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Examining Water Safety and Innovative Alternative Solutions: A Case Study of the Himalayan Nation of Nepal

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ABSTRACT

This paper looks at drinking water safety in Nepal, focusing on how climate vulnerability, weak governance, and limited monitoring shape the problem. It also considers whether low-cost optical fluorescence tools like RealtimeWAS could help improve water testing in decentralized systems. By bringing together public health evidence, policy analysis, and technology, the study argues that safer water in Nepal will require both stronger institutions and practical tools that fit local conditions.

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INTRODUCTION

In 2024, 2.1 billion people still lacked access to safely managed drinking water, despite substantial global progress in expanding access to improved sources, the persistence of this gap indicates that expansion in coverage alone has not translated into water safety (World Health Organization & United Nations Children's Fund, 2025). In low- and middle-income countries, improved sources do not guarantee microbiological or chemical safety; water safety depends on treatment efficacy and contamination control at the point of use–all of which are conditions that are absent in such countries. Therefore, water-safety shortfalls are disproportionately concentrated in these low- and middle-income countries, where delivery systems are fragile, and governance constraints undermine risk management (World Health Organization & United Nations Children's Fund, 2025). Climate events increasingly amplify these vulnerabilities by disrupting reliability and increasing contamination risk during floods and extreme rainfall, which can overwhelm sanitation systems (Sharma et al., 2021). The nation of Nepal reflects these global patterns, as a country with high climate vulnerability and a decentralized service reality, making it a critical case study to understand how water safety is compromised even where water is abundant and coverage is high.

Nepal recorded 3,067 diarrheal disease deaths in 2023, a substantial toll for a population of roughly 30 million (IHME, 2023). This corresponds to 9.87 deaths per 100,000 people, which is nearly four times the United States rate of 2.51 per 100,000, highlighting a disproportionate risk (IHME, 2023). The burden extends beyond mortality: Nepal lost 117,250 disability-adjusted life years (DALYs) to diarrheal disease in 2023, equivalent to 377.45 DALYs per 100,000, compared with 48.13 per 100,000 people in the United States (IHME, 2023). High DALY loss indicates prolonged illness, disability, and lost economic productivity linked to the diseases from unsafe water exposure, mostly attributed to fecal coliforms and Rotavirus in Nepal (Hay et al., 2023). In the national context, the disease metrics reveal that water safety is not only a Water, Sanitation, and Hygiene (WASH) sector issue but also a binding constraint on human development in the nation.

This paper addresses three connected research questions. First, how do unsafe water and climate-change-related risks disproportionately affect Nepal relative to higher-income settings? Second, why do governance and regulatory systems fail to ensure water safety even when policy frameworks and constitutional rights exist? Third, what technologies are suitable for Nepal's constraints and needs, particularly in decentralized systems? Nepal's case study shows how climate vulnerability, weak enforcement of water policy, and development trajectories that prioritized coverage over safety sustain the risk of waterborne disease (Biggs et al., 2013; Kafle, 2018). Many frameworks emphasize preventive risk management and early warning, yet decentralized systems also require routine, post-hoc. In places with weak infrastructure and frequent sewage infiltration into distribution lines, point-of-care detection becomes particularly valuable because safety can change rapidly across time and space. Low-cost sensing technologies can be revolutionary for water safety, but only if embedded in realistic governance pathways that mandate monitoring, standardize interpretation, and trigger response.

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SOURCES OF WATER IN THE KATHMANDU VALLEY OF NEPAL

To interpret Nepal's water safety shortcomings, a clear service map is essential, because households often rely on multiple sources that vary in reliability and risk. In Kathmandu Valley, the formal municipal network is managed by Kathmandu Upatyaka Khanepani Limited (KUKL), and supply is drawn from a mix of surface sources and deep tube wells (KUKL PID, 2018). KUKL reports strong seasonal variation in production (approximately 100 million liters/day in the dry season and 150 million liters/day in the monsoon) suggesting that intermittent supply is common for households and coping strategies to combat the difference are common (KUKL PID, 2018). Even where households are connected to the piped network, water is typically delivered only a few times per week for limited hours, often as infrequently as once every four days for around 12 hours, so households must invest in storage capacity such as overhead tanks and ground-level reservoirs to ensure continuous access (KUKL PID, 2018; Pandey et al., 2020). As a result, being classified as having "piped water" does not equate to 24/7 availability or consistent safety at the tap (WHO & UNICEF, 2025).

The valley's portfolio includes 31 surface sources and 75 deep tube wells routed to 21 water treatment plants, totaling about 85 million liters/day treatment capacity, and implying that demand often exceeds treated supply, especially during high-use or disrupted periods (KUKL PID, 2018). Household behavior reflects this gap: a Kathmandu Valley household water-use study documents widespread coping strategies involving multiple sources for different uses (ICRE, 2015). For example, piped water is used when available, but when not purchased water or other sources are utilizes, highlighting the lack of reliance on one consistently safe service (ICRE, 2015). This evidence reveals that households may be counted as having an improved source while continuing to use alternative sources when piped service is intermittent or distrusted.

Beyond KUKL, communities also rely on community-based water user and sanitation groups – which also provide piped water, traditional sources such as stone spouts (*hitis*), and commercial jar water (19-liter containers) for drinking, especially when municipal supply is unreliable. A Nepal study of bottled and jar water quality reported that 52% of sampled bottled water was unacceptable based on the threshold for total coliform present in the sample, as per Nepal's Department of Food Technology and Quality Control standards (Gautam et al., 2020). Jar water is often substituted for unreliable municipal supply, meaning households may pay more for water without reliably reducing microbial risk (Gautam et al., 2020). Jar-water contamination also indicates that risk is a regulatory failure, where enforcement and surveillance across private supply chains are insufficient (Gautam et al., 2020).

Conventional Water Surveillance is Unrealistic in Nepal

Nepal operates approximately 25,000 piped water schemes, most of them small and community-managed (Khatri & Heijnen, 2011). This system structure creates a fundamental scalability problem for water surveillance testing: external laboratory monitoring of every scheme is financially and logistically infeasible, especially where laboratories and trained personnel are limited, and resources are scarce nationwide (Khatri & Heijnen, 2011). Conventional surveillance typically requires culture-based microbiological testing for fecal indicator bacteria, turbidity measurement, and analysis of chemical parameters such as metals, all of which demand equipment, reagents, and technical expertise (Maharjan et

al., 2024; WHO, 2017). Even where sources may be relatively safe, systems remain vulnerable to contamination at intake structures, transmission lines, distribution networks, and household taps, leaving citizens unaware of the safety of their water (Khatri & Heijnen, 2011). Only 28.13% of drinking-water schemes are fully function in the nation, indicating systemic weaknesses that increase the probability of intermittent service and inconsistent treatment (Sharma et al., 2021). In a decentralized governance environment, community management is often the only feasible operational model, but it also means safety depends on local capacity for routine safety checks–precisely the capacity that is typically the weakest, making it extremely difficult to detect water safety.

UNSAFE WATER AND CLIMATE-CHANGE-RELATED RISKS DISPROPORTIONATELY AFFECT NEPAL

Climate Vulnerability

Nepal's climate is shaped by the Himalayan range and the South Asian monsoon, creating strong seasonal variability in water availability and water-quality stress (Sharma et al., 2021). Nepal has already experienced significant warming: an annual maximum temperature increase of 0.056°C per year and a total increase of about 1.8°C between 1975 and 2006, exceeding the global average warming range cited for comparable periods (Sharma et al., 2021). Climate-sensitive water sources (glacier melt, snowmelt, rain-fed springs, and groundwater recharge) are strongly influenced by changing temperature and precipitation patterns, and Nepal is experiencing more extremes that stress already fragile distribution systems (Sharma et al., 2021). Consequently, water supply is inadequate and low quality even in the capital city of Nepal, the Kathmandu Valley, highlighting how risk is not confined to rural or remote areas. These climate changes undermine reliability and can cause water that is safe at source to contaminate water after intake or within distribution, delivering unsafe water to users during precisely the moments when health risk is the highest.

Monsoon Flooding

Monsoon rainfall increases surface runoff and can overwhelm sanitation infrastructure, bypassing safeguards that focus only on source protection (Sharma et al., 2021). Flooding mobilizes fecal matter from open defecation areas into water sources, particularly in rural and peri-urban settings where sanitation coverage and containment are weaker (Khatri & Heijnen, 2011). Nepal's water contamination risk is further intensified by sewage infiltration linked to inadequate sewerage infrastructure and the proximity of water distribution pipes to sewage lines. Diarrheal disease outbreaks and cholera remain regular occurrences during monsoon and flood-risk periods (Khatri & Heijnen, 2011). Seasonal turbidity spikes also lower treatment effectiveness, especially in small community schemes where filtration and disinfection may be inconsistent or absent (Khatri & Heijnen, 2011).

Glacier Flooding

Nepal's Himalayan geography adds a layer of climate variability that disrupts water safety. Nepal sits in the Hindu Kush Himalaya region, where warming-driven glacier retreat is rapidly expanding and destabilizing glacial lakes, increasing the likelihood of glacial lake outburst floods (GLOFs) that can

greatly damage WASH infrastructure and contaminate water supplies downstream (Sharma et al., 2021). In Nepal, these flood events generate acute water-quality shocks by mobilizing sediments, organic matter, and fecal contamination into surface and groundwater sources, often overwhelming small-scale treatment systems and bypassing limited monitoring capacity (Shah et al., 2025).

These climate-driven disruptions intersect with existing structural weaknesses in Nepal's water systems. A substantial portion of drinking-water contamination occurs after collection or within distribution networks, meaning that exposure remains high even when initial sources are classified as "improved" (Khatri & Heijnen, 2011). GLOF- and monsoon-related flooding exacerbate this vulnerability by damaging infrastructure, increasing leakage and sewage infiltration in aging pipe networks, and creating periods of high turbidity during which treatment effectiveness is reduced (Khatri & Heijnen, 2011). Waterborne disease risk in Nepal comes from the combined effects of various climate stressors and weak detection capacity. These patterns make clear that water safety in Nepal cannot be achieved through infrastructure expansion alone; it also relies on the ability of institutions to govern risk, enforce standards, and detect contamination in real time.

GOVERNANCE AND REGULATORY RESTRAINTS THAT PREVENT WATER SAFETY

Drinking Water as a Human Right

In 2010, the United Nations General Assembly recognized access to safe and clean drinking water and sanitation as a human right, affirming water safety as essential to the full enjoyment of life and all other human rights (United Nations General Assembly, 2010). This recognition frames water as an obligation requiring water to be sufficient, safe, acceptable, physically accessible, and affordable, meaning that intermittent, contaminated, or unverified supplies can violate the right (United Nations General Assembly, 2010). The human rights framing shifts responsibility towards states and institutions, implying a duty to regulate, monitor, and ensure accountability. In low-income and climate-vulnerable countries such as Nepal, this highlights a central contradiction: formal rights commitments may exist, but enforcement capacity, especially routine verification, remains limited.

UNICEF Target Product Profiles

Recognizing that laboratory-based testing is often incompatible with low-resource settings, UNICEF developed Target Product Profiles (TPPs) to guide water-quality monitoring tools suited to humanitarian and low-income contexts (UNICEF, 2023). UNICEF's rapid water-quality testing TPP emphasizes affordability, ease of use, minimal training, rapid results, and on-field deployability, directly addressing limitations of culture-based methods (UNICEF, 2023). The TPP framework explicitly acknowledges that waiting 24-48 hours for laboratory results undermines protection during emergencies, floods, or system failures where immediate decisions are required (UNICEF, 2023). Importantly, the TPP approach would allow proxy indicators when direct water safety testing is impractical, if the tools are scientifically validated and operational reliability is demonstrated (UNICEF, 2023). For Nepal, where thousands of community-managed schemes operate with limited laboratory access, adhering to the TPP guidelines for new water-detection innovations is vital for their practicality in the nation's socioeconomic status, and similar needs are evident across the broader Global South.

Nepal's Constitutional Guarantees Vs Implementation Reality

Nepal's Constitution guarantees the right to clean drinking water as a fundamental right (Article 35(4)), establishing water safety as a state obligation rather than a discretionary service (Kafle, 2018). However, constitutional rights require enabling laws, institutions, financing, and enforcement mechanisms to become real, particularly where most schemes are community-managed (Kafle, 2018). Nepal's legal framework has not been fully updated to align with federal constitutional structures, contributing to gaps in clarity and accountability (Kafle, 2018). In practice, overlapping authority leads to coordination failures and unclear accountability, which undermines consistent implementation (Biggs et al., 2013). Local governments often lack technical capacity and sustainable financing mechanisms, which limit their ability to integrate climate resilience, enforce monitoring, and maintain service continuity (Manandhar-Sherpa et al., 2024).

Nepal exceeded Millennium Development Goals (MDGs) access targets but did not meet its goal of universal basic services by 2017, and policy has historically prioritized coverage expansion over quality improvement (Kafle, 2018). This emphasis produces a predictable outcome: *access* improves on paper while unsafe water persists in practice, sustaining water safety disease burden (Kafle, 2018). Regulatory laws exist but are inadequate for consistent nationwide enforcement across thousands of schemes, especially when decentralized governance makes consolidation difficult (Kafle, 2018). When coverage is rewarded more than safety, incentives shift toward building systems rather than maintaining safe service. The result is an institutionalized risk of water contamination: unsafe systems remain in operation without the verification capacity needed to identify and fix failures.

Water Safety Plans (WSPs)

Nepal adopted the WHO Water Safety Plan framework to manage risk from catchment to consumer, relying on community management due to the large number of small systems (Khatri & Heijnen, 2011). WSPs aim to embed preventive risk management within local operations rather than depending on external laboratory control (Khatri & Heijnen, 2011). However, in practice, the accuracy of verification is unclear in documentation: forms, plans, and checklists may be completed without actual microbial monitoring to confirm safety at delivery points (Khatri & Heijnen, 2011). Where actual consistent safety tests are replaced by visual inspection, taste, or user satisfaction, it is extremely common for unsafe water to persist undetected (Khatri & Heijnen, 2011). In addition, grant-funded laboratories or pilot monitoring programs often collapse when external funding ends, leaving communities without sustainable operating budgets for consumables, equipment maintenance, or staffing, and making these structures completely impractical for the country (Khatri & Heijnen, 2011). These realities and governance struggles point to the fact that Nepal lacks a scalable, low-cost, routine method for water-safety testing across systems.

TECHNOLOGICAL INNOVATIONS SUITED TO NEPAL'S CONTEXT

Conventional Fecal Testing Fails Operationally

Standard fecal contamination testing often relies on culturing fecal indicator organisms such as *Escherichia coli* through culturing techniques (Maharjan et al., 2024). These methods require reagents, laboratories, and skilled personnel, all of which are rare in Nepal (Maharjan et al., 2023). Incubation alone takes at least 18 hours, and total delays can reach 36-48 hours due to logistics, transport, and workflow constraints (Maharjan et al., 2024). These delays undermine early warning during monsoon floods or infrastructure failures and are impractical for high-frequency monitoring across thousands of schemes (Maharjan et al., 2024). Conventional methods also impose ongoing operating costs and supply-chain burdens that are difficult to sustain once short-term funding ends. Therefore, even where culture-based methods remain the regulatory "gold standard," their real-world feasibility in Nepal is extremely limited.

Optical Solutions as an Alternative

Tryptophan-like fluorescence provides a reagent less optical measurement by proxy for microbial contamination because ultraviolet excitation can induce emission from dissolved organic compounds associated with fecal matter and microbial metabolism (Sorensen et al., 2020). TLF is characterized by excitation of a sample of light at a wavelength of around ~280 nm and emission near ~350 nm, a signature that aligns with the fluorescence properties of L-tryptophan, an amino acid present in biological materials (Waiba et al., 2023). Coliforms such as E. coli contribute intracellular and extracellular organic compounds that correlate with elevated TLF signals, helping explain the observed relationship between TLF intensity and fecal contamination (Sorensen et al., 2020). Fluorescence detection measures the optical properties of dissolved organic matter directly, enabling immediate inference of contamination risk without requiring microbial growth or incubation (Waiba et al., 2023). Optical fluorescence sensing is reagentless, reducing per-test costs, avoiding chemical supply chains, and minimizing secondary risks associated with reagent handling. The approach can also be expanded beyond TLF: humic-like fluorescence and turbidity can be integrated as additional parameters, supporting more comprehensive water-quality interpretation when fluorescence is influenced by background organic matter.

A Prototype Solution Developed in Nepal for Local Use

A tool, recently developed by researchers at the Phutung Research Institute in Kathmandu, Nepal, is designed as a low-cost, portable, reagent-free device that enables real-time detection of fecal contamination in drinking water using fluorescence measurement (Waiba et al., 2023). The device, named RealtimeWAS, is physically suited for field deployment because it is compact (approximately 15 cm × 16 cm × 19 cm), weighs under 1.4 kg, and operates on battery power, making it viable in remote and off-grid settings common across Nepal's mountainous terrain and rural settlements (Waiba et al., 2023). Manufacturing cost is approximately USD 400 per unit when produced at modest scale (100 units), more than an order of magnitude cheaper than commercial fluorometers, enabling distribution across many sites rather than reliance on centralized laboratories (Waiba et al., 2023). In a context where external laboratory monitoring of 25,000 different water schemes is infeasible, this cost and portability profile directly addresses the scale problem (Khatri & Heijnen, 2011). These innovations also raise broader questions about how similar devices might be deployed in other low-resource settings facing comparable constraints.

Usability and TPP Fit

RealtimeWAS is explicitly designed for non-specialist users, requiring less than five minutes of training regardless of education level, which is an essential feature in Nepal's community-managed water systems (Waiba et al., 2023). Results are delivered in under one minute, enabling immediate decision-making during contamination events such as monsoon flooding or infrastructure failures (Waiba et al., 2023). Outputs are intentionally easy to interpret: the device provides a numerical display of fluorescent dissolved organic matter and LED-based risk categories, enabling rapid understanding without technical expertise (Waiba et al., 2023). This interpretability is what makes routine monitoring plausible where technical capacity is limited and where WSPs require local operators to take action. By enabling frequent testing, RealtimeWAS addresses a core governance gap in Nepal's water sector.

RealtimeWAS also aligns strongly with UNICEF's TPP priorities. It is low-cost, portable, and designed for rapid results and minimal training, matching UNICEF's emphasis on tools that work in low-resource and humanitarian contexts (UNICEF, 2023; Waiba et al., 2023). Its reagent-free optical sensing avoids consumables and supply-chain complexity, consistent with TPP guidance to minimize dependencies that are difficult to sustain in low- and middle-income countries (UNICEF, 2023). Battery operation and its compact form support remote and disaster-prone environments, while the one-button input reduces procedural errors and supports consistent use. Near real-time outputs support immediate protective actions during time-sensitive events when lab results would be unavailable in time (UNICEF, 2023).

However, a policy gap remains: surveillance norms and guidelines often prioritize culture-based water testing, creating bias against new technologies such as RealtimeWAS, even when they are scientifically sound and operationally superior for rapid detection in specific contexts (Pichel, 2023). For Nepal, the challenge is not merely inventing a workable device but establishing regulatory pathways that recognize proxy detection devices as legitimate for action within WSPs and public health response systems. Ultimately, these realities suggest that policymakers in low-income countries could not rely exclusively on global laboratory "gold standard" water safety tests, due to their impracticability in the nation's socioeconomic context. Instead, they should also incorporate validated proxy tools that can provide earlier, more frequent, and more equitable protection for at-risk populations.

CONCLUSION

Nepal's water safety crisis is not caused by a lack of water resources but by climate vulnerability, fragmented governance, and an institutional emphasis on coverage rather than safety. Climate change intensifies these weaknesses by increasing contamination pathways during floods. Existing policies, such as Water Safety Plans, provide a valuable risk-management framework, but effectiveness is limited greatly by weak enforcement, insufficient surveillance, and a lack of real-time monitoring capacity. Low-cost, reagentless optical sensing technologies, such as RealtimeWAS, can directly address these gaps by enabling decentralized, rapid, and frequent verification in community-managed systems. Yet technology alone is insufficient unless embedded in governance structures that allow for new proxies and integrate climate risk into operational planning for water safety.

Ultimately, the case study of Nepal offers a broader lesson for climate-vulnerable, low-income settings that safe drinking water requires a higher capacity of institutions to govern risk through continuous verification, integrating technological innovation with governance. As fluorescence-based tools are further tested, validated, and adapted to diverse climate and infrastructural conditions, they have the potential to be scaled beyond Nepal to other parts of the world that face similar constraints in surveillance and governance. Although RealtimeWAS is promising, it should be treated as an early-stage proxy tool rather than a complete substitute for laboratory confirmation, especially for regulatory decisions, long-term surveillance, and settings where background fluorescence may complicate interpretation. Investing in such innovations, and in the regulation needed to integrate them, may be a test worth pursuing sooner rather than later for countries seeking resilient, climate-aware pathways to water safety.

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