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Comparative Analysis of Water Quality and Attributable Risk in Villages Receiving Piped and Non-piped Water Supply in Western India

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***Abstract*: Sustainable provision of safe drinking water is necessary for rural development. In India, about 62% of villages receive a piped water supply, and the rest rely on unimproved, non-piped alternatives. The reliance on a non-piped water supply is mainly due to limited accessibility and affordability. The potability of the water received through non-piped alternatives cannot be guaranteed. Thus, it is important to quantify the health risks associated with a non-piped water supply. This study aimed to compare the performance of rural water supply in the villages receiving piped and non-piped water supply modes to understand challenges in rural water supply. Accordingly, critical sanitation factors and water quality data were collected and analyzed. The study results show that microbiological contamination is present in both types of supply modes because of multiple contributing factors. It was evidenced that villages with poorly maintained supply systems or operationally flawed systems had to rely on non-piped means of water supply despite having a piped water supply network. The study also highlights the need for an integrated approach to improve water supplies in rural areas, including environmental, socio-economic, and ethical perspectives.**

Keywords: Non-piped water supply, Piped water supply, Rural Water Supply, Waterborne disease burden, Water quality monitoring

I. Introduction

An equitable and universal access to potable drinking water is a basic human right that benefits human well-being beyond health impacts. In this context, the Sustainable Development Goals (SDGs) from 2015 deem potable drinking water access as a crucial global target. Despite substantial water access expansion during the Sustainable Development Goals (SDGs) era, estimates indicate that more than 25% of the population in many developing countries lacked access to improved facilities. As per the WHO/UNICEF data from 2017, in low- and middle-income countries, major gaps in terms of water access remain, with around 49.7% of the total population in such countries lacking access to piped water supply (Local Burden of Disease WaSH Collaborators, 2020). These gaps increase public health risks and waterborne disease burdens. It is estimated that 36% of the annual diarrheal deaths can be attributed to contaminated drinking in low-income and middle-income countries (Prüss-Ustün et al., 2019). In India, approximately 2,03,863 cases of diarrheal infections can be attributed to unsafe drinking water (WHO, 2022).

Considering health risks associated with unsafe drinking water and sanitation, implementing piped water supply remains one of the most optimal approaches for reducing largely preventable waterborne diseases. Studies have documented a magnitude of benefits associated with the provision of drinking water through piped water supply, including improved water quality, an increase in the amount of water available for community members to use for personal hygiene purposes thereby improving sanitation, time savings, and an increased human productivity and development on a broader scale. (Reese et al., 2019; Bisung et al., 2019; McGuinness et al., 2020).

Non-piped water supply is a critical aspect contributing to high waterborne disease burden. Within India, 61.83% of households have tap water connections as of date (JJM

Dashboard, n.d). Most of these tap water connections are concentrated in urban areas, and a large proportion of the rural population still does not have access to safe drinking water. While access to piped water supplies in India is increasing, financial and logistical barriers hinder the widespread implementation in several rural parts of India. In the absence of piped water supplies, communities from such areas often rely on public or unimproved water sources, such as hand pumps, wells, and surface water bodies for drinking water (WHO/UNICEF, 2015). The water availability and quality at these unimproved sources are often governed by seasons, geology, climate, and storage conditions. Moreover, water quality and access are also influenced by various cultural, political, and socio-economic drivers and overall quality of life in rural communities (Bandyopadhyay, 2016). Thus, the need for a piped water supply becomes significantly crucial when considered along with fragile and highly vulnerable supply infrastructure for water, deficit sanitation infrastructures, rapidly growing habitations, and limitations on hygiene practices in rural India.

It should be noted that even in rural areas that receive piped water, the supply occurs intermittently. This intermittent supply mode has been linked to the deterioration of water quality at consumer ends (Bivins et al., 2021; Ercumen et al., 2015; Adane et al., 2017). The issue is further complicated due to prolonged household storage, inadequate sewerage systems, and surveillance. Additionally, sanitation practices in rural India are often limited because of the irregular or intermittent water supply. Hence, despite being considered the highest category of improved source, piped water supply in rural areas can become prone to quality deficiencies.

In light of this, quantitative and qualitative data on the true impact of both piped and non-piped water supply on public health and well-being becomes important. The current study aims to present a cross-sectional study to: (i) assess the water quality in rural areas receiving piped and non-piped water supply modes and (ii) explore the relationship between various aspects such as water quality, quality of life, attributable risk, and relative risk concerning supply modes in rural communities in India.

II. Materials and Methods

Study Area

The study was conducted in six villages with populations ranging from 100 to 1000 in the Nagpur district, Maharashtra, India. Among the selected villages, three villages, namely Khatmari, Linga, and Ladhai, received piped water supply, and three, namely Banwadi, Bodhla, and Besa, did not receive piped water supply.

In the villages receiving piped water, the bulk of the water supply intended for drinking and domestic purposes was treated groundwater, delivered via transmission mains (pumping and gravity) first to main storage reservoirs and then to consumers through the distribution network pipes intermittently. During the study duration, it was reported that the water supply occurs daily for at least two hours in all three villages. It was also reported that additional chlorination is also performed at storage reservoirs, if necessary.

In Banwadi and Bodhala, villages without piped water supply, communities rely on groundwater from handpumps and borewells; in Besa, communities rely on both groundwaters and tanker trucks. Infrastructure for a piped distribution network was present both in Banwadi and Bodhala; however, the distribution system was rendered non-functional in Bodhala due to water scarcity at the source and pipe breaks in Banwadi. In Besa, building the distribution network was in progress but not functional. The study was conducted within the span of one month. Sampling locations were selected randomly in each village, and location coordinates for all the sampling locations were collected via cell phone GPS (Figure 1).

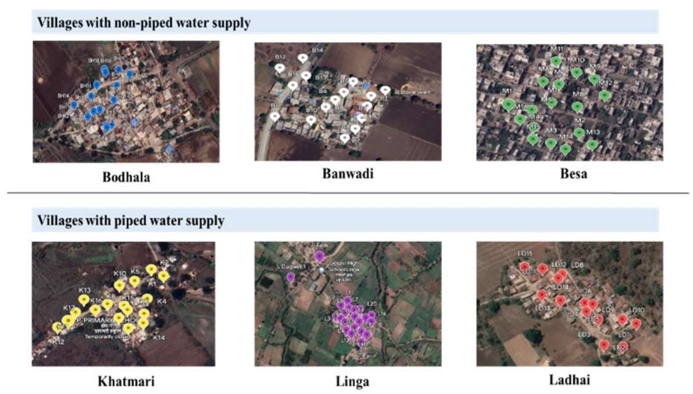

Figure 1: Sampling locations in six villages (via Google Earth)

Household Survey

A questionnaire survey was designed to record data for the following components:

(i) *General demographic data* including the number of residents in the household, ages and genders of residents, educational levels of residents, and average household income level, location of the household.
(ii) *Incidence data on waterborne diseases* (as reported by consumers), including Cholera, Typhoid, Acute gastrointestinal infection, and Dysentry during the past year. Details regarding the medical treatment received were also recorded.
(iii) *Exposure indicators* include household storage and cleaning practices, use of point-of-use (POU) treatment devices, personal hygiene practices, status and location of sewage systems, and average water consumption rate.
(iv) Quality of life (QoL), including general health of residents, physical health status, mental health, emotional health, social functioning, vitality, physical functioning, and bodily pain. The questionnaire survey for QoL was composed of 10 questions in total designed using WHO's SF-36 questionnaire (Framework, 1992; Shayan et al., 2020; Yan & Cui, 2025; Sajjad & Jyoti, 2014; Jerome & Pius, 2010)

The questionnaire survey was administered at each sampling location using the KoboToolBox application.

Sample collection and analysis

Samples for physicochemical and microbial analysis were collected at each location. Samples were analyzed for pH, turbidity, Total dissolved solids (TDS), total alkalinity, hardness, sulfate, nitrate, phosphate, calcium, magnesium, chloride, sodium, and potassium for physicochemical parameters. Total chlorine and free chlorine levels were also measured for each sample onsite using the N, N-Diethyl-p-Phenylenediamine (DPD) Colorimetric Method with a Hach Pocket Colorimeter II (Hach, Loveland, USA).

For microbial analysis, samples were collected in pre-sterilized 500mL polypropylene bottles and transported in an icebox to CSIR-NEERI's laboratory. The collected samples were analyzed for the presence of total coliforms (TC), fecal coliforms (FC), and Salmonella sp. using Standard Membrane Filtration Technique (APHA 9222).

Data Analysis

The tabulation and graphical descriptions of data and the calculations of the water quality index and population-attributable risks were performed using Microsoft Excel. To quantify and compare the water quality in villages with piped water supply and non-piped water supply, the CCME Water Quality Index was used to assign each village a score in terms of water quality. Permissible ranges for each parameter, according to the Bureau of Indian Standards (IS 10500), were followed when calculating the Index (BIS, 2012). The relationship between water quality and quality of life was assessed using the Pearson correlation.

III. RESULTS AND DISCUSSION

Comparison of water quality in the villages

Physicochemical parameters

Ninety-seven water samples were collected from six villages and were analyzed for physicochemical parameters such as pH, electrical conductivity (EC), Total dissolved solids (TDS), turbidity, total alkalinity, hardness, sulphate, nitrate, phosphate, chloride, sodium, and potassium. Calcium and magnesium ion concentrations were then calculated using data from total hardness. Tables 1 & 2 summarise the physicochemical water quality in the villages.

Regarding water quality, the villages with piped water supply have constant water quality in all households as water to the entire village is supplied from the same water source. All water quality parameters from Linga and Khatmari villages were within acceptable limits as per drinking water standard ISO 10500. All samples collected from Ladhai have all water quality parameters within acceptable limits except the Nitrate. The nitrate in the source water is above the permissible limit as per BIS standard (Figure 2).

The water quality in the villages with the non-piped water supply differs at each household. In Bodhala, Banwadi, and Besa, the TDS and other parameters differ at each location. The very low TDS at a few locations was mainly because of the use of household water treatment units. Only at Bodhala the Nitrate in groundwater is above the permissible limits as per standard, as shown in Figure 3, whereas other water quality parameters are within the limits as per standard.

Figure 4 represents Piper diagrams for villages with non-piped water supply. The Piper diagram shows that the water quality in piped water supply villages, Linga and Ladhai, is of calcium magnesium chloride sulphate type to mixed type. In both the villages, calcium and magnesium dominate cations and chloride and sulphate in anions. In Khatmari, it was the mixed type with no dominant cations, and chloride is a dominant anion for all samples.

The Piper diagrams for villages with piped water supply are shown in Figure 5. The water quality in all the three villages was different and was of calcium magnesium chloride sulphate based. And different along the village due to different water sources. Although calcium and magnesium dominate in cations, Chloride is the dominating anion whose concentration varies in all samples.

Microbial parameters

All the samples collected from villages were tested for total coliform, fecal coliform, and Salmonella sp. within 24 hours of collection. The main parameters of interest for this exploration are fecal coliform and Salmonella as a pathogen. The village-wise drinking water samples contaminated with fecal and Salmonella are shown in Figure 6. Results indicated higher fecal coliform and Salmonella contamination in water samples from villages without piped-water supply. Notably, however, it was observed that microbial contamination was also found even in samples from the piped water supply.

In non-piped water supply villages, drinking water samples from 73% of households were contaminated by Fecal contamination, and 62.5% of drinking water samples were contaminated by salmonella. The contamination locations were 46% and 56% for fecal and Salmonella at Pipelined water supply villages, respectively. The individual log-wise contamination in piped and non-piped villages is also shown in Figures 7 & 8. As shown in the figures, the contamination extent is also high in the non-piped water villages as compared to piped water-supplied villages. This can be largely attributed to unsanitary storage conditions and intermittent water supply in the piped distribution network. Further analysis reveals that a lower percentage of samples from piped water supply have higher densities of microbial contamination for both fecal and Salmonella contamination.

TABLE 1
Overview of physicochemical parameters in Non-piped water supply villages

Parameter	Unit	Bodhala (Range)	Banwadi (Range)	Besa (Range)
pH	-	7.2 - 8.0	7.7 – 7.7	7.3 – 7.9
TDS	mg/L	60 – 1012	491 – 560	73 – 490
Turbidity	NTU	0.5 - 4.0	0.6 – 1.2	0.1 – 1.6
Total alkalinity	mg/L	236.5 - 322.5	260 – 320	30 – 260
Total hardness	mg/L	40 – 550	300 – 340	40 – 300
Sulfate	mg/L	10.7 - 82.1	61.1 – 71.1	3.6 – 51
Nitrate	mg/L	34.1 - 82.9	23 – 41.1	0.4 – 38.8
Phosphate	mg/L	0.6 - 0.9	0.0 – 0.6	1 – 7.1
Chloride	mg/L	10 – 165	35 – 45	10 – 65
Sodium	mg/L	5.5 - 109.3	19.8 – 35	3.6 – 31.1
Potassium	mg/L	0.7 - 3.0	0.6 – 1.3	0.1 – 1.4
Calcium	mg/L	12 – 116	44 – 56	8 – 64
Magnesium	mg/L	2.4 – 79	43.2 – 55.2	4.8 – 38.4

TABLE 2
Overview of physicochemical parameters at Piped Supply villages

Parameter	Unit	Linga (Range)	Ladhai (Range)	Khatmari (Range)
pH	-	7.3 – 7.6	7.4 – 7.7	7.2 – 7.8
TDS	mg/L	465 – 489	584 – 630	674 – 722
Turbidity	NTU	0.9 – 3.9	0.3 – 1.0	0 – 1
Total alkalinity	mg/L	220 – 250	230 – 290	310 – 370
Total hardness	mg/L	220 – 280	290 – 380	290 – 350
Sulfate	mg/L	11.9–25.8	28.8–37.4	55 – 77
Nitrate	mg/L	13.6–18.3	52.3–59.2	12.8–17.4
Phosphate	mg/L	11.4–24.0	2 – 8.7	5 – 11
Chloride	mg/L	30 – 40	40 – 55	70 – 80
Sodium	mg/L	23.6–27.5	21.1–38.5	63.4–81.7
Potassium	mg/L	1.2 – 1.9	8.6 – 14.2	2.6 – 3.3
Calcium	mg/L	32 – 52	52 – 96	56 – 72
Magnesium	mg/L	26.4–36.0	24.0–48.0	21.6–38.4

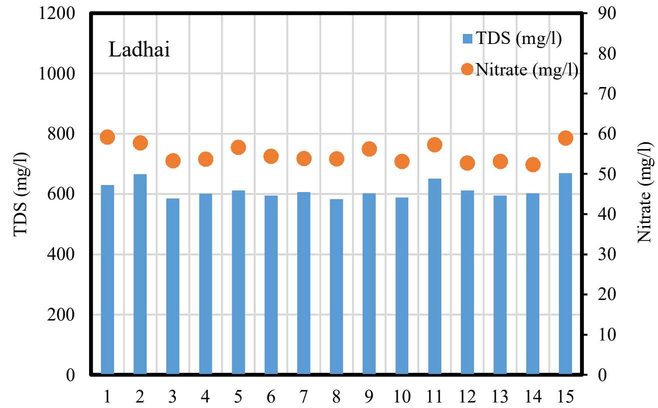

Figure 2: Water quality results for *Ladhai* village (piped)

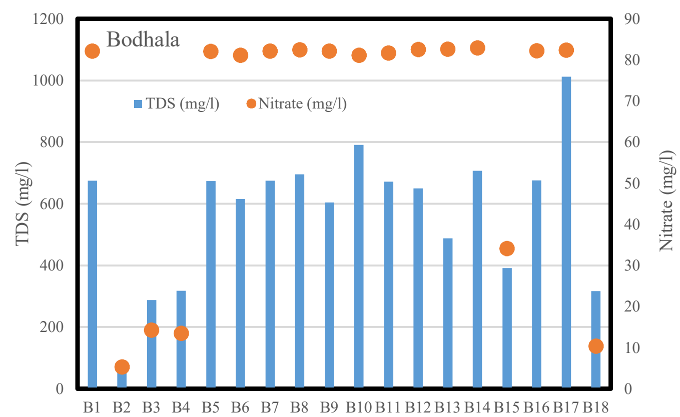

Figure 3: Water quality results for Bodhala village (Non piped)

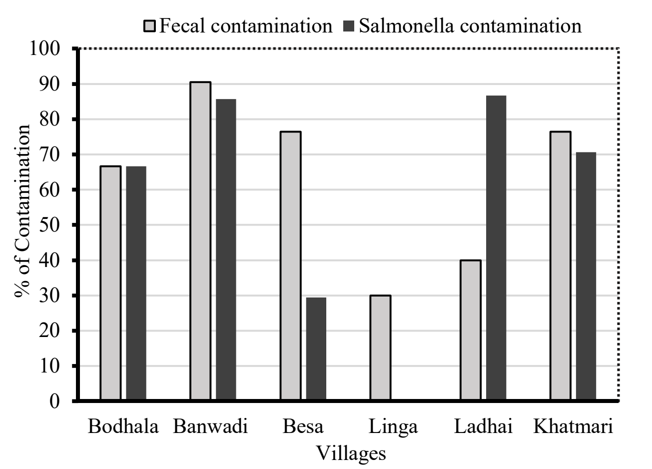

Figure 6: Faecal coliform and *Salmonella* contamination in villages with Non-piped and piped water supply

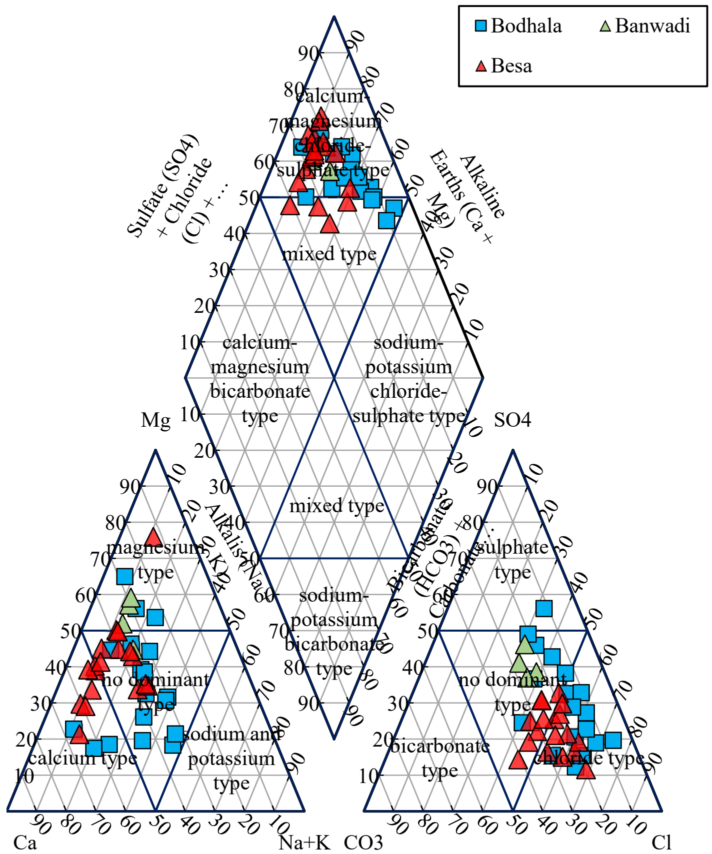

Figure 4: Piper Diagram for villages with Non-piped water supply

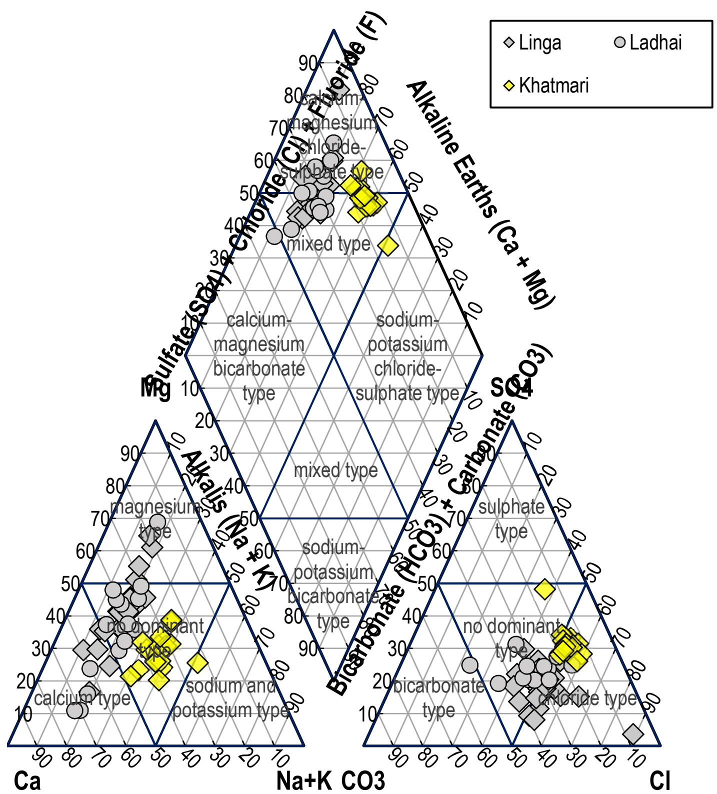

Figure 5: Piper Diagram for villages with piped water supply

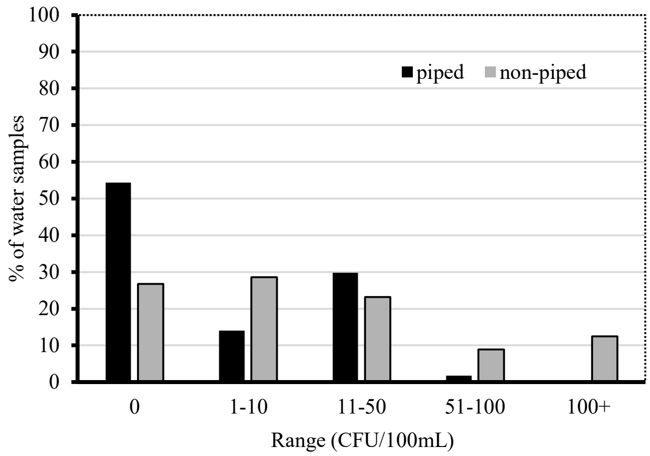

Figure 7: Comparison of faecal coliform contamination for the samples from the piped and non-piped supply villages

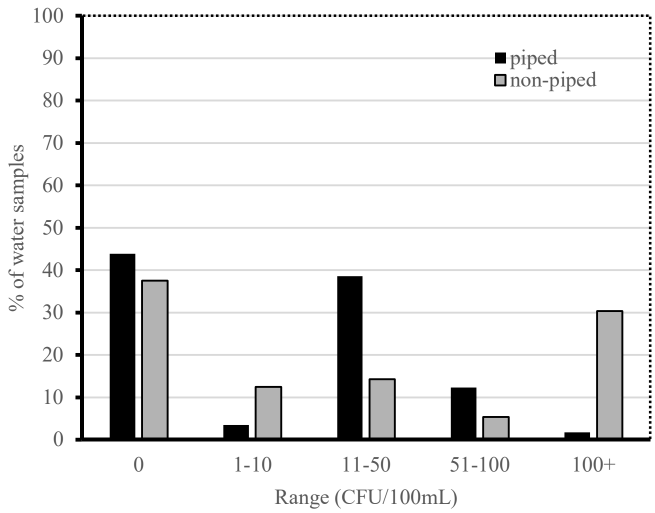

Figure 8: Comparison of Salmonella contamination in drinking water samples from Villages with piped and non-piped water supply

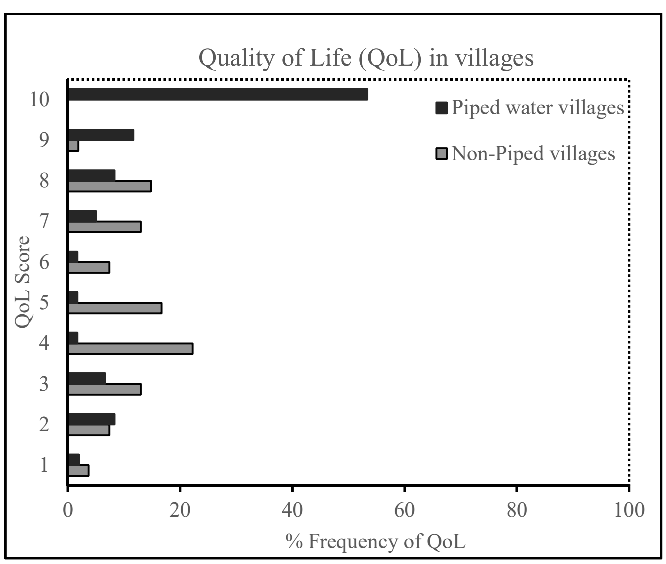

Figure 9: Comparison of QoL scores between villages with piped and non-piped water supply

Although piped water supply at households tried to ensure a safe water supply, the quality of water in terms of microbiological contamination mainly depends on handling and storage practices at each household from the time of supply until its consumption. This study also suggests that the only supplied pipe water supply does not ensure safe water until consumption. Microbiological contamination is also greatly caused by leakages in the supply line and at the diversion valve location. Dosing appropriate chlorine will address this issue up to a certain extent. However, it still has its limitations in the secondary metabolism of DBPs formations, which is again not a recommended option.

Water Quality Index

The CCME WQI is calculated by considering three variables: F_1 = Scope, F_2 = Frequency, and F_3 = Amplitude. The water quality index is calculated using the formula (CCME, 2001):

$$\text{CCME WQI} = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732}\right)$$

The divisor 1.732 normalizes the resultant values to 0 and 100. The CCME WQI for the villages is represented in Table 3.

These results were because Nitrate values were the only ones above the permissible range for Bodhala and Ladhai villages. All other parameters of all villages fell under permissible ranges. Hence, the water quality for all villages explored in this research, piped or non-piped, is excellent, according to CCME WQI. Differences, however, are seen in the quality of life of people in the villages and its connection to microbial quality results.

Correlation of water quality with quality of life (QoL)

The quality of life score for a sampling location was obtained by summing up the total individual scores of questions in the sanitary surveillance questionnaire. For each positive consumer response, the question was scored 1. The responses were recorded and uniformized such that the highest score (i.e., 10) refers to the highest quality of life, and the lowest score (i.e., 1), refers to the lowest quality of life. The QoL scores for villages with piped and non-piped water supply were compared (Figure 9).

Following this, Pearson correlation correlated water quality data to consumer responses. QoL and microbial water quality showed a linear correlation with an “r-value” of 0.22. The p-value was found to be 0.02, which is significant.

Correlation of water quality with population attributable risk for waterborne diseases

The association between supply modes and waterborne diseases was measured by calculating population attributable risk. In this case, population attributable risk is used to assess the incidences that occur when population is exposed or unexposed to Salmonella in both piped and non-piped water supply modes. Using microbial water quality results and results from the survey, population-attributable risk (Equation i) and population-attributable risk percentage (Equation ii) were calculated (Kaelin et al., 2004; Askari et al., 2020). The results for both modes are presented in Table 4.

$$PAR = I - c \quad \text{.................. (Equation i)}$$

Where PAR = Population Attributable risk
I = Incidence rate of typhoid in the total population
c = Incidence rate in unexposed population

$$\%PAR = \frac{PAR}{I} \times 100 \quad \text{.............. (Equation ii)}$$

Where PAR = Population Attributable risk
I = Incidence rate of typhoid in the total population

TABLE 3
CCME Water Quality Index in the piped and non-piped water supply villages

Village	Observed WQI value	Water quality as per score
Villages with non-piped water supply		
Bodhala	93.5	Good
Banwadi	100	Excellent
Besa	100	Excellent
Villages with non-piped water supply		
Linga	100	Excellent
Ladhai	93.1	Good
Khatmari	100	Excellent

TABLE 4
Population attributable risk as per microbial water quality results

Population attributable risks		
	Piped water supply	**Non-piped water supply**
Population attributable risk	0.138	0.185
Population exposure	56.14%	62.5%
Population attributable risk percentage	46.35%	49.21%

The results show that population-attributable risk, population exposure, and population-attributable risk percentage are all higher for samples from non-piped water supply villages. Hence, piped water supply can be considered safer in terms of contamination and risk of waterborne diseases.

Discussion

Safe drinking water is critical for safeguarding public health. The current study aimed to evaluate the true impact of piped and non-piped water supply on several aspects, such as water quality, quality of life, and disease risk. In terms of water quality, ideally, the piped water supply should have little to no risk of contamination, being an improved water source. However, the results indicate that the risk of microbial contamination is not eradicated completely in the piped water supply. This can be largely attributed to the intermittent water supply in villages with piped distribution. Since the supply is intermittent, communities in these villages practice water storage for prolonged periods. It was observed that the residual chlorine levels in the stored water decreased below standard values (0.2 mg/L), and storage conditions in the households were often unsanitary. This results in diminishing the benefits of the piped water supply. In villages without piped water supply, the contamination was found to be much higher than those with piped water supply. Additionally, the CFU ranges of microbial contamination were also observed to be higher in the absence of piped water. The results highlight the necessity to raise awareness of safe storage conditions and habits and also implement continuous water supply schemes in rural communities.

In terms of quality of life, the study establishes a linear correlation between quality of life and water quality. It was observed that the overall QoL scores were much higher in villages with piped water supply, corresponding to better QoL than in villages without piped water supply. Similarly, the attributable risk was also observed to be much lower in villages with piped water supply, indicating that piped water supply is more beneficial for improving public health and well-being.

A key observation of the current study was that the pipe distribution network infrastructure was present but non-functional in the villages without piped water supply. This can be attributed to various reasons, such as a lack of financial resources, a skilled workforce, and support infrastructure increased with the massive deployment of water supply systems. The financial allocations and deployment of skilled manpower do not match the actual requirements for efficient operation and maintenance of the water infrastructure, thus resulting in a non-piped water supply. Our results indicate that the mere expansion of piped distribution networks is not enough to ensure public health and safety; rather, it is important to establish protected and continuous water supply schemes with distribution networks.

The study establishes the broader role of supply mode in the overall development of rural communities. The study establishes that there is a direct correlation between the water supply mode and water quality and quality of life. Water quality and quality of life were improved in villages with piped water supply. However, bacterial contamination was still present in many piped water supply samples. Merely having a piped water supply did not achieve the target of supplying safe and sufficient water to every household. Proper operation and maintenance and regular water quality monitoring protocol are extremely needed to ensure safe water for everyone. Efforts should also be made to educate the rural population regarding safe hygiene practices. Ultimately, our estimates aim to provide a resource for researchers and policymakers to improve access to safe drinking water in line with SDG targets, ensuring that all have access to this fundamental human right.

IV. Conclusion

The study highlights the need for tailored interventions which include strengthening basic infrastructure through improved piped networks, upgrading treatment facilities, promoting affordable household water purification technologies, implementing contaminant-specific solutions such as defluoridation, arsenic removal, reducing the disparities in water supply in rural areas to achieve equitable access to safe drinking water and improve the quality of life. Along with these governance reforms, such as technical capacity, monitoring systems are also important. Despite substantial improvements in some rural regions over the past decade, an accelerated pace in implementing continuous water supply schemes will be necessary to provide safe drinking water.

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