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DYNAMIC CAPABILITIES: VALIDATION OF A BENCH FOR SMALL WATER METERS UNDER SUSPENDED SOLIDS AND ANALYSIS USING SEM/PLS-SEM

CAPACIDADES DINÁMICAS: VALIDACIÓN DE UN BANCO PARA MICROMEDIDORES BAJO SÓLIDOS EN SUSPENSIÓN Y ANÁLISIS BAJO SEM/PLS-SEM

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Dynamic capabilities: validation of a bench for small water meters under suspended solids and analysis using SEM/PLS-SEM

Capacidades dinámicas: validación de un banco para micromedidores bajo sólidos en suspensión y análisis bajo SEM/PLS-SEM

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ABSTRACT

Accurate flow measurement in domestic drinking-water networks is challenged by suspended solids that degrade meter performance. This study introduces a high-fidelity suspended-solids calibration bench for ½″–1″ meters and evaluates its acceptance and impact using a sequential mixed-methods design and SEM/PLS-SEM. The method combined a survey (n=135) with semi-structured interviews (n=5). The bench integrates traceable references, TSS/turbidity monitoring, and controlled particle dosing to replicate real network conditions. Quantitative results show that perceived reliability, cost reduction, time efficiency, regulatory traceability, and environmental sustainability significantly predict adoption intentions among utilities, suppliers, and industrial users. Qualitative interviews corroborate demand for formal reporting, certification readiness, and framework agreements. Conceptually, we operationalize metrological capability as a microfoundation of dynamic capabilities—sensing, seizing, and reconfiguring—linking measurement infrastructure to organizational resilience, innovative, learning, and competitive positioning.

Keywords: dynamic capabilities; suspended solids; water meter homologation; metrological capability; SEM/PLS-SEM

RESUMEN

La medición precisa de caudal en redes domésticas de agua potable se ve desafiada por los sólidos en suspensión que degradan el desempeño de los medidores. Este estudio introduce un banco de calibración de alta fidelidad para sólidos en suspensión en medidores de ½″–1″ y evalúa su aceptación e impacto mediante un diseño secuencial de métodos mixtos y SEM/PLS-SEM. El método combinó una encuesta (n=135) con entrevistas semiestructuradas (n=5). El banco integra referencias trazables, monitoreo de SST/turbidez y dosificación controlada de partículas para replicar condiciones reales de red. Los resultados cuantitativos muestran que la confiabilidad percibida, la reducción de costos, la eficiencia en tiempos, la trazabilidad regulatoria y la sostenibilidad ambiental predicen significativamente las intenciones de adopción entre empresas de servicios públicos, proveedores e industrias. Las entrevistas cualitativas corroboran la demanda de informes formales, preparación para certificación y acuerdos marco. Conceptualmente, se operacionalizó la capacidad metrológica como una microfundación de las capacidades dinámicas —detectar, aprovechar y reconfigurar— vinculando la infraestructura de medición con la resiliencia organizacional, la innovación, el aprendizaje y el posicionamiento competitivo.

Palabras clave: capacidades dinámicas; sólidos en suspensión; homologación de medidores de agua; capacidad metrológica; ecuaciones estructurales-SEM

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INTRODUCTION

Flow measurement in drinking water systems is essential for sustainability, fair billing, and efficient resource management. In domestic contexts, small-diameter meters (½″–1″) dominate, yet their accuracy is compromised by suspended solids that cause abrasion, obstruction, or signal interference. Existing international standards, such as ISO 4064 and OIML R49, assume clean water conditions, leaving a gap in evaluating meters under real, sediment-laden environments.

The behavior of suspended particles—shaped by size, density, and velocity—creates heterogeneous flow conditions that affect each meter technology differently: mechanical meters suffer abrasion and clogging, ultrasonic devices face signal scattering and attenuation, and electromagnetic meters encounter conductivity variations. Despite its significance, global literature on test benches for suspended solids is fragmented, with prototypes in Mexico, "slug" tests in the U.S., agricultural studies in China, and impurity-sensitivity analyses in Europe. None provide a standardized, reproducible solution aligned with real network conditions.

This gap translates into operational and strategic risks: utilities and industries acquire meters without empirical validation, leading to premature failures, higher costs, and disputes, while suppliers lack independent evidence for homologation under sediment exposure. The absence of high-fidelity benches also constrains innovation, as predictive models of meter performance cannot be reliably developed. The problem is especially critical in Latin America, where sediments are recurrent and utilities face growing demands for efficiency and transparency.

In response, the Metrology Laboratory of Aguas de Cartagena S.A. developed an innovative suspended-solids calibration bench that integrates traceable references, advanced instrumentation, and controlled suspension systems to replicate real network conditions. This study evaluates its acceptance and impact through SEM/PLS-SEM, linking perceived reliability, cost reduction, efficiency, traceability, and sustainability with adoption intentions. Conceptually, it frames metrological capability as a microfoundation of dynamic capabilities—sensing, seizing, and reconfiguring—positioning measurement infrastructure as both a technical solution and a strategic driver of organizational resilience, innovation, and competitiveness.

THEORETICAL FRAMEWORK

Flow measurement in drinking water networks constitutes a fundamental pillar for the efficient management of water resources, fair billing, and the reliability of hydraulic infrastructure. In particular, small-diameter meters (½” to 1”) are the most common in domestic applications, and therefore have been the subject of multiple studies on their behavior under non-ideal operating conditions (International Organization for Standardization, 2014). However, a critical factor affecting their accuracy is the presence of suspended solids, which can induce phenomena such as abrasion, partial obstruction, or biases in the measurement signal, depending on the meter technology (Bonola-Alonso et al., 2011).

International standards ISO 4064 and OIML R 49 establish the metrological and technical requirements for drinking water meters, including conditions of accuracy and repeatability under minimum (Q1), transitional (Q2), nominal (Q3), and overload (Q4) flow rates (International Organization for Standardization, 2014; International Organization of Legal Metrology, 2013). Nevertheless, these standards assume as a reference condition the circulation of clean water, without solid particles. Therefore, experimentation with suspended solids requires specialized benches capable of maintaining controlled and reproducible particle concentrations in order to evaluate the real response of measuring instruments.

The transport of solid particles in a liquid flow is governed by the interaction of gravitational, drag, and turbulence forces. For small-diameter particles (<100 μm), sedimentation can be modeled using Stokes' law, whereas for larger particles it is necessary to apply correlations such as Schiller–Naumann (Crowe, Sommerfeld & Tsuji, 1998). Factors such as mean particle size (d50), the relative density of solids with respect to water, and flow velocity determine whether the particles remain in suspension or tend to deposit on pipe walls (Chhabra, 2007).

In metrological terms, the effects of solids differ according to the technology. Mechanical meters (e.g. multi-jet, oscillating piston, turbine) are susceptible to bearing abrasion, clogging of moving parts, and increases in head loss (Bonola-Alonso et al., 2011). Ultrasonic meters, on the other hand, face problems of dispersion and attenuation of the acoustic signal, which may alter the interpretation of the velocity profile and generate biases dependent on particle concentration and granulometry (Li & Ren, 2011).

To reproducibly evaluate these effects, it is necessary to design test benches with recirculation and agitation systems that ensure suspension homogeneity, avoiding low-energy zones where sedimentation may occur. The use of flow standards with metrological traceability —such as Coriolis meters or gravimetric systems— is essential to guarantee the accuracy of the results and to allow proper estimation of measurement uncertainty, following the guidelines of the Guide to the Expression of Uncertainty in Measurement (JCGM, 2008). Likewise, the characterization of solids should be performed using standardized methods, such as the determination of total suspended solids (TSS) or turbidity measurement (APHA, AWWA & WEF, 2017).

In summary, the literature shows that the presence of suspended solids can significantly compromise the performance of drinking water meters, and that test benches are indispensable tools to study these phenomena under controlled conditions. The integration of normative criteria, fundamentals of two-phase fluid mechanics, and methodologies of metrological assurance enables the development of a robust experimental framework for the homologation and improvement of measurement technologies in real operating contexts.

International Experiences with Benches for Analyzing Suspended Solids in Small Water Meters

The international literature specifically addressing suspended solids in test benches for small-diameter meters (½″–1″) is relatively limited, but representative experiences in the Americas, Europe, and Asia provide useful technical guidelines and design lessons.

Mexico (water–sediment bench for household meters)

One of the most cited precedents in Ibero-America is the bench developed by Bonola-Alonso et al., (2011), designed to subject small-diameter meters to controlled conditions of water with sediments. The study describes the construction stages of the bench, the experimental program, and the results: in addition to the recirculation system and particle dosing, it demonstrates that damage and metrological bias are not limited to moving components but also affect bearings and supports, leading to increased head loss and drift depending on particle size. This work is a regional milestone, as it explicitly documents a liquid–solid two-phase bench for small meters, serving as a guide for the design of mixing, conditioning, and TSS/PSD sampling lines. Nevertheless, the bench was a low-fidelity prototype with reproducibility limitations.

United States (sand “slug” tests in new meters).

Buck et al., (2012) evaluated the effect of mineral particles (sand) deliberately introduced into a bench to assess the performance of commercial technologies representative of the residential market. They found that oscillating piston meters were the most affected by sand injection, while multi-jet and fluidic oscillator designs tolerated abrasion and clogging better, showing distinct error and degradation patterns after exposure. Although the protocol focused on a “slug” injection rather than prolonged regimes, the methodology of reference and cross-comparison among technologies stands out as a good bench practice to characterize sensitivity to particulates. In summary, the bench developed by Buck et al. (2012) was innovative in clearly demonstrating the vulnerability of certain meters to solid particles; however, it did not reach the level of a comprehensive system for homologation or long-term evaluation, remaining instead as a comparative laboratory test rather than a reference bench.

China (comparative benches with water–sand in pressurized irrigation).

In the agricultural sector (diameters and flow rates comparable to household use), a test bench was reported with sediment concentrations ranging 0.2–7.19% and three velocity levels, using a triangular weir as the reference to compare an electromagnetic, an ultrasonic, and a domestic water meter. Results showed that the electromagnetic meter maintained the best reliability with water–sand mixtures, while the transit-time ultrasonic and the mechanical meter exhibited higher error dispersion with increasing concentration and velocity variations. The study highlights the importance of ensuring homogeneous suspension and critical velocities during testing to avoid deposition (Su et al., 2021). However, its main limitation lies in its focus on the agricultural sector, which means that its extrapolation to domestic drinking water networks requires adjustments in flow conditions, pressures, and applicable regulations.

Europe (EMPIR/Flow Measurement infrastructure: "close-to-use" benches and impurity sensitivity).

In Europe, metrology consortia have extended benches to replicate "real-life" conditions (dynamic profiles, transients, valves, and others). Although these projects (e.g., MetroWaMet) focus on hydraulic dynamics rather than particulates, their guidelines on flow conditioning, traceability, and testing under perturbations are applicable to solid-laden flows. In parallel, regulatory manuals such as the UK's Ofwat (2022) highlight that in volumetric/PD meters, particle presence may clog or erode chambers, causing permanent head loss, reinforcing the relevance of benches capable of introducing and controlling solid impurities for robustness testing. However, it was not established as a comprehensive reference bench, but rather as a methodological platform aimed at the oversight of suppliers and water companies under specific regulatory parameters.

Ultrasonic meters: evidence of attenuation and dispersion by particles.

Laboratory tests and technical notes in Europe and Italy on ultrasonic meters indicate that suspended particles attenuate and scatter acoustic signals, reducing operating range and affecting linearity, hence recommending their preferential use in "clean water" conditions. From a bench-testing standpoint, these publications support the need for on-line turbidity/TSS instrumentation and air control to properly interpret signal degradation and time-of-flight bias in the presence of solids (Ciaravino et al., 2011). Nevertheless, its scope was more focused on exploratory laboratory tests, with limitations in terms of portability, large-scale replicability, and linkage with formal homologation processes. In this sense, the bench developed by Ciaravino et al. served as a solid academic precedent but did not consolidate as a reference infrastructure broadly applicable in public services or industrial contexts.

Synthesis of bench design lessons.

Across regions, experiences converge on four main criteria: (i) homogeneous mixing and critical velocity control to avoid deposition (agitated tanks/recirculation loops and straight sections with "solid-compatible" conditioners); (ii) traceable references (gravimetric, Coriolis, or weir) to separate meter error from suspension inhomogeneity; (iii) solid characterization (TSS/PSD) and isokinetic sampling to reduce point bias; and (iv) before–during–after sequences (baseline with clear water, exposure with graded TSS levels, and post-exposure) to measure drift and damage. Empirical evidence suggests that mechanical meters are more vulnerable to sand (abrasion/clogging), transit-time ultrasonic meters to signal scattering/attenuation, and electromagnetic meters exhibit greater stability with water–sand mixtures. Consequently, any bench should be designed to test multiple technologies and controlled ranges of concentration/particle size. But with the indicated limitations.

Test bench for suspended solids analysis

The test bench developed by the staff of the Metrology Laboratory of Aguas de Cartagena S.A., in collaboration with a local metalworking company, arises as a response to a widely recognized need in the literature: the absence of high-fidelity experimental platforms capable of evaluating the performance of small potable water meters (½" to 1") under real operating conditions, specifically in the presence of suspended solids, and above all, that are original, innovative, and traceable, ensuring reproducible conditions comparable at an international level.

While most traditional benches focus on tests with clean water and are limited by the constraints already discussed, this development makes it possible to simulate scenarios that more accurately represent the daily operation of distribution networks, where solid particles are present and directly affect the accuracy, durability, and reliability of the equipment. In terms of instrumentation, the bench is equipped with pressure and temperature transmitters, flowmeters, and a specialized analyzer for online monitoring of suspended solids and turbidity, enabling real-time characterization of suspension homogeneity. The equipment designed and implemented is original, innovative, and capable of delivering reproducible results.

Based on the review of scientific and technical literature, this bench currently constitutes the first and only system reported worldwide that integrates a design adaptable to different particle sizes and solid densities, as well as to different types of small meters, within a controlled laboratory environment. This characteristic makes it an unprecedented tool for applied research and for the homologation of measurement technologies, while addressing a critical gap in global metrological infrastructure. The sediment concentrations and velocity variations method is the Laboratory's competitive advantage and therefore cannot be disclosed in this work.

Its relevance, therefore, lies in providing an experimental environment that reproduces the real conditions of drinking water networks, strengthening the link between laboratory metrology and field practice, and delivering a significant advance in terms of innovation and technology transfer. Likewise, it can be portable for on-site use at the client's facilities. The suspended solids analysis bench also makes it possible to carry out around three additional tests, beyond the suspended solids analysis itself, which together amount to more than eleven procedures. Collectively, these are referred to as homologation tests for potable water meters ranging from ½" to 1". This service is offered by the Metrology Laboratory of Aguas de Cartagena S.A., in line with Mendoza Betin (2025d).

Knowledge gap

The review of international literature shows that, although there are precedents of test benches in Mexico, the United States, China, and Europe to study the interaction of suspended solids and drinking water meters, no specialized bench has been documented so far that operates under controlled laboratory conditions while simultaneously reproducing real distribution network conditions for small diameters (½"–1").

The absence of such platforms generates three main gaps:

1. Metrological: the lack of experimental data linking measurement error, solid concentration, and meter technology (mechanical, ultrasonic, electromagnetic) limits the development of reliable predictive performance models in Colombia.
2. Operational: public utilities, meter suppliers and industrial users lack empirical criteria to determine whether a given meter is suitable for the specific conditions of their network (sediments, water quality, particle size distribution).
3. Technological and commercial policy: meter providers do not have local and independent evidence to homologate technologies under solid-laden water scenarios, which creates uncertainty in acquisition, regulation, and control processes.
4. Reproducibility: the lack of standardized, repeatable testing conditions prevents the generation of comparable and universally valid results.

Research hypothesis

To structure a structural equation model (SEM/PLS-SEM) linking technology acceptance and performance under suspended solids conditions, the following hypotheses are proposed:

- **H1:** The perceived reliability of meters under suspended solids conditions positively influences the intention to adopt by public utilities, meter suppliers and industrial companies.
- **H2:** The reduction of operational costs resulting from fewer failures, replacements, or claims positively influences the acceptance of the bench as a reference for technological homologation.
- **H3:** The efficiency in calibration and testing times offered by the suspended solids bench significantly impacts the perceived added value among meter providers.
- **H4:** Traceability and regulatory compliance (ISO 4064, OIML R49, GUM) under suspended solids conditions strengthen the regulatory legitimacy of the results, increasing the likelihood of adoption in certification processes.
- **H5:** The impact on environmental sustainability (avoiding water waste, characterizing particles, minimizing residues) has a positive effect on the corporate and social image of participating companies, fostering collaboration and use of the bench.
- **H6:** The perception of innovation associated with the bench mediates the relationship between technical benefits (H1–H5) and the final decision of adoption and technological homologation in the sector.

Research objective

General: To evaluate, through a structural equation modeling approach (SEM/PLS-SEM), the acceptance and impact of the suspended solids test bench on the homologation and selection of drinking water meters (½” to 1”) in Colombia, considering the perceptions of public utilities, meter providers, and industrial water users, in order to identify the determining factors of adoption and to establish technical criteria of metrological validity under real conditions reproduced in a laboratory environment.

Specific:

1. To determine the effects of reliability, cost reduction, testing time efficiency, regulatory traceability, and environmental sustainability on the perception of bench acceptance.

2. To analyze the relationship between the perception of innovation of the bench and the intention of adoption by public utilities, providers, and industrial users.

3. To build a predictive model of technological acceptance that projects the bench's relevance in regulation and in strategic decision-making for meter purchase and homologation.

4. To generate guidelines for technological and commercial policies on meter adoption in Colombia, based on experimental evidence reproduced under controlled conditions.

METHODOLOGY

Research Design

The study employs a non-experimental design and utilizes a sequential mixed-methods strategy (Quantitative and Qualitative) with both exploratory and explanatory–descriptive purposes. It was conducted over a three-month period (August–November 2025) within a cross-sectional framework, planned for execution during the fourth quarter of 2025.

From the quantitative perspective, the research analyzes the relationship between the dependent variables—intention to adopt, reduction of operational costs derived from failures, efficiency in calibration and testing times provided by the suspended solids bench, traceability and regulatory compliance, and environmental sustainability—and the independent variable, defined as the availability of a calibration bench for small drinking water meters (½”–1”) based on suspended solids analysis. The aim is to study both the acceptance and impact of this bench on the homologation and selection of potable small water meters. A structured questionnaire was administered to a representative sample of professionals in quality, process engineering, and reliability management from public water and sewer utilities, meter suppliers in Colombia, and industrial companies located in Cartagena de Indias.

The qualitative phase was designed to deepen the interpretation of quantitative results by exploring how industry professionals themselves perceive and contextualize the findings, thus providing a richer and more comprehensive understanding of the phenomenon.

Population and Sample

- Target population: Professionals from the mentioned economic sectors working in quality assurance, process management, and reliability engineering.
- Quantitative sample: A total of 135 professionals were chosen through purposive non-probability sampling, based on three criteria: (a) at least four years of professional experience, (b) holding a formal leadership role in their organizations, and (c) willingness to voluntarily participate.
- Qualitative sample: Five (5) respondents were intentionally selected from the quantitative pool to provide deeper insights into the results, while meeting the same criteria.

Data Collection Techniques and Instruments

Quantitative Component

A custom-designed structured ad hoc questionnaire of 30 Likert-scale items (1–5) was developed to assess six dimensions corresponding to the dependent and independent variables. The instrument design was guided by previous research in flow metrology, solids analysis, and organizational innovation (Bonola-Alonso et al., 2011; Mendoza Betin, 2018a, 2025a; Su et al., 2021).

The construction process followed four sequential phases:

1. **Initial design**
   - Review of the relevant literature and adaptation of validated scales from prior studies.
   - Development of items consistent with the objectives and hypotheses of the study.
2. **Content validity**
   - Expert assessment by three specialists (One PhDs in metrology and two with a Master's in suspended solids analysis methods), following the criteria of Hernández-Nieto (2011) and Lynn (1986).
   - Based on feedback, four items per dimension were refined, and one item from each variable was removed.
3. **Pilot testing and adjustments**
   - Piloting with 15 professionals from the sectors considered (outside the final sample), in line with recommendations from Hair et al. (2010).
   - Adjustments were made to improve clarity, simplify technical terminology, and optimize item length and structure. Three items were rewritten.
4. **Final administration**
   - The survey was distributed online between August and November 2025 to all 135 participants, including the 15 from the pilot test.
   - The response rate was 98%, resulting in 118 valid questionnaires, considering only the final 120 completed questionnaires.

Internal reliability was evaluated using Cronbach's alpha, which yielded an overall coefficient of 0.96. Sub-dimensions ranged between 0.88 and 0.95, indicating very high reliability. For data analysis, Structural Equation Modeling (SEM) was applied, in line with the methodological recommendations of Lloret-Segura et al. (2014), MacCallum et al. (1999), and Preacher & MacCallum (2003).

Qualitative Component

1. To complement the survey findings, five semi-structured interviews were carried out with selected participants.
2. Each interview lasted 60–90 minutes, was recorded with prior consent, and later transcribed verbatim.
3. Thematic coding and qualitative analysis allowed the identification of perceptions, interpretations, and reflections on the adoption of the suspended solids test bench within the mentioned sectors.
4. This stage provided a more detailed and integrated perspective of the phenomenon under investigation.

RESULT

The outcomes of this study, interpreted from a constructive standpoint, stem from a thorough examination of the data in accordance with the predefined methodology. By applying structural equation modeling, the hypotheses were tested, uncovering significant patterns, interrelations, and effects among the analyzed variables. This section provides an integrated summary of the results, which includes the creation of predictive models, the assessment of model fit indicators, and the estimation of essential parameters. Taken together, these elements deliver a precise and comprehensive understanding of the factors examined and their relevance within the research context.

The contrast analysis, aimed at evaluating the impact of the dependent variables—intention to adopt, reduction of operational costs caused by failures, efficiency in calibration and testing times offered by the suspended solids bench, traceability and regulatory compliance, and environmental sustainability—on the independent variable (availability of a calibration bench for small drinking water meters (½”–1”) based on suspended solids analysis), was conducted using SPSS and PLS software, both widely acknowledged as suitable for exploratory

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research. Following Cohen (1998), the f^2 index for the five variables demonstrated a strong association with the coefficient of determination (R^2), which reached 84.07%. This outcome highlights a substantial degree of dependence and significance among the variables under consideration.

Table 1

The Effects of Dependent Variables on the Independent Variable

Variables	**Effects $f2$**	**Total Effect**
Intention to adopt	0.344	Adequate or Relevant
Reduction of operational costs caused by failures	0.337	Adequate or Relevant
Efficiency in calibration and testing times offered by the suspended solids bench	0.339	Adequate or Relevant
Traceability and regulatory compliance	0.336	Adequate or Relevant
Environmental sustainability	0.323	Adequate or Relevant
Availability of a calibration bench for small drinking water meters (½”–1”) based on suspended solids analysis	0.327	Adequate or Relevant

Note: Based on proprietary measurements analyzed using SPSS and PLS (2025)

When evaluating the structural equation model (SEM) through the PLS method, it is essential that Q^2 values are greater than zero to demonstrate the existence of an endogenous latent variable. As presented in Figure 1, the obtained Q^2 value was 0.496, which significantly surpasses the minimum criterion. This result reinforces the robustness of the model and confirms its predictive relevance.

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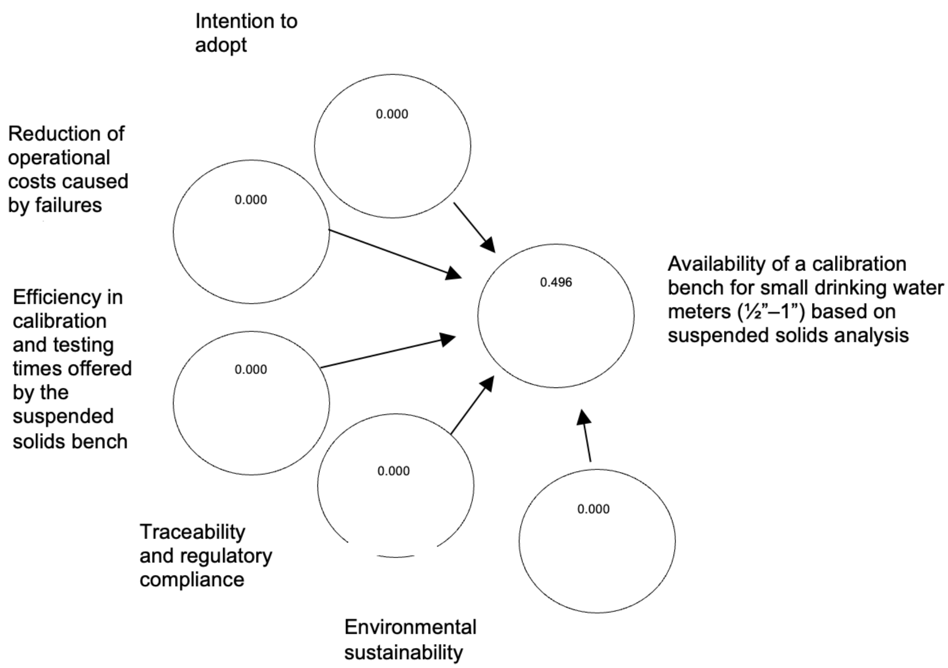
Figure 1

Predictive model



Note: Prepared based on calculations in SPSS and PLS (2025)

The Goodness-of-Fit index (GOF) was applied to determine how well the model aligns with and captures the empirical data. This index ranges between 0 and 1, with commonly accepted thresholds indicating that 0.10 reflects a weak fit, 0.25 a moderate fit, and 0.36 a strong fit. The evaluation results revealed that the model is both parsimonious and consistent with the data observed. The GOF value was computed as the geometric mean of the average communality —referred to as the Average Variance Extracted (AVE)— and the mean of the R^2 values, thereby strengthening the evidence of the model's overall validity.

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Table 2

Computation of the Goodness-of-Fit (GOF) Index

Constructs	**AVE**	**R2**
Intention to adopt	0.678	
Reduction of operational costs caused by failures	0.668	
Efficiency in calibration and testing times offered by the suspended solids bench	0.643	
Traceability and regulatory compliance	0.657	
Environmental sustainability	0.655	
Availability of a calibration bench for small drinking water meters (½”–1”) based on suspended solids analysis	0.667	0.7475
Average Values	3.819	0.7475
AVE * R2	0.4985	
GOF = √AVE * R2	0.7065	

Note: Based on proprietary measurements analyzed using SPSS and PLS (2025)

The Standardized Root Mean Square Residual (SRMR), derived from the differences between the observed correlations and the estimated covariance matrices, yielded a value of 0.064. Since this falls within the acceptable threshold (SRMR ≤ 0.09), the model can be regarded as having an adequate fit. Furthermore, the Chi-square statistic was 1914.082, and the Normed Fit Index (NFI) reached 0.807, both providing additional confirmation that the measurement model is suitable.

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Table 3

Model estimators

Model estimators	
SRMR	0.064
d_ULS	1.643
d_G1	0.936
d_G2	0.787
Chi-Square	1.914.082
NFI	0.807

Note: Based on proprietary measurements analyzed using SPSS and PLS (2025)

Finally, Table 4 presents the correlation coefficients among the latent variables, which makes it possible to infer a strong association between the exogenous latent constructs and the endogenous observed variables.

Table 4

Correlation of latent and observable variables

Variables	IA	ROC	EIC	TRC	ES	ACB
Intention to adopt	**1.000**					
Reduction of operational costs caused by failures	0.277	**1.000**				
Efficiency in calibration and testing times offered by the suspended solids bench	0.281	0.282	**1.000**			
Traceability and regulatory compliance	0.283	0.275	0.291	**1.000**		
Environmental sustainability	0.292	0.312	0.297	0.298	**1.000**	

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Availability of a calibration bench for small drinking water meters (½”–1”) based on suspended solids analysis	0.287	0.295	0.285	0.275	0.273	**1.000**

Note: Based on proprietary measurements analyzed using SPSS and PLS (2025)

The evaluation of the measurement model confirmed its suitability as a confirmatory framework, demonstrating that all proposed hypotheses reached statistical significance and were therefore validated. The results of this study reveal that the analyzed factors exerted a positive impact on fostering broad acceptance among water meter suppliers, public water and sewerage companies in Colombia, and industrial firms in Cartagena de Indias regarding the adoption of homologation tests for small meters (½” to 1”). These tests, which include more than eleven procedures such as suspended solids analysis using the test bench, aim to guarantee proper acquisition and identify opportunities for improvement in meter performance. This underscores the technical, economic, and environmental importance of such practices in flow measurement, while also reinforcing their theoretical foundation. Nonetheless, the extent to which these findings can be generalized will depend on subsequent research employing similar methodological designs.

Qualitative Component

The qualitative phase of the study, conducted through semi-structured interviews with five employees from organizations operating in the Colombian Caribbean region and the city of Cartagena de Indias, revealed a consistent endorsement of the suspended solids analysis method. At the same time, respondents described the calibration bench as innovative, original, and unprecedented in the national context, noting that *“we had not seen a bench with these characteristics in Colombia.”* While participants requested confidentiality regarding their names and professional roles, their testimonies converged in recognizing the value and potential of the calibration bench developed by Aguas de Cartagena S.A.

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Interviewees acknowledged prior familiarity with suspended solids testing and regarded its formal incorporation into a regional and national calibration infrastructure as an important step toward reinforcing trust in both traceability and the reliability of measurement results. Their acceptance, however, was not limited to the suspended solids method alone: several participants emphasized their interest in exploring the broader set of eleven homologation tests available at the laboratory, particularly given the explicit alignment of these services with sustainability practices.

A recurrent concern across organizations was the financial dimension of the service. Respondents underscored the need for transparency regarding calibration and homologation fees, while also noting the relevance of volume-based discounts and contractual schemes designed for recurring clients. In their view, such mechanisms would facilitate not only affordability but also continuity in the application of these methods.

Beyond cost considerations, the interviews revealed a strong expectation for formal certification and compliance mechanisms. For most participants, the inclusion of detailed reports constituted a non-negotiable requirement, serving both as internal decision-making support and as indispensable documentation for external audits. Closely tied to this expectation was the demand for added value in the form of comprehensive technical analyses, rapid turnaround of results, and sustained post-service support—factors described as decisive in procurement processes.

Interestingly, some respondents interpreted the bench not only as a technical tool but also as a strategic asset for enhancing corporate legitimacy. By reducing water consumption and contributing to lower carbon emissions, the service was viewed as an opportunity to project a stronger image of environmental and social responsibility before regulators and international clients. In this sense, the bench was perceived as both a metrological innovation and a reputational instrument.

In light of these findings, interviewees proposed the establishment of framework agreements that would regulate annual or semi-annual calibrations and homologation tests. Such agreements, they argued, would guarantee priority access to the laboratory while offering more favorable financial conditions, thereby fostering stronger and longer-term partnerships with client companies.

DISCUSSION

The results obtained in this study contribute to advancing the theoretical understanding of flow metrology under non-ideal conditions by linking suspended solids analysis to the technological acceptance of calibration benches. In line with the framework of dynamic capabilities (Mendoza Betin, 2018a, 2018b, 2019a), the suspended solids test bench represents an organizational mechanism to sense and respond to environmental contingencies —in this case, the operational variability of drinking water networks. The study reinforces the notion that innovation in metrological infrastructure is not only a matter of technical optimization but also a generator of legitimacy, resilience, and adaptive capacity for public utilities and industrial actors (Mendoza-Betin, 2021a, 2025b,c).

Theoretical contributions

From a theoretical perspective, this research bridges metrology, innovation management, and organizational theory. The suspended solids bench embodies a dynamic capability that enables companies to reconfigure their testing and homologation processes, responding to market pressures for sustainability and regulatory compliance. This resonates with Mendoza-Betin (2019b, 2021b), who underscores process innovation and knowledge transfer as key levers for competitiveness. By demonstrating the predictive power of factors such as perceived reliability, cost reduction, and environmental sustainability, the model expands the explanatory scope of prior works on calibration and dimensioning of water meters (Mendoza-Betin et al., 2024).

Practical implications

The practical implications are equally significant. For water utilities, suppliers, and industrial firms, the availability of a reproducible suspended solids analysis bench translates into operational benefits: better-informed procurement decisions, reduction of maintenance costs, and enhanced capacity to meet regulatory requirements. Moreover, it strengthens the corporate image of organizations by aligning technical practices with sustainability commitments, especially good leadership practices and EFR standards, echoing the findings of Mendoza-Betin (2025e, 2025f). The proposal of framework agreements, voiced in the qualitative phase, highlights a concrete path for institutionalizing these practices and fostering long-term partnerships between laboratories and clients.

Limitations and future research

However, limitations must be acknowledged. First, the study's scope was geographically bounded to Cartagena and the Colombian Caribbean region, which may restrict the generalization of findings to other contexts with different hydraulic and regulatory conditions. Second, the quantitative survey relied on purposive sampling, limiting the representativeness of the population. Third, although the predictive model demonstrated robustness, future research should incorporate longitudinal data to assess adoption over time. Additionally, given the laboratory's competitive advantage, some technical details —such as the sediment concentration and velocity variation method— could not be disclosed, which may constrain replicability.

Future research should therefore expand in three directions. At the metrological level, comparative studies across diverse particle types and sizes would enhance the predictive validity of the model. At the organizational level, cross-country analyses would test whether innovation adoption patterns replicate under different institutional frameworks. Finally, at the policy level, research should explore how suspended solids testing can be integrated into regulatory regimes, procurement guidelines, and sustainability standards. These agendas align with Mendoza-Betin (2022, 2025c, 2025e) arguments on the generative role of dynamic capabilities in shaping both technical innovation, leadership and social legitimacy.

CONCLUSION

This study demonstrates that the suspended solids calibration bench developed by Aguas de Cartagena S.A. constitutes an original and innovative contribution to flow metrology, bridging laboratory experimentation with the real conditions of drinking water networks. By integrating quantitative and qualitative evidence, it validates that perceived reliability, cost efficiency, time optimization, regulatory traceability, and sustainability significantly drive the acceptance and adoption of this technology. The findings also resonate with international precedents, such as the early prototype documented by Bonola-Alonso et al. (2011) in Mexico, the experimental lessons reported in Asia by Su et al. (2021), and the organizational innovation approaches framed by Mendoza Betin (2018, 2025a) in the Colombian context.

Together, these works reinforce the idea that suspended solids testing benches not only provide technical validation but also represent strategic assets that enhance corporate legitimacy, promote sustainability, and strengthen innovation capabilities in the water sector. While limitations regarding geographical scope and non-disclosed methods remain, the evidence gathered provides a robust foundation for future research and policy development. In doing so, this work not only fills a critical knowledge gap in global metrological infrastructure but also situates Colombia as a reference point in the advancement of applied metrology for public utilities and industrial contexts.

Notwithstanding the above, this case supports the perspective of Corporate Entrepreneurship proposed by Mendoza Betin, Arrieta Rojas, Llorente Tovar, & Paternina Barros (2020).

Declaration of conflict of interest

The researchers declare that there is no conflict of interest related to this research.

Author contribution statement

The authors: conceptualization, formal data analysis, investigation, methodology, project administration, resources, software, supervision, validation, visualization, writing – original draft, review and editing.

Statement on the use of Artificial Intelligence

The authors declare that Artificial Intelligence was used as a support tool for this article, and that this tool in no way replaced the intellectual task or process. The authors expressly state and acknowledge that this work is the result of their own intellectual effort and has not been published on any electronic artificial intelligence platform.

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