Metrology for Real-World Domestic Water Metering

FINAL PUBLISHABLE REPORT

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RMG: -		

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1 Overview

Smart water meters are fast becoming a selling point, as they provide, for example, convenient access for consumers at any time to monitor water consumption or leakage. However, such real time metering requires adequate meter sensitivity and resolution, especially at low flow rates below 3 L/h, paired with pattern recognition. The aim of this project was to provide European water meter manufacturers and water suppliers with reliable and trustworthy measurement capabilities. This was achieved by realising a new measurement infrastructure which enables testing of domestic water meters in simulated conditions that closely resemble the real-world. Conditions include dynamic flow changes as seen in water consumption in households, water quality related aspects, and withdrawal of low amounts of water. Guidelines and publications were prepared which enable stakeholders to take up the project outputs.

2 Need

For European manufacturers of domestic water meters and water suppliers to meet present day demands for accurate metering under real world operation conditions, it is desirable to test meters under close to real world and not only under laboratory conditions as was the case at the beginning of the project. In the last decades, the state of the art for water meters has progressed considerably. Materials and fabrications have changed, additionally meters based on new technologies have been deployed. At the same time, the consumption behaviour of consumers and the technical equipment in dwellings have also changed significantly.

Actual water consumption profiles represent dynamic load changes which therefore deviate strongly from the well defined, constant and reproducible reference flows as prescribed in legal metrology documentation (such as OIML R49 and ISO 4064: Technical requirements for water meters for cold potable water and hot water). This means that the domestic water meters might meet requirements at the test points, excluding the required cumulative uncertainty. This issue had already become a work item for WELMEC WG13 (European Cooperation in Legal Metrology) and could develop as a work item for CEN/TC92/WG2 (European Committee for Standardisation - Water meters). There was no clear view on how different types of domestic water meters actually perform under dynamic load changes, as the metrology for this was missing.

The performance of domestic water meters under real world operation conditions such as typical water qualities, age and wear is a further matter of concern, particularly for extending or shortening calibration periods. By undergoing sampling, the operation times of water meters could be extended. In order to do so, it is necessary to ensure that the meters remain within the maximum permissible error in the calibration period, otherwise they need to be replaced. Short calibration periods of a few years can result in significant effort and high costs of several million € per year for meter replacements, which make it unattractive for water suppliers to deploy high quality flow meters. This ultimately may lead to the adoption of sub optimal technologies with a reduced metering quality, which is not in the interest of consumer protection. Moreover, any costs related to replacements are passed on to consumers leading to increased costs for water supply. Furthermore, a systematic assessment of water meter performance for common operation conditions, combined with metrologically backed scenarios for standardised real-world test conditions related to water quality and a means to estimate meter performance for given conditions was needed.

While water meter manufacturers already offer devices with implemented leakage detection, the criterion by which a leak is defined, is commonly an economic one, based on the smallest flow rate that their domestic flow meter can easily identify. Given that leakage is frequently the cause for increased water consumption in a household and leakage related damage, claims have been rising significantly for several years. There was a clear need for more sophisticated leak detection based on leak signatures and quality assessment that could enable early action and thereby minimise the damage and repair costs caused due to undetected leakage.

3 Objectives

The overall aim of this project was to provide European manufacturers of water meters and water suppliers with needed trusted measurement capabilities to assess the measurement performance of domestic water meters close to real world conditions.

The specific objectives of the project were:

1.To develop test rigs and provide protocols beyond the current methods of OIML R49 for the calibration/verification of domestic water meters under dynamic load changes; this includes the determination of typical consumption profiles and based on this the derivation of one or more pre normative reference profiles. Furthermore, inter comparisons and a rigorous uncertainty assessment will be carried out.

2.To assess the performance of domestic water meters under realistic operation conditions such as typical water qualities (hardness, pH and particles such as rust, sediments) as well as age and wear in general by experiments and where appropriate modelling including a determination of the related uncertainties. Scenarios for more real-world test conditions will be defined as basis for future standardised tests.

3.To foster smart metering by determining the requirements for a real time monitoring of water consumption, the development and adaption of intelligent algorithms for the detection of leakage and by setting up a feasibility study about domestic water meters suitable for the detection of small flow rates (i.e. below 3 L/h).

4.To develop a virtual flow meter to simulate effects of the operation conditions on the performance of water meters, to estimate the uncertainty and to predict effects due to ageing or wear of water meters based on data of used devices.

5. To engage with water meter manufacturers and water suppliers to facilitate the take up of the technology and measurement infrastructure developed in the project by end users (e.g. water meter manufacturers and water suppliers), thereby enhancing the competitiveness of EU industry and to provide input into relevant organisations, e.g. WELMEC WG13, CEN/TC92/WG2 and ISO/TC 30/SC 7.

4 Results

The Metrowamet project developed the necessary metrological infrastructure for the characterization of the measurement performance of domestic water meters under simulated real-world conditions with the aim of supporting European manufacturers of water meters and water utility companies in obtaining more accurate assessments of their performance. Through its four technical objectives, the project successfully addressed the following measurement challenges related to water meter performance:

- Calibration of water meters under dynamic load changes
- Determination of the performance of domestic water meters under realistic operation conditions such as typical water qualities (pH, total hardness, particles)
- Determination of the requirements for real-time monitoring of water consumption and development of algorithms for leak detection
- Development of a virtual flow meter to simulate effects of the operation conditions on the performance of water meters

Objective 1

To develop test rigs and provide protocols beyond the current methods of OIML R49 for the calibration/verification of domestic water meters under dynamic load changes; this includes the determination of typical consumption profiles and based on this the derivation of one or more pre normative reference profiles. Furthermore, inter comparisons and a rigorous uncertainty assessment will be carried out.

In order to further develop the existing test procedures as described in OIML R49:2013 (E), the first task was to determine the flows to which installed domestic water meters are typically exposed and how variable these are by looking at data from different European countries or different seasons. For this purpose, consumption data from surveys which were carried out before this project (available to DVGW/PTB, DTI) and additional surveys carried out by CMI, TUBITAK and FORCE in their home countries within Metrowamet were jointly analysed by PTB. The result of this study which comprised meter sizes of Q_3=4 m³/h and Q_3=2.5 m³/h was that water consumption is fairly similar in Central Europe (excluding situations where a storage tank is used) with no significant seasonal differences. In consequence, it was sufficient to use one merged consumption data set to derive the key consumption characteristics such as the frequency distribution of flow rates, number of zero flows or the duration of flow events. Under the leadership of FORCE and with support by collaborator Aqua, recommendations were developed on how consumption surveys should be conducted. The recommendations are available for downloading from the project's website (https://www.ptb.de/empir2018/de/metrowamet/information-communication/downloads/).

Using the key consumption characteristics, the essential requirements that must be fulfilled by test rigs to assess water meter performance under dynamic load changes were derived:

- a change in the flow rate within 1 s – this means realizing a maximum flow rate change of 1000 L/h in 0.1 s to 0.3 s
- an almost instantaneous flow rate change from 0 L/h up to at least 1000 L/h to be realized with one test rig
- a temporal resolution of monitoring changes in the reference value equal or better 0.3 s; this means a high resolution of the reference value is required in grams, litres, ms.

Based on an algorithm developed at PTB and using the consumption data available, PTB derived three flow profiles (Figure 1) which can be considered as representation of water consumption characteristics of European households which do not rely on a water tank as intermediate storage. In principle, any number of representative profiles can be generated with this algorithm. However, it was decided to focus on these three profiles as they come with different start and end conditions as well as total volumes. These make them suitable to assess the performance of test rigs capable of generating and measuring dynamic load changes, which were developed in the frame of Metrowamet.

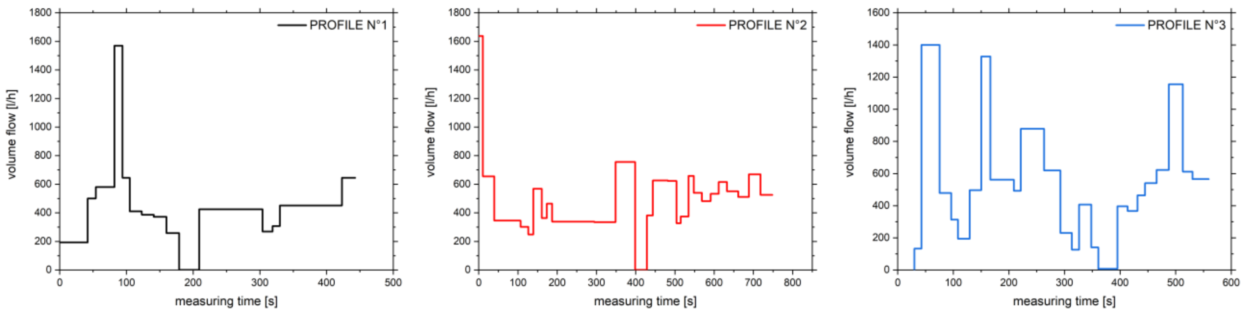


Figure 1 Flow profiles comprising water consumption characteristics of European households. These profiles were used in the EURAMET pilot study No 1506 as well as in the exemplary measurements of water meters using the dynamic test regime developed in the project.

In the frame of a EURAMET pilot study (EURAMET project No. 1506) the metrological comparability concerning dynamic flow profile capability of the dynamic test rigs was assessed, which was a first in flow metrology. For the purpose of the inter-comparison, CETIAT developed a dedicated transfer standard using a Coriolis mass flow meter.

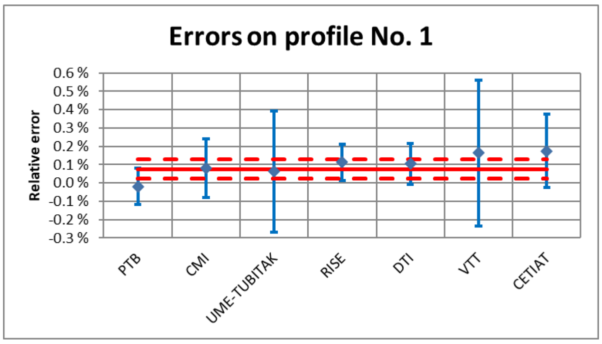
All laboratories participating in the inter-comparison were partners of the project and used their own calibration procedures to calibrate the transfer standard. In Table 1 an overview of the participating laboratories, the type of facility and calibration procedure is given. All laboratories used a dynamic method of measurement and are independent.

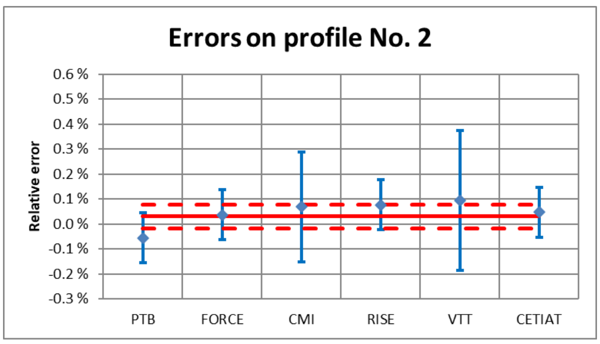
Table 1 Participants and information about the test rigs used in the inter-comparison.

Institute	Country	Test rig, method of measurement	Flow profile measured (No.)	Flow change (s)	Flow change technology
CETIAT	France	Gravimetric with weighing system	1, 2, 3	< 1	Fast valves

(PILOT)					
PTB	Germany	Gravimetric with weighing system	1, 2, 3	<0.1	Cavitation nozzles
FORCE	Denmark	Gravimetric with weighing system	2		Fast valves
CMI	Czech Republic	Volumetric with piston prover	1, 2, 3	<0.32	Fast piston position changes
RISE	Sweden	Volumetric with piston prover plus integrated measuring system (IMS)	1, 2, 3	< 0.1	12-bit digital valves (pneumatically con-trolled modular on–off bits of binary sized flow resistors)
DTI	Denmark	Gravimetric with weighing system	1, 2, 3		Fast valves
VTT	Finland	Gravimetric with weighing system	1, 2, 3		Fast valves
UME TUBITAK	Turkey	Reference flow meter	1		Fast valves

In the evaluation, the procedure according to Cox (2002) was used. The key comparison reference value (KCRV) and its associated uncertainty were determined for all individual flow profiles by using the weighted average of the uncertainties of the participating laboratories. All results were compared against this reference value. The X-squared test was used for a consistency check of the laboratory results. The measurement errors associated with the three profiles at the eight laboratories are shown in Figure 2.





With the dynamic test regime, the intercomparison goes beyond the scope of previous intercomparisons in flow measurement as the quality with which the specified profiles were realised was also be addressed. By recording the parameters pressure, temperature and flow rate with the validation module at a frequency of 20 Hz, a good basis was created to compare more parameters between the test rigs in addition to the measurement deviation. However, these parameters are also essential for the evaluation as far as the realisation of the profiles is concerned since different technologies were used and hence the profile generation was also implemented differently. Therefore, further evaluation criteria were jointly developed:

- the repeatability of the generated flow rates
- the mean of the residuals
- the duration of a flow change
- the relative deviation of the measured total mass

compared to the nominal total mass of a flow profile.

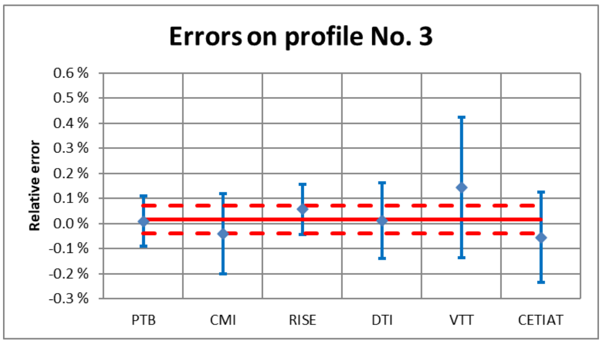


Figure 2 Measurement errors of the participating laboratories for flow profiles No. 1 - 3

In Figure 3, the results of the analysis according to these criteria are compiled. These evaluation criteria are transferable to other areas where the quality with which dynamic flow changes are generated plays a role. These further areas of application are already emerging.

The degrees of equivalence (Figure 4) observed in the inter-comparison show that the test facilities for dynamic liquid flow calibrations of the participating laboratories are in very good agreement. Despite the fact that three different technologies were used for the realization of the load changes, the relative errors for the three flow profiles agrees within a span of -0.1 % to 0.2 %. The participating laboratories stated expanded measurement uncertainties of their test facilities between 0.1 % and 0.4 % (*k=2*).

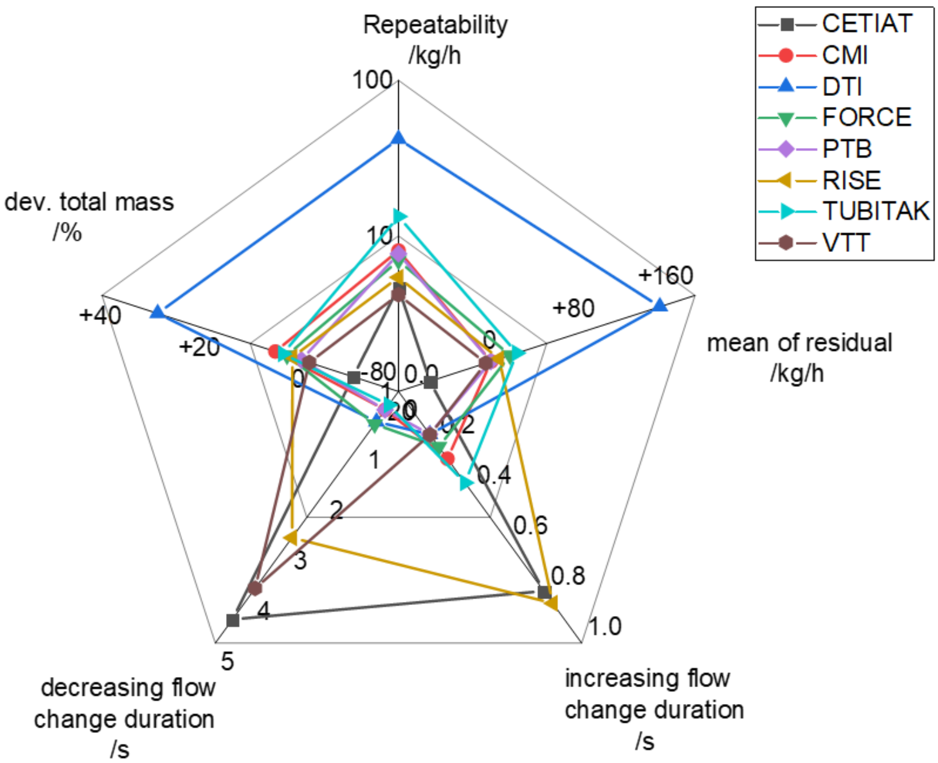


Figure 3 Repeatability, mean of residual, flow change duration for increasing and decreasing flow rates and deviation of the total mass according to table 14 and 15 for profile no. 2 of the participating laboratories and profile no. 1 for TUBITAK alternatively

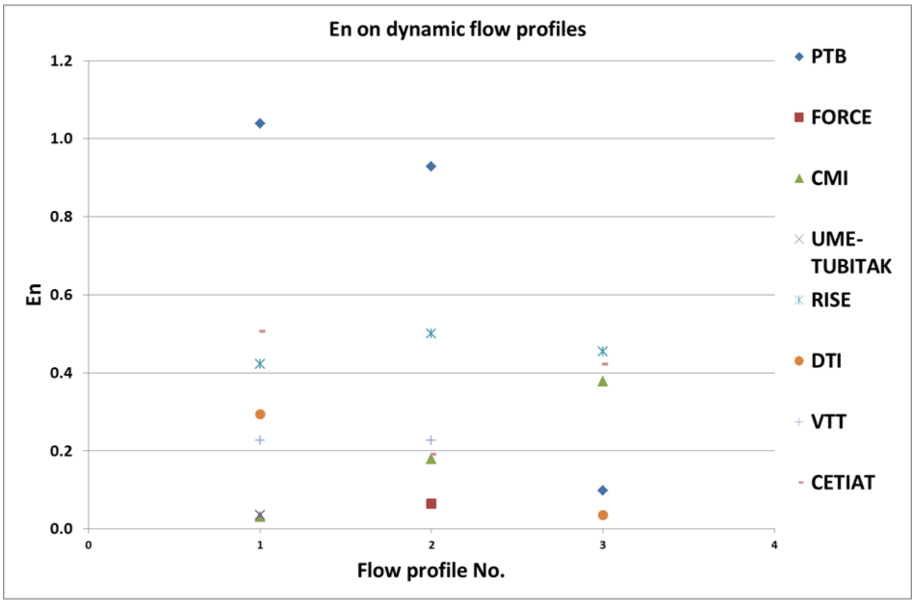


Figure 4 Degree of equivalence of the participating laboratories

In a further step, the measurement performance of a variety of domestic water meters was exemplarily compared by CMI, DTI, FORCE, PTB, RISE and TUBITAK with a conventional static test regime and a dynamic one. Details on the water meters tested are given in Table 2.

Table 2 Water meters tested with a conventional static test regime and the newly developed dynamic test regime at different partners

CMI Number of meter types: 4 Quantity per meter type: 3 (= 12 pcs total) 3 dynamic profiles each Pulse output, flying start-and-stop	
Meter A Type: Piston water meter Size: DN15 Q_3: 2.5 m^3/h R: 400 k-factor: 58 p/L	Meter B Type: Magnetic inductive Size: DN15 Q_3: 2.5 m^3/h R: 800 k-factor: 100 p/L
Meter C Type: Multi-jet Size: DN15 Q_3: 2.5 m^3/h R: 160 k-factor: 199.776 p/L	Meter D Type: Single-jet Size: DN15 Q_3: 2.5 m^3/h R: 80 k-factor: 235.4 p/L

DTI Number of meter types: 3 Quantity per meter type: 2 (= 6 pcs total) 3 dynamic profiles each Pulse output (flying start-and-stop) & display reading (standing start-and-stop)	
Meter A Type: Ultrasonic Size: DN20 Q_3: 2.5 m³/h R: 250 k-factor: 100 p/L	Meter B Type: Multi-jet Size: DN20 Q_3: 2.5 m³/h R: 160 display reading
Meter C Type: Volumetric Size: DN20 Q_3: 2.5 m³/h R: 160 display reading	

PTB Number of meter types: 3 Quantity per meter type: 1 (= 3 pcs total) 3 dynamic profiles each Pulse output, flying start-and-stop	
Meter A Type: Multi-jet Size: DN20 Q_3: 2.5 m³/h R: 160 k-factor: 66.667 p/L	Meter B Type: Piston meter Size: DN15 Q_3: 2.5 m³/h R: 160 k-factor: 150.462 p/L
Meter C Type: Ultrasonic Size: DN20 Q_3: 2.5 m³/h R: 400 k-factor: 10 p/L	

RISE Number of meter types: 2 Quantity per meter type: 3 (= 6 pcs total) 3 dynamic profiles each Pulse output, flying start-and-stop	
Meter A Type: Ultrasonic Size: DN20 Q_3: 2.5 m³/h R: 100 k-factor: 100 p/L	Meter B Type: Multi-jet Size: DN20 Q_3: 2.5 m³/h R: 160 k-factor: 176.136 p/L

TUBITAK Number of meter types: 2 Quantity per meter type: 1 (= 2 pcs total) 1 dynamic profile each Display reading, standing start-and-stop	
Meter A Type: Ultrasonic Size: DN20 Q_3: 2.5 m³/h R: 250 display reading	Meter B Type: Multi-jet Size: DN20 Q_3: 2.5 m³/h R: 160 display reading

VTT Number of meter types: 1 Quantity per meter type: 1 (= 1 pcs total) 3 dynamic profile Display reading (resolution 0.001 L)	
Meter A Type: Ultrasonic Size: DN20 Q_3: 2.5 m³/h R: 250 display reading	

The report prepared by RISE on the measurements shows that all investigated types of water meters, with a few exceptions, remain within the (static) maximum permissible error (MPE) limits also for the dynamic measurements. A possible adaption of the maximum permissible error (MPE) for measurements under dynamic load changes, for example by weighing mean for MPE 5 % and 2 %, is a further task that has to be solved together with national and international committees dealing with water metering, in particular WELMEC WG13, OIML TC8/SC5 and ISO/TC 30/SC 7. However, one third of the 39 water meters tested failed the classical static performance test.

It was the first time that the measurement performance of water meters was evaluated with realistic flow rate changes based on different test rig technologies. The evaluated infrastructures and demonstration of their fitness for purpose also create the conditions for a timely transfer of test rig technology and the new test regime into practical application.

All contents of Objective 1 have been entirely fulfilled. The test rigs for dynamic flow changes linked to household water consumption were realized. Statistically assured test profiles reflecting water consumption characteristics were derived. The capabilities and quality of the newly developed metrological infrastructure were demonstrated in an inter-comparison. The applicability of the new regime to performance tests of domestic water meters was shown. By providing guidelines and publications, the uptake of the project outputs related to Objective 1 is facilitated.

Objective 2:

To assess the performance of domestic water meters under realistic operation conditions such as typical water qualities (hardness, pH and particles such as rust, sediments) as well as age and wear in general by experiments and where appropriate modelling including a determination of the related uncertainties. Scenarios for more real-world test conditions will be defined as basis for future standardised tests.

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. It is rare to find a direct correlation between parameters characterising water quality and their effect on a water meter's measurement behaviour. Duration tests as described e.g. in OIML R 49:2013(E) are more aimed at the mechanical stress of meters and not effects related to water properties. It would be therefore extremely helpful if suitable laboratory tests can be carried out to supplement the field experience in order to be able to anticipate eventual problems. To realise this, a validated test regime is needed that reflects real conditions but is still practicable in terms of time. For Central Europe, a proposal for such a test procedure related to chemo-physical water properties has been developed within Metrowamet. A good practice guide is available for downloading at https://www.ptb.de/empir2018/de/metrowamet/information-communication/downloads/.

For the development of a test procedure to enable a systematic investigation of the influence of water quality on the measurement performance of domestic water meters, various input information was 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 water meter is typically exposed to and what parameter values, in turn, represent significant deviations from this.

PTB together with CMI, DTI, DVGW, FORCE and TUBITAK 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 was on domestic water meters, meters of a size Q_3= 2.5 m³/h were considered since they are prevalent as a survey led by PTB showed. For these water meters, a throughput of 189 m³ per year is a common consumption amount as could be shown from studies outside the project. This value was used for the parameter “total throughput” in the test regime. It determined the duration of the experiments for a given flow rate or flow rate profile. It was found that the most frequently occurring flow rates for this water meter size are between 750 L/h and 800 L/h. In principle, there are two possible test regimes:

- a static test regime in which the flow rate is kept constant and
- a dynamic test regime in which a flow profile is repeatedly run

For the dynamic test regime PTB derived a consumption profile.

DVGW with support from CETIAT, FORCE and PTB carried out a survey of typical operation conditions regarding water quality for water meters (e.g. hardness, pH, suspended particles particle size distributions) encountered in Europe from literature including the results of a Europe wide survey of the inorganic chemical composition of tap water. Based on the survey data, DVGW together with CETIAT, FORCE, PTB, RISE, and TUBITAK decided to use the 25 %-, 50 %- and 75 %- quantiles for pH and total hardness. These values were 1 mmol/L, 2 mmol/L and 3 mmol/L for total hardness, and 6.5, 7.7 and 9.5 for pH. These values relate to common and not extreme values encountered in tap water.

For particle tests, quartz sand with concentrations of 2.8 mg/L, 6.2 mg/L and 20 mg/L and a grain size of 0 – 63 µm and 60 µm – 300 µm was used.

In order to ensure the significance of the tests and thus the results, an essential factor in the test regime is the stability, consistency and reproducibility of a given test water. For this purpose, DVGW derived and tested a stock solution, which served as reference water, and mixing recipes for obtaining the total hardness and pH values given above.

CMI, DVGW, FORCE, PTB, RISE and TUBITAK set up the required test infrastructure in their laboratories and divided the experiments between them (Table 3). As can be seen from Table 3, two types of measurement infrastructure were used: test rigs by CMI, FORCE, RISE and TUBITAK and small-scale model networks by DVGW and PTB.

Table 3. Division of water quality experiments in the project

Partner				PTB	CMI	FORCE	RISE	DVGW	TUBITAK
Water meter	**Measuring principle**	**Range**	**Position at test rig**						
Type Q_3 2.5 DN15	Single-jet	R80	H↑	-	R80	-	-	R80	R160
	Single-jet	R80	V	-	R80	-	-	-	-
	Multi-jet	R160	H↑	R160	R160	R160	R160	R100	R160
	Multi-jet	R160	V	R80	-	-	-	-	-
	Piston	R160	H↑	R160	R160	R160	-	R160	-
	Ultrasonic *)	R160	H↑	R400	-	R250	R100	R160	R250
	Magnetic inductive *)	R160	H↑	R160	R160	-	-	-	-
Parameters	Particle concentration			x	-	-	-	x	-
	Hardness			x	x	x	x	x	x
	pH			x	x	x	x	x	x
Infrastructure	Test rig				x	x	x		x
	Model network			x				x	
Flow profile for parameters measurements	Constant flow				x		x		x
	Dynamic flow			x		x		x	

H↑ - horizontal installation with the dial up

V – vertical position up and down

*) used in user mode

An overview of the water meters measured in the water quality- related experiments is given in Table 4. Altogether 196 water meters of different types from nine manufacturers were investigated.

Table 4 Water meters investigated in the water quality experiments carried out in Metrowamet

Company	Single-Jet R80	Single-jet R160	Multi-jet R100	Multi-jet R160	Piston R160	Piston R400	Magn. -ind. R160	Ultra-sonic R100	Ultra-sonic R160	Ultra-sonic R250	Ultra-sonic R400
A	11										
B	4		4		4				4		15
C		18		18						18	
D				3							
E				19							
F				18							
G					3						
H				3	16	3	14				
I								18		3	

A test protocol was developed in which all essential information and measurement results for the experiments were 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 day and 3 days typically using hand-held devices (pH: typical resolution: 0.01; accuracy: ± 0.02; hardness: typical resolution: 0.02 mmol/L, accuracy: ± 5 %). RISE logged pH and total hardness (and sampling temperature) every 2 min by an online measuring system. FORCE, RISE and TZW also carried out laboratory measurements.

Before exposing the water meters to any test water, the measurement deviation 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 %). After each experiment the measurement deviation of the water meters was determined once again at these test points. Depending on the partner, the measurement regime was standing start-stop or flying start-stop. Typically, the verification measurements were repeated three to five times.

At a second stage the measurement program was expanded 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 measurement 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 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.

The individual results obtained for the base measurements of multi-jet, piston and ultrasonic water meters exemplarily shown in Figure 5 illustrate the spread in the water meter performance observed.

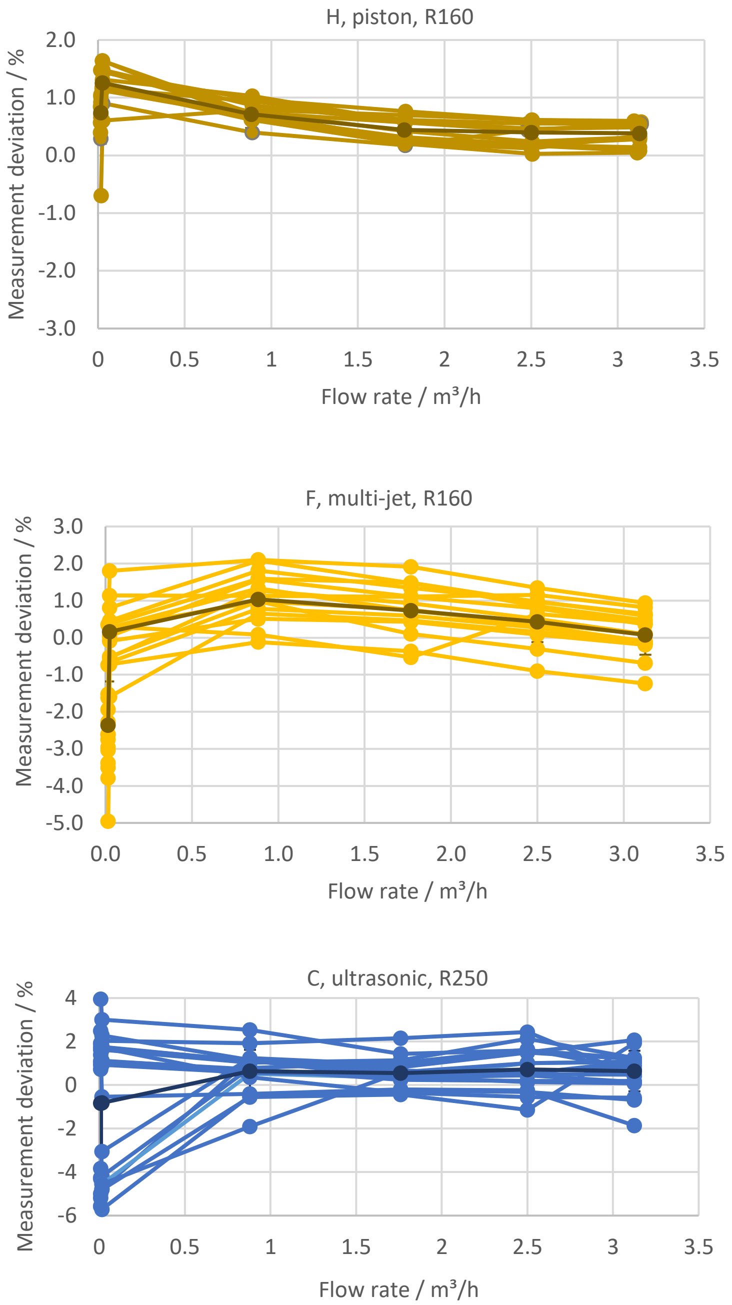


Figure 5 Examples of measurement deviations of multi-jet, piston and ultrasonic water meters in mint condition; note the different y-axis scaling.

The results of the base measurements can be summarized as follows:

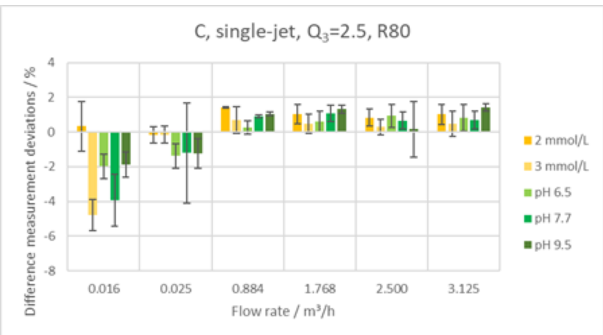
- The measurement deviations for a meter type and manufacturer can vary considerably.
- For the most part, water meters based on an electronic measuring principle show smaller measurement deviations. But there are exceptions, e.g. piston-based meters can have similar measurement deviations in a comparable order of magnitude as ultrasonic or magnetic-inductive water meters. An

ultrasonic water meter (e.g. manufacturer C) can have larger measurement deviations than mechanical water meters.

- The largest measurement deviations do not necessarily occur at small flow rates at or below a few tenths m³/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. However, for the meters of manufacturer I this could not be detected.

In the evaluation of the impact water quality has on water meter performance, both the changes in the measurement deviations in absolute terms and in relation to the base measurement of the individual water meters were considered. Figure 6 gives an impression of the experimental results. As already observed for the base measurements, the results for the influence of the water quality on the measurement performance of the water meters are also extremely heterogeneous:

- Effects of the water due to hardness, pH value or particle load can cause measurement deviations in water meter performances. In many cases, the changes in the measurement deviations are in the range of up to 1 %, commonly well below.
- No consistent change can be found in the measurement deviations compared to the base measurement, i.e. no systematically increasing or decreasing errors.
- The largest effects do not necessarily occur at the lowest flow rates or the poorest water quality. Several examples were found where maximum effects occurred at pH 7.7 and flow rates between 0.8 m³/h and 1.8 m³/h.
- Compared to the results of the continuous stress test according to OIML R49:2013(E), the water quality-related changes in the measurement deviations tend to be at least of a similar order of magnitude, frequently significantly larger (up to a factor of 10).
- Water meters deploying 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.
- In the examples where single-jet and multi-jet water meters were installed vertically and horizontally, the vertically installed meters had the greater effects.
- The combination of a high hardness value and particles did not lead to significantly different measurement deviations than those of the individual effects.
- The extension of the experiment time by about another two 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 deviations after extending the experiment duration by another two weeks.



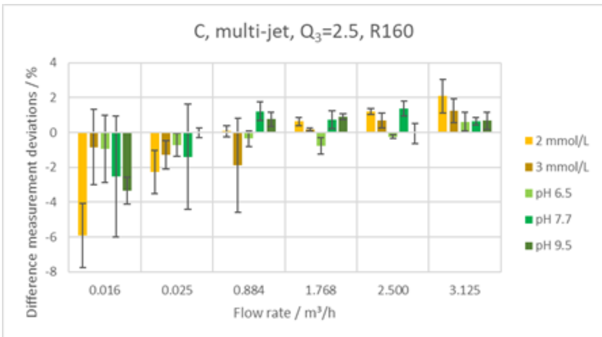


Figure 6 Difference between the measurement deviations obtained at the end of a water quality experiment and the ones for the base measurement. Where standard deviations are included, the average of the results of several water meters is shown. Note the partially different scaling.

Objective 2 was fully achieved through the work detailed above. The conditions to which a domestic water meter is typically exposed in Europe were derived. From surveys on consumption characteristics and tap water quality boundary conditions for a water quality-related test regime were identified. Based on these, mixing recipes for different water qualities (PH, total hardness, suspended particles) were developed, which ensured the comparability and repeatability of the test water properties. All of this has gone into the development of a new metrologically validated test regime for evaluating the measurement performance of domestic water meters depending on water quality. A comparison with the conventional endurance test as prescribed e.g. in OIML R49:2013(E) was carried out. By providing guidelines and publications the uptake of the project outputs related to Objective 2 is facilitated.

Objective 3

To foster smart metering by determining the requirements for a real-time monitoring of water consumption, the development and adaption of intelligent algorithms for the detection of leakage and by setting up a feasibility study about domestic water meters suitable for the detection of small flow rates (i.e. below 3 L/h).

A survey among manufacturers and water utilities along with a literature review was carried out under the lead of DTI to get an overview of leak detection approaches and related infrastructure. AQUA provided manufacturers' insights into the performance capabilities of different water meter technologies. Based on this, water meter types were selected for monitoring small flow rates in the project. In parallel, test infrastructure for leakage detection was set up. Data sets containing defined leakage were e.g. derived by PTB. Among others these were used to derive requirements which need to be fulfilled by devices for leakage detection in households based on flow measurements.

Dynamic profiles for low flows were developed by PTB and implemented by the project partners DTI and CETIAT. To evaluate the setup for generating and measuring dynamic load profiles at low flows an intercomparison between CETIAT and DTI was carried out.

Three different types of water meters representing different measurement technologies were selected for testing their measurement performances in the flow range relevant for leakage. The specifications for the three water meter types are listed in Table . As can be seen from Table , the water meters have different Q_1 performances, which is expected due to different measuring technology. The water meter's ability to measure different low flow rates were tested for static and dynamic flow rate regimes at DTI. For each test the two dynamic flow profiles were repeated 150 times resulting in a total volume flow of 207 L (profile 1) and 173 L (profile 2), respectively.

Table 5 Water meters used for performance tests at low flow rates.

	Ultrasonic	Multi-jet	Piston	Unit
Resolution, display readout	1	0,05	0,05	L
Nominal flow (Q_3)	2.5	2.5	2.5	m^3/h
Dynamic range (Q_3/Q_1)	250	160	400	
Max. flow (Q_4)	3.1	3.125	3.125	m^3/h
Minimum flow (Q_1)	10	15	6.25	L/h
Transition flow (Q_2)	16	25	10	L/h
Min. cutoff flow	2			L/h

Table 6 The average errors for the test of water meters under dynamic load for profile 1 and profile 2.

	Profile 1		**Profile 2**	
	Avg. error	**Avg. unc. (k=2)**	**Avg. error**	**Avg. unc. (k=2)**
	[%]	**[%]**	**[%]**	**[%]**
Ultrasonic water meter	-4.15	0.66	-1.97	0.74
Multi-jet water meter	-67.59	0.34	-64.89	0.33
Piston water meter	-0.72	0.30	-4.,29	0.30

In Table the results of the test of the three types of water meters under dynamic load can be seen. It is evident that the multi-jet water meter is unable to measure the dynamic load profiles at low flow resulting in large errors for both profiles. The performances of both the ultrasonic and the piston water meters are acceptable for both profiles. The larger uncertainty for the ultrasonic water meter is due to a lower digital readout display resolution at only 1 L, where the two other water meters has a mechanical display readout with a resolution at 0.05 L.

Smart meters which provide data with high temporal resolution increase possibilities for smarter leakage detection. However, any leakage detection requires a suitable algorithm which can reliably identify leakage. In the project, DVGW demonstrated that statistical pattern recognition which enables the extraction of normal and anormal components from a consumption profile can be successfully used for this purpose. The approach is a mixture of the Minimum Night Flow (MNF) and the Data Driven Demand Forecast (DDF).

The algorithm thus developed was tested on simulated leakage data inserted into real consumption data. It was found that the algorithm was able to accurately extract the underlying base profiles (4 pcs.) and the slowly increasing leakage rate from all randomly generated daily profiles (365 pcs.). Figure 7 shows an example of one of the extracted base profiles and the recovered leakage rate.

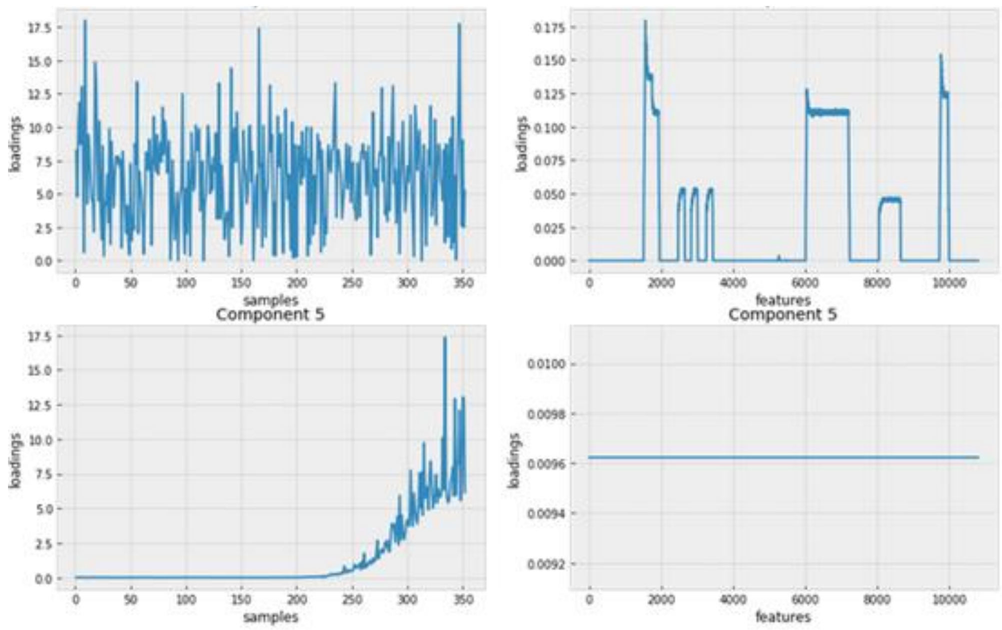


Figure 7 Top row: recovered base profile No. 4 (right) with its loadings for each day (left), Bottom row: recovered leakage rate (right) with its loadings for each day (left).

Furthermore, a hardware platform was developed in the project by UNISA (Figure 8) for detecting small flow on domestic water meters using image-based correlation. The platform was tested among others in collaboration with CETIAT.

With this platform, older analogue water meters can be upgraded to a meter with a digital output which then can be combined with a leakage detection algorithm. The hardware platform is generic and is ready for implementing leak detection algorithms.

Figure 8 Hardware platform developed for leakage detection based on a low voltage CMOS image sensor, a general-purpose ARM®Cortex®-M4 and a communication part consisting of a RF receiver and a RF front-end module; The electronic device is battery powered with up to 2 low discharge lithium batteries.

Objective 3 was fully achieved. Requirements for a real-time monitoring of water consumption were derived. An intelligent algorithm for the detection of leakage at household level was developed and successfully tested. Furthermore, a feasibility study was carried out about domestic water meters suitable for the detection of small flow rates (i.e. below 3 L/h). To facilitate the uptake of the project outputs related to Objective 3 the associated deliverables were made available for downloading on the project's website.

Objective 4

To develop a virtual flow meter, to simulate effects of the operation conditions on the performance of water meters, to estimate the uncertainty and to predict effects due to ageing or wear of water meters based on data of used devices.

The purpose of the virtual flow meter is to make measurement results obtained within the Metrowamet project related the effect of water quality on the performance of domestic water meters available to all interested parties via a user interface. The information is passed on anonymously with regard to the meter manufacturers. Different manufacturers were assigned an arbitrarily assigned letter. VTT, DVGW, and TUBITAK tested the user interface with regard to user friendliness and glitches.

The database and user interface were both developed and implemented at PTB. Two factors played an essential role in the conception and implementation: On the one hand, everything had to be designed in such a way so that it was expandable and could be made available in the long term. This required a certain flexibility in the realisation. Secondly, data protection and IT security had to be taken into account so that the user interface did not inadvertently allow access to other IT infrastructure of the PTB. This resulted in a significant additional effort in programming and a second IT security review which continued beyond the end of the project. While the review continues, the performance data and their diagramming are provided via an excel-application available at the project website. The interface is based on HTML, CSS and JavaScript. The JavaScript-library "jQuery" and the framework "bootstrap" were used.

It was originally planned to describe changes in the measurement performance of the water meters depending on water quality empirically via formulas instead of providing the individual data sets. This proved to be not feasible because the changes in the measurement deviations turned out to be too heterogeneous. The concrete changes in meter performance apparently depend at least on the combination of water meter type and manufacturer, maybe sometimes even on the meter batch. In consequence, misleading interpretations would be obtained if empirical descriptions were to be used. As a result, the interface had to be designed differently. It was now necessary to be able to represent measurement deviations of many devices in an appropriate manner.

On the user interface, there are five categories from which selections can be made using dropdown lists:

- Manufacturer (anonymized)
- Water meter type
    - Selection of meters 1, 2, 3, …
- Water meter size
- R-value
- Measurement errors depending on flow rate for water meters
    - in mint condition
    - exposed to a water containing particles of a certain concentration and particle grain size
    - exposed to a water of a specific total hardness
    - exposed to a water of a specific pH value
    - exposed to a combination of a total hardness level and particle concentration of a certain grain size range
    - exposed to a continuous stress test at Q4 according to OIML R49:2013(E).

Data obtained in the scope of the work performed under Objective 2 is stored in the database. Additional data from outside the project will also be incorporated in the post-project period. Figure 9 gives an impression of the user interface in the test environment. Figure 10 shows an example of a comparison of different performance data for one water meter type and size from one manufacturer. From figure 10 an impression of the breadth of the data stored in the database can be gained. As of the end of the project, more than 560 data sets were stored in the data base including some which were obtained outside the Metrowamet project. Figure 11 gives an example of the measurement data together with their meta data and nomenclature.

All selected data sets are plotted in one line diagram. Different colours and a legend enable the allocation of the curves to the selected parameters.

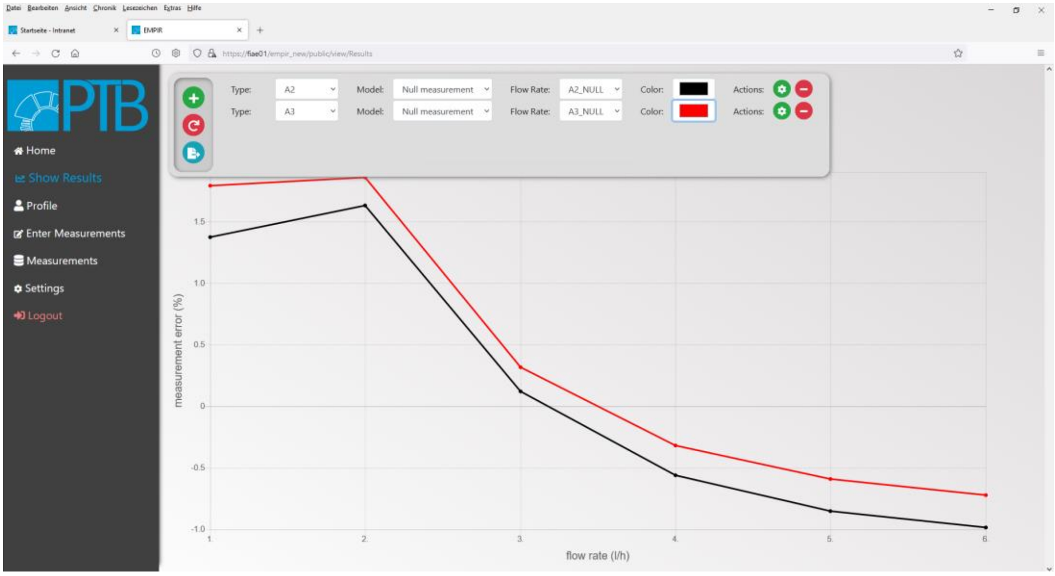


Figure 9. Impression of the user interface of the virtual flowmeter in the test environment.

Figure 10. Example for a comparison of the performance of a water meter type from one manufacturer at different conditions. The upper row gives an impression of the variety of the deposited data.

Meter type	Meter identification	Size	Ratio	Measurement parameter	No	Flow rate / m³/h	Measurement error / %	Standard deviation / %	Pressure 1 / bar	Pressure 2 / bar	Temperature 1 / °C	Temperature 2 / °C	Legend
Piston	BPI01	2.5	160	baseline	1	0.01502176	-0.222773711	0.080541722	2.99878	3.03316	22.15754304	22.34075037	BPI01, baseline
Piston	BPI01	2.5	160	baseline	2	0.02509543	0.144602699	0.075213419	2.99972	3.0337	22.28527807	22.37905278	BPI01, baseline
Piston	BPI01	2.5	160	baseline	3	0.88578409	-1.302379142	0.008229161	2.99926	2.64854	20.12285548	20.21175643	BPI01, baseline
Piston	BPI01	2.5	160	baseline	4	1.77613054	-1.912434241	0.013947528	3.00078	1.55096	19.59081543	19.69338878	BPI01, baseline
Piston	BPI01	2.5	160	baseline	5	2.50268276	-2.169103056	0.008308594	3.2988	0.42546	19.67967893	19.81209116	BPI01, baseline
Piston	BPI01	2.5	160	baseline	6	3.01035465	-2.335397754	0.014618389	4.49874	0.34998	19.97876176	20.13666685	BPI01, baseline
Piston	BPI01	2.5	160	hardness, 3 mmol/L	1	0.01578331	0.582473009	0	3.004129594	3.031776835	21.88658248	21.82889568	BPI01, hardness, 3 mmol/L
Piston	BPI01	2.5	160	hardness, 3 mmol/L	2	0.02513129	0.326365949	0.021725394	2.999962492	3.026968606	22.36396291	22.49355216	BPI01, hardness, 3 mmol/L
Piston	BPI01	2.5	160	hardness, 3 mmol/L	3	0.8901931	-1.480262815	0.006740765	2.999481673	2.723462005	21.24535995	21.26668715	BPI01, hardness, 3 mmol/L
Piston	BPI01	2.5	160	hardness, 3 mmol/L	4	1.77524332	-2.156013707	0.006953146	3.002486797	1.876660284	20.55580634	20.59284729	BPI01, hardness, 3 mmol/L
Piston	BPI01	2.5	160	hardness, 3 mmol/L	5	2.51113262	-2.452011036	0.008120074	3.302509937	1.050125657	20.28900022	20.35383538	BPI01, hardness, 3 mmol/L
Piston	BPI01	2.5	160	hardness, 3 mmol/L	6	3.1335378	-2.618281784	0.005483503	4.805089151	1.303234025	20.51132496	20.60537025	BPI01, hardness, 3 mmol/L
Piston	BPI02	2.5	160	baseline	1	0.01502176	-0.133667792	0.087310868	2.99878	3.03316	22.15754304	22.34075037	BPI02, baseline
Piston	BPI02	2.5	160	baseline	2	0.02509543	0.11942156	0.067615736	2.99972	3.0337	22.28527807	22.37905278	BPI02, baseline
Piston	BPI02	2.5	160	baseline	3	0.88578409	-1.367268455	0.02524407	2.99926	2.64854	20.12285548	20.21175643	BPI02, baseline
Piston	BPI02	2.5	160	baseline	4	1.77613054	-2.038268566	0.018596501	3.00078	1.55096	19.59081543	19.69338878	BPI02, baseline
Piston	BPI02	2.5	160	baseline	5	2.50268276	-2.324844277	0.014423652	3.2988	0.42546	19.67967893	19.81209116	BPI02, baseline
Piston	BPI02	2.5	160	baseline	6	3.01035465	-2.455702352	0.020648965	4.49874	0.34998	19.97876176	20.13666685	BPI02, baseline
Piston	BPI02	2.5	160	hardness, 2 mmol/L	1	0.01578331	-0.037258802	0	3.004129594	3.031776835	21.88658248	21.82889568	BPI02, hardness, 2 mmol/L
Piston	BPI02	2.5	160	hardness, 2 mmol/L	2	0.02513129	0.241453915	0.187235158	2.999962492	3.026968606	22.36396291	22.49355216	BPI02, hardness, 2 mmol/L
Piston	BPI02	2.5	160	hardness, 2 mmol/L	3	0.8901931	-1.584502301	0.013884022	2.999481673	2.723462005	21.24535995	21.26668715	BPI02, hardness, 2 mmol/L
Piston	BPI02	2.5	160	hardness, 2 mmol/L	4	1.77524332	-2.240771329	0.009102425	3.002486797	1.876660284	20.55580634	20.59284729	BPI02, hardness, 2 mmol/L
Piston	BPI02	2.5	160	hardness, 2 mmol/L	5	2.51113262	-2.538900295	0.007291993	3.302509937	1.050125657	20.28900022	20.35383538	BPI02, hardness, 2 mmol/L
Piston	BPI02	2.5	160	hardness, 2 mmol/L	6	3.1335378	-2.775234922	0.004497769	4.805089151	1.303234025	20.51132496	20.60537025	BPI02, hardness, 2 mmol/L
Piston	BPI03	2.5	160	baseline	1	0.01502176	0.277627329	0.144724289	2.99878	3.03316	22.15754304	22.34075037	BPI03, baseline
Piston	BPI03	2.5	160	baseline	2	0.02509543	0.344359053	0.108044394	2.99972	3.0337	22.28527807	22.37905278	BPI03, baseline
Piston	BPI03	2.5	160	baseline	3	0.88578409	-1.173909536	0.016414361	2.99926	2.64854	20.12285548	20.21175643	BPI03, baseline
Piston	BPI03	2.5	160	baseline	4	1.77613054	-1.800272447	0.009238891	3.00078	1.55096	19.59081543	19.69338878	BPI03, baseline
Piston	BPI03	2.5	160	baseline	5	2.50268276	-2.068183899	0.022234348	3.2988	0.42546	19.67967893	19.81209116	BPI03, baseline
Piston	BPI03	2.5	160	baseline	6	3.01035465	-2.196785012	0.014937037	4.49874	0.34998	19.97876176	20.13666685	BPI03, baseline
Piston	BPI04	2.5	160	baseline	1	0.01502176	0.144204589	0.020586105	2.99878	3.03316	22.15754304	22.34075037	BPI04, baseline
Piston	BPI04	2.5	160	baseline	2	0.02509543	0.244010819	0.040152743	2.99972	3.0337	22.28527807	22.37905278	BPI04, baseline
Piston	BPI04	2.5	160	baseline	3	0.88578409	-1.205133681	0.044383324	2.99926	2.64854	20.12285548	20.21175643	BPI04, baseline
Piston	BPI04	2.5	160	baseline	4	1.77613054	-1.91866783	0.011400653	3.00078	1.55096	19.59081543	19.69338878	BPI04, baseline
Piston	BPI04	2.5	160	baseline	5	2.50268276	-2.195269365	0.023649871	3.2988	0.42546	19.67967893	19.81209116	BPI04, baseline
Piston	BPI04	2.5	160	baseline	6	3.01035465	-2.368089735	0.016408173	4.49874	0.34998	19.97876176	20.13666685	BPI04, baseline
Piston	BPI04	2.5	160	hardness, 1 mmol/L	1	0.01578331	0.272607103	0	3.004129594	3.031776835	21.88658248	21.82889568	BPI04, hardness, 1 mmol/L
Piston	BPI04	2.5	160	hardness, 1 mmol/L	2	0.02513129	0.719955714	0.747900634	2.999962492	3.026968606	22.36396291	22.49355216	BPI04, hardness, 1 mmol/L

Figure 11. Example of the measurement data and the meta data stored in the database.

Information about the measurements and the conditions under which the water meters were operated are provided in a separate document which is available for downloading from the website of the user interface. This document also contains information on the topic of standard deviations as well as links to further information and publications. The user interface is accessible via the project website at https://www.ptb.de/empir2018/metrowamet/information-communication/downloads/.

As the virtual flow meter could not be realised as envisioned due to the highly heterogenous nature of the measurement results concerning water meter performance, Objective 4 was partially achieved.

5 Impact

Eight presentations were given by the project partners at European and international conferences. As of the end of the project, the project's progress was presented at ten events organised by the project consortium. In November 2019, a one-day dissemination workshop was held at CETIAT. The focus was on dynamic measurements methods and consumption measurements in water metering. In June 2020, a first webinar covering Metrowamet results was held. A second webinar giving updates on project results took place in June 2021. In September 2021, an online dissemination workshop was organised at which all project outcomes were presented and discussed. Furthermore, an outlook was given on how to proceed with the project findings. The presentations of the dissemination workshop can be downloaded here. With more than sixty participants from all over the world, the webinars as well as the dissemination workshop were well attended. Representatives from water meter manufacturers, regulatory authorities participated as well as members of metrological institutes and representatives from relevant associations.

An end-user advisory board was set up, comprised of water meter manufacturers, water utilities and standardisation bodies. Further to this, AQUA, given their long-term and diverse experience, provided useful insights from a water meter manufacturer's perspective. WRC Ltd contributed the perspective of water utilities. In addition, articles on the Metrowamet project appeared in four newsletters related to water utilities in Germany and Denmark. One trade article was published on the WaterTech website which is targeted at professionals working with water and water circuits.

Impact on industrial and other user communities

As a result of the project, metrological infrastructure and protocols are available to assess domestic water meters under dynamics load changes in the future. The rigs developed in the project for meter tests under dynamic load changes were realised based on different principles, which facilitates uptake by stakeholders (e.g. manufacturers of water meters) and strengthens confidence in the novel test regime and associated measurement uncertainties.

International key players in the manufacturing of high-quality domestic water meters are located in Europe. The project outputs will thus strengthen the position of European manufacturers of domestic water meters as it will render the deployment of low-cost meters with low performance quality unattractive. By this, the outputs of the project will simultaneously support consumer protection. Water utilities will be supported to better demonstrate the quality of water meter performance in case of customer enquiries.

All aspects in the project related to measurements under dynamic load changes are of interest to the entire community active in liquid flow measurements as dynamic calibrations are moving more and more into focus. Moreover, due to forthcoming developments, the reaction of fast responding heat meters to real world-loads is under discussion. The outcomes of the Metrowamet project can be used to pave the way to solve these issues.

The project brings benefits to water utilities, by providing for the first time, a concise overview of potential deterioration of water meter performance due to operating conditions and a user interface to assess overall potential risks of legal non-compliance when participating in sampling procedures. The compilation of typical operating conditions in Europe and the provision of assorted test scenarios supports meter manufacturers and testing laboratories to set up dedicated performance tests of water meters in the future. This will be of further interest when meters based on novel technologies are put on the market, as they need to undergo a procedure of qualification and their measurement stability needs to be demonstrated beforehand. Thus, the outputs of the project will contribute to a shorter time window between meter development and market maturity.

Impact on the metrology and scientific communities

Based on the outputs of the project, NMIs (National Metrology Institutes) and DIs (Designated Institutes) will be able to establish new capabilities at their institutions for calibrations under dynamic flow conditions. A metrological framework is available now to address water meter performance under real-world operation conditions. The comprehensive insights gained in the project and the facilities available will enable the metrological community to better support their industrial stakeholders (i.e. manufacturers of water meters, water suppliers) in this regard.

Knowhow and capabilities established at NMI and DI level on device assessment for rapidly changing flows and small flows (lower than 3 L/h) will prove to be extremely useful for reliable flow measurements in other applications, such as nozzle-specific optimised fuel injections in engines or process control by monitoring the momentary flow e.g. in pharmaceutical and food industries.

The composition of usage and peak factors related to water consumption in households, including other outputs of the public supply networks and their potential developments with regards to climate and socio-economic changes are of major interest and thus, are the topic of various research projects. Any in-depth studies related to these factors or differentiated forecasts on future consumptions, including correlations with climate changes or socio-economic factors, rely amongst others on time-resolved water consumption data from households. The recommendations developed in this project for consumption monitoring and reliability assessment of water meters will support research in this regard.

Impact on relevant standards

Since actual water consumption profiles deviate strongly from the well-defined, constant and reproducible reference flows as prescribed in existing documents in legal metrology such as OIML R49 or ISO 4064, this might affect the cumulative uncertainty of water meters which is not seen in the standard continuous test regime. The research carried out in this project and the infrastructure and protocols established in this context will contribute towards solving this key issue. The project has already delivered input and will continue to do so to all relevant international and national bodies dealing with sampling of water meters as it will provide systematic insights on how real-world conditions may affect water meter performance, including associated measurement deviations, and the means to estimate their effects.

In particular, the project and its progress were presented at CEN/TC92/WG2 “Water meters - General Requirements”. Further reports were presented at meetings of working groups dedicated to water meters of national bodies and associations. The WELMEC WG13 “Water and heat meters” received updates about the project on a regular basis. Furthermore, ISO-TC 30 “Water meters” and OIML-TC 8 “Water meters” were provided with brief reports on the project linked to their meetings.

Longer-term economic, social and environmental impacts

Water is about to become the most valuable resource on Earth, taking in account that aquifers and river basins are depleted or polluted, and reservoir capacities prove insufficient in many regions. New technologies like smart meters as supported by this project are progressively playing a more important role within the water sector by helping to gather information from consumers, which is the first requirement for developing an efficient water management system. The progress made in the project regarding leakage detection and monitoring of small flow rates can be put to direct use in this context and will contribute to the European Commission's s goal for rational and responsible use of Europe's water resources. An approach which can contribute towards prolonging the lifetime of a water meter or provide incentives for conserving water as envisaged by this project, will help to ensure affordable access to this commodity in Europe. Since shorter verification periods for water meters can lead to immediate and high basic costs for consumers, an improved understanding of meter performance under real-world operation conditions will help water suppliers to get a better grasp of the metering quality and enable them to plan accordingly.

Used water meters are thrown away as it is not economically viable to have them maintained. However, if the operating period of a batch could be prolonged by improved knowledge on meter performance under real-world operation conditions as gained by this project, then fewer meters would have to be thrown away and a significant amount of material and energy resources could be saved.

Extensive installation networks, changes to materials used for buildings and installations as well as popular do-it-yourself (DIY) works in households have led to a significant rise in water pipe damages. Methods which enable the early detection of unusual water consumption will help insurance companies and individuals to save damage related costs. The outputs of the projects related to background leakage detection such as the leakage detection algorithm can contribute to mitigating these risks.

The European water sector is characterised by a complicated regulatory environment across various political hierarchy levels which results in fragmentation such as varying regulations and standards in different countries. This severely hampers overarching innovations in the water sector, hence a much-needed pan-European approach in this field was prepared in this project, with the intention to lessen barriers.

6 List of publications

Carratù, M., Dello Iacono, S., Di Leo, G., Liguori, C., Pietrosanto, A. 2021. Image Processing Technique for Improving the Sensitivity of Mechanical Register Water Meters to Very Small Leaks. Sensors, 21, 7251. https://doi.org/10.3390/s21217251

Büker, O., Stolt, K., Lindström, K., Wennergren, P., Pentinnen, O., Mattiason, K., 2021. A unique test facility for calibration of domestic flow meters under dynamic flow conditions. Flow Measurements and Instrumentation., vol. 79, June 2021. https://doi.org/10.1016/j.flowmeasinst.2021.101934

Büker, O., Stolt, K., Kroner, C., Benkova, M., Pavlas, J., Seypka, V., 2021. Investigations on the influence of total water hardness and pH value on the measurement accuracy of domestic cold water meters. Water, doi: 10.3390/w13192701

Pietrosanto, A., Carratù, M., Liguori, C., 2021. Sensitivity of water meters to small leakage. Measurement, vol. 168, https://doi.org/10.1016/j.measurement.2020.108479

Schumann, D., Kroner, C., Unsal, B., Haack, S., Kondrup, J., Christophersen, N., Benkova, M., Knotek, S., 2021. Measurements of water consumption for the development of a new test regime for domestic water meters. Flow Measurements and Instrumentation, vol. 19, June 2021. https://doi.org/10.1016/j.flowmeasinst.2021.101963

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/