

Assessing Groundwater Quality in Prayagraj City: Spatial Patterns of pH, Hardness, TDS and Major Ions

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ABSTRACT

Tube wells supply about 77% of Prayagraj's piped water, so the chemical quality of its groundwater bears directly on public health and on the condition of its water infrastructure. This study examines ten parameters (temperature, pH, total hardness, turbidity, dissolved oxygen, total dissolved solids (TDS), calcium, magnesium, chloride and bicarbonate) at 16 sites in Prayagraj city and compares them with the Indian drinking-water standard IS 10500:2012 and WHO guidance. pH (7.2–7.8) and chloride (49–94 mg/L) met the standards at every site. Hardness (198–329 mg/L), TDS (341–811 mg/L), calcium, magnesium and alkalinity exceeded the acceptable limits at most sites, but none exceeded a permissible limit. Turbidity (0.9–7.1 NTU) was the only parameter above a permissible limit, at six sites, and every site exceeded the acceptable limit for at least five of the seven parameters assessed. A weighted-arithmetic water quality index ranged from 20.7 to 103.3, placing one site in the excellent and two in the unfit class, with turbidity supplying about three-quarters of the index value on average. Civil Lines had the highest TDS and magnesium and the lowest dissolved oxygen, whereas Allenganj had the lowest TDS but the second-highest turbidity, so no part of the city is uniformly better. TDS was significantly correlated only with magnesium ($r = 0.56$, $p = 0.024$). The results indicate a water resource that is usable under BIS provisions yet falls short of acceptable limits almost everywhere, and they point to turbidity control, selective treatment, wider parameter coverage and repeated, georeferenced monitoring as priorities.

Keywords- groundwater quality; Prayagraj; total dissolved solids; hardness; water quality index; IS 10500:2012.

I. INTRODUCTION

Groundwater is the backbone of urban water supply in much of India, and Prayagraj is no exception. According to the records of the Jal Kal Vibhag, 238 of the 308 million litres per day (MLD) supplied to the city, or 77%, are drawn from tube wells, with the Yamuna contributing the remainder. Public wells and hand pumps serve residents who are not reached, or not reliably reached, by the piped network. For these reasons the chemical character of the city's groundwater is a matter of everyday concern, not merely of academic interest.

Each parameter examined here has a practical meaning. pH governs corrosion and the efficiency of chlorine disinfection. Hardness, derived mainly from calcium and magnesium, causes scale in pipes and appliances and raises soap consumption. TDS and chloride affect taste and corrosiveness. Bicarbonate determines alkalinity and buffers pH. Turbidity reflects suspended particles and can shield microorganisms from disinfection, while temperature and dissolved oxygen describe the condition of the sample (Chapman, 1996; Patil et al., 2012; WHO, 2017). WHO does not set health-based guideline values for pH, hardness or TDS, which it treats mainly as matters of acceptability, whereas the Indian standard IS 10500:2012 prescribes an acceptable limit and a higher permissible limit that applies only where no alternative source exists (BIS, 2012).

Aggregate statements about "city water quality" can hide strong differences between neighbourhoods. This paper therefore asks how each parameter varies across 16 sites in Prayagraj, how the readings compare with national and international standards, whether the sites can be ranked on a composite index, and which parameters move together. Its

objectives are: (i) to describe the spatial variation of ten parameters; (ii) to assess compliance with IS 10500:2012; (iii) to compute a composite water quality index for each site; (iv) to examine relationships among parameters; and (v) to draw out implications for monitoring and treatment.

II. STUDY AREA

Prayagraj (formerly Allahabad) lies at the confluence of the Ganga and the Yamuna in the south-east of Uttar Pradesh. The municipal area covers about 75 km², and the 2011 Census recorded 1,112,544 persons in the city and 1,212,395 in the urban agglomeration. Sixteen sampling sites were selected to represent a range of urban conditions, from densely populated residential neighbourhoods to less developed areas (Figure 1). They include sites in the old and central city (Mutthiganj, Katra, Civil Lines, Georgetown, Rajapur), along the river front near the confluence (Daraganj, Rasoolabad, Salori, Teliyarganj) and towards the western edge (Sulem Sarai, Dhoomanganj), together with Allenganj, Beli, Kareli, Beniganj and Ashok Nagar.



Figure 1. Sampling sites in Prayagraj city. Labels show site name and TDS (mg/L). Source: prepared by the authors.

III. MATERIALS AND METHODS

3.1 Sampling and parameters

Water samples were collected at 16 sites following standard protocols, stored in sterilised containers and transported promptly to the laboratory. Ten parameters were reported for each site: temperature (°C), pH, total hardness, turbidity (NTU), dissolved oxygen (DO), TDS, magnesium, calcium, chloride and bicarbonate. Concentrations are in mg/L unless stated.

3.2 Standards used

Results were compared with the acceptable and permissible limits of IS 10500:2012 (BIS, 2012): turbidity 1 and 5 NTU; TDS 500 and 2,000 mg/L; total hardness 200 and 600 mg/L as CaCO₃; calcium 75 and 200 mg/L; magnesium 30 and 100 mg/L; chloride 250 and 1,000 mg/L; alkalinity 200 and 600 mg/L as CaCO₃; and pH 6.5–8.5 with no relaxation. Temperature and DO have no limit in the standard and are described only. WHO (2017) guidance on taste thresholds and disinfection was used as a secondary reference. Hardness was also grouped by the commonly used classification (soft 0–60, moderately hard 61–120, hard 121–180, very hard above 180 mg/L).

3.3 Derived indicators

Alkalinity as CaCO₃ was estimated from bicarbonate as $\text{HCO}_3^- \times 50/61$, because bicarbonate dominates alkalinity at pH 7.2–7.8. A composite index was computed with the weighted arithmetic method (Brown et al., 1972) for eight parameters (pH, turbidity, TDS, hardness, calcium, magnesium, chloride and alkalinity). The unit weight of each parameter is $W_i = K/S_i$, where S_i is its permissible limit and $K = 1/\sum(1/S_i)$. The quality rating is $q_i = 100 \times (V_i - V_0)/(S_i - V_0)$, with $V_0 = 7$ for pH and 0 for all other parameters, and $WQI = \sum(W_i q_i)/\sum W_i$. Classes are: excellent (≤ 25), good (26–50), poor (51–75), very poor (76–100) and unfit (>100). Permissible limits were used as standards because IS

10500:2012 allows them where no alternative source exists; the sensitivity of the index to this choice is discussed in Section 4.7.

Internal consistency was checked in two ways: hardness was recalculated from calcium and magnesium as $2.497 \times \text{Ca} + 4.118 \times \text{Mg}$, and the sum of Ca, Mg, Cl and HCO_3 was compared with TDS.

3.4 Statistical treatment

Descriptive statistics (minimum, maximum, mean, standard deviation and coefficient of variation) were computed for each parameter, and exceedances were counted against the standards. Pearson correlation coefficients were calculated among all ten parameters ($n = 16$; $|r| \geq 0.497$ is significant at $p < 0.05$, two-tailed). Because 45 pairs were tested, about two significant results are expected by chance, so correlations are treated as exploratory. Spatial patterns are described from the site map, since site coordinates were not available for interpolation.

IV. RESULTS AND DISCUSSION

4.1 Overview of the dataset

Table 1 lists the measured values and Table 2 summarises them against the standards. The parameters differ greatly in variability. Temperature (CV 3.1%) and pH (2.6%) are nearly uniform across the city, while turbidity is by far the most variable (CV 52.2%), followed by TDS (24.2%) and calcium (22.0%).

Table 1. Measured water quality parameters at the 16 sampling sites

Site	Temp (°C)	pH	Hard.	Turb. (NTU)	DO	TDS	Mg	Ca	Cl	HCO_3
Daraganj	32.4	7.3	312	0.9	6.8	641	63.2	76	71.8	512
Katra	32.1	7.5	220	4.6	8.1	689	75.8	84	83.73	421
Georgetown	30.4	7.2	272	6.2	7.3	586	83.9	108	79.53	413
Civil Lines	32.4	7.8	296	5.9	5.7	811	88.5	92	61.1	436
Teliyarganj	31.5	7.3	304	3.3	6.1	479	78.33	134	75.6	563
Mutthiganj	31.3	7.2	291	1.4	8.15	765	83.49	105	92.4	299
Salori	31.2	7.6	317	1.8	7.7	551	49.5	69	93.9	524
Rajapur	33.1	7.4	325	6.6	6.5	476	61.21	146	78.2	336
Sulem Sarai	33.2	7.5	240	2.7	7.05	671	64.58	78	51.13	345
Ashok Nagar	32.7	7.3	238	3.5	7.6	535	42.75	86	49.13	320
Beniganj	33.3	7.5	256	5.7	6.89	405	56.37	100	56.9	596
Allenganj	32.6	7.8	261	6.9	8.05	341	52.48	107	68.3	488
Beli	30.8	7.6	329	2.2	7.58	504	65.1	84	82.5	548
Kareli	33.1	7.7	236	4.5	8.01	386	74.84	96	80.95	404
Rasoolabad	30.7	7.5	198	1.9	6.38	523	58.8	99	78.6	470
Dhoomanganj	32.9	7.6	277	7.1	7.05	702	79.31	73	90.8	436

Hard. = total hardness as CaCO_3 . All concentrations in mg/L except DO (mg/L) and where stated. Source: compiled from the thesis dataset.

Table 2. Descriptive statistics and compliance with IS 10500:2012

Parameter	Unit	Min	Max	Mean	SD	CV (%)	Acc. limit	Perm. limit	Sites > acc.	Sites > perm.
Temperature	°C	30.4	33.3	32.1	1	3.1	—	—	—	—
pH	—	7.2	7.8	7.49	0.19	2.6	6.5–8.5	None	0	0
Turbidity	NTU	0.9	7.1	4.1	2.1	52.2	1	5	15	6
Dissolved oxygen	mg/L	5.7	8.15	7.18	0.76	10.5	—	—	—	—
TDS	mg/L	341	811	567	137	24.2	500	2000	11	0
Total hardness	mg/L	198	329	273	40	14.5	200	600	15	0
Calcium	mg/L	69	146	96	21	22	75	200	14	0
Magnesium	mg/L	42.8	88.5	67.4	13.6	20.2	30	100	16	0
Chloride	mg/L	49.1	93.9	74.7	14	18.7	250	1000	0	0
Bicarbonate	mg/L	299	596	444	90	20.4	—	—	—	—
Alkalinity (as CaCO_3)	mg/L	245	489	364	74	20.4	200	600	16	0

Acc. = acceptable; Perm. = permissible (IS 10500:2012; BIS, 2012). Alkalinity is derived from bicarbonate. $n = 16$. “—” indicates no limit in the standard; pH has no permissible relaxation.

4.2 Temperature and pH

Temperature ranged from 30.4 °C (Georgetown) to 33.3 °C (Beniganj), with a mean of 32.1 °C. These values are warm for water from a deeper aquifer, which usually stays close to the mean annual air temperature, and may reflect shallow sources, exposure of the samples or the season of sampling. The warmest samples (33.1–33.3 °C) came from Beniganj, Sulem Sarai, Rajapur and Kareli, and the coolest (30.4–30.8 °C) from Georgetown, Rasoolabad and Beli.

pH was slightly alkaline everywhere (7.2–7.8, mean 7.49) and well inside the 6.5–8.5 range, so no site raises a corrosion or acidity concern. The highest values occurred at Civil Lines and Allenganj (7.8), the lowest at Georgetown and Mutthiganj (7.2). Six sites exceeded 7.5. This mildly alkaline reaction is consistent with the carbonate-buffered character indicated by bicarbonate of 299–596 mg/L. WHO notes that disinfection works best below about pH 8 (WHO, 2017), a condition met at all sites.

4.3 Hardness, calcium and magnesium

Total hardness ranged from 198 mg/L (Rasoolabad) to 329 mg/L (Beli), with a mean of 273 mg/L. Fifteen of 16 sites exceeded the acceptable limit of 200 mg/L, but none approached the permissible limit of 600 mg/L. All sites fall in the “very hard” class (above 180 mg/L). Five sites (Beli 329, Rajapur 325, Salori 317, Daraganj 312 and Teliyarganj 304) also exceed the older 300 mg/L limit of IS 10500:1991. Hardness is not a health-based parameter in WHO guidance, but it affects scale formation and soap use, and the epidemiological literature on hardness and cardiovascular disease has been reviewed by Catling et al. (2008).

Calcium (69–146 mg/L, mean 96.1) exceeded the acceptable limit of 75 mg/L at 14 sites, and magnesium (42.8–88.5 mg/L, mean 67.4) exceeded 30 mg/L at all 16 and 50 mg/L at 14; neither reached its permissible limit. The highest calcium occurred at Rajapur (146) and Teliyarganj (134), and the highest magnesium at Civil Lines (88.5), Georgetown (83.9) and Mutthiganj (83.5). Magnesium is notable: expressed in milliequivalents, it exceeds calcium at 10 of 16 sites and in the mean (5.55 against 4.79 meq/L). Without data on aquifer mineralogy, sodium or potassium, the cause cannot be identified, but the pattern merits geochemical follow-up.

4.4 Total dissolved solids and chloride

TDS ranged from 341 mg/L (Allenganj) to 811 mg/L (Civil Lines), with a mean of 567 mg/L. Eleven of 16 sites exceeded the acceptable limit of 500 mg/L, none approached the permissible limit of 2,000 mg/L, and all stayed below 1,000 mg/L, the level above which WHO reports water as increasingly unpalatable (WHO, 2017). Six sites exceeded 600 mg/L, the level up to which WHO regards palatability as good: Civil Lines (811), Mutthiganj (765), Dhoomanganj (702), Katra (689), Sulem Sarai (671) and Daraganj (641). The lowest values occurred at Allenganj (341), Kareli (386), Beniganj (405), Rajapur (476) and Teliyarganj (479). TDS is therefore an acceptability problem for most of the city rather than a hazard threshold.

Chloride (49.1–93.9 mg/L, mean 74.7) was well below the 250 mg/L limit at every site, so no site shows taste or corrosion problems from chloride, and no strong sign of saline or sewage-related enrichment. The highest values occurred at Salori (93.9), Mutthiganj (92.4) and Dhoomanganj (90.8), the lowest at Ashok Nagar (49.1) and Sulem Sarai (51.1).

4.5 Turbidity and dissolved oxygen

Turbidity was the most problematic parameter. Values ranged from 0.9 NTU (Daraganj) to 7.1 NTU (Dhoomanganj), with a mean of 4.1 NTU. Only Daraganj met the acceptable limit of 1 NTU, and six sites exceeded the permissible limit of 5 NTU: Dhoomanganj (7.1), Allenganj (6.9), Rajapur (6.6), Georgetown (6.2), Civil Lines (5.9) and Beniganj (5.7). Such values suggest suspended particles from poorly protected sources, sediment in pipes or storage, or contamination of shallow wells. They are also relevant to disinfection, because WHO advises keeping turbidity below 1 NTU for effective treatment (WHO, 2017). Because turbidity can accompany microbial contamination, these six sites merit microbiological testing, which the dataset does not include.

DO ranged from 5.7 mg/L (Civil Lines) to 8.15 mg/L (Mutthiganj), with a mean of 7.18 mg/L. Only Civil Lines fell below 6 mg/L. DO has no limit in the drinking-water standard; the generally high values indicate well-aerated samples. DO was unrelated to temperature ($r = -0.05$) and turbidity ($r = -0.11$).

4.6 Bicarbonate and alkalinity

Bicarbonate ranged from 299 mg/L (Mutthiganj) to 596 mg/L (Beniganj), with a mean of 444 mg/L, equivalent to alkalinity of 245–489 mg/L as CaCO_3 . All 16 sites exceeded the acceptable alkalinity limit of 200 mg/L, but none reached the permissible limit of 600 mg/L. The highest values occurred at Beniganj (596), Teliyarganj (563), Beli (548), Salori (524) and Daraganj (512). Together with hardness, high alkalinity favours scale deposition in pipes and heating appliances, which is of practical interest to households and the water utility.

4.7 Compliance and composite quality

Figure 2 shows each site's values against the acceptable and permissible limits, and Figure 3 summarises the result as a compliance matrix. Chloride and pH were within the acceptable range everywhere. Magnesium and alkalinity exceeded the acceptable limits at all 16 sites, hardness and turbidity at 15, calcium at 14 and TDS at 11. Every site exceeded the acceptable limit for at least five of the seven parameters assessed (Table 3), and seven sites (Katra, Georgetown, Civil Lines, Mutthiganj, Sulem Sarai, Ashok Nagar and Beli) exceeded six. Only turbidity crossed a permissible limit. In the terms of IS 10500:2012, the water is therefore usable where no alternative exists but does not meet the acceptable standard at any site.

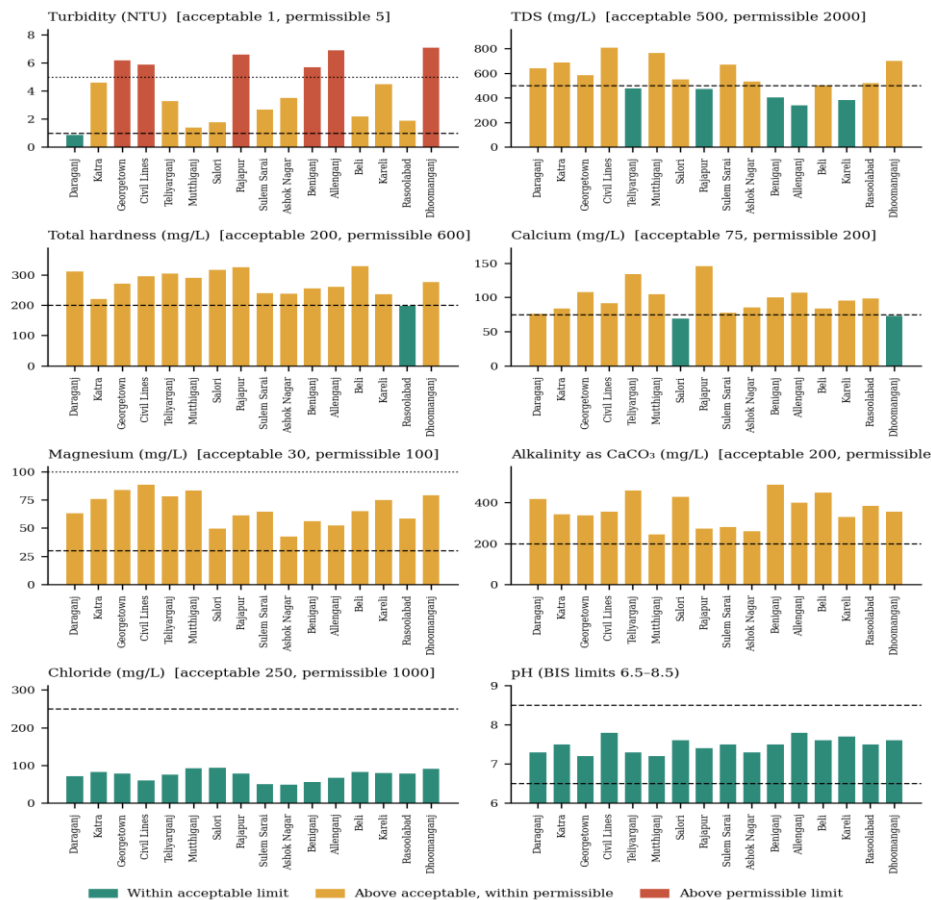


Figure 2. Site-wise values of eight parameters against IS 10500:2012 limits (dashed: acceptable; dotted: permissible). Alkalinity is derived from bicarbonate. Source: computed from the thesis dataset.

	pH	Turbidity	TDS	Hardness	Calcium	Magnesium	Chloride	Alkalinity
Daraganj	7.3	0.9	641	312	76	63	72	420
Katra	7.5	4.6	689	220	84	76	84	345
Georgetown	7.2	6.2	586	272	108	84	80	339
Civil Lines	7.8	5.9	811	296	92	88	61	357
Teliyarganj	7.3	3.3	479	304	134	78	76	461
Mutthiganj	7.2	1.4	765	291	105	83	92	245
Salori	7.6	1.8	551	317	69	50	94	430
Rajapur	7.4	6.6	476	325	146	61	78	275
Sulem Sarai	7.5	2.7	671	240	78	65	51	283
Ashok Nagar	7.3	3.5	535	238	86	43	49	262
Beniganj	7.5	5.7	405	256	100	56	57	489
Allenganj	7.8	6.9	341	261	107	52	68	400
Bell	7.6	2.2	504	329	84	65	82	449
Kareli	7.7	4.5	386	236	96	75	81	331
Rasoolabad	7.5	1.9	523	198	99	59	79	385
Dhoomanganj	7.6	7.1	702	277	73	79	91	357

Figure 3. Compliance matrix of 16 sites and eight parameters; cell values are measured concentrations (turbidity in NTU). Source: computed from the thesis dataset.

The water quality index ranged from 20.7 (Daraganj) to 103.3 (Allenganj), with a mean of 62.9 (Table 3). One site fell in the excellent class, five in good, four in poor, four in very poor and two (Dhoomanganj and Allenganj) in the unfit class. The ranking is dominated by turbidity, which supplies about 73% of the index value on average, because its permissible

limit is tight relative to the observed values. The index is also sensitive to the standards adopted: with the stricter acceptable limits as standards, 15 of 16 sites exceed 100. Rankings should therefore be read as relative, and not as verdicts on safety.

Table 3. Water quality index (WQI) and exceedances by site, ranked from best to worst

Site	WQI	Class	Parameters above acceptable limit (of 7)
Daraganj	20.7	Excellent	5
Mutthiganj	25.0	Good	6
Rasoolabad	37.2	Good	5
Salori	37.9	Good	5
Beli	43.3	Good	6
Sulem Sarai	46.6	Good	6
Teliyarganj	50.1	Poor	5
Ashok Nagar	50.8	Poor	6
Katra	69.6	Poor	6
Kareli	73.1	Poor	5
Georgetown	82.0	Very poor	6
Beniganj	82.3	Very poor	5
Rajapur	91.0	Very poor	5
Civil Lines	92.4	Very poor	6
Dhoomanganj	101.6	Unfit	5
Allenganj	103.3	Unfit	5

WQI computed from eight parameters with IS 10500:2012 permissible limits as standards (Section 3.3).

4.8 Spatial pattern and relationships among parameters

No part of the city is uniformly better or worse; the pattern differs by parameter. In the central old city, Civil Lines, Georgetown and Mutthiganj hold the three highest magnesium values, and Civil Lines and Mutthiganj the two highest TDS values. Civil Lines also has the lowest DO and a turbidity of 5.9 NTU. Along the river front near the confluence, Daraganj has the lowest turbidity (0.9 NTU) yet hardness of 312 mg/L and TDS of 641 mg/L, while Allenganj has the lowest TDS (341 mg/L) but the second-highest turbidity (6.9 NTU) and the highest (worst) index. At the western edge, Dhoomanganj combines high TDS (702 mg/L) with the highest turbidity (7.1 NTU), whereas Sulem Sarai has high TDS (671 mg/L) but low chloride. Turbidity exceeds the permissible limit at sites spread across the central, eastern and western parts of the city, which suggests that it reflects local source and distribution conditions rather than a single regional cause.

Only two correlations were significant (Figure 4): TDS with magnesium ($r = 0.56$, $p = 0.024$) and temperature with chloride ($r = -0.51$, $p = 0.046$). With 45 pairs tested, these may be chance findings. Notably, TDS was not significantly related to calcium ($r = -0.38$), bicarbonate ($r = -0.39$) or chloride ($r = 0.12$), and hardness was not related to calcium ($r = 0.18$) or magnesium ($r = 0.12$), which is chemically unexpected and prompts the consistency check below.

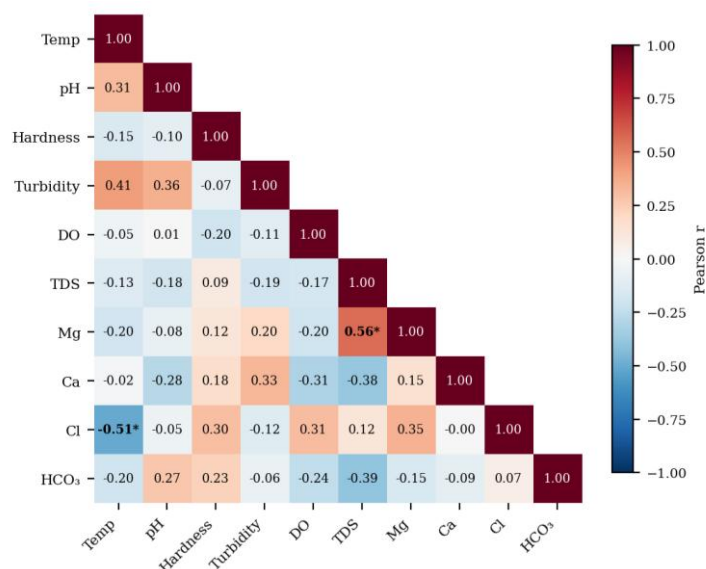


Figure 4. Pearson correlation matrix of ten parameters (n = 16). Asterisks mark $p < 0.05$. Source: computed from the thesis dataset.

4.9 Internal consistency of the dataset

Hardness recalculated from the reported calcium and magnesium ranges from 376 to 657 mg/L (mean 517 mg/L), about 1.2 to 2.5 times the reported hardness (mean 273 mg/L). The sum of Ca, Mg, Cl and HCO_3 also exceeds the reported TDS at 10 of 16 sites (ratio 0.76 to 2.10). Differences of this size are unlikely to arise from rounding. They may reflect different analytical methods or units for individual parameters, or transcription differences, and they limit confidence in the absolute concentrations and in any chemical interpretation that depends on ion balance. The exceedance counts and rankings above rely on each parameter's own reported value, and would change if any parameter were revised. We recommend that the underlying laboratory records be re-examined before the values are used for regulatory or health decisions.

V. IMPLICATIONS AND RECOMMENDATIONS

1. **Address turbidity first.** The six sites above 5 NTU (Dhoomanganj, Allenganj, Rajapur, Georgetown, Civil Lines and Beniganj) should be inspected for source protection, well sanitation, and sediment in pipes and storage, and retested after sedimentation or filtration.
2. **Use selective treatment for TDS.** Where TDS exceeds 600 mg/L (Civil Lines, Mutthiganj, Dhoomanganj, Katra, Sulem Sarai and Daraganj), point-of-use treatment may be justified for drinking water. Indiscriminate demineralisation at sites with lower TDS is unnecessary and wastes water.
3. **Manage scale.** High hardness and alkalinity warrant descaling and softening provisions for households and for heaters and pumps, and attention to scale in the utility's pipes.
4. **Widen the parameter set.** Microbiological indicators, nitrate, fluoride, iron, sulphate, sodium, potassium and trace metals should be added so that safety, not only acceptability, can be judged, and so that the ion balance can be closed.
5. **Monitor repeatedly and spatially.** Seasonal (pre- and post-monsoon) sampling with recorded source type, depth and GPS coordinates would allow interpolation (for example inverse distance weighting or kriging) and trend detection.
6. **Reconcile laboratory records.** The inconsistencies in Section 4.9 should be resolved before the dataset is used for policy.

VI. LIMITATIONS

The study rests on a single sampling round at 16 sites, so seasonal variation is not captured. The type and depth of the sampled sources and the sampling period must be stated in the methods. Only physico-chemical parameters were assessed; microbial, nitrate, fluoride, iron and trace-metal data are lacking, so the results speak to acceptability and chemical character, not to overall safety. The inconsistencies in Section 4.9 limit chemical interpretation. With 16 sites, correlations are weak evidence, and spatial description relies on the site map because coordinates were unavailable for interpolation. The water quality index depends on the standards and parameters chosen. Finally, the causes suggested for patterns (geology, wastewater, storage conditions) are hypotheses that this dataset cannot test.

VII. CONCLUSION

At 16 sites in Prayagraj, pH and chloride met the standards everywhere, while hardness, TDS, calcium, magnesium and alkalinity exceeded acceptable limits at most sites without reaching permissible limits. Turbidity was the only parameter above a permissible limit, at six sites, and it largely determines the composite index, which ranges from excellent at Daraganj to unfit at Dhoomanganj and Allenganj. Every site exceeded at least five acceptable limits, and the spatial pattern differs by parameter, so no neighbourhood is uniformly favourable. Priorities are turbidity control, selective treatment where TDS is high, a wider set of tested parameters, reconciliation of laboratory records, and repeated, georeferenced sampling to support a defensible spatial assessment.

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