

Final Technical Report

for

Research Project

Drinking water quality in Bhutan: Trend and compliance (2017-2024)

Principal Investigator: Pema Chopel (RCDC)

Co-Investigator(s): Pema Chopel (RCDC), Chimmi Dorji (RCDC), Amin Ngawang Tashi (RCDC), Rinzin Wangdi (RCDC)

2025.40.NW

September 2025

Final Technical Report

Disclaimer

This article is not a peer reviewed article and the views expressed in the article are solely those of the author(s) and do not necessarily reflect the views of the publication, its editors, or its affiliates. The information provided in this article is for general informational purposes only and should not be construed as professional advice. Readers are encouraged to consult with appropriate professionals for advice tailored to their specific situations or contact the investigator for details.

Drinking water quality surveillance in Bhutan: trend and compliance (2017–2024)

Pema Chopel ^{*}, Amin Ngawang Tashi , Rinzin Wangdi  and Chimmi Dorji 

Royal Centers for Disease Control, Royal Government of Bhutan, Thimphu 11001, Bhutan

^{*}Corresponding author. E-mail: pchopel@health.gov.bt

 PC, 0009-0000-6900-6417; ANT, 0009-0001-7109-7351; RW, 0009-0004-9927-6185; CD, 0009-0006-9556-3931

ABSTRACT

Clean and safe drinking water is essential for public health. Despite substantial infrastructure investments, ensuring water safety remains a challenge in Bhutan. The objective of the study is to provide a nationwide assessment of drinking water quality from 2017 to 2024, covering 20 dzongkhags samples from 31 urban ($n = 20,982$) and 242 rural ($n = 14,361$) surveillance sites. Data were retrieved from the Water Quality Monitoring Information System and analyzed for compliance with Bhutan Drinking Water Quality Standards and WHO guidelines. Only 52.8% of urban samples met the microbial standard (0 CFU/100 mL), with the Eastern region showing the lowest compliance. Residual chlorine compliance was critically low (11.9%), indicating inadequate disinfection. While turbidity met Bhutan's standard (95.2%), only 67.3% complied with WHO's health-based guideline (1 NTU). Other parameters, such as pH and conductivity, showed high compliance (>96%). Rural systems, largely untreated, showed better microbial compliance (70.1%), though methodological differences limit direct comparison. Health risk classification showed seasonal deterioration in safety, particularly during the monsoon in urban and rural areas. The study recommends shifting to risk-based water safety management, including upgrading treatment capacity, standardizing testing methodology, and implementing and auditing water safety plans to meet Bhutan's Five-Year Plan targets and Sustainable Development Goal 6.

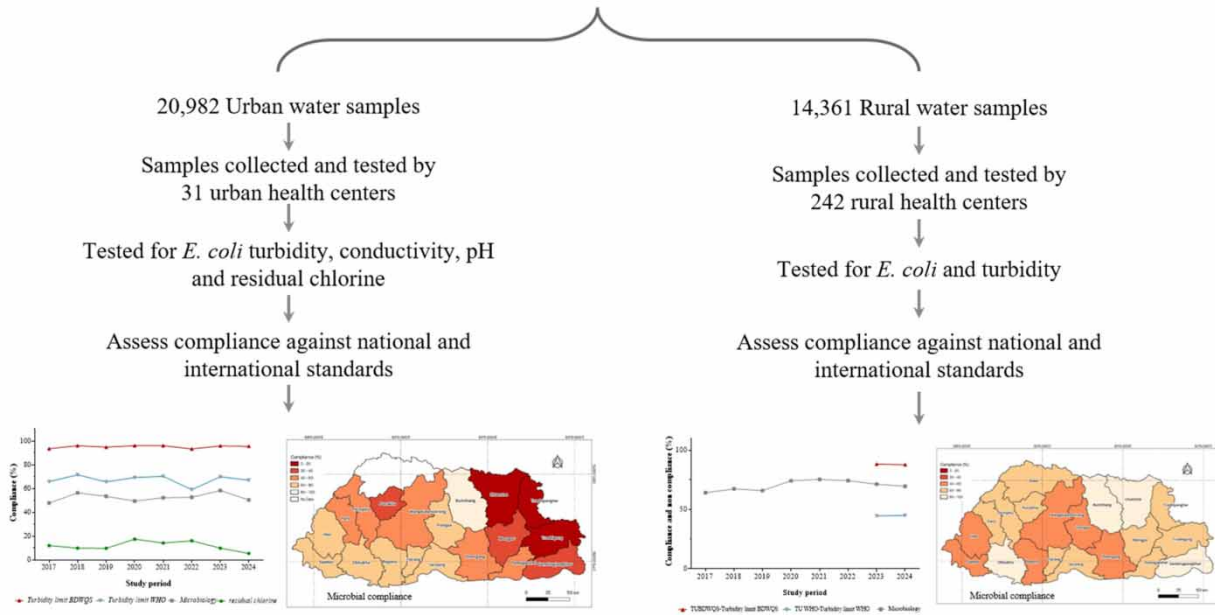
Key words: Bhutan, drinking water quality surveillance, microbial contamination, rural and urban water

HIGHLIGHTS

- Microbial compliance in drinking water was very low, with no improvement from 2017 to 2024.
- Residual chlorine was critically low, indicating inadequate disinfection practices.
- Turbidity met national standards but not the WHO health-based guideline values.
- Seasonal declines in water quality were observed during the monsoon.
- The study calls for risk-based water safety management and implementation of water safety plans.

GRAPHICAL ABSTRACT

Drinking water samples were tested across Bhutan from 2017 to 2024



INTRODUCTION

Clean and safe drinking water is a fundamental necessity for human well-being. It is crucial not only for survival but also for supporting public health, economic growth, and social progress. Despite its importance, providing safe and affordable drinking water for all continues to be a global challenge. According to the World Health Organization (WHO) and UNICEF's Joint Monitoring Programme (JMP), approximately 2.2 billion people worldwide do not have safely managed drinking water services, and 785 million people lack basic drinking water infrastructure (WHO/UNICEF 2023). Contaminated drinking water is a major cause of waterborne diseases, such as diarrhea, cholera, typhoid fever, dysentery, and hepatitis A, contributing to over 500,000 deaths annually, with 485,000 occurring in children under five (World Health Organization (WHO) 2023). Additionally, lack of access to safe water particularly affects vulnerable groups of the population, including children (Luby *et al.* 2018), pregnant women (Rani & Dhok 2023), and the elderly (Kumar *et al.* 2022).

Ensuring access to safe drinking water is crucial for the fulfillment of Target 6.1 under Sustainable Development Goal 6, which seeks to ensure universal and equitable access to safe and affordable drinking water for all by 2030 (United Nations 2024). While Bhutan benefits from abundant freshwater resources, including rivers, glacial lakes, and groundwater reserves, the country faces significant challenges in ensuring safe drinking water for all. The country's rugged terrain makes accessing water sources difficult, with many communities situated in hilly or mountainous regions, while rivers flow through deep valleys, making water sources difficult to access. The impacts of climate change, such as unpredictable weather patterns and drying of water sources, further affect the availability and reliability of water supplies. Likewise, rapid developmental activities and urbanization have put additional pressure on water resources, impacting water quality and quantity.

Despite the challenges, Bhutan has made notable progress, with 99.7% of the population having access to improved drinking water sources, as reported in the National Health Survey (Ministry of Health 2023). Moreover, the country has implemented a drinking water quality surveillance system to safeguard public health by monitoring water quality at various stages of the water supply system, as its model is recognized as an example for small water supply systems (WHO 2024). However, there is a lack of comprehensive analysis of water quality test data produced over the years for urban and rural settings. As a result, critical gaps persist in linking surveillance data to effective decision-making, highlighting the need for a thorough data analysis to inform corrective interventions and improve drinking water quality and public health outcomes. As it is widely known, many water monitoring programmes are described as 'data-rich but information-poor,' prioritizing test implementation over strategic risk mitigation and policy development (Ward *et al.* 1986).

This study aims to evaluate the temporal trends in drinking water quality from 2017 to 2024 and assess compliance with the Bhutan Drinking Water Quality Standard, 2016 (BDWQS) and WHO guidelines. By analyzing the existing data, this study will provide evidence-based recommendations for improving surveillance practices and policymaking. Ultimately, these findings will support Bhutan's efforts to achieve SDG 6 and ensure safe drinking water for all.

MATERIALS AND METHODS

Study design

Drinking water quality surveillance in Bhutan is managed by the Ministry of Health, as the Royal Center for Disease Control (RCDC) serves as the national reference laboratory. This nationwide surveillance is conducted by 31 urban health centers and 242 rural health centers, including primary health centers and sub-posts. The existing Bhutan drinking water quality surveillance data flow is illustrated in Figure 1. The sample collection and processing are performed as per the standard operating procedures for respective parameters, and overall guidance for sample collection, handling, testing, and reporting is outlined in the national guideline for Drinking Water Quality Surveillance, 2019 (NGDWQS) (RCDC 2019).

Sample collection and testing methods

Water samples for microbial analysis were collected in sterile containers following standardized procedures. Before sampling, water was allowed to flow for 1–2 min to ensure representative sampling. Collected samples were immediately placed in cold chain containers and transported to the laboratory to be processed within 2–6 h.

In urban surveillance sites, microbial testing was conducted using the membrane filtration technique, in which 100 mL of water was passed through a 0.45- μ m membrane filter and cultured using HiCrome™ Chromogenic Coliform agar to detect *Escherichia coli*. In rural areas, where laboratory infrastructure is limited, *E. coli* testing was conducted using the 3M

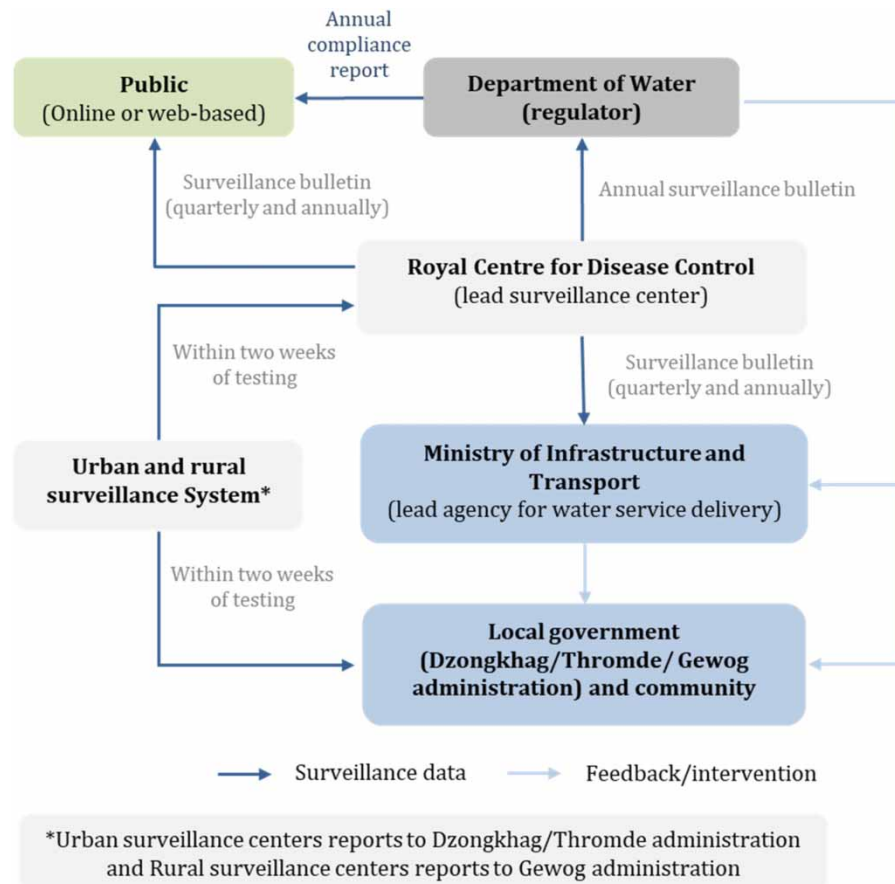


Figure 1 | Surveillance data flow and feedback mechanism as per the national standard and guideline for surveillance.

Petrifilm™ technique. Here, 1 mL of the sample was plated and incubated at body temperature. Precautions are taken to avoid contamination at all steps.

For other physical and chemical parameters, containers are washed with samples and tested 2–3 times, before collecting the samples. Residual chlorine and pH are measured at the site of sample collection. Given the laboratory capacity, the test parameters and methodology employed may differ for urban, rural, and the reference laboratory (RCDC). The test parameters and methods used for analysis at different surveillance sites are given in Table 1.

Data analysis

The analysis for water quality results in this study was done using administrative data retrieved from the Water Quality Monitoring Information System (WQMIS) from 2017 to 2023. The WQMIS is the centralized repository for recording data collected by all surveillance sites responsible for monitoring drinking water quality throughout Bhutan. It includes records of microbial, physical, and chemical parameters that are monitored as per the requirements of BDWQS and NGDWQS.

Graphpad Prism 8.0 software (GraphPad) and Microsoft Excel 2016 were employed to observe descriptive statistics, analyze trends, and develop tables and graphs. All sets of data are presented as the mean $\pm$ SEM. A linear regression model was used to assess the association between the turbidity of water samples and the concentration of *E. coli*, log-transformed ($\log_{10}[x + 1]$) to address skewness and zero values. To compare microbial compliance across urban regions (four regions divided as per the national urbanization strategy (MoIT 2008) (Supplementary Material, Table S1), a one-way analysis of variance (ANOVA) was performed, followed by Tukey's post-hoc test to identify specific pairwise differences. A *p*-value of < 0.05 was statistically significant.

RESULTS

Urban drinking water quality

For this study, data from 31 health centers across 19 dzongkhags (districts) were analyzed for urban drinking water quality. One dzongkhag (Gasa) was excluded due to the lack of data in the WAQMIS system. A total of 20,982 samples were included in the study for urban water quality. The results showed fluctuations in compliance across key microbial and physical parameters with no improvement in the consecutive years (Figure 2).

The majority of samples (90.1%) were sourced from streams. The remaining samples were obtained from springs (2.8%), rivers (2.3%), and groundwater (1.8%), while a small proportion had unspecified sources.

Microbiological compliance

Between 2017 and 2024, a total of 13,640 samples were tested for microbiological contamination from 31 health centers. As shown in Figure 2, the microbial quality showed a notable concern, with only 52.8% ($n = 7,213$) of samples, on average, meeting the regulatory standard of 0 CFU/100 mL, indicating widespread and persistent issues related to microbial contamination. Figure 3 presents microbial compliance across 20 dzongkhags in urban areas. As shown in Figure 3, dzongkhags, including Trashiyangtse, Trashigang, Lhuentse, Samdrupjongkhar, Mongar, Punakha, Wangduephodrang, and Zhemgang, recorded average compliance rates below 50%. Additionally, a one-way ANOVA test showed a significant difference in compliance

Table 1 | Test parameters and test methods used at different facilities

Test category	Parameter	Surveillance sites (Urban)	Surveillance sites (Rural) ^a	Surveillance site (Reference laboratory)
Microbiology	<i>E. coli</i>	Membrane filtration	3M Petrifilm™ (<i>E. coli</i>) using 1 mL of sample	Membrane filtration
Physical	Turbidity	pH comparator using phenol red	Not performed	HACH 2100Q turbidimeter (Iowa, USA)
	pH		pH comparator using phenol red	portable pH meter (Mettler Toledo FiveGo, Switzerland)
	Conductivity		Not performed	Orion star A220, portable meter (Thermo Fisher Scientific, US)
Chemical	Free residual chlorine	Chlorine comparator using DPD-1	Not performed	DPD-based colorimeter (HACH Pocket Colorimeter II)

^aIn rural surveillance sites, due to the lack of incubation facilities, *E. coli* testing was conducted using the 3M Petrifilm™ technique, which utilized 1 mL of sample and incubated with body heat.

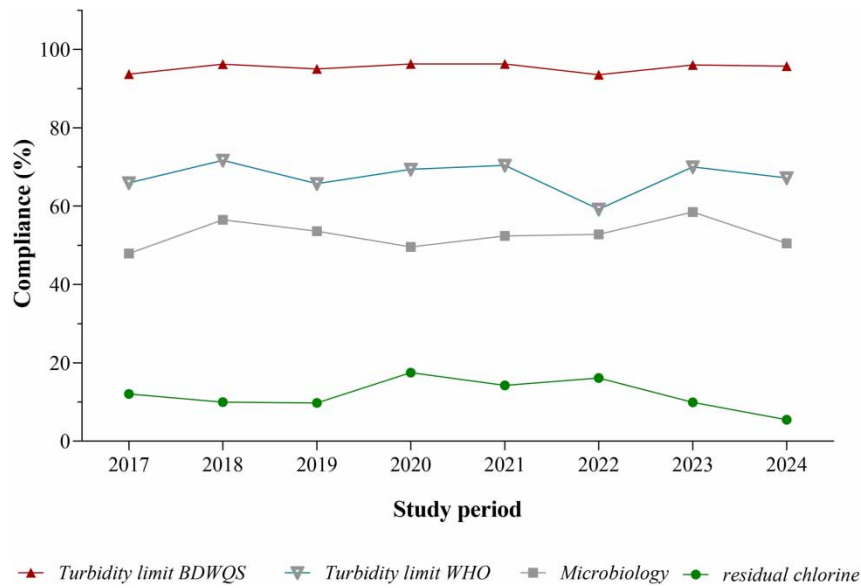


Figure 2 | The proportion of compliance and trend of urban drinking water samples for various parameters from 2017 to 2024.

rate between the Eastern region with other regions. Microbial compliance trends across the years for all dzongkhags are given in Table 2, and compliance trends for individual surveillance sites are given in Supplementary Material, Table S2.

Physio-chemical parameters' compliance

Turbidity

Turbidity is a measurement of the cloudiness of water caused by chemical and biological suspended particles, and serves as a key indicator of water quality. A total of 10,972 samples were analyzed for turbidity with a median value of 29.45, ranging from 0.00 to 275 NTU. Most of the samples generally met the requirements for BDWQS (5 NTU), with an average compliance rate of 95.2% ($n = 10,448$). However, when assessed against the WHO guideline (<1 NTU), compliance declined substantially, with only 67.3% ($n = 7,386$) of samples meeting the recommended level (Figure 2). The average compliance for turbidity over the years across all the dzongkhags is given in Supplementary Material, Table S3. At the dzongkhag level, the turbidity compliance was below 50% in Wangduephodrang, Trashiyangtse, and Haa when assessed against the WHO standard.

Residual chlorine

A total of 7,094 water samples were analyzed for residual chlorine, with an average concentration of 0.11 mg/L, ranging from 0.00 to 6.8 mg/L. From the samples tested, only 11.9% ($n = 835$) complied with national and international standards (Figure 2). This consistently low performance underscores significant challenges in maintaining adequate levels of disinfection throughout the distribution system. The average compliance for residual chlorine over the years across all the dzongkhags is given in Supplementary Material, Table S4. A statistically significant negative correlation was observed between residual chlorine levels and microbial contamination ($r = -0.06$, $p < 0.05$), suggesting that lower residual chlorine levels may be associated with higher microbial presence.

pH

A total of 11,086 samples were tested for pH, of which 96.3% ($n = 10,677$) were within the acceptable limit. The mean pH value was 7.2 which ranged between 4.0 and 10.6. Instances of extremely low or high pH were not consistently associated with specific sampling points, suggesting the possibility of operational issues or measurement errors. All dzongkhags reported pH compliance rates above 90%, except for Wangduephodrang, where the compliance rate was notably lower at 66.0%. No significant variation in pH levels was observed across different seasons.

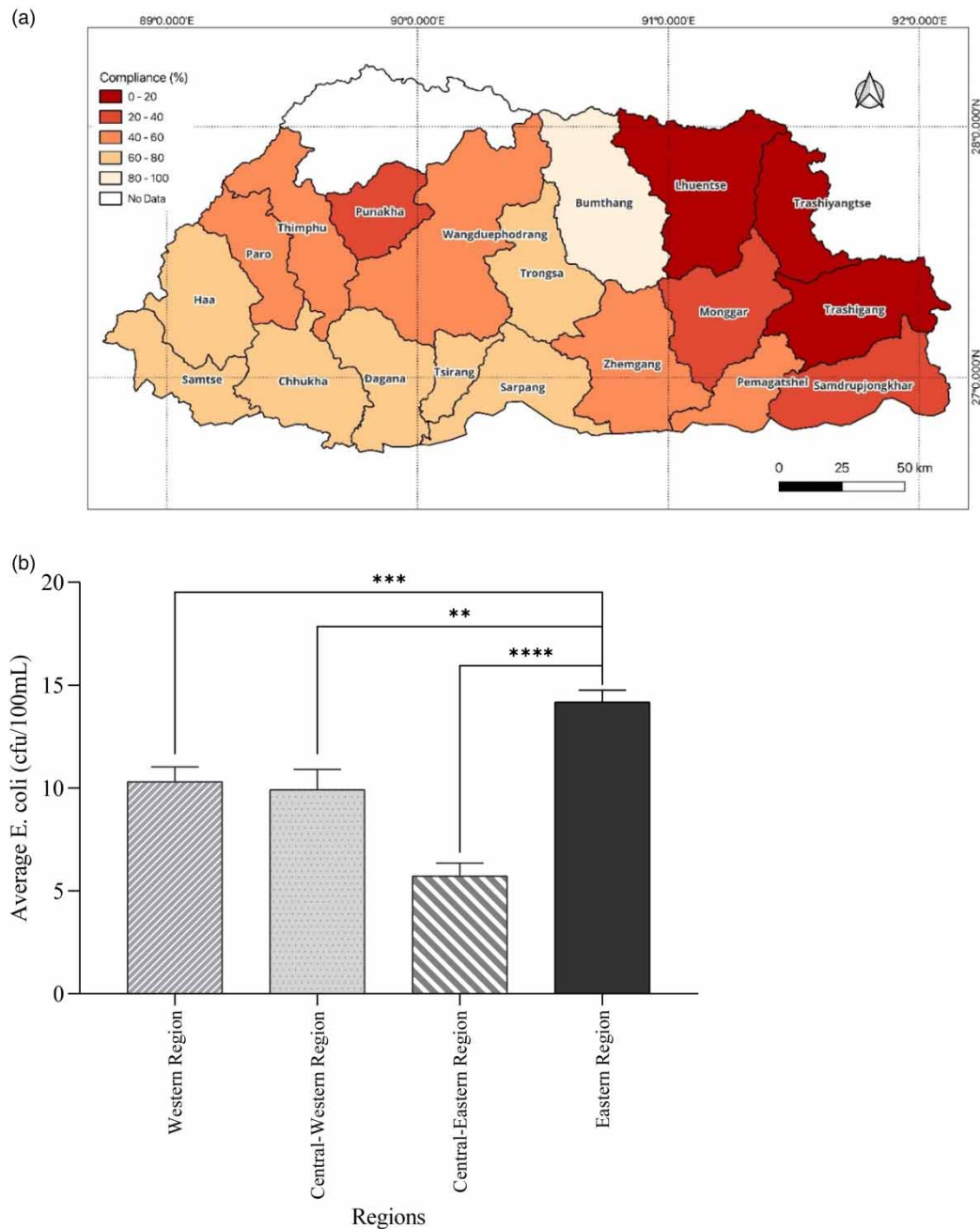


Figure 3 | (a) Microbial compliance for 20 districts and (b) average *E. coli* concentration of four regions in urban areas.

Conductivity and TDS

A total of 2,449 samples were tested for conductivity, of which all the samples met the regulatory requirements ($<1,000 \mu\text{S}/\text{min}$). The highest mean concentration of conductivity was observed for Pemagatshel ($314.6 \pm 15.8 \mu\text{S}/\text{min}$), followed by Samdrupjongkhar ($212.1 \pm 27.1 \mu\text{S}/\text{min}$). The least conductivity was observed in Tsirang (17.9 ± 0.5). In regard to TDS, 1,125 samples were tested, with a mean TDS of $43.8 \pm 1.4 \text{ mg}/\text{L}$. The highest mean TDS was observed in Pemagatshel ($170.5 \pm 5.9 \text{ mg}/\text{L}$), followed by Samdrupjongkhar ($106.0 \pm 13.6 \text{ mg}/\text{L}$). The least was observed in Wangdiphodrang ($12.3 \pm 3.4 \text{ mg}/\text{L}$). Mean conductivity across all the dzongkhags is given in Supplementary Material, Figure S1. There was not much variation in conductivity and TDS with seasonal changes across all the dzongkhags.

Table 2 | Microbial compliance trends across the study period for all dzongkhags

Dzongkhag	Non-compliance (%)								Total non-compliance (%)
	2017	2018	2019	2020	2021	2022	2023	2024	
Bumthang	56 (98.2)	65 (100)	50 (84.7)	28 (59.6)	35 (61.4)	89 (98.9)	85 (85.9)	60 (66.7)	468 (81.9)
Chhukha	184 (68.4)	201 (76.7)	179 (83.6)	70 (77.8)	35 (59.3)	104 (62.3)	142 (80.2)	71 (44.1)	986 (69.0)
Dagana	63 (62.4)	79 (65.8)	70 (63.6)	2 (6.7)	32 (62.7)	95 (86.4)	94 (94)	105 (76.1)	540 (64.7)
Haa	19 (47.5)	23 (92)	35 (70)	34 (75.6)	43 (71.7)	33 (75)	33 (66)	11 (73.3)	231 (71.4)
Lhuentse	16 (22.2)	15 (20.8)	1 (1.4)	2 (2.8)	12 (16.7)	24 (34.3)	19 (28.8)	20 (27.8)	109 (19.4)
Mongar	7 (10.6)	11 (30.6)	22 (33.8)	12 (18.5)	12 (21.4)	24 (27.3)	57 (67.1)	46 (54.8)	191 (33.0)
Paro	15 (20.5)	22 (31.4)	36 (42.4)	33 (61.1)	15 (50)	14 (63.6)	29 (44.6)	19 (95)	183 (51.1)
Pemagatshel	26 (38.2)	23 (35.4)	8 (22.9)	14 (56)	6 (37.5)	31 (88.6)	31 (68.9)	31 (57.4)	170 (50.6)
Punakha	10 (12.8)	34 (47.2)	39 (54.2)	25 (34.7)	23 (41.1)	16 (28.6)	39 (37.5)	25 (25.3)	211 (35.2)
Samdrupjongkhar	29 (30.9)	10 (11.4)	9 (13.4)	1 (2.2)	6 (40)	17 (37.8)	13 (31)	14 (21.2)	99 (23.5)
Samtse	68 (48.6)	85 (59)	98 (63.6)	113 (72.9)	71 (67.6)	102 (70.8)	124 (82.7)	51 (63)	712 (66.0)
Sarpang	97 (50.5)	105 (72.9)	76 (76.8)	39 (70.9)	NA	26 (41.9)	82 (65.1)	71 (65.7)	496 (63.4)
Thimphu	291 (66.1)	311 (72.2)	263 (66.9)	86 (55.5)	136 (59.4)	143 (43.9)	252 (58.1)	248 (60.6)	1,730 (60.3)
Trashigang	4 (3.6)	15 (14.3)	3 (3.1)	6 (11.1)	13 (31)	48 (41.7)	27 (19.4)	9 (7.8)	125 (16.5)
Trashiyangtse	6 (7.5)	9 (11.4)	11 (13.4)	10 (18.9)	3 (10.7)	7 (9.2)	7 (12.5)	9 (13.6)	62 (12.2)
Trongsa	46 (55.4)	23 (27.4)	35 (71.4)	8 (100)	8 (100)	24 (75)	8 (100)	NA	152 (75.6)
Tsirang	48 (66.7)	57 (79.2)	61 (84.7)	52 (72.2)	34 (64.2)	27 (56.2)	48 (66.7)	48 (66.7)	375 (69.6)
Wangduephodrang	23 (24)	23 (32.9)	8 (14.3)	5 (35.7)	NA	NA	8 (66.7)	11 (78.6)	78 (42.0)
Zhemgang	61 (62.9)	54 (93.1)	33 (32)	55 (61.1)	42 (62.7)	12 (22.6)	17 (22.7)	21 (36.2)	295 (49.2)

NA data not available.

Seasonal variation and compliance

As shown in [Figure 4](#), the average microbial compliance rate varied between 39.9 and 63.3%. The compliance during rainy seasons (May to September) was comparatively lower than the dry season, suggesting a seasonal impact on microbial contamination.

Similarly, seasonal turbidity compliance (<1 NTU, as per the WHO guideline) ranged from 56.8 to 76.4%, as illustrated in [Figure 4](#). Similar to microbial compliance patterns, compliance for turbidity was lower during the rainy season (May to September), with the highest average turbidity recorded in July at 2.3 NTU.

Rural drinking water quality

For this study, data from 242 health centers across 20 dzongkhags were analyzed for rural drinking water quality. In rural areas, drinking water is supplied without treatment and is generally managed by consumers or community groups, with governmental support limited to the initial establishment of water supply schemes. In some cases, particularly in isolated areas where community supply is not feasible, private water supplies are utilized. A total of 1,715 sampling points were included in the analysis, with the majority of samples (95.3%) sourced from streams. The remaining samples were collected from springs (3.9%) and other unspecified sources. Overall, the results showed no improvement in the consecutive years for microbial and physical parameters ([Figure 5](#)).

Microbial compliance

Between 2017 and 2024, a total of 14,361 samples were tested for *E. coli*, which present the overall microbial compliance and the number of samples tested in rural areas during the study period. The results indicate that 70.3% ($n = 10,094$) of the rural drinking water samples met the national regulatory requirement of 0 CFU/mL. [Figure 6](#) shows microbial compliance across 20 dzongkhags in rural areas. Only Dagana dzongkhags recorded average compliance rates below 50%. Microbial compliance trends across the years for all dzongkhags in rural areas are given in Supplementary Material, Table S5. According

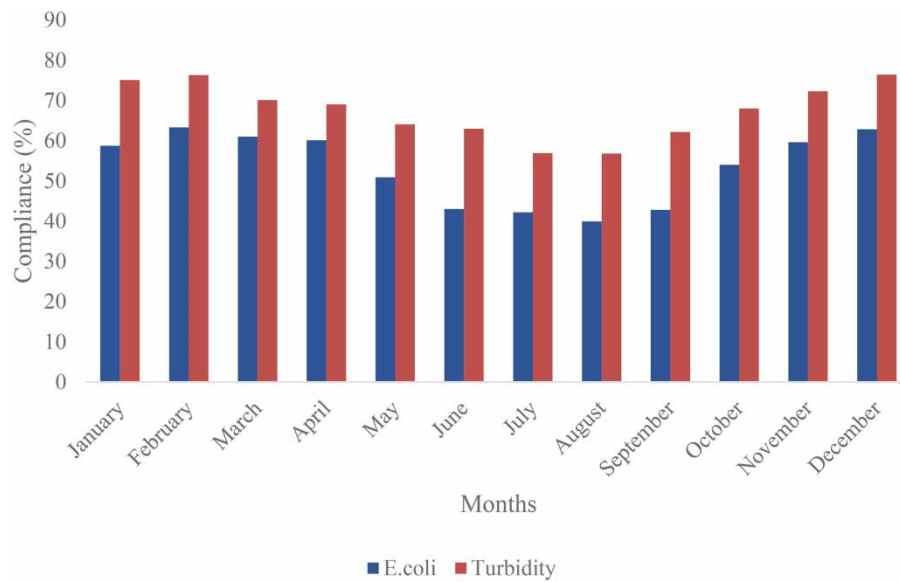


Figure 4 | Seasonal variation of microbial and turbidity compliance in urban areas.

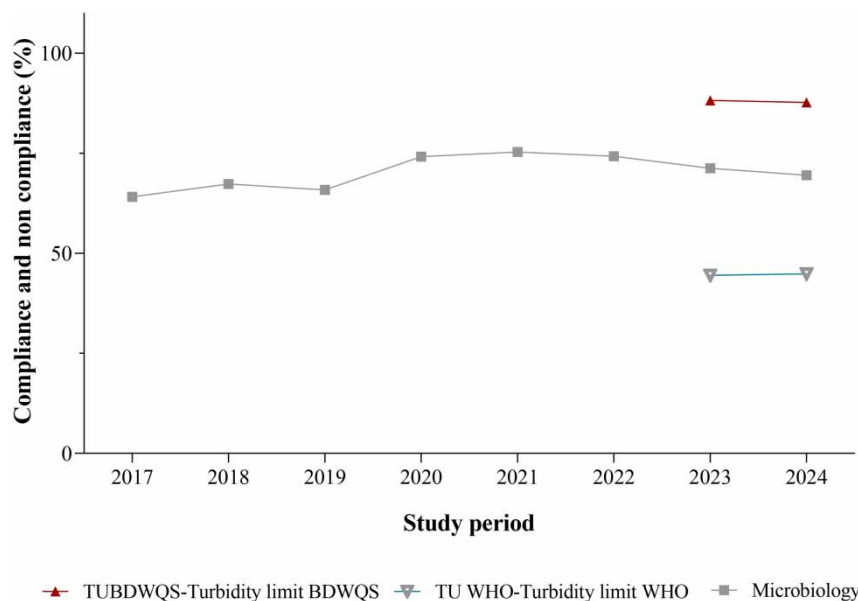


Figure 5 | The proportion of compliance and trend of rural drinking water samples for various parameters from 2017 to 2024.

to the BDWQS, the rural water standard is based on risk categories. In this context, as shown in Figure 7, 70.3% ($n = 10,094$) of rural water supplies were low-risk categories, while only 0.5% ($n = 77$) of the samples were grossly contaminated.

Turbidity

Turbidity testing capacity for most of the rural health centers was established in 2022, so the results in this study were based on the reports generated between 2023 and 2024 (Figure 5). A total of 2,569 samples were tested with a median value of 1 NTU that ranged from 0.00 to 110.00 NTU. From the sample tested, 87.9% ($n = 2,259$) of the samples met the BDWQS requirement. However, compared to WHO-recommended values only, 44.7% ($n = 1,148$) of the samples met the guideline values.

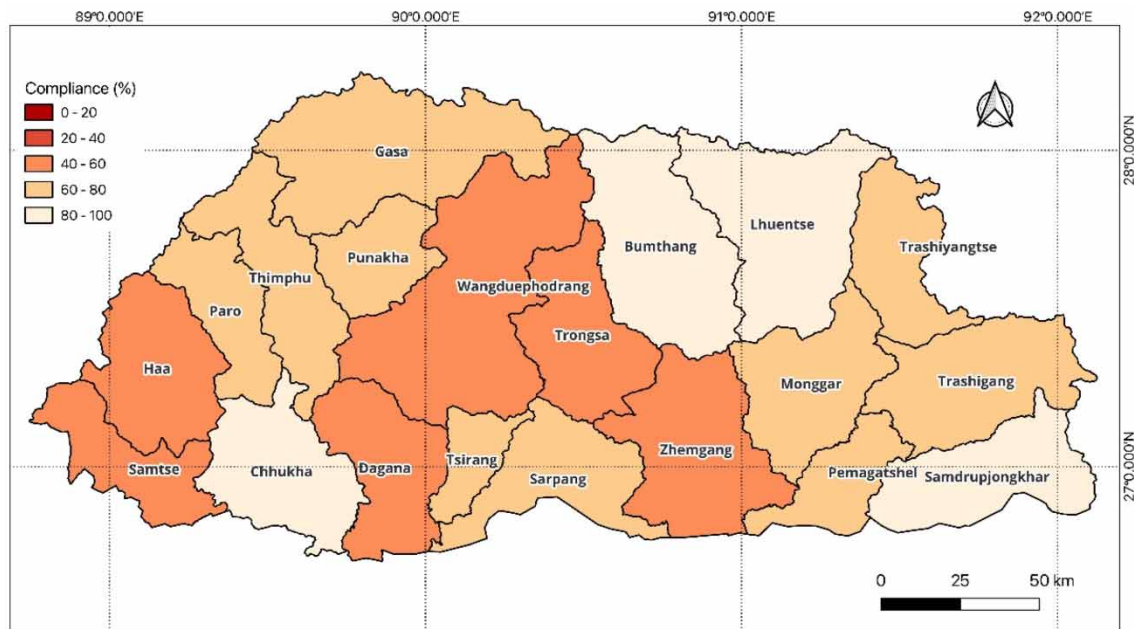


Figure 6 | Microbial compliance for 20 districts in rural areas.

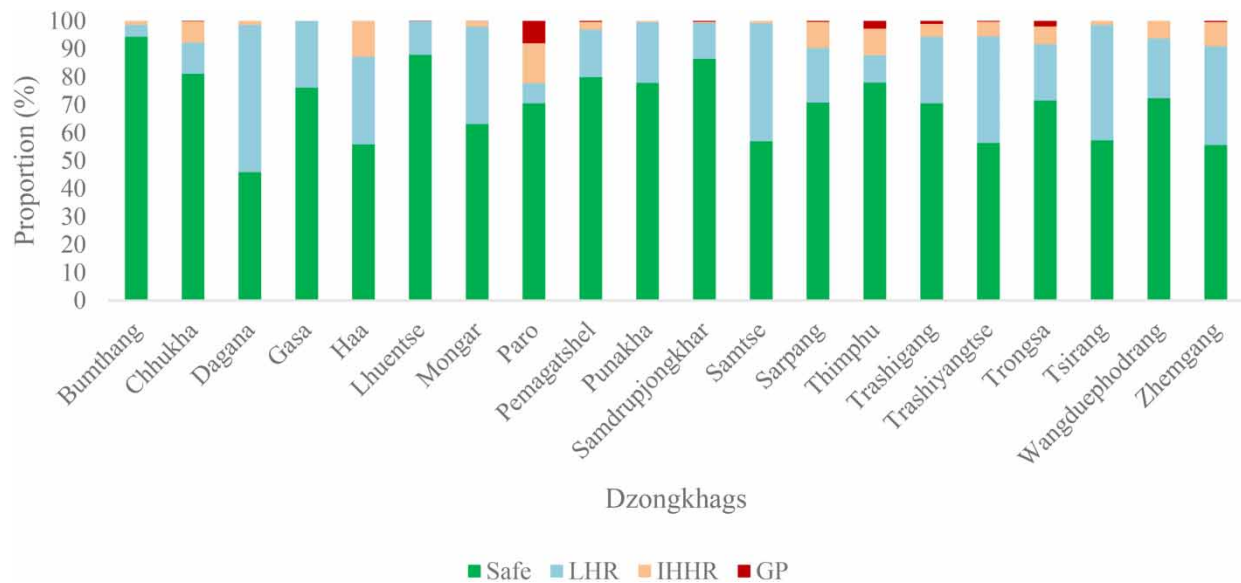


Figure 7 | Risk category of microbial contamination across different dzongkhags.

Seasonal variation of compliance

The average seasonal variation in microbial compliance varied between 48.6% (during May) to 86.8% (in February) (Figure 8). Similar to urban, the microbial compliance during rainy seasons (May to September) was comparatively lower than the dry season. A total of 7,505 samples were tested during the dry season and 6,856 samples during the monsoon season. During the dry season, most samples (73.8%) were safe, followed by 22.4% in the low health risk (LHR), 3.6% in intermediate to high health risk (IHHR), and only 0.3% in the grossly polluted (GP) category. In contrast, during the monsoon season, the proportion of safe samples decreased to 66.5%, while the proportions of LHR, IHHR, and GP increased to 28.2, 4.5, and 0.8%, respectively (Supplementary Material, Figure S2).

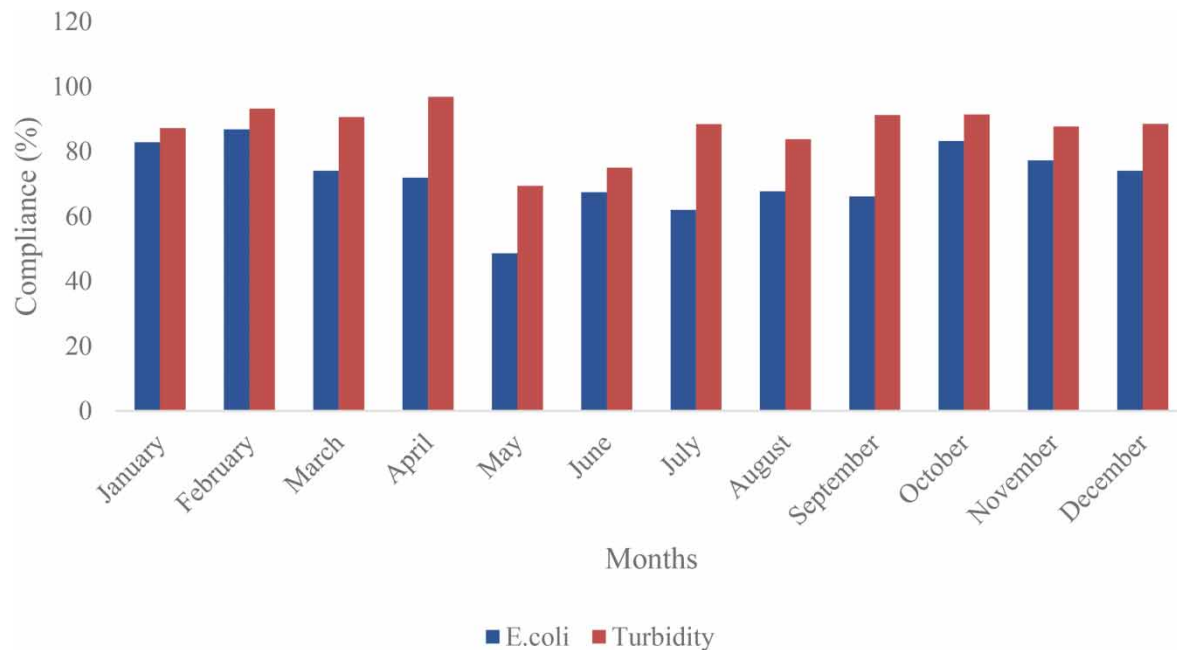


Figure 8 | Seasonal variation of microbial and turbidity compliance in rural areas.

Relationship between turbidity and microbial contamination

The linear regression model, between the turbidity of water samples and the concentration of *E. coli*, log-transformed ($\log_{10}[x + 1]$) and showed a statistically significant positive relationship ($p < 0.001$), indicating that higher turbidity was associated with higher *E. coli* concentrations. However, the strength of the association was low ($R^2 = 0.025$; Supplementary Material, Figure S3).

DISCUSSION

Urban drinking water

This study highlights important challenges and progress in the microbial and physicochemical quality of urban drinking water in Bhutan over the past eight years. The most critical concern identified was the consistently poor microbial quality of drinking water. On average, only 52.8% ($n = 7,213$) of samples complied with the Bhutan BDWQS of 0 CFU/100 mL for microbial contamination. Eight dzongkhags (Trashiyangtse, Trashigang, Lhuentse, Samdrupjongkhar, Mongar, Punakha, Wangduephodrang, and Zhemgang) with average compliance rates below 50% with no consistency in improvement across all the regions are of concern and warrant necessary interventions. A significant regional disparity was observed, particularly lower compliance in the Eastern region, suggesting the need for region-specific interventions.

Seasonal patterns contributed to microbial compliance in drinking water quality, but significant non-compliance during the rainy season was observed in other studies (Kostyla *et al.* 2015). Additionally, microbial risk increased during the monsoon season as the proportion of safe samples dropped from 73.8% in the dry season to 66.5% in the monsoon. This seasonal decline is likely attributable to increased surface runoff, elevated turbidity, and higher contamination of source waters during the monsoon (Tornevi *et al.* 2014; Moreira & Bondelind 2016).

Microbial contamination is a major issue in low- and middle-income countries, often exacerbated by inadequate sanitation and ageing infrastructure (Bain *et al.* 2021; Rath 2021). Studies in neighboring countries also highlight persistent challenges in ensuring microbial safety (Maharjan *et al.* 2018; Koley *et al.* 2024). Water distribution systems in Bhutan, often reliant on gravity-fed pipelines, are prone to contamination through pipe damage, illegal connections, or biofilm formation (Moreira & Bondelind 2016; Rath 2021).

Despite the government's efforts, including a flagship programme targeting a 24/7 safe water supply (Pema Tshewang 2019), these findings indicate that the goal of universal access to safe drinking water has not been fully achieved. This

may be associated with a lack of awareness on water quality, priority for other competing sectors (pandemic, quantity over quality, etc.), lack of technical capacity, and/or lack of enforcement. However, immediate priorities may include capacity building for water suppliers, strengthening surveillance, and enforcement mechanisms. Adopting comprehensive risk-based strategies like water safety plans (WSPs) has proven effective globally (WHO 2023). WSPs help identify vulnerabilities across the entire supply chain from source to tap and allow proactive interventions. WSPs have significant improvements in regard to collaboration among stakeholders, improved quality monitoring, and systematic tracking of consumer satisfaction (Kumpel *et al.* 2018). Their implementation, followed by WSP auditing by surveillance and water authorities, could strengthen compliance and achieve the national goal to achieve the 5-year plan commitment to achieve 90% safely managed drinking water (Ministry of Health 2024) and SDG 6 (United Nations 2024).

Turbidity, although it had a high compliance rate against national standards (95.2% compliance with the 5 NTU limit), the compliance against the more health-protective WHO guideline of <1 NTU was only 67.3%. Dzongkhags, such as Wangduephodrang, Samdrupjongkhar, Haa, Mongar, and Trashigang, recorded compliance rates below 50%, indicating critical areas requiring targeted improvement. The results suggest that although water may meet national regulations, further efforts are needed to align with international health-based benchmarks. This is particularly important because higher turbidity can reduce disinfection efficacy by shielding microorganisms, thereby increasing the risk of microbial contamination (Farrell *et al.* 2018). Seasonal variation also indicated variations of turbidity, with an average peak observed during July, indicating the influence of seasonal dynamics on water quality. This highlights the need for strengthened water treatment and monitoring strategies, particularly during heavy rainfall.

On the other hand, the physical parameters of pH and conductivity showed high and consistent compliance of 96.3 and 100%, respectively. These parameters are important for assessing water quality and treatment effectiveness (WHO 2011). These consistently acceptable values in these parameters suggest that the fundamental water chemistry remains stable, reflecting the reliability of source water quality and the operational efficiency of treatment facilities.

Residual chlorine compliance was alarmingly low, with only 11.9% of treated water samples meeting the recommended threshold. Contributing factors likely include inadequate chlorine dosing, lack of technical training, chlorine decay in ageing or lengthy distribution networks, and minimal operational oversight. Bhutan's typical gravity-fed systems and treatment plants located far from end-users exacerbate chlorine decay (Kwio-Tamale & Onyutha 2024). Studies have shown that water meeting quality standards at the treatment plant can still become contaminated before it reaches consumers if residual disinfection is inadequate (Barrett 2014), highlighting the need for robust disinfection strategies beyond the treatment plant. Installing booster chlorination stations at key points like storage tanks has improved microbial safety without relying on excessive disinfectant use (Propato & Uber 2004).

Although results for chemical compliance could not be assessed due to limited data covering whole dzongkhags, previous studies suggest that chemicals and heavy metal content in Bhutan's drinking water remained within permissible limits, aligning with national and international standards (Dorji & Chophel 2023). Given the health effects of chemical contamination in drinking water, there is a need for continued monitoring of chemicals and heavy metals across the nation.

Rural drinking water

Despite the absence of formal treatment, 70.1% of rural water samples complied with the national microbial standard of 0 CFU/mL. Only Dagana Dzongkhag recorded an average compliance below 50%. However, comparability with urban data is limited due to methodological differences. In rural settings, where laboratory infrastructure is limited, 1 mL water samples were analyzed using 3M Petrifilm™ *E. coli* plates incubated with body heat. In contrast, urban samples were tested using standard membrane filtration methods with 100 mL volumes. Although practical under resource constraints, this approach introduces variability and reduces sensitivity, particularly for low-level contamination. Compared to the 100 mL membrane filtration, this likely underestimates microbial contamination in rural samples, as the detection probability for low bacterial counts decreases with smaller sample sizes.

To have a more robust comparison of water quality between urban and rural areas, adopting the standard method of membrane filtration technique for rural surveillance would enable direct alignment with international guidelines. For this transition, updating Bhutan's national standards to express microbial limits in CFU/100 mL is recommended, though it would require capacity building and logistical support for rural testing facilities.

Turbidity results for rural areas revealed similar results to urban areas, wherein 88.3% of samples met the national standard (≤ 5 NTU), but when compared against the WHO guideline (1 NTU), only 47.6% complied, indicating potential risks for

microbial contamination of drinking water (De Roos *et al.* 2017). Like urban, seasonal analysis showed significantly higher microbial non-compliance during the monsoon in rural areas. Additionally, health risk classification showed seasonal deterioration in safety from 73.8% in the dry season to 66.5% in the monsoon. Correspondingly, LHR, IHHR, and GP categories increased during the monsoon. These findings stress the importance of risk-based surveillance, source protection, and alignment with international standards to ensure safe rural water supply.

Impact of turbidity on microbial contamination

The regression analysis showed a statistically significant positive relationship between turbidity and *E. coli* concentrations ($p < 0.001$), indicating that microbial contamination tends to increase with turbidity. However, the strength of the association was weak ($R^2 = 0.025$), suggesting that turbidity alone accounts for only a small fraction of the variation in *E. coli* concentration. Although turbidity is commonly used as a proxy for microbial risk, its effectiveness is limited by interference from non-microbial particulates, such as colloids (Jung *et al.* 2014). Similar to the current study, other studies have observed correlations between turbidity and *E. coli* in agricultural settings, but these relationships are often non-linear (Smith *et al.* 2008). Therefore, turbidity should be complemented with direct microbial testing for reliable water quality assessment.

CONCLUSION

This study highlights persistent challenges in ensuring safe drinking water in Bhutan, with microbial contamination emerging as the most critical issue. Only 52.8% of urban and 70.1% of rural samples met national microbial standards, with significant seasonal non-compliance during the monsoon. Despite having infrastructure and operational capacity, consistent non-compliance over the past eight years in water quality highlights vulnerabilities in source protection and process control. Critically low residual chlorine compliance levels (11.9%) raise serious concerns about treatment effectiveness and distribution system integrity. Additionally, parameters like turbidity, where only 67.3% of urban samples met the WHO's < 1 NTU guideline, can impact disinfection efficacy. This study found a statistically significant, though weak, correlation between turbidity and *E. coli* concentrations. This suggests that while turbidity is not a strong standalone predictor, it remains an important early warning indicator of microbial risk.

Improving urban water quality is achievable with targeted investments. Upgrading treatment facilities, ensuring consistent residual disinfection, and enhancing monitoring can significantly improve safety outcomes. Standardizing microbial testing (CFU/100 mL) across rural and urban systems will enable reliable surveillance. Implementing and routinely auditing WSPs and the WSP auditing water supply system can strengthen collaboration, operational oversight, and accountability. These reforms are critical to achieving Bhutan's Five-Year Plan target of 90% safely managed drinking water coverage and advancing progress toward SDG 6, ensuring universal access to safe and sustainably managed drinking water.

ACKNOWLEDGEMENTS

We acknowledge the dedicated efforts of the surveillance staff and laboratory technicians involved in sample collection, testing, and data reporting across urban and rural surveillance sites. Special thanks are extended to the Technical Board of RCDC and Mr Tshering Dorji for their support, technical oversight, and for ensuring the quality of data.

FUNDING

This study did not receive any specific grant from funding agencies. The analysis was based on administrative data retrieved from the national Water Quality Monitoring Information System.

AUTHOR CONTRIBUTIONS

P.C. and C.D. conceptualized the study design. P.C. carried out data compilation, analysis, and drafted the article. A.N.T. and R.W. assisted with data acquisition and interpretation. A.N.T. and C.D. reviewed and edited the article. All authors read and approved the final article.

ETHICS STATEMENT

As this study did not involve human or animal subjects, an ethics waiver was obtained from the Research Ethics Board of Health, Bhutan (Proposal No. 2025.40.NW), and the study was exempted from review. Administrative clearance was obtained from the Ministry of Health before initiating the study.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

- Bain, R., Johnston, R., Khan, S., Hancioglu, A. & Slaymaker, T. (2021) [Monitoring drinking water quality in nationally representative household surveys in low- and middle-income countries: cross-sectional analysis of 27 multiple indicator cluster surveys 2014–2020](#), *Environmental Health Perspectives*, **129**, 097010.
- Barrett, J. R. (2014) Plugging the holes in water distribution systems: deficiencies may contribute to gastrointestinal illnesses, *Environmental Health Perspectives*, **122**, A195–A195.
- De Roos, A. J., Gurian, P. L., Robinson, L. F., Rai, A., Zakeri, I. F. & Kondo, M. C. (2017) [Review of epidemiological studies of drinking-water turbidity in relation to acute gastrointestinal illness](#), *Environmental Health Perspectives*, **125**, 086003.
- Dorji, C. & Chopel, P. (2023) [Determination of water quality indices and assessment of heavy metal pollution of drinking water sources in Thimphu](#), *Bhutan Health Journal*, **9**, 16–21.
- Farrell, C., Hassard, F., Jefferson, B., Leziart, T., Nocker, A. & Jarvis, P. (2018) [Turbidity composition and the relationship with microbial attachment and UV inactivation efficacy](#), *Science of The Total Environment*, **624**, 638–647.
- Jung, A.-V., Le Cann, P., Roig, B., Thomas, O., Baurès, E. & Thomas, M.-F. (2014) [Microbial contamination detection in water resources: interest of current optical methods, trends and needs in the context of climate change](#), *International Journal of Environmental Research and Public Health*, **11**, 4292–4310.
- Koley, S., Rao, K. B., Khwairakpam, M. & Kalamdhad, A. S. (2024) [Identification and assessment of critical parameters affecting drinking water quality: a case study of water treatment plants of India](#), *Groundwater for Sustainable Development*, **26**, 101221.
- Kostyla, C., Bain, R., Cronk, R. & Bartram, J. (2015) [Seasonal variation of fecal contamination in drinking water sources in developing countries: a systematic review](#), *Science of the Total Environment*, **514**, 333–343.
- Kumar, P., Srivastava, S., Banerjee, A. & Banerjee, S. (2022) [Prevalence and predictors of water-borne diseases among elderly people in India: evidence from longitudinal ageing study in India, 2017–18](#), *BMC Public Health*, **22**, 993.
- Kumpel, E., Delaire, C., Peletz, R., Kisiangani, J., Rinehold, A., De France, J., Sutherland, D. & Khush, R. (2018) [Measuring the impacts of water safety plans in the Asia-Pacific region](#), *International Journal of Environmental Research and Public Health*, **15**, 1223.
- Kwio-Tamale, J. C. & Onyutha, C. (2024) [Influence of physical and water quality parameters on residual chlorine decay in water distribution network](#), *Heliyon*, **10**, e30892.
- Luby, S. P., Rahman, M., Arnold, B. F., Unicomb, L., Ashraf, S., Winch, P. J., Stewart, C. P., Begum, F., Hussain, F., Benjamin-Chung, J., Leontsini, E., Naser, A. M., Parvez, S. M., Hubbard, A. E., Lin, A., Nizame, F. A., Jannat, K., Ercumen, A., Ram, P. K., Das, K. K., Abedin, J., Clasen, T. F., Dewey, K. G., Fernald, L. C., Null, C., Ahmed, T. & Colford Jr., J. M. (2018) [Effects of water quality, sanitation, handwashing, and nutritional interventions on diarrhoea and child growth in rural Bangladesh: a cluster randomised controlled trial](#), *Lancet Glob Health*, **6**, e302–e315.
- Maharjan, S., Joshi, T. P. & Shrestha, S. M. (2018) [Poor quality of treated water in Kathmandu: comparison with Nepal drinking water quality standards](#), *Tribhuvan University Journal of Microbiology*, **5**, 83–88.
- Ministry of Health (2023) *5th National Health Survey: Integrated Stepwise Household Survey Thimphu*. Bhutan: Ministry of Health, Royal Government of Bhutan.
- Ministry of Health (2024) *Healthy Drugyul Program: the Health Sector's 13th Five Year Plan*. Thimphu: Ministry of Health, Royal Government of Bhutan.
- MOIT (2008) *Bhutan National Urbanization Strategy*. Thimphu, Bhutan: Policy and Planning Division, Ministry of Infrastructure and Transport.
- Moreira, N. A. & Bondelind, M. (2016) [Safe drinking water and waterborne outbreaks](#), *Journal of Water and Health*, **15**, 83–96.
- Pema Tshewang. (2019) Water flagship programme; to ensure 24/7 drinking and irrigation water across the country. *Bhutan Broadcasting Service (BBS)* 7 Oct 2019.
- Propato, M. & Uber, J. G. (2004) [Vulnerability of water distribution systems to pathogen intrusion: how effective is a disinfectant residual?](#), *Environmental Science & Technology*, **38** (13), 3713–3722.
- Rani, P. & Dhok, A. (2023) Effects of pollution on pregnancy and infants, *Cureus*, **15**, e33906.
- Rath, S., (2021) Microbial contamination of drinking water. In: Singh, A., Agrawal, M. & Agrawal, S. B. (eds.) *Water Pollution and Management Practices*, Singapore: Springer Singapore.
- Redc (2019) National guideline for drinking water quality surveillance, first edition, 2019. In: CONTROL, R. C. F. D. (ed.). Thimphu, Bhutan: Royal Center for Disease Control.
- Smith, R. P., Paiba, G. A. & Ellis-Iversen, J. (2008) [Short communication: turbidity as an indicator of Escherichia coli presence in water troughs on cattle farms](#), *Journal of Dairy Science*, **91**, 2082–2085.

- Tornevi, A., Bergstedt, O. & Forsberg, B. (2014) Precipitation effects on microbial pollution in a river: lag structures and seasonal effect modification, *PLOS ONE*, **9**, e98546.
- United Nations (2024) *Goal 6: clean water and sanitation* [Online]. (Accessed: 26 March 2025).
- Ward, R. C., Loftis, J. C. & McBride, G. B. (1986) The 'data-rich but information-poor' syndrome in water quality monitoring, *Environmental Management*, **10**, 291–297.
- WHO (2011) Guidelines for drinking water quality-Fourth edition. *WHO chronicle*, **38**, 104-8.
- WHO (2023) *Water Safety Plan Manual: Step-by-Step Risk Management for Drinking-Water Suppliers*. Geneva, Switzerland: World Health Organization.
- WHO (2024) *Guidelines for Drinking-Water Quality: Small Water Supplies*. Geneva, Switzerland: World Health Organization.
- WHO/UNICEF (2023) *WHO/UNICEF Joint Monitoring Programme update report 2023: Progress on household drinking water, sanitation and hygiene 2000–2022: Special focus on gender*. New York: United Nations Children's Fund (UNICEF) and World Health Organization (WHO).
- World Health Organization (WHO) (2023) *Drinking-Water*. Geneva, Switzerland: WHO. Available at: <https://www.who.int/news-room/fact-sheets/detail/drinking-water> (Accessed: 27 March 2025).

First received 26 May 2025; accepted in revised form 8 August 2025. Available online 19 August 2025