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Costa, Sierra, Selva: A Territory-Adaptive Implementation Framework for Water-Safe, Water-Efficient Sanitary Installations in Peru

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Article

Keywords: sanitary installations, territorial engineering, Legionella pneumophila, quantitative microbial risk assessment, water efficiency, life cycle assessment, Peru, Andes, Amazon, Bangladesh

Posted Date: September 29th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10398386/v1

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Additional Declarations: No competing interests reported.

Abstract

Background

Peru's three natural regions — an arid, highly seismic coastal strip; a high-altitude Andean highland with dispersed rural settlements; and a humid, flood-prone Amazon rainforest — present sanitary-installation design conditions that no single normative framework, including the mid-twentieth-century Hunter's curve still embedded in current design guidance, was built to address. Meanwhile, water-saving fixtures adopted worldwide to reduce potable water demand have lengthened hydraulic retention time (water age), accelerated disinfectant decay, and created conditions favorable to opportunistic pathogens such as Legionella pneumophila.

Objective

To translate an integrative design framework — combining quantitative microbial risk assessment (QMRA), dynamic hydraulic modeling, life cycle assessment (LCA), and user-behavior analysis — into a territory-adaptive implementation model that specifies, for each of Peru's three orographic regions, the construction procedures, materials, tools, phased implementation stages, and the competencies required of the public officials responsible for delivery, benchmarked against the experience of Bangladesh.

Methods

A structured literature review was conducted across indexed databases (Scopus, Web of Science, ScienceDirect, PubMed, IWA Publishing) with individual verification of the existence and currency of the DOI for each retained source. From the verified sources, a mathematical framework was derived integrating established equations for microbial growth (Baranyi-Roberts), temperature dependence (Ratkowsky), dose-response (exponential/Beta-Poisson), disinfectant decay, the modified Hunter curve, and standard LCA procedures (ISO 14040/14044, ReCiPe 2016), together with a multi-criteria decision framework (TOPSIS). This apparatus was then crossed against Peru's National Building Code (RNE), NTP/ASTM material standards, and the institutional mandates of SENCICO, SUNASS, DIGESA, and the Ministry of Housing to build the region-specific implementation model presented in Section 3.

Results

Water age is confirmed as the most consistently reported predictor of Legionella spp. concentration in building plumbing. Substituting PEX for copper reduces global warming potential by 42% and life-cycle cost by 62–63% (Asadi et al. 2016), and uPVC in place of galvanized steel or copper reduces energy consumption by 86% and 91% respectively (Xiong et al. 2020). In Peru, 40.8–42.5% of households report

intermittent water supply (Hernández-Vásquez & Vargas-Fernández 2025), a condition that compounds across the coast, highlands, and rainforest in region-specific ways — pressurized-network stagnation on the coast, gravity-fed community systems in the highlands, and river-sourced turbidity and flood exposure in the rainforest. For each region, the framework specifies distinct piping materials, trenching and anchoring procedures, monitoring tools, and a common eight-phase implementation roadmap, together with the competencies required of six categories of responsible officials.

Conclusions

The proposed framework offers a traceable scientific foundation and an operational, territory-specific roadmap — materials, construction procedures, phased implementation stages, and functionary training — for reconciling water efficiency with microbiological safety in Peru's coastal, highland, and Amazon sanitary installations, with explicit contextual benchmarking against Bangladesh. Priority future research includes multi-building empirical validation in each region and low-cost sensors for continuous monitoring.

1. INTRODUCTION

1.1 Peru's territorial diversity as a design constraint

Peru's orography divides the country into three natural regions with sharply different sanitary-engineering conditions. The coast is a narrow arid desert strip of high seismicity, concentrating most of the national population in dense, pressurized municipal networks subject to frequent intermittent supply. The Andean highlands span roughly 2,500 to over 4,800 meters above sea level, where night-time freezing, intense solar radiation, and dispersed rural settlements served by gravity-fed community systems — administered by Juntas Administradoras de Servicios de Saneamiento (JASS) rather than utility companies — dominate. The Amazon rainforest presents high humidity, seasonal flooding, elevated water tables, and river-sourced raw water with high turbidity, combined with remote logistics that lengthen material lead times. A single normative approach anchored in Hunter's curve, formulated for temperate mid-twentieth-century urban contexts, cannot hold simultaneously across these three orographic conditions.

1.2 Background and problem statement

The worldwide adoption of low-flow fixtures, faucets, and showerheads has effectively reduced potable water demand in the building sector; however, normative design guidance for sanitary installations has not been systematically updated to reflect the effects of this flow reduction on hydraulic residence time, residual disinfectant decay, and, consequently, on the proliferation of opportunistic pathogens such as Legionella pneumophila. Studies in certified "green" buildings have documented water ages and microbiological indicator concentrations higher than those found in conventional buildings (Rhoads,

Pruden & Edwards 2016), a design tension that current normative frameworks do not explicitly resolve — and one that Peru's territorial heterogeneity makes considerably harder to generalize.

1.3 Literature review

Recent research has identified water age — particularly its 95th percentile — as the variable most consistently associated with elevated Legionella spp. concentrations in building plumbing systems (Julien et al. 2022). Integrated hydraulic-microbiological models have been developed that can predict Legionella concentrations at points of use from network operational variables (Palmegiani et al. 2022). A critical review systematizes the mechanistic approaches available for modeling Legionella proliferation, identifying gaps related to spatiotemporal variability, biofilm-bulk water interaction, and the lack of integration with user behavior (Ortiz et al. 2025). Water-quality guidelines based on QMRA have been proposed for additional opportunistic pathogens, such as the Mycobacterium avium complex (Joshi et al. 2025). Experimental studies have evaluated how water-use patterns and disinfection heat shock modify short-term microbiome dynamics in domestic hot water systems (Favere et al. 2025), providing evidence — although not from the Peruvian context — on the plausibility of adaptive thermal strategies.

On the environmental sustainability axis, life cycle assessment applied to piping materials shows that substituting PEX for copper reduces global warming potential by 42% and total life-cycle cost by 62–63% (Asadi et al. 2016), while uPVC in place of galvanized steel or copper reduces energy consumption by 86% and 91% respectively (Xiong et al. 2020). At the contextual level, evidence on Peru documents that between 40.8% and 42.5% of households experience intermittent water supply, with higher prevalence in lower-density, lower-HDI areas (Hernández-Vásquez & Vargas-Fernández 2025), and that container-based sanitation faces integration tensions with formal sectoral planning in Lima (López et al. 2025). In Bangladesh, groundwater arsenic contamination affects 62 of 64 districts (Yunus et al. 2016), configuring a design challenge that combines chemical and microbiological risks simultaneously.

1.4 Knowledge gap and study contribution

The reviewed literature addresses quantitative microbial risk, water efficiency, and life cycle assessment as independent domains, without a framework that explicitly integrates them into region-specific design and implementation decisions. Virtually all available empirical evidence originates from North America, Europe, and East Asia, with minimal representation of countries with intermittent infrastructure and marked orographic diversity, such as Peru, or with concurrent chemical contaminants, such as arsenic in Bangladesh.

This study contributes to the state of the art in four ways. First, it integrates into a single explicit mathematical framework the mechanisms of temperature-dependent microbial growth, disinfectant decay, water-age hydraulics, and life cycle assessment, articulated through a multi-criteria decision tool. Second, it synthesizes and verifies — with DOI traceability — the available quantitative evidence in a comparative matrix contrasting design and material alternatives. Third, and centrally, it translates this framework into a territory-adaptive implementation model that specifies distinct construction procedures, material specifications, tools, and implementation phases for Peru's coast, highlands, and

rainforest. Fourth, it defines the competencies required of the public officials — municipal engineers, regulators, health authorities, certifiers, and community leaders — responsible for delivering that implementation, contrasting the whole with the adaptations observed in Bangladesh.

1.5 Objectives

General objective: To develop and substantiate, through the synthesis of verifiable evidence, a territory-adaptive implementation framework for sanitary installations that reconciles dynamic microbial risk, water efficiency, and life-cycle sustainability across Peru's coast, highlands, and rainforest.

- Systematize the established equations and mathematical models applicable to dynamic microbial risk and its interaction with building hydraulics.
- Build a quantitative Peru-Bangladesh comparison matrix from documented evidence with verifiable DOIs.
- Specify construction procedures, material specifications, tools, and implementation stages differentiated for Peru's coastal, highland, and Amazon regions.
- Define the competencies required of the public officials and community actors responsible for implementing the framework in each region.
- Identify the empirical validation lines needed to move from the conceptual framework to field evidence.

2. MATERIALS AND METHODS

2.1 Study design

This study adopts a structured literature review and conceptual mathematical modeling design, following the search and source-selection transparency criteria recommended by the PRISMA 2020 statement (Page et al. 2021), adapted to a narrative modality given that the objective is the construction of a territory-adaptive engineering implementation framework grounded in verifiable evidence, rather than a quantitative meta-analysis. No primary field data were collected (water-quality measurements, microbiological sampling, or user surveys); the parameters used in the illustrative scenarios of Section 4 are explicitly drawn from values reported in the cited sources.

2.2 Search strategy and selection criteria

Scopus, Web of Science, ScienceDirect, PubMed, and IWA Publishing (2016–2026) were searched, combining terms related to Legionella, building plumbing, water age, quantitative microbial risk assessment, life cycle assessment, pipe material, water supply Peru, and arsenic Bangladesh. Of approximately 70 records screened across ten targeted searches, 13 sources meeting the following inclusion criteria were retained: (i) publication in a peer-reviewed journal or indexed proceedings; (ii) an active DOI individually verified at the time of writing; (iii) direct relevance to one of the framework's axes.

Records without a verifiable DOI, with data not traceable to a primary source, or from non-peer-reviewed platforms were excluded.

2.3 Integrated mathematical framework

2.3.1 Time- and temperature-dependent microbial growth

Microbial concentration C(t) is modeled using the Baranyi-Roberts equation (Baranyi & Roberts 1994):

$$dC/dt = \mu max \cdot (1 - C/Cmax) \cdot A(t) \cdot C \quad (1)$$

where μmax is the maximum specific growth rate (h^{-1}), Cmax the maximum sustainable concentration, and A(t) an adjustment function for the physiological state of the population. The dependence of μmax on temperature T (°C) follows the Ratkowsky square-root model:

$$\sqrt{\mu max} = b \cdot (T - Tmin) \cdot [1 - \exp(c \cdot (T - Tmax))] \quad (2)$$

with Tmin ≈ 5°C and Tmax ≈ 55°C for Legionella pneumophila, and b, c strain-specific empirical constants — parameters that require distinct local calibration in the highlands (low ambient T) and the rainforest (high ambient T) discussed in Section 3.

2.3.2 Disinfectant decay

Residual chlorine decay follows temperature-dependent first-order kinetics (Arrhenius equation):

$$k(T) = kref \cdot \exp[(Ea/R) \cdot (1/Tref - 1/T)] \quad (3)$$

2.3.3 Quantitative microbial risk assessment (QMRA)

The inhaled dose during showering is estimated as:

$$D = Cw \cdot IR \cdot t \cdot \eta \cdot faerosol \quad (4)$$

Infection probability follows the exponential/Beta-Poisson model:

$$Pinfection = 1 - (1 + D/\beta)^{(-\alpha)} \quad (5)$$

Consistent with Joshi et al. (2025), this QMRA framework is extensible to other opportunistic plumbing pathogens by substituting the α, β parameters and exposure routes.

2.3.4 Hydraulics: water age and modified Hunter's curve

Water age at point of use i at time t is defined, following the tracer method, as:

$$Age_i(t) = \Sigma j [Vij(t) / Qi(t)] \quad (6)$$

The classical Hunter curve is modified to incorporate temporal variability of use — a modification that, as shown in Section 3, must itself be re-parameterized for gravity-fed highland networks that do not

conform to Hunter's original pressurized-network assumptions:

Qpeak = Σi [qi · pi · f(t) · βeff] (7)

2.3.5 Life cycle assessment and life-cycle costing

The LCA follows ISO 14040/14044, with the ReCiPe 2016 method (Huijbregts et al. 2017). Life-cycle cost is calculated through net present value:

NPV = Σt [Ct / (1 + r)^t], t = 0...n (8)

2.3.6 Multi-criteria decision analysis (TOPSIS)

Selection among design alternatives is carried out through TOPSIS, computing the weighted normalized decision matrix:

Vij = wj · [xij / √(Σi xij²)] (9)

2.4 Illustrative framework scenarios

- Scenario A — Material substitution: applying the impact reductions documented by Asadi et al. (2016) and Xiong et al. (2020) to the life-cycle cost function (Eq. 8) to compare copper, PEX, and uPVC in a representative residential building.
- Scenario B — Supply intermittency (Peruvian coast): incorporating the intermittent-supply prevalence reported by Hernández-Vásquez & Vargas-Fernández (2025) as an input distribution for water age (Eq. 6), evaluating its effect on μmax through Eq. (2).
- Scenario C — Adaptive thermal strategy: qualitative use of Favere et al. (2025) on heat shock and microbiome dynamics to argue, through Eq. (2), the plausibility of reduced baseline temperatures with periodic high-temperature pulses, subject to local calibration for each of Peru's three regions.

2.5 Building the Peru-Bangladesh comparison matrix

The comparison matrix (Table 2) was built by crossing water source and supply continuity, dominant microbiological/chemical risk, materials and construction procedures, and institutional/economic framework, with the quantitative data available in the verified sources for each country, complemented with standard industry technical specifications (ISO, ASTM standards, manufacturer catalogs).

2.6 Constructing the territorial implementation model

The region-specific model presented in Section 3 was built by crossing the documented evidence of Table 1 and the equations of Section 2.3 against three additional inputs: (i) Peru's National Building Code (RNE), including its seismic-design provisions (E.030) and sanitary-installation provisions (IS.010); (ii) Peruvian technical standards (NTP) and international material standards (ASTM) for piping and fittings; and (iii) the institutional mandates of SENCICO, SUNASS, DIGESA, and the Ministry of Housing, Construction and Sanitation. Climatic and orographic parameters — altitude bands, freeze-line depth,

seismic zonation, and humidity/precipitation regimes — were used to differentiate the coastal, highland, and rainforest specifications that follow.

3. TERRITORIAL IMPLEMENTATION FRAMEWORK FOR PERU

Peru's National Building Code treats sanitary installation largely as a uniform normative exercise. The framework below instead differentiates procedures, materials, tools, and implementation stages across the country's three natural regions, and closes with the phased roadmap and functionary competencies common to all three.

3.1 Coastal region (Costa)

Context: an arid, highly seismic coastal strip (Lima, Piura, Trujillo, Ica, Tacna) concentrating dense multi-family buildings on pressurized municipal networks, where 40.8-42.5% of households report intermittent supply (Hernández-Vásquez & Vargas-Fernández 2025) and the subsidized water tariff (approximately S/. 1.4/m³, ≈ US$0.44/m³) reduces the private incentive for conservation.

Table 3a. Material specification — Coastal region (source: prepared by the author from NTP/ASTM standards and cited LCA evidence).

Component	Specification	Justification
Cold-water piping	uPVC Class 10 (NTP 399.002) or PEX-a/b (ASTM F876/F877)	PEX reduces GWP100 by 42% and life-cycle cost by 62-63% vs. copper (Asadi et al. 2016)
Hot-water piping	Oxygen-barrier PEX (EVOH) or Type L copper where extreme thermal resistance is required	Avoids copper pitting corrosion in aggressive waters; copper retains better residual disinfection performance
Storage	UV-stabilized polyethylene tanks, sealed lid, bottom flushing system	Minimizes contaminant intrusion; enables periodic draining for stagnation control
Terminal fixtures	Silver-ion coated fixtures at high-risk points (showers)	Reduces surface colonization without replacing active water-age management
Joints and risers	Heat fusion (PEX/PP-R) or lead-free solder; flexible joints / sliding supports on vertical runs	Minimizes leak points and joint-associated biofilm; accommodates coastal seismicity

Procedures: trenching to a minimum depth of 0.60 m (no frost-protection requirement) with 0.10 m sand bedding; minimum 1% slope on horizontal runs; hydrostatic testing at 1.5 times operating pressure for at least 1 hour; commissioning chlorination at 50 mg/L for 24 hours followed by flushing to a residual ≤0.5 mg/L; and an operational flushing program targeting terminal fixtures after periods of low occupancy, calibrated to the intermittency documented for the coast.

Tools: EPANET 2.2 with the EPANET-MSX extension for pressurized-network water-quality simulation; portable kits for residual chlorine, temperature, and turbidity; openLCA for material comparison; R or Python for implementing equations (1)-(9).

3.2 Highland region (Sierra)

Context: Andean highlands (Cusco, Puno, Huancayo, Ayacucho) between roughly 2,500 and over 4,800 masl, where night-time freezing, intense solar radiation, and dispersed rural populations served by gravity-fed systems administered by Juntas Administradoras de Servicios de Saneamiento (JASS) replace the pressurized-municipal-network assumptions embedded in Hunter's curve and in most of the international literature synthesized in Table 1.

Table 3b. Material specification — Highland region (source: prepared by the author from RNE, NTP/ASTM standards, and JASS operational practice).

Component	Specification	Justification
Piping	HDPE PE100 in place of rigid uPVC	HDPE tolerates freeze-thaw flexing; rigid uPVC is prone to cracking under Andean night frost
Trenching depth	0.90-1.20 m in puna zones above 3,800 masl (frost-protection depth), vs. 0.60 m on the coast	Places piping below the seasonal frost line
Exposed risers	Thermal insulation sleeves or heat-tracing	Prevents freezing of above-grade piping segments
Gravity network fittings	Pressure-break chambers (cámaras rompe-presión) approximately every 50 m of elevation drop	Controls excess static pressure inherent to gravity-fed spring supply, which Hunter's curve does not model
Storage	Insulated-jacket tanks with freeze-protection	Prevents freezing of stored water at high altitude
Disinfection	Community-managed hypochlorination	Matches remote-logistics and electricity constraints; comparable to community-based monitoring adaptations documented for Bangladesh

Procedures: hydraulic design based on gravity-flow head calculations rather than the pump-driven Hunter curve of equation (7); participatory design with JASS leadership; extended commissioning timelines that account for remote logistics; and freeze-protection valve installation on exposed segments.

Tools: simplified, gravity-mode EPANET modeling; portable colorimetric test kits favored over electronic sensors given limited connectivity and electricity access; bilingual (Quechua-Spanish) training materials for JASS operators.

3.3 Amazon region (Selva)

Context: the Amazon rainforest (Iquitos, Pucallpa, Madre de Dios, Amazonas) presents high humidity, seasonal flooding, elevated water tables, river-sourced raw water with high turbidity and organic content, stilted (palafito) construction in flood-prone riverside settlements, and long material lead times driven by river- and air-based logistics.

Table 3c. Material specification — Amazon region (source: prepared by the author from RNE, NTP/ASTM standards, and documented river-basin construction practice).

Component	Specification	Justification
Piping and storage placement	Elevated above the historical flood level, on palafito-anchored supports	Protects the system from seasonal river flooding
Pipe material	HDPE or UV-stabilized uPVC in place of galvanized steel or copper	Corrosion resistance under sustained high humidity; UV stabilization for solar-exposed runs
Pretreatment	Enhanced turbidity/sediment filtration ahead of disinfection	Compensates for the high turbidity and organic load typical of river-sourced supply
Storage tanks	Sealed, vector-proof lids	Prevents mosquito breeding, aligning sanitary design with regional vector-borne-disease control
Metallic fixtures (where unavoidable)	Anti-corrosion coatings	Extends service life under sustained humidity exposure
Disinfection	Solar-powered UV or hypochlorite dosing	Matches unreliable grid electricity in remote riverine settlements

Procedures: elevated foundation and anchoring design for palafito-type construction; procurement schedules that build in extended river/air-freight lead times; solar-powered disinfection where grid electricity is unreliable; and coordination with regional health authorities where sanitary works overlap with vector-control programs.

Tools: portable turbidity and chlorine test kits; solar-powered disinfection units; radio or satellite-based reporting for remote monitoring where cellular connectivity is unavailable.

3.4 Common phased implementation roadmap

Across all three regions, implementation follows the same eight phases; what changes is the content of each phase, as detailed in Sections 3.1-3.3.

Table 4. Common eight-phase implementation roadmap (source: prepared by the author).

Phase	Core activity	Responsible actor
0. Territorial diagnosis	Topographic, seismic, climatic, and hydrological survey; water-source and baseline quality assessment	Municipal/regional engineering office
1. Hydraulic and risk design	EPANET/QMRA modeling with region-specific parameters (equations 1-9)	Design consultant, SENCICO-certified reviewer
2. Material specification and procurement	Region-specific bill of materials; lead-time adjustment for highland/rainforest logistics	Procurement office
3. Institutional and community capacity-building	SENCICO certification course; JASS training in highland/rainforest settlements	SENCICO, local government
4. Construction and installation	Region-specific procedures per Sections 3.1-3.3	Certified installers, geotechnical/sanitary supervision
5. Commissioning	Disinfection protocol adapted to source-water quality; verification	Installer, DIGESA (health authority)
6. Operation and maintenance	Flushing protocols, seasonal recalibration	Building/system operator, JASS
7. Monitoring and continuous improvement	Low-cost sensor deployment, periodic recalibration, WSP review	SUNASS, DIGESA, operator

3.5 Functionary competencies

Delivering the framework above depends on defined competencies across six categories of public officials and community actors, distinct from — and complementary to — the installer-level training summarized in Table 6.

Table 5. Functionary and community-actor competency matrix (source: prepared by the author).

Role	Required competencies	Training pathway
Municipal/regional civil engineers	Hydraulic modeling (EPANET); RNE E.030/IS.010 compliance; seismic and geotechnical coordination for regional adaptation	SENCICO continuing-education modules; university extension courses
SUNASS regulators	Tariff design balancing conservation incentives with universal access; economic regulation of water-safety investment	Internal SUNASS technical training; WHO water-safety-plan guidance
Ministry of Housing, Construction and Sanitation officials	National Building Code updating; water safety plan (WSP) mandate drafting; inter-ministerial coordination	Policy technical assistance; WHO/PAHO WSP framework
Ministry of Health / DIGESA officials	Water-quality standards enforcement; epidemiological surveillance of Legionella and waterborne disease; commissioning verification	DIGESA technical training; epidemiological surveillance courses
SENCICO instructors/certifiers	Curriculum design for the "Water Safety Technician" certification; field assessment protocols	SENCICO instructor accreditation program
JASS community leaders (highlands/rainforest)	Basic water-quality testing; gravity-system operation; minor maintenance; community mobilization	JASS training modules (bilingual where applicable); SUNASS rural-sanitation technical assistance

4. RESULTS

4.1 Quantitative synthesis of the evidence

Table 1 synthesizes the verified quantitative findings from the literature used as inputs to the framework. These values constitute the only numerical outcome data reported in this study; no original inferential statistics attributed to the author's own measurements are presented, given that the study design is one of documentary synthesis and modeling, not primary empirical research.

Table 1. Quantitative synthesis matrix of the verified evidence (source: prepared by the author from the cited references).

Dimension	Documented finding	Source (DOI)
Predictor of Legionella spp.	Water age (95th percentile) is the variable most consistently associated with elevated Legionella concentrations in building plumbing	Julien et al. 2022 — 10.1002/aws2.1267
Hydraulic-microbiological modeling	Integrated hydraulic-water quality models can predict Legionella concentrations at points of use from operational variables	Palmegiani et al. 2022 — 10.1002/aws2.1280
Extended stagnation	Extended stagnation in building pipes increases microbiological risk and requires flushing protocols after prolonged closures	Proctor et al. 2020 — 10.1002/aws2.1186
"Green" buildings	Certified buildings with water-saving strategies show higher water age and microbiological markers than conventional buildings	Rhoads et al. 2016 — 10.1039/C5EW00221D
Mechanistic modeling	Critical review identifies gaps in spatiotemporal and biofilm-bulk water integration of available Legionella models	Ortiz et al. 2025 — 10.1016/j.scitotenv.2025.179169
QMRA extended to other pathogens	Proposed QMRA framework to set water-quality guidelines against Mycobacterium avium complex in building plumbing	Joshi et al. 2025 — 10.1016/j.watres.2025.124054
Heat shock and microbiome	Water-use patterns and disinfection heat shock modify short-term microbiome dynamics in domestic hot water	Favere et al. 2025 — 10.1016/j.jwpe.2025.107662
LCA — PEX vs. copper	42% reduction in GWP100 and 62-63% reduction in life-cycle cost when substituting PEX for copper	Asadi et al. 2016 — 10.1016/j.jclepro.2016.08.006
LCA — uPVC vs. steel/copper	86% (vs. galvanized steel) and 91% (vs. copper) reduction in supply-system energy consumption	Xiong et al. 2020 — 10.1016/j.scs.2020.102267
Supply intermittency — Peru	40.8-42.5% of Peruvian households report intermittent water supply (2017-2022), with higher prevalence in low-density, low-HDI areas	Hernández-Vásquez & Vargas-Fernández 2025 — 10.2166/wh.2025.386
Sanitation in informal settlements — Lima	Container-based sanitation faces integration tensions with formal sectoral planning in Lima	López et al. 2025 — 10.2166/washdev.2025.124

Dimension	Documented finding	Source (DOI)
Groundwater arsenic — Bangladesh	Arsenic contamination documented in 62 of 64 Bangladeshi districts, with concentrations exceeding the WHO limit of 50 µg/L	Yunus et al. 2016 — 10.3390/ijerph13020215

4.2 Illustrative application scenarios

Scenario A (materials): applying the documented reduction factors (Table 1) to the net present value equation (equation 8) for an 8-story, 64-unit residential building in Lima, substituting PEX for copper projects a substantial reduction in both the environmental component (GWP100) and total life-cycle cost, consistent with Asadi et al. (2016), without this by itself implying an increase in microbiological risk.

Scenario B (intermittency, coastal Peru): introducing the intermittent-supply prevalence reported by Hernández-Vásquez & Vargas-Fernández (2025) as an input parameter of the water-age distribution (equation 6), the framework predicts — qualitatively and consistent with Julien et al. (2022) — that sectors with intermittent supply face structurally higher microbiological risk, supporting the scheduled-flushing procedures specified for the coastal region in Section 3.1.

Scenario C (thermal strategy, highlands and rainforest): the evidence from Favere et al. (2025) on use patterns and heat shock supports, through equation (2), the hypothesis that moderate baseline temperatures combined with periodic high-temperature pulses may constitute a plausible control strategy; however, the b and c Ratkowsky coefficients and heat-shock thresholds require specific calibration for each region's water matrix, which is not available in the reviewed literature.

4.3 Peru-Bangladesh comparison matrix

Table 2. Peru-Bangladesh comparison matrix (source: prepared by the author from the cited references and standard industry technical specifications).

Dimension	Peru (coastal-urban context, Lima)	Bangladesh (dense urban context, Dhaka)
Water source and continuity	Municipal network with intermittent supply in 40.8-42.5% of households (Hernández-Vásquez & Vargas-Fernández 2025)	Groundwater (tube wells) and rainwater harvesting; availability affected by seasonal flooding
Dominant risk	Microbiological (Legionella spp., HPC) associated with water age and intermittency-driven stagnation	Dual: chemical (arsenic, up to 62/64 districts affected; Yunus et al. 2016) and microbiological
Recommended piping materials	PEX and uPVC (flexible joints for seismic risk); copper where high thermal resistance is required	HDPE and galvanized iron (GI) due to local availability; uPVC where a certified supply chain exists
Disinfection/control	Commissioning shock chlorination (50 mg/L, 24 h) + scheduled flushing	Sand filtration + chlorination; community arsenic monitoring
Regulatory framework	National Building Code (RNE); opportunity to incorporate water safety plans (WSPs)	Department of Public Health Engineering (DPHE) standards; arsenic mitigation programs
Installer training	Certification proposed through SENCICO in "water safety in sanitary installations"	Community-based training in operation and maintenance of filtration and rainwater-harvesting systems
Economic constraint	Subsidized water tariff (S/. 1.4/m³ ≈ US$0.44), limiting the economic incentive for conservation	High energy costs; opportunity for solar water heating given high solar irradiance

4.4 Sanitary installer capacities

Complementing the functionary competencies of Table 5, installer-level training targets the field personnel who execute the procedures of Sections 3.1-3.3.

Table 6. Capacity-building program for sanitary installers in Peru (source: prepared by the author).

Training module	Content	Expected outcome
Water safety fundamentals	Water safety plans (WSPs), exposure pathways, basic QMRA concepts	Recognition of critical control points in the installation
Legionella and opportunistic pathogens	Legionella spp. life cycle, favorable conditions (temperature, stagnation, biofilm)	Identification of risk-prone configurations in the installation design
Region-specific maintenance procedures	Flushing protocols, temperature monitoring, periodic disinfection, adapted to Costa/Sierra/Selva conditions	Autonomous execution of preventive maintenance routines
Use of field kits	Measurement of residual chlorine, temperature, and turbidity with portable equipment	On-site verification of critical parameters without relying on external laboratories
Certification	Theoretical-practical assessment leading to "Water Safety Technician in Sanitary Installations" certification (proposed through SENCICO)	National standardization of installer competencies

5. DISCUSSION

5.1 Interpretation of findings

The evidence synthesis confirms that the conflict between water efficiency and microbiological safety cannot be resolved through isolated design decisions, and that Peru's orographic diversity compounds this further: flow reduction, material choice, set-point temperature, and supply continuity interact non-linearly on water age, but the weight of each factor differs by region. On the coast, intermittency-driven stagnation dominates; in the highlands, gravity-fed distribution and freeze exposure dominate; in the rainforest, source-water turbidity and flood exposure dominate. The proposed framework reconciles water efficiency and microbiological safety through three mechanisms — material selection with lower biofilm-formation potential and lower life-cycle impact, active water-age management through region-calibrated flushing, and adaptive thermal strategies pending local calibration — each instantiated differently across Costa, Sierra, and Selva in Section 3.

5.2 Comparison with the literature and transferability to Bangladesh

The synthesized findings are consistent with the research trajectory developed by the research group associated with AWWA Water Science (Julien et al. 2022; Palmegiani et al. 2022; Proctor et al. 2020), which has established water age as a central design variable. The critical review by Ortiz et al. (2025) confirms that integrating user behavior and life cycle assessment into mechanistic Legionella models remains an unresolved gap internationally, supporting the relevance of the territorial implementation model proposed here. Bangladesh shares with Peru's rainforest region the challenge of high humidity and seasonal flooding, but additionally faces groundwater arsenic contamination in 62 of 64 districts

(Yunus et al. 2016). Adaptations documented for Bangladesh — locally available materials (HDPE, galvanized iron) instead of imported PEX or copper, solar water heating, community-based water-quality monitoring, and elevated storage above flood level — parallel, and in several cases directly inform, the highland and rainforest specifications of Sections 3.2–3.3, illustrating that the framework's conceptual structure transfers across countries even as its input parameters and, in Bangladesh's case, an additional chemical-risk module, must be adjusted.

5.3 Limitations

- This study is documentary and conceptual-modeling in nature; it does not include primary field data, so the scenarios of Section 4.2 should be interpreted as illustrations of the framework's application, not as empirical validation results.
- The available quantitative evidence on materials and life cycle mostly originates from North American and East Asian contexts; its transfer to Peru's coastal, highland, and rainforest energy and cost matrices requires adjustment with local inventory data.
- The empirical coefficients of the microbial growth (Ratkowsky) and disinfectant decay models are strain- and water-matrix-specific; their application in each of Peru's regions and in Bangladesh requires local calibration before use in regulatory decisions.
- The literature review, although structured, does not constitute an exhaustive meta-analysis with a prospectively registered PRISMA protocol; its scope is limited to the sources identified and verified within the period and databases indicated in Section 2.2.

6. CONCLUSIONS AND FUTURE DIRECTIONS

6.1 Summary of findings

- Water age is consolidated, in the verified literature, as the most consistent predictor of microbiological risk in building sanitary installations, though the dominant driver of water age differs by Peruvian region.
- Substituting PEX or uPVC for copper offers documented environmental (42%) and energy (86–91%) impact reductions with no evidence, in the reviewed literature, of increased microbiological risk — a substitution specified for the coast in Section 3.1 and adapted for the highlands and rainforest in Sections 3.2–3.3.
- A single national procedure cannot serve Peru's three natural regions: the coast requires seismic-resilient pressurized-network design, the highlands require frost-protected gravity-fed design managed by JASS, and the rainforest requires elevated, corrosion-resistant, flood-adapted design.
- Delivering this territorial model depends on defined competencies across six categories of officials and community actors, not on installer training alone.
- Bangladesh provides a relevant contextual lesson, particularly for Peru's rainforest region: sanitary installation design in humid, flood-prone, resource-constrained settings must simultaneously

consider chemical and microbiological risks when both coexist in the water source.

6.2 Practical implications

Building designers should incorporate region-specific water-age calculation and dynamic hydraulic simulation from the early design stages. Operators should implement flushing and temperature-monitoring schedules based on actual occupancy patterns and regional climate. Peruvian regulators have a concrete opportunity to update the National Building Code to incorporate water safety plans and the region-differentiated material and procedural specifications proposed here, in line with World Health Organization recommendations.

6.3 Future research

- Multi-building empirical validation of the proposed framework across Peru's coast, highlands, and rainforest.
- Development and validation of low-cost sensors for continuous monitoring of temperature, residual chlorine, and turbidity, adapted to each region's connectivity and electricity constraints.
- Local calibration of the microbial-growth and disinfectant-decay model coefficients for the water matrices of Lima, the Andean highlands, and the Amazon basin.
- Extension of the life cycle assessment to incorporate social impacts, including the disease burden associated with exposure to opportunistic pathogens.

Declarations

Conflict of interest:

the author declares no conflict of interest.

Ethical approval:

not applicable. This study did not involve the collection of primary data from human or animal subjects; it is based exclusively on the synthesis of published literature and conceptual mathematical modeling.

Funding:

no external funding was received for this study.

Data availability: no original primary datasets were generated by the author; all cited quantitative values are drawn from the referenced sources and can be verified through the indicated DOIs.

Figure contribution: Figs. 1 and 2 are original work by the author (Paul Ricardo Prudencio Gálvez, 2026); the numerical data represented in Fig. 2 come from the sources cited in its caption.

Author Contribution

Author Contributions StatementP.R.P.G. conceived the study, conducted the literature search and analysis, performed the technical calculations, prepared the figures and tables, and wrote the main manuscript text.

Acknowledgement

I would like to express my deepest gratitude to my professor and mentor, Dr. Tech. María Magdalena Cárdenas Gaudry, for her invaluable teaching and for warmly opening the doors to the world of research for me.

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