identical. The spectrum in terms of magnitude ranges from similar order of magnitude to differences by a factor of 2–3 up to a factor of 10 in individual cases depending on the water quality considered. As a rule, the conventional stress test leads to the smaller measurement errors.

## CONCLUSIONS

In the scope of the present work a metrologically validated test regime was developed which enables the assessment of domestic water meters depending on chemo-physical properties of the water commonly encountered during operating periods and conditions in Europe. In order to ensure defined and reproducible test waters, mixing recipes for the preparation of different types of water were developed. Currently, it is not noticeable in the results whether the water meters are tested with a constant flow or a flow profile representing typical consumption. Meter-specific effects have a much stronger impact than a reliable statement can be made on this.

It was found that compared to the conventional stress tests according to OIML R49:2013(E) and ISO 4064:2014, the tests developed in the project generally lead to somewhat stronger changes in the measurement errors of the water meters at several test points. The investigations also demonstrated that the water meters in mint condition can already have a variability in their measurement errors in the range of 0.1% to several percent, depending on the meter type, manufacturer and flow rate.

As observed for the water meters in mint condition, the changes in the measurement errors after exposing the meters to different water qualities are quite varied. The largest effects do not necessarily occur at the lowest flow rates or the poorer water qualities. Several examples were found where maximum effects occurred at a pH-value of 7.7 and flow rates between 0.8 and 1.8 $m^3/h$. However, for a water meter from a later batch this effect did not occur. In many cases, the changes in the measurement errors are in the range of up to 1%, often well below.

As a general rule, water meters based on an electronic measuring principle tend to have smaller measurement errors than meters based on a mechanical measuring principle. However, this is not the case without exception.

It follows from the results of the study that when investigating the influence of water quality on the measurement accuracy of water meters, no general statement can be made regarding the type of water meter. The same meter type, but from a different manufacturer, may behave differently.

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## DATA AVAILABILITY STATEMENT

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

## REFERENCES

Arregui, F., Cabrera Jr., E., Cobacho, R. & García-Serra, J. 2005 Key factors affecting water meter accuracy. In: *IWA Water Loss Conference*, Sept. 2005, Halifax.

Arregui, F., Gavara, F., Soriano, J. & Pastor-Jabaloyes, L. 2018 Performance analysis of ageing single-jet water meters for measuring residential water consumption. *Water* **10** (5), 612. https://doi.org/10.3390/w10050612.

Banks, D., Birke, M., Flem, B. & Reimann, C. 2015 Inorganic chemical quality of European tap water: 1. Distribution of parameters and regulatory compliance. *Appl. Geochem.* **59**, 200–210. http://dx.doi.org/10.1016/j.apgeochem.2014.10.016.

Barbeau, B., Gauthier, V., Julienne, K. & Carriere, A. 2005 Dead-end flushing of a distribution system: short and long-term effects on water quality. *J. Water Supply: Res. Technol. – AQUA* **54**, 371–383.

Cichoń, T. & Królikowska, J. 2020 Solid particles and their impact on water meter operation. *Desalination and Water Treatment* **199**, 415–419. http://dx.doi.org/10.5004/dwt.2020.26234.

DIN 38406-3:2002-03 German standard methods for the examination of water, waste water and sludge – Cations (group E) - Part 3: Determination of calcium and magnesium, complexometric method (E 3)

Elster 2007 *Elster Group – Corporate Profile*, p. 9. Available from: http://2.imimg.com/data2/BB/IH/MY-/elster-history.pdf

Gauthier, V., Gerard, B., Portal, J. M., Block, J. C. & Gatel, D. 1999 Organic matter as loose deposits in a drinking water distribution system. *Wat. Res.* **33** (4), 1014–1026.

Hutter, G., Thin, G. & Turnwald, L. 2005 *Wasserzähler – Erhebung 2005 (Water Meters – Survey 2005)*. Final report, BEV-PTP. Available from: http://www.metrologie.at/index.html/bericht_erhebung_wasserzaehler2005.pdf

Kroner, C., Schonlau, H., Oldörp, T., Schumann, D. & Liebig, J. 2019 *Entwicklung Eines Praxisorientierten und Gesetzeskonformen Stichprobenverfahrens für Wasserzähler (Development of A Practice-Oriented and Legally Compliant Sampling Procedure for Water Meters)*. PTB-Report MA-100. Physikalisch-Technische Bundesanstalt (PTB). DOI: https://doi.org/10.7795/110.20220224.

Milota, P. 2019 Analysis of historic data – Presentation of results of BEV/PTP. In: *Presentation at the 3rd Metrowamet Project Meeting*, 12–13 November 2019, Villeurbanne.

Schulz, W. 1985 Richtigkeitsprüfungen an Kaltwasserzählern nach Ablauf der Eichgültigkeitsdauer. (*Correctness tests on cold water meters after expiry of the calibration validity period*). *PTB-Mitteilungen* **95** (1985), 102–108.

Schumann, D., Kroner, C., Unsal, B., Haack, S., Christophersen, N., Benková, M. & Knotek, S. 2020 Measurement of water consumption for the development of a new test regime for domestic water meters. *Flow Meas. Instr.* doi.org/10.1016/j.flowmeasinst.2021.101963.

Vreeburg, J. H. G., Schippers, D., Verberk, J. Q. J. C. & Van Dijk, J. C. 2008 Impact of particles on sediment accumulation in a drinking water distribution system. *Water Res.* **42** (16), 4233–4242.

Wendt, G., Schumann, D., Hünemeyer, C., Oldörp, T. & Schonlau, H. 2017 Investigation of domestic water meters with regard to their measuring stability during installation in communal water supply networks. *OIML Bull.* **58** (4), 10–16.

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