

SOURCE TO TAP ASSESSMENT OF PHYSICOCHEMICAL AND MICROBIOLOGICAL DRINKING WATER QUALITY IN POKHARA METROPOLITAN CITY, NEPAL

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ABSTRACT

Ensuring the safety of drinking water requires not only expanded access but also sustained compliance with physicochemical and microbiological quality standards throughout the supply chain. This study presents a source-to-tap assessment of drinking water quality across major supply schemes serving wards 26–32 of Pokhara Metropolitan City, Nepal. A cross-sectional sampling design was adopted, covering surface and groundwater sources, reservoirs, and household taps operated under both centralized and community-managed systems. In total, 31 water samples (11 source, 5 reservoir, 15 household tap) were analysed for physical (pH, electrical conductivity, turbidity, total dissolved solids), chemical (total hardness, calcium, chloride, ammonia, iron, nitrate, arsenic, free residual chlorine), and microbiological (*Escherichia coli*, total coliform) parameters following Standard Methods for the Examination of Water and Wastewater (APHA, 24th ed.). Observed values were evaluated against the National Drinking Water Quality Standards (NDWQS, 2079) and WHO guidelines. Results indicate that most physicochemical parameters across schemes complied with national guideline values, reflecting generally acceptable chemical quality. Microbiological contamination was widespread: *E. coli* reached 51 CFU/100 mL at the LWSO surface intake, 18–22 CFU/100 mL at LWSO household taps, and was too numerous to count (TMTc) in the Chainapur and Malmul community schemes, while deep-borehole groundwater sources showed no detectable *E. coli*. In contrast, microbiological contamination was detected in several surface-water-based and community-managed schemes, with *E. coli* and total coliform counts exceeding permissible limits at multiple intake points and household taps. Free residual chlorine was detected only in the LWSO system and declined from ~0.34 mg/L in early distribution to undetectable at terminal taps; this decline was concurrent with higher microbial counts at consumer endpoints. Treated and groundwater-based supplies showed comparatively lower microbiological risk, underscoring the influence of source type, treatment, and distribution integrity on water safety.

The findings highlight that compliance with physicochemical standards alone is insufficient to ensure safe drinking water in multi-scheme urban settings. Strengthening residual disinfection, protecting source waters, and prioritizing distribution-level monitoring are critical for reducing public health risks. This study provides localized evidence to support operational improvements and reinforces the importance of routine source-to-tap surveillance in heterogeneous water supply systems. This study provides localized evidence to support operational improvements and reinforces the importance of routine source-to-tap surveillance in heterogeneous water supply systems.

Keywords: Water quality, Source-to-tap assessment, Microbiological contamination, physicochemical parameters

1. Introduction

Safe drinking water is a fundamental determinant of public health and socioeconomic development. Although many countries have expanded access to piped supplies, access does not necessarily equate to safety: physicochemical compliance can coexist with persistent microbiological contamination within distribution systems (Manna & Biswas, 2023). Globally, waterborne infections remain an important cause of morbidity, particularly in low- and middle-income countries where aging infrastructure, intermittent supply, and inadequate treatment can undermine water safety at the point of use (Mengstie et al., 2023).

In Nepal, national policy and planning documents emphasize improved access and service quality, yet monitoring and water-quality outcomes remain variable across regions. National targets articulated in sector policy documents and the National Drinking Water Quality Standards (NDWQS), 2079 (2022) set the benchmarks for both physicochemical and microbiological parameters, but field studies indicate recurring non-compliance with microbial indicators even where chemical parameters meet guideline values (National Water Supply and Sanitation Sector Policy, 2014); (Maharjan et al., 2018). Several Nepalese investigations have reported widespread coliform contamination of tap and community sources, highlighting distribution-level vulnerability and the need for systematic source-to-tap assessment (Nicholson et al., 2017; N. D. Pant et al., 2016; Sarkar et al., 2022).

Regional studies further illustrate this pattern. In Kathmandu Valley and other urban centres, treated water samples have at times failed microbiological criteria despite routine treatment, suggesting post-treatment recontamination or residual-disinfectant decay in distribution networks (Maharjan et al., 2018; Pandit, 2017). Comparable findings from South Asia and other low-resource settings show that intermittent supply, aging pipes, and inadequate residual disinfection commonly contribute to higher *E. coli* and total coliform counts at household taps than at source points (Ali et al., 2021; Riaz et al., 2021). Conversely, studies from settings with protected groundwater and continuous distribution report lower microbiological risk, underscoring the influence of source type and system management on water safety (Mengstie et al., 2023; N. D. Pant et al., 2016).

Methodological advances and integrated approaches have improved detection and interpretation of water-quality problems. Water Quality Indices (WQI), GIS-based mapping, and hybrid statistical models facilitate spatially explicit assessments and risk prioritization (Jha et al., 2020). At the same time, comparative studies emphasize the value of source-to-tap sampling designs that explicitly evaluate changes in water quality along the supply chain rather than relying solely on source or consumer samples (Gaihre et al., 2022). Beyond compliance-based assessment, recent literature emphasizes the public-health relevance of indicator-based monitoring and its relationship with disease risk and system reliability. Microbiological indicators such as *E. coli* and total coliforms are widely used not only as regulatory benchmarks but also as proxies for faecal intrusion and treatment or distribution failure, particularly in intermittent supply systems (Nicholson et al., 2017). Studies from urban and peri-urban settings demonstrate that even low-level microbial contamination can be associated with elevated diarrheal disease risk, underscoring the importance of routine surveillance at the consumer level (Sarkar et al., 2022).

These findings reinforce the need for scheme-level comparative evidence to inform context-specific interventions rather than uniform, source-focused monitoring alone. Such designs are particularly useful for differentiating source contamination from distribution-related deterioration and for

identifying critical control points where operational improvements would most effectively reduce health risks.

Despite the recognized need for source-to-tap evidence, localized comparative assessments remain limited for many Nepali towns. Lekhnath (now part of Pokhara Metropolitan City) hosts multiple, heterogeneous supply schemes—ranging from centralized treatment with chlorination to small community-managed gravity systems—creating an ideal setting to evaluate how source type, treatment, and distribution interact to determine water quality at the consumer end. Available project reports document extensive pipe networks, diverse source types (surface intakes, sump wells, and deep bores), and sizable consumer connections, but peer-reviewed evidence on the current water-quality status across these schemes.

This study therefore adopts a source-to-tap cross-sectional design to evaluate physicochemical and microbiological quality across major supply schemes serving wards 26–32 of Pokhara Metropolitan City. Specifically, the study measures a core set of physical and chemical parameters and standard bacteriological indicators at source, reservoir, and household taps and (compares observed parameter values with the NDWQS (2079) to identify compliance patterns.

By combining standardized laboratory analysis with a distributed sampling strategy, the research aims to provide actionable evidence for local managers and policymakers and to contribute to the regional literature on distribution-level microbiological risk.

This research contributes practical improvements in water treatment, distribution, and monitoring systems in Pokhara, confirming safer and more reliable drinking water for communities. It directly progresses United Nations Sustainable Development Goals (SDG) 6 by improving water quality, whereas indirectly promoting public health under SDG 3 and boosting resilient and sustainable urban water management practices associated with SDG 11 in fast growing cities.

2. Materials and methods

2.1 Study design

This study employed a cross-sectional observational design to assess the physicochemical and microbiological quality of drinking water across selected water supply schemes in Lekhnath, Pokhara Metropolitan City, Nepal. The investigation was structured as a source-to-tap assessment, encompassing water sources, intermediate storage reservoirs, and household-level distribution points to capture potential changes in water quality along the supply chain. This assessment was conceived as a pilot cross-sectional study intended to characterise water-quality patterns across heterogeneous supply schemes and to generate hypotheses for subsequent larger-scale, seasonally-stratified monitoring.

Water sampling was conducted during multiple periods in 2024, covering both warmer and cooler seasons, to account for possible seasonal variation in water quality parameters. The study design integrated field sampling, laboratory-based analysis, and standards-based evaluation, with all measured parameters assessed against the National Drinking Water Quality Standards (NDWQS, 2079 (2022) of Nepal).

2.2 Study area and water supply systems

The study was conducted in Lekhnath, a sub-metropolitan area within Pokhara Metropolitan City, located in western Nepal. According to the most recent national census data, Lekhnath has

experienced rapid population growth over recent decades, resulting in increasing demand on existing drinking water supply systems. The area comprises a mix of urbanizing settlements and semi-urban communities, where drinking water is supplied through multiple centralized and community-managed schemes.

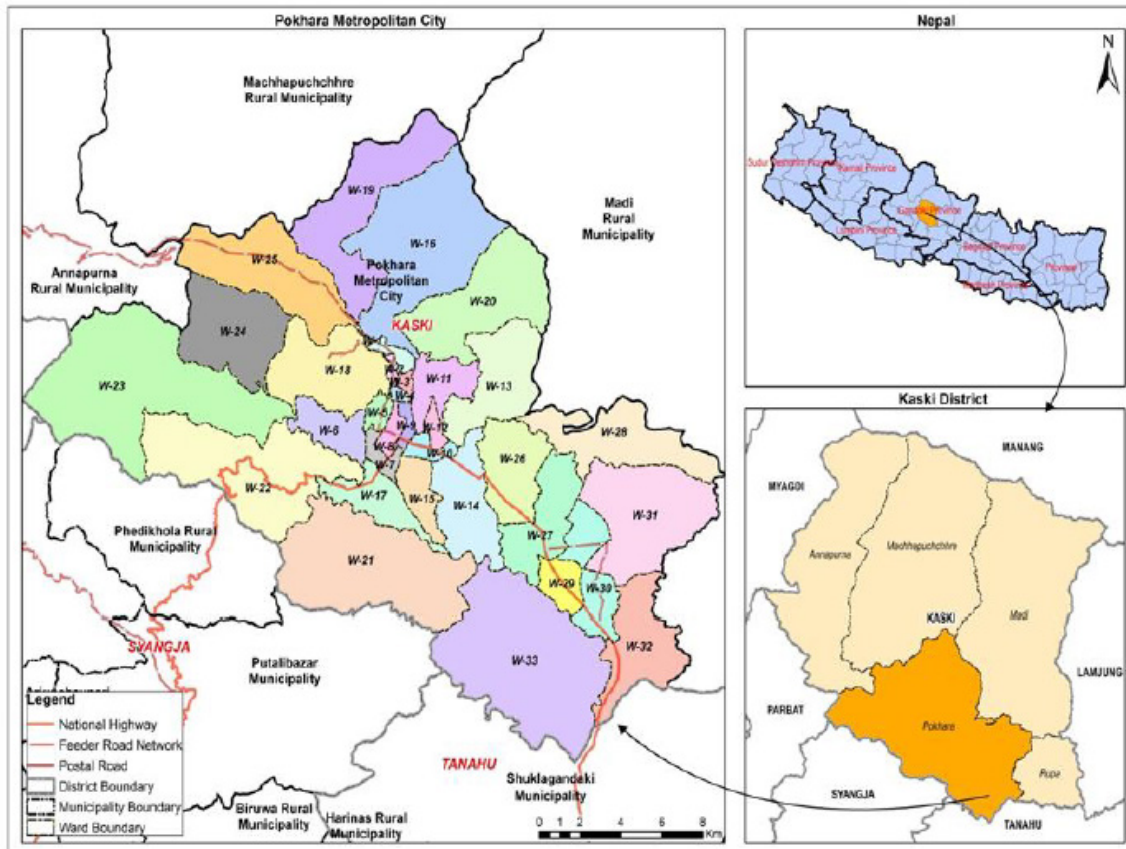


Figure 1. Map of Study Area (Source: Gurung and Poudel, 2025)

This research focused on wards 26, 27, 28, 29, 30, 31, and 32 of Pokhara Metropolitan City, which together represent the principal service area of the Lekhnath drinking water supply network. These wards are served by several water supply schemes that vary in terms of source type, treatment infrastructure, and distribution mechanisms.

The major water supply schemes operating within the study area include:

- Lekhnath Water Supply Organization (LWSO),
- Bhupu Khanepani
- Gagangauda Khanepani,
- Chainapur Khanepani,
- Malmul Archale Khanepani, and
- Red Cross Khanepani.

Among these, LWSO is the dominant utility, supplying drinking water to the majority of households in Lekhnath. LWSO operates centralized treatment facilities that include sedimentation and filtration units followed by chlorination, and utilizes multiple water sources such as surface water, sump wells, and deep bore wells. In contrast, the remaining schemes are small-scale, community-managed systems, many of which rely primarily on surface water sources and distribute water through public or limited private tap connections, with minimal or no formal treatment processes.

The presence of heterogeneous water supply systems-ranging from fully treated centralized schemes to untreated community supplies-provided an appropriate setting for comparative assessment of drinking water quality across different supply modalities. This diversity enabled the evaluation of water quality variations associated with source characteristics, treatment practices, and distribution systems within the same geographic and climatic context.

2.3 Sampling strategy and sample size

A multistage sampling strategy was adopted to capture drinking water quality variations across different components of the water supply system within the study area. Sampling locations were selected to represent key points along the supply chain, including water sources, storage reservoirs, and end-user distribution points (household taps).

A total of 31 water samples were collected for analysis. These samples comprised 11 source samples (S), 5 reservoir samples (R), and 15 household tap samples (T) distributed across the selected wards and water supply schemes.

The sample size of 31 was determined by the number of distinct, operationally-accessible sampling points across the six supply schemes rather than by a power calculation, consistent with the pilot, hypothesis-generating objective of the study. All major sources and reservoirs in the study area were sampled exhaustively (a census of these points), while household taps were selected to span service zones and scheme types. This point-representative design is comparable to that used in other South Asian source-to-tap pilot assessments (Gaihre et al., 2022; Pant et al., 2016), where scheme coverage rather than sample count governs interpretive scope.

Water samples were collected from all major water sources and reservoirs, while household tap samples were selected randomly from households with active water supply connections within each ward.

Within each ward (26–32) served by the Lekhnath Water Supply User Committee and community-managed schemes, household tap samples were selected from households with active water supply connections using cluster-based random sampling. The population within each ward was first divided into geographic clusters representing distinct service zones within each supply scheme (Lekhnath Water Supply (LWSO), Archale, Red Cross, Chainapur, Malmul, and Gagangaunda systems). From each cluster, households were randomly selected to ensure geographic representation and service-mode diversity (LWSO centralized distribution vs. community-managed gravity systems). Institutional premises including schools, hospitals, the university, colleges, and public buildings were included purposively to capture high-occupancy points and diverse water-use patterns. Selection of household sampling sites was constrained by accessibility to the sampling team, household consent for sample collection, and continuity of water supply on the sampling day.

To enhance representativeness, sampling included both institutional and residential settings, with consideration given to locations such as schools, hospitals, universities, colleges, and public

buildings. In residential areas, households were grouped into clusters, and tap water samples were selected to ensure coverage across different service zones within each ward.

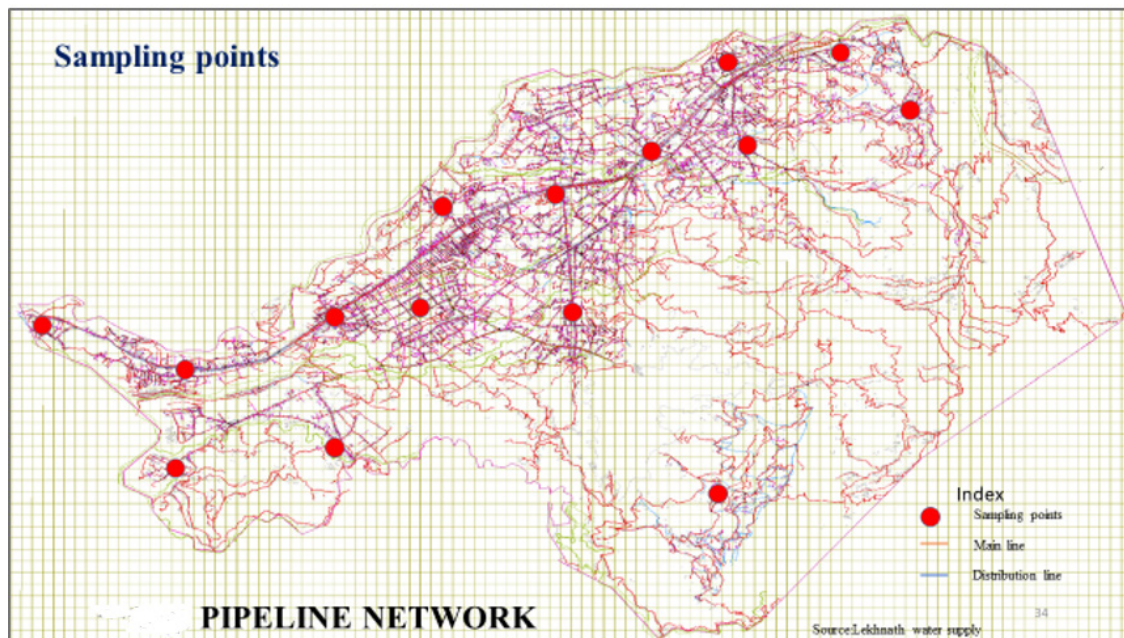


Figure 2. Water sampling points

Sampling was conducted during both warmer and cooler seasons in 2024 to account for potential seasonal variability in water quality parameters. Water samples were collected continuously from April 9 to October 22, 2024, across warmer (April–June) and cooler (September–October) seasons. All 31 samples (11 source, 5 reservoir, 15 household taps) were collected in accordance with APHA guidelines (APHA, 2023). While the temporal spread spans both pre- and post-monsoon periods, the data represent a single observational campaign conducted at a point in time. Formal seasonal comparison across multiple years would be needed to establish robust seasonal patterns; we recommend this as future work.

2.4 Sample collection and preservation

Water samples were collected from identified sources, reservoirs, and household taps across wards 26–32 of Pokhara Metropolitan City following standard procedures for drinking water quality assessment. All sampling, handling, and preservation protocols adhered to the Standard Methods for the Examination of Water and Wastewater (American Public Health Association (APHA), 2023, 24th ed.).

Sampling for field and laboratory analyses was conducted using separate containers to minimize contamination and ensure analytical accuracy. Prior to sample collection, containers were thoroughly cleaned and, where applicable, sterilized according to the requirements of the target parameters. Three types of sample bottles were used. Field analysis samples were collected in 1000 mL plastic bottles for on-site measurement of parameters including pH, temperature, electrical conductivity, chloride, alkalinity, total hardness, and free carbon dioxide (CO₂). Laboratory analysis samples were collected in 1000 mL pre-cleaned bottles for chemical parameter analysis, including ammonia,

nitrate, phosphate, iron, and arsenic. To preserve samples intended for metal analysis, concentrated sulphuric acid (H_2SO_4) and nitric acid (HNO_3) were added immediately after collection to reduce the sample pH below 2, in accordance with standard preservation guidelines.

Microbiological samples were collected in 125 mL sterilized poly-reagent plastic bottles. These bottles were handled aseptically to prevent external contamination during collection and transport. All samples were clearly labelled with sampling location, sample type, and collection date and were transported under controlled conditions. Samples designated for microbiological analysis were delivered to the Federal Water Supply and Sewerage Management Project Laboratory, Pokhara, within six hours of collection.

2.5 Laboratory analysis

All physicochemical and microbiological parameters were analysed using standardized analytical techniques in accordance with the Standard Methods for the Examination of Water and Wastewater (APHA, 2023, 24th ed.). Laboratory analyses were conducted at the Lekhnath Water Supply Laboratory and the Federal Water Supply and Sewerage Management Project Laboratory, Pokhara, following established quality control procedures.

2.5.1 Physicochemical Analysis

Field measurements of pH, electrical conductivity (EC), turbidity, and total dissolved solids (TDS) were carried out using calibrated digital instruments at the time of sample collection. Chemical parameters (total hardness as CaCO_3 , calcium, chloride, ammonia, iron, nitrate, arsenic, and free residual chlorine) were analysed using titrimetric, spectrophotometric, and instrumental techniques as specified by APHA standard methods. Iron was analysed using the phenanthroline method; arsenic by atomic absorption spectrophotometry.

Table 1. Physicochemical Parameters, Analytical Methods, Instruments, and Drinking Water Quality Standards

Parameter	Instrument/Method	APHA Standard Method	NDWQS 2079 Standard	Remarks
pH	Portable pH meter (calibrated)	4500-H ⁺ B	6.5–8.5	Field measurement
Temperature	Digital thermometer	2550 B	Reference value	Field measurement
Electrical Conductivity (EC)	Conductivity meter	2510 B	≤1500 $\mu\text{S}/\text{cm}$	Field measurement
Turbidity	Nephelometric Turbidimeter	2130 B	≤5 NTU	Laboratory analysis
Total Hardness	EDTA titrimetric method	2340 C	≤500 mg/L	Laboratory analysis
Alkalinity	Acid titration method	2320 B	No guideline value	Laboratory analysis

Parameter	Instrument/Method	APHA Standard Method	NDWQS 2079 Standard	Remarks
Chloride	Argentometric (Mohr) titration	4500-Cl ⁻ B	≤250 mg/L	Laboratory analysis
Free Carbon Dioxide (CO ₂)	Titrimetric method	4500-CO ₂ C	No guideline value	Laboratory analysis
Ammonia	Spectrophotometric (Nesslerization)	4500-NH ₃ F	≤0.1 mg/L	Laboratory analysis
Nitrate	UV Spectrophotometric method	4500-NO ₃ ⁻ B/E	≤50 mg/L	Laboratory analysis
Phosphate	Ascorbic Acid Spectrophotometric Method	4500-P E	No guideline value	Laboratory analysis
Iron (Fe)	Spectrophotometric (Phenanthroline)	3500-Fe B	≤0.3 mg/L	Laboratory analysis
Arsenic (As)	Atomic Absorption Spectrophotometer (Hydride Generation)	3500-As B	≤0.05 mg/L	Laboratory analysis

2.5.2 Microbiological Analysis

Microbiological quality was assessed by enumerating *Escherichia coli* and total coliform bacteria using the membrane filtration technique, following APHA Method 9222 D for *E. coli* and 9222 B for total coliforms. Results were expressed as colony-forming units per 100 mL (CFU/100 mL).

Table 2. Microbiological Parameters, Analytical Methods, and Drinking Water Quality Standards

Parameter	Instrument/Method	APHA Standard Method	NDWQS 2079 Standard	Remarks
Total Coliform	Membrane Filtration (MF)	9222 B	0 CFU/100 mL	Incubation at 35 ± 0.5°C
<i>Escherichia coli</i> (<i>E. coli</i>)	Membrane Filtration (MF)	9222 D	0 CFU/100 mL	Confirmatory test

2.5.3 Quality Assurance and Quality Control

Quality assurance and quality control procedures followed APHA Standard Methods (2023) guidelines. Analytical instruments were calibrated before each measurement batch using certified standard solutions. Method detection limits (MDLs) were determined according to APHA 2023; typical MDLs included iron 0.01 mg/L, arsenic < 0.005 mg/L, FRC ± 0.01 mg/L, and microbiological detection ≥ 1 CFU/100 mL. Laboratory blanks were processed in parallel with sample batches and returned values below the MDL. Duplicate samples were analyzed for approximately 10% of sample batches, with acceptable relative percent differences (RPD) maintained within acceptable limits.

(± 5 –10% for chemistry, ± 30 % for microbiology). All microbiological media controls remained sterile, confirming analytical validity.

Table 3. Quality Assurance and Quality Control (QA/QC) Procedures Adopted During Sample Collection, Preservation, and Laboratory Analysis

QA/QC Measure	Procedure
Sample preservation	Samples preserved according to APHA (1998); acidified with concentrated H_2SO_4 and HNO_3 for metal analysis ($\text{pH} < 2$).
Microbiological samples	Collected in sterile 125 mL bottles and transported to the laboratory within 6 hours.
Calibration	Instruments calibrated according to manufacturer recommendations before analysis. (Verify from laboratory SOP.)
Method blanks	Processed with each analytical batch. (Verify from laboratory records.)
Duplicate samples	As per laboratory quality control protocol. (Specify actual percentage if available.)
Standard methods	All analyses performed following APHA Standard Methods for the Examination of Water and Wastewater (1998).

2.6 Data analysis and statistical methods

All field and laboratory data were organized and analysed using Microsoft Excel. Raw data were coded by sampling location (source, reservoir, and household tap) and by water supply scheme to facilitate structured comparison. Data were screened for completeness and consistency prior to analysis, and no data transformation or imputation was applied.

Statistical analysis focused on summarizing observed values, ranges, and scheme-wise variation of physicochemical, chemical, and microbiological parameters, presented using tables and graphical representations. Parameters were evaluated by direct comparison with the NDWQS (2079) and WHO drinking-water guidelines.

Beyond descriptive summaries, the association between free residual chlorine (FRC) presence and microbiological compliance was examined using a Fisher's exact test on the 2×2 table of FRC detectable (yes/no) vs. *E. coli* detected (yes/no), appropriate for the small sample size. The relationship between FRC concentration and *E. coli* count along the LWSO distribution gradient was assessed using Spearman's rank correlation. Source-type groups (surface vs. groundwater/treated) were compared for *E. coli* count using the Mann–Whitney U test. Given the pilot sample size, inferential results are reported with exact p-values and interpreted as indicative rather than confirmatory.

3. Results

3.1. Physical Parameters

3.1.1. Turbidity, Electrical conductivity, Total dissolved solid

Most samples exhibited turbidity within the permissible limit of 5 Nephelometric Turbidity Unit (NTU). Turbidity at the Gujee Khola intake exceeded the guideline, reaching 10 NTU. Elevated turbidity was also observed at two household taps—Ram Bahadur Gurung (Talchowk) and Man Maya (Hamalchowk)—at 14.6 NTU and 7.2 NTU, respectively.

Electrical conductivity across all locations remained well below the NDWQS limit of 1500 $\mu\text{S}/\text{cm}$. EC for the LWSO boring source was approximately 400 $\mu\text{S}/\text{cm}$, while Archale, Red Cross, Chainapur, and Malmul schemes showed values of 26, 36, 55, and 39 $\mu\text{S}/\text{cm}$, respectively. Total dissolved solids at all sites were within the 1000 mg/L limit.

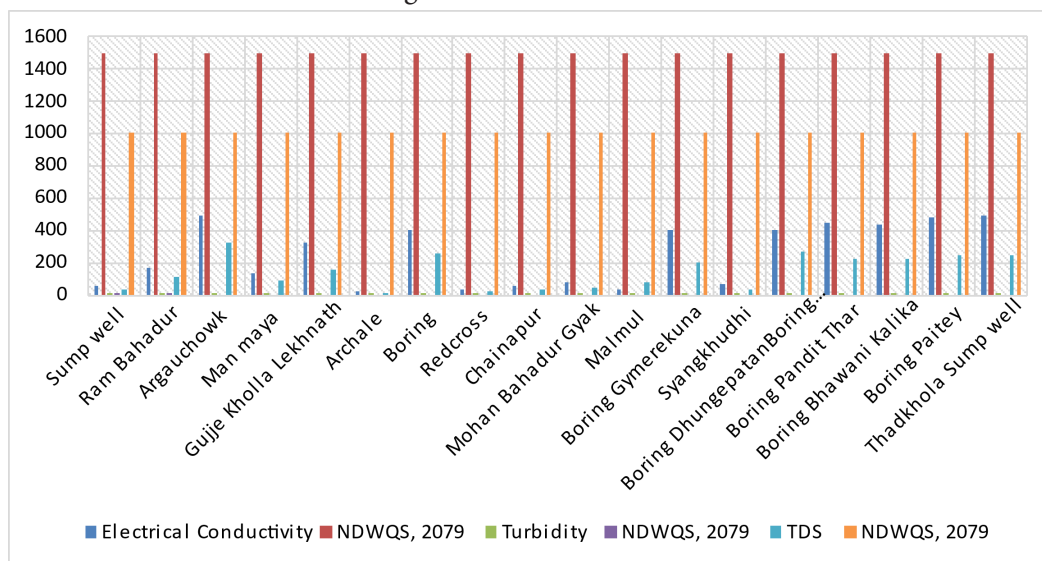


Figure 3. EC, Turbidity and TDS of water samples

pH:

Measured pH across all schemes was within the acceptable range of 6.5–8.5, ranging from 6.7 at the Thadkhola source to 8.2 in the LWSO system. All samples complied with the national guideline.

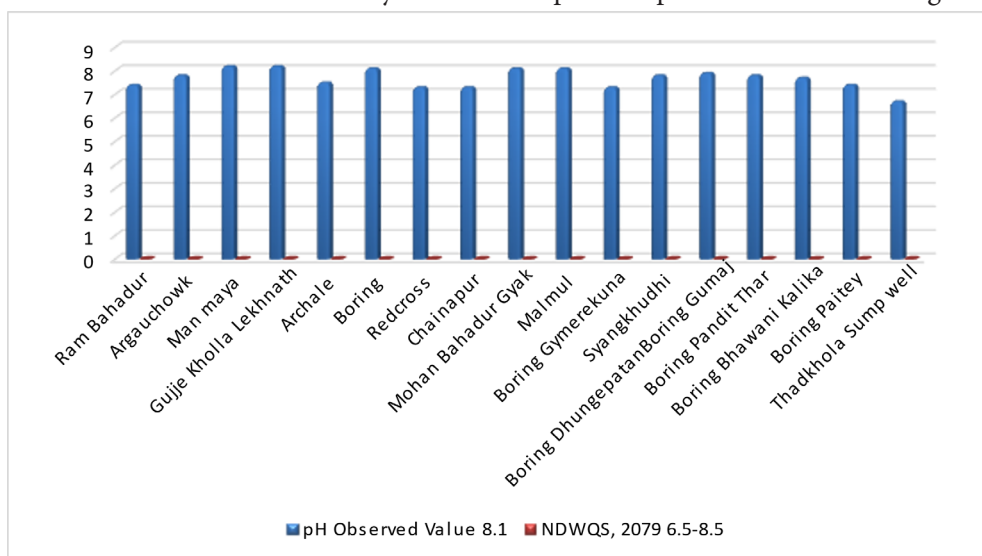


Figure 4. pH of water sample

3.2. Chemical Parameters

Iron

Iron in most sources complied with the 0.3 mg/L limit. Elevated iron was detected in untreated LWSO boreholes at Panditthar (1.2 mg/L) and Dhungepatan (1.6 mg/L); after pressure filtration these were reduced to approximately 0.1 mg/L, within the permissible range.

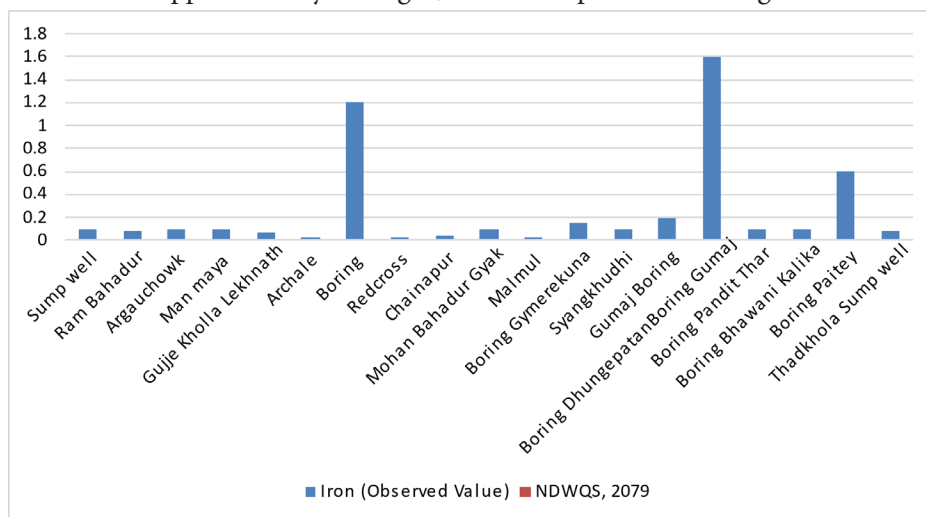


Figure 5. Iron level of water samples

Total hardness, calcium and chloride

Total hardness ranged from 24 to 276 mg/L, calcium from 3 to 54 mg/L, 44 and chloride from 4 to 24 mg/L, all well below NDWQS 2079 limits of 500, 45200, and 250 mg/L, respectively.

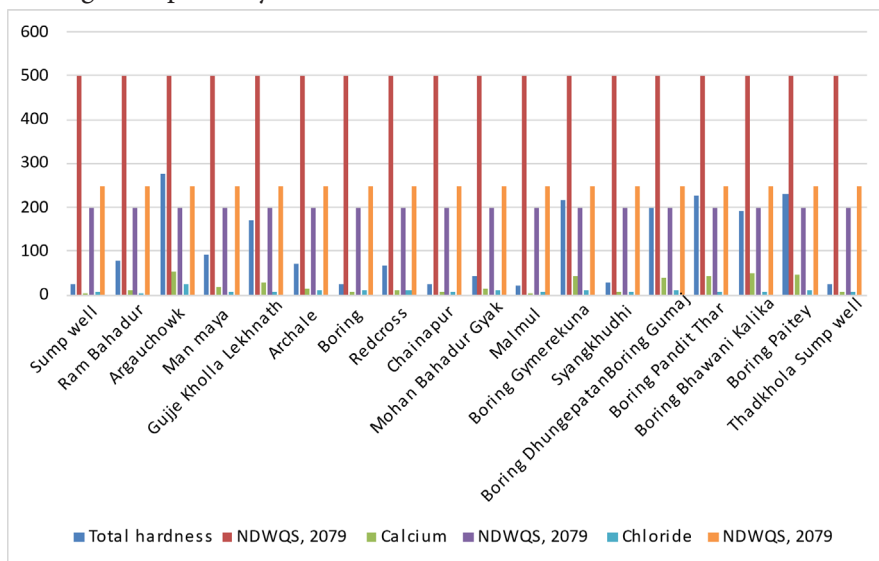


Figure 6. Total Hardness, Calcium and Chloride of water samples

Arsenic

Arsenic was not detected in any sample (< 0.005 mg/L detection limit), 50 confirming compliance with the NDWQS 2079 limit of 0.05 mg/L. This is represented in Figure 7.

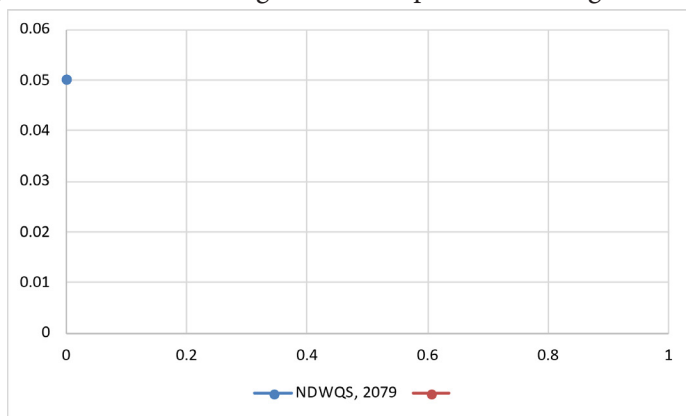


Figure 7. Arsenic of water samples

Nitrate

Nitrate ranged from 0.20 to 0.59 mg/L across all schemes, well below the 50 mg/L limit which can be seen in Figure 8.

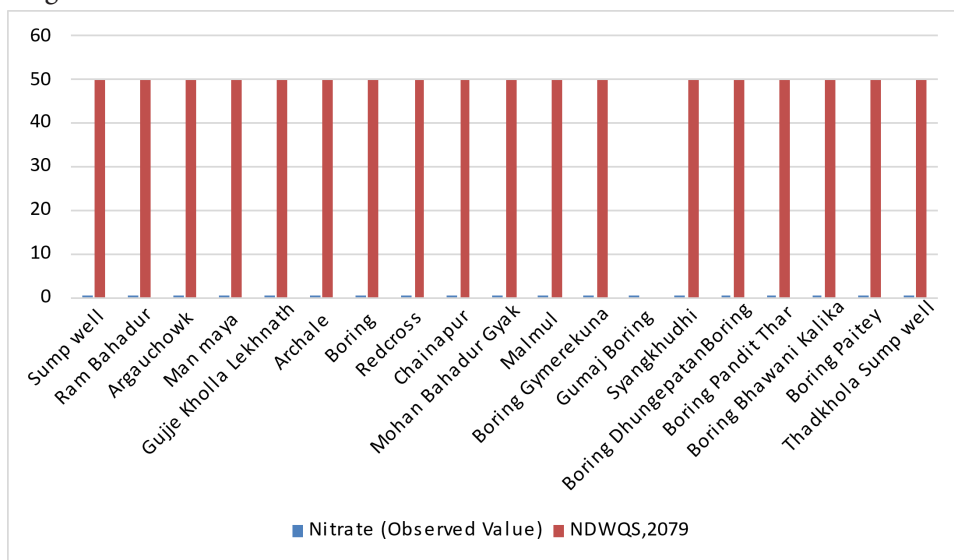


Figure 8. Nitrate of water samples

Ammonia

Figure 9, depicts the ammonia content which was observed at 0.1 mg/L across all supply schemes, within the NDWQS Guideline.

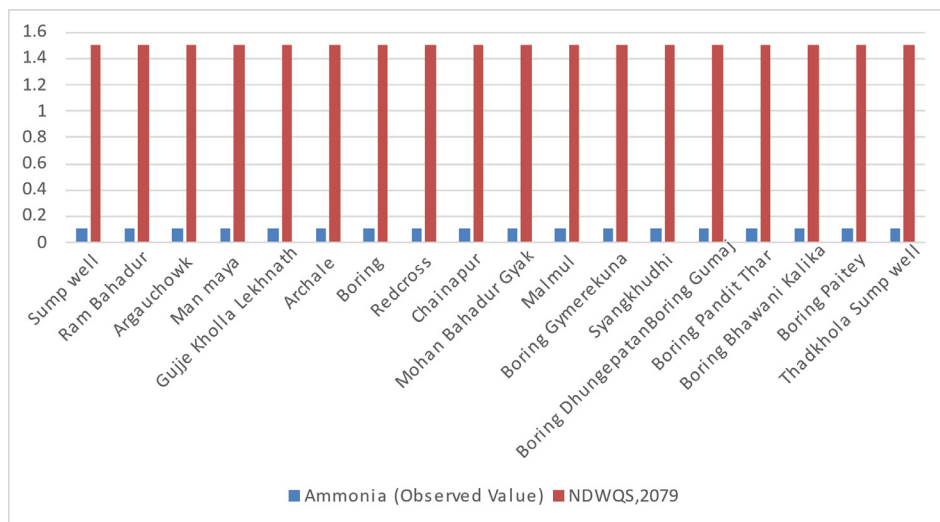


Figure 9. Ammonia of water samples

Free Residual Chlorine (FRC)

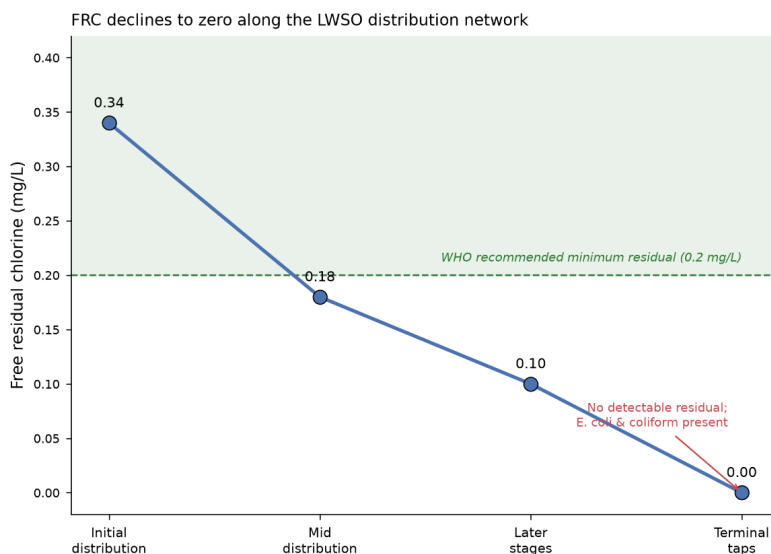


Figure 10. Free residual chlorine along the LWSO distribution network

FRC was detected only in the LWSO system. FRC was approximately 0.34 mg/L at the initial distribution stage, 0.18 mg/L in the mid-distribution section, and 0.10 mg/L toward later stages; at

terminal points FRC was not detected. No measurable FRC was observed in the community-managed schemes.

3.3. Microbiological parameters

E. coli

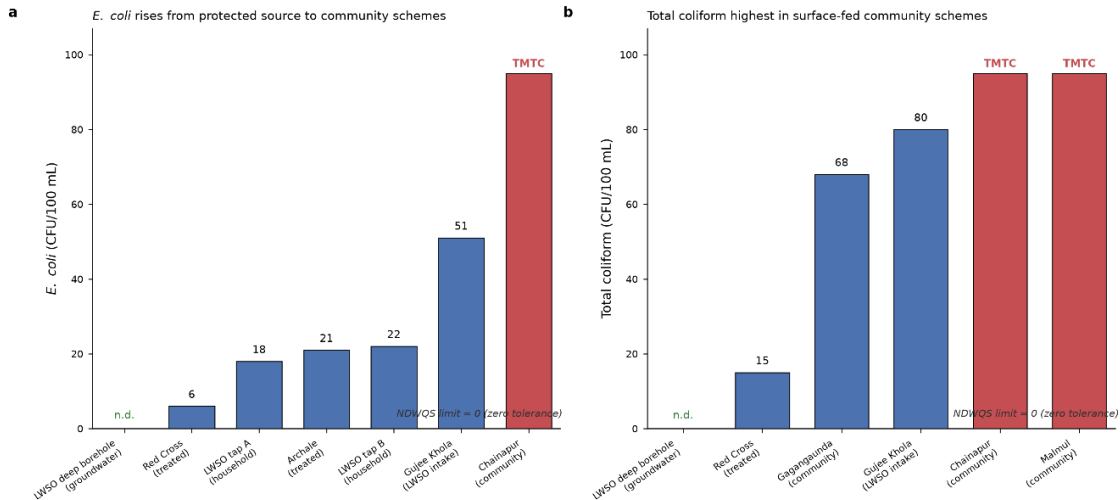


Figure 11. *E.coli* and Total coliform in the study area

NDWQS (2079) specifies zero tolerance for *E. coli*. Detectable *E. coli* was observed in several source and household samples. At the LWSO intake (Gujee Khola), *E. coli* reached 51 CFU/100 mL. Treated supplies from Archale and Red Cross showed 21 and 6 CFU/100 mL. LWSO household taps recorded 18 and 22 CFU/100 mL. Samples from the Chainapur scheme were too numerous to count (TMTC).

The presence of FRC was significantly associated with the absence of *E. coli* (Fisher's exact test, $p = 0.033$), and *E. coli* counts were significantly higher in surface-fed than in groundwater sources (Mann-Whitney U, $p = 0.039$).



Figure (a)



Figure (b)

Figure 12: Culture of bacteria present of *E.coli* and Total Coliform

Total Coliform

NDWQS requires total coliform to be absent. Gravity-fed LWSO surface sources showed 5–80 CFU/100 mL (highest at the Gujee Khola intake). Gagangaunda (68 CFU/100 mL) and Red Cross (15 CFU/100 mL) also showed elevated counts. Chainapur and Malmul were TMTC. Deep-borehole LWSO sources showed no detectable total coliform.

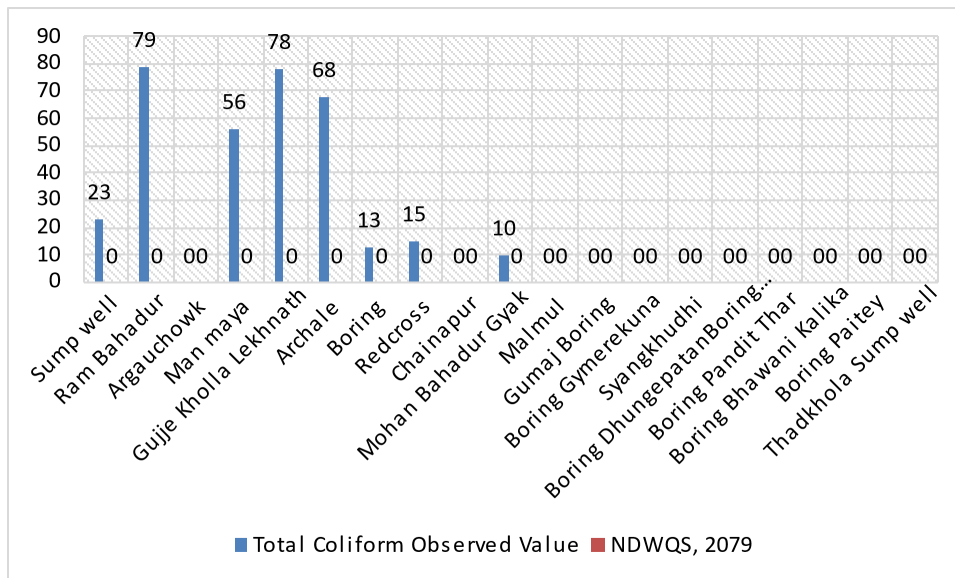


Figure 13: Total Coliform of water samples

4. Discussion

4.1 Physicochemical quality in context

Physicochemical parameters broadly complied with NDWQS 2079 across all schemes, consistent with surveys from Kathmandu Valley and other Nepali urban centres where chemical quality often meets standards even when microbiological compliance is poor (Maharjan et al., 2018; Pant et al., 2023). The localized turbidity exceedances at the Gujee Khola surface intake (10 NTU) is characteristic of surface sources following rainfall, and iron exceedances in untreated boreholes (1.2–1.6 mg/L) were effectively removed by pressure filtration (to ~0.1 mg/L), demonstrating that existing treatment can control chemical parameters when source quality is suboptimal. The central implication is that chemical compliance alone does not ensure safety: microbiological quality is the governing vulnerability.

4.2 Microbiological contamination pathway and FRC decay

Microbiological results contrast sharply with physicochemical compliance. The data are consistent with a source-to-tap contamination pathway shaped by three interacting factors: source type and protection, free residual chlorine (FRC) maintenance, and scheme management.

First, source type strongly influenced baseline quality. Surface-fed community schemes (Chainapur, Malmul, Gagangaunda) showed TMTC or high *E. coli* counts, whereas protected deep-borehole groundwater showed no detectable *E. coli*. This difference was statistically significant (Mann–Whitney U, $p = 0.039$) and mirrors South Asian findings that protected groundwater with treatment carries

the lowest microbiological risk (Mengstie et al., 2023; Pant et al., 2016).

Second, and most consequential for management, FRC presence was significantly associated with the absence of *E. coli* (Fisher's exact test, $p = 0.033$). Within the LWSO network, FRC declined from ~ 0.34 mg/L in early distribution to undetectable at terminal taps, and *E. coli* counts rose along this same gradient (Spearman $\rho = -0.78$; the gradient trend did not reach significance at $n = 4$, $p = 0.23$). This pattern — residual decay followed by microbial reappearance — is consistent with chlorine-decay kinetics in distribution systems and may reflect (a) normal chemical decay through reaction with pipe materials and organic matter, (b) ingress of contaminated water through pipe leaks or cross-connections, (c) stagnation and biofilm formation under intermittent supply, and (d) dilution of residual under peak demand. Notably, LWSO household taps (18–22 CFU/100 mL) were more contaminated than the treated intake, indicating that the loss of safety occurs within the distribution network rather than at treatment — a distinction also reported by (Maharjan et al., 2018; Riaz et al., 2021).

Third, community-managed schemes showed higher and more consistent contamination than LWSO. Capacity constraints, ageing gravity-fed infrastructure, absence of disinfection, and intermittent supply are plausible contributors (Nicholson et al., 2017; Sarkar et al., 2022), consistent with evidence that management intensity and infrastructure investment predict water safety (Ali et al., 2021; Mengstie et al., 2023).

4.3 WHO risk categorization and public-health significance

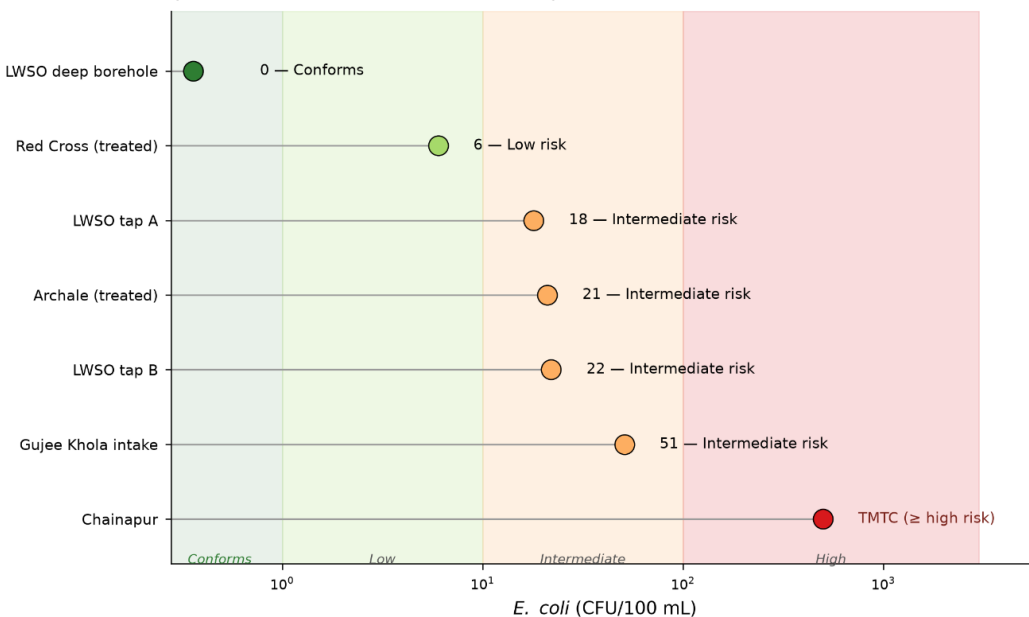


Figure 14: WHO risk categorization by *E. coli* count

Interpreting the *E. coli* results against WHO risk categories stratifies the schemes by health risk: deep borehole groundwater conforms (0 CFU/100 mL); Red Cross falls in the low-risk band (1–10 CFU/100 mL); LWSO household taps, Archale, and the Gujee Khola intake fall in the intermediate-risk band (11–100 CFU/100 mL); and the Chainapur and Malmul community

schemes (TMTC) fall in the high/very-high-risk band. The presence of intermediate- to high-risk supplies at consumer endpoints in a growing urban centre is a public-health concern, particularly for children, the elderly, and immunocompromised residents.

4.4 Comparison with regional studies

The findings align with documented Nepali and South Asian patterns: substantial within-city variation driven by source type and treatment capacity (N. D. Pant et al., 2016); post-treatment recontamination at household taps despite functional treatment (Maharjan et al., 2018); protected groundwater outperforming surface sources (Mengstie et al., 2023); and distribution-level FRC decay as a primary driver of tap contamination (Riaz et al., 2021; Sarkar et al., 2022). Placing Pokhara in this regional context indicates that its contamination profile is typical of intermittent, multi-scheme South Asian systems rather than anomalous.

4.5 Critical control points and operational implications

For LWSO (centralized, treated): optimize chlorination to maintain 0.2–0.5 mg/L free residual at network extremities; implement residual monitoring at multiple points; establish leak detection and repair; and move toward continuous (24/7) supply to reduce stagnation and backflow. For community-managed schemes: introduce or upgrade source protection at intakes; establish basic chlorination and residual testing; build operator capacity; and develop scheme-level Water Safety Plans. These are scheme-specific critical control points at which modest operational investment would most effectively reduce health risk.

4.6 Limitations

This pilot cross-sectional study has several limitations that bound interpretation. The sample size (31 points) reflects operational coverage of the six schemes rather than a power calculation, so inferential results are indicative rather than confirmatory. Household taps were not selected by probability sampling, limiting statistical representativeness. TMTC microbiological results place a ceiling on quantitative comparison for the most contaminated schemes. Seasonal inference is constrained by the number of sampling rounds. These limitations motivate a larger, seasonally-stratified, probability-based follow-up with quantified plate counts.

5. Conclusions

This study evaluated the physicochemical and microbiological quality of drinking water supplied through multiple schemes in selected wards of Pokhara Metropolitan City. Most physical and chemical parameters complied with the Nepal Drinking Water Quality Standards. However, detectable *E. coli* and total coliforms at several source and household tap locations indicate localized microbiological contamination and distribution-level vulnerability despite acceptable source-water chemical quality. The presence of free residual chlorine was significantly associated with microbiological compliance, and surface-fed sources carried significantly higher contamination than protected groundwater, underscoring residual maintenance and source protection as priority interventions.

Based on these findings, strengthening routine microbiological monitoring, maintaining adequate disinfectant residuals throughout the distribution network, and improving operational oversight at community-managed schemes are recommended. Future studies should incorporate seasonal monitoring, probability-based household sampling, and larger spatial coverage to capture temporal variation and identify critical control points within the supply chain.

Conflict of Interest

There are no any conflict of interest while doing this study.

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