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High-Frequency IoT-Based Comparative Physicochemical Assessment of Treated Municipal Water and Decentralized Groundwater in Bragança, NE Portugal

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Abstract

Drinking water quality is essential for public health and requires monitoring approaches able to capture both regulatory compliance and short-term variability. This study presents a high-frequency IoT-based comparative physicochemical assessment of two drinking-water sources in Bragança, NE Portugal: treated municipal water derived from surface water and groundwater abstracted from a decentralized supply system. A low-cost IoT monitoring system was used to measure pH, electrical conductivity, temperature, oxidation-reduction potential, and total dissolved solids. Monitoring campaigns were conducted between January and March 2026 at two treated-water points within the public supply system and three groundwater points, complemented by municipal records from 2023 to 2025. The treated municipal supply showed a more stable physicochemical profile and lower variability, whereas groundwater was associated with higher mineralization and stronger temporal fluctuations. Significant differences were found for electrical conductivity, total dissolved solids, oxidation-reduction potential, temperature, and pH. High-frequency monitoring enabled the identification of dynamic patterns and transient fluctuations that would be difficult to detect through discrete sampling alone.

Keywords: drinking water; treated surface water; groundwater; decentralized supply; high-frequency IoT monitoring; physicochemical variability

1. Introduction

Access to safe drinking water remains a central public health concern and a key requirement for sustainable water management. Although groundwater is often perceived as a naturally protected resource, its quality may vary substantially depending on geological substrate, recharge conditions, hydrological dynamics, seasonal influences, and potential contamination sources [1–3]. By contrast, the physicochemical profile of treated municipal water reflects both source-water characteristics and treatment processes. Within the European Union, drinking-water quality is regulated under Directive (EU) 2020/2184, which reinforces a risk-based approach to water intended for human consumption [4]. In Portugal, this framework was transposed by Decree-Law No. 69/2023, which defines quality requirements, monitoring obligations, and the responsibilities of entities involved in water supply management [5]. In this context, water supplied through public distribution systems is generally subject to treatment, monitoring, and regulatory control, whereas decentralized groundwater sources may require greater attention where treatment, monitoring, user responsibilities, and institutional oversight are less structured [6]. Comparative assessments of treated municipal water and decentralized groundwater can therefore provide useful information on source-specific differences and temporal variability under contrasting supply conditions.

In recent years, Internet of Things (IoT) technologies have emerged as promising tools for water-quality monitoring [7–10]. By enabling automated, networked, and relatively low-cost data acquisition, these systems make real-time or high-frequency monitoring increasingly feasible in contexts where conventional monitoring is often based on discrete sampling. IoT-based systems can measure parameters such as pH, electrical conductivity, temperature, total dissolved solids, turbidity, and oxidation-reduction potential, generating continuous datasets that are difficult to obtain through punctual campaigns alone [11–13]. Although limitations remain regarding calibration, long-term stability, and interoperability, recent studies have highlighted the potential of these systems for distributed and decentralized monitoring applications [14,15]. Their use is especially valuable in comparative studies involving different water sources because the same IoT-based framework can be applied under distinct supply conditions [9,10]. In this context, the importance of IoT lies not only in remote data transmission, but also in its ability to support high-frequency monitoring and thereby improve the characterization of short-term variability and temporal dynamics. As highlighted by [16–18], this type of monitoring can reveal short-lived variability and temporal patterns that may be missed by discrete sampling campaigns, including in groundwater settings, while supporting interpretation and assessment rather than technology-driven claims.

Bragança, in northeastern Portugal, provides an appropriate setting for this comparison because it combines a regulated public water supply based on treated surface-water-derived municipal water with a decentralized groundwater source serving part of the local higher education campus. This context makes it possible to compare treated municipal water and decentralized groundwater under the same monitoring framework and local environmental conditions. The aim of this study was therefore to compare two drinking-water sources in Bragança, Portugal—treated municipal water derived from surface water and groundwater abstracted from a decentralized supply system—using a high-frequency IoT-based monitoring approach. The study also examined temporal variability and the usefulness of continuous monitoring as a complementary tool for water-quality assessment and management. In this region, this appears to be the first application of a high-frequency IoT-based approach to compare treated municipal water and decentralized groundwater under the same local conditions. Available information for groundwater remains scarce and is largely limited to punctual water-quality analyses. Rather than claiming novelty in IoT itself, this study contributes by applying high-frequency comparative monitoring to two contrasting drinking-water supply systems within the same local setting. This approach makes it possible to characterize temporal stability, variability, and source-specific heterogeneity more clearly than punctual sampling alone.

2. Materials and Methods

This section describes the procedures used for the comparative assessment of drinking-water quality from different sources in Bragança, Portugal. It includes the study area, the monitored water sources, the sampling points, the monitoring campaigns, and the methods used to measure physicochemical and microbiological parameters. The data acquisition system, statistical analyses, and criteria adopted to ensure measurement reliability are also presented, providing a framework for the consistent and comparable evaluation of treated surface-water-derived municipal water and groundwater.

2.1. Study Area

Bragança is a medium-sized city located in northeastern Portugal (41°48′10″ N, 6°45′25″ W; 673 m a.s.l.), with 34,582 inhabitants [19]. The region is characterized by a predominantly continental

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climate with Mediterranean influence, marked by cold winters, dry summers, and annual precipitation ranging from 700 to 1000 mm, most of which occurs during autumn and winter [20]. The treated surface-water-derived municipal water source is Serra Serrada reservoir, located in a predominantly granitic setting in northeastern Portugal [21]. The groundwater source corresponds to a local decentralized abstraction system in the Bragança area, within a regional geological context that includes granitic and metasedimentary units [22].

2.2. Study Design and Water Supply Contexts

This study followed a comparative observational design based on repeated monitoring of two drinking-water source types in Bragança, Portugal. One source corresponded to treated surface-water-derived municipal water from the public supply system, monitored at two treated-water points: the outlet of the water treatment plant (ETA) and the distribution reservoir (MAE). The other source corresponded to groundwater from a decentralized supply system, monitored at three sampling points located on the local higher education campus (ESA, ESE, and ESTIG). The characterization of the sampling points is presented in Table 1.

Table 1. Characterization of the sampling points included in the study.

Code	Sampling Point	Supply Type	Water Source	Description
ETA	Water treatment plant outlet	Public supply	Treated surface water	Outlet of the water treatment plant
MAE	Distribution reservoir	Public supply	Treated surface water	Post-treatment distribution reservoir
ESA	School of Agriculture	Decentralized supply	Groundwater	Indoor sampling point
ESE	School of Education	Decentralized supply	Groundwater	Indoor sampling point
ESTIG	School of Technology and Management	Decentralized supply	Groundwater	Indoor sampling point

Monitoring campaigns were conducted between January and March 2026. In addition, municipal records from 2023 to 2025 were consulted as complementary background information [23].

As supplementary information, microbiological analyses were performed only on groundwater samples. According to [5], water intended for human consumption must be free of fecal indicator microorganisms, including *Escherichia coli*, intestinal enterococci, and *Clostridium perfringens*, in a 100 mL sample. In the present study, these analyses were considered only as complementary information for the assessment of groundwater quality.

2.3. Monitoring System

Comparative monitoring was performed using a portable multiparameter meter (HI98195, Hanna Instruments) integrated into an IoT based architecture. The same equipment and monitoring logic were applied to both source types. The system was used to measure pH, electrical conductivity (EC), temperature (TEMP), oxidation-reduction potential (ORP), and total dissolved solids (TDS). To minimize stagnation effects and ensure representative hydraulic conditions, the probe was installed in a flow chamber directly connected to the water supply line, allowing continuous water renewal during each monitoring session. In the public supply system, a DULCOMETER diaLog DACb (ProMinent) was also available as part of the operational monitoring infrastructure and was used only as a supplementary reference to check the consistency of the measurements obtained with the equipment described above. The IoT architecture enabled automatic data acquisition, local storage, remote transmission via MQTT and HTTP, and timestamp synchronization via NTP (Network Time Protocol). The data were stored in a MySQL database and subsequently processed in Python using the Pandas, NumPy, and SciPy libraries.

Each of the five sampling points was monitored during three campaigns, with each campaign consisting of approximately 60 consecutive readings taken at 10-second intervals over a 10-minute period. This resulted in approximately 180 measurements per point and about 900 observations in total.

2.4. Data Treatment and Statistical Analysis

Descriptive statistics were used to summarize the monitored parameters, including mean, median, standard deviation, quartiles, and coefficient of variation. Temporal variation was examined across campaigns and sampling points. Data distribution was assessed using the Shapiro–Wilk test. Depending on normality, differences between the two water-source groups were evaluated using Student’s t-test or the Mann–Whitney U test. Correlations among parameters were analyzed using Spearman’s correlation coefficients, as appropriate. Statistical significance was considered at $\alpha = 0.05$.

3. Results and Discussion

This section presents the comparative results for treated surface-water-derived municipal water and groundwater in Bragança, Portugal, focusing on physicochemical characteristics, microbiological quality, statistical differences, temporal variability, and parameter correlations. The analysis highlights contrast in mineralization, stability, and heterogeneity between the regulated municipal supply and the naturally more variable decentralized groundwater sources.

3.1. Physicochemical Characterization of the Two Water Sources

Treated municipal water from the public supply system and groundwater from the decentralized supply system showed clear physicochemical differences. Treated municipal water displayed a narrow range of variation, with pH values between 7.35 and 7.58, EC between 32 and 57 µS/cm, TDS between 21 and 37 ppm, and ORP between 620 and 667 mV. By contrast, groundwater showed much wider variation, with pH ranging from 5.65 to 8.22, EC from 54 to 470 µS/cm, TDS from 25 to 235 ppm, and ORP from 220.6 to 408.1 mV. Overall, groundwater exhibited markedly higher EC and TDS values, indicating greater mineralization, whereas treated municipal water showed substantially higher ORP values (Tables A1 and A2, Appendix A). This contrast is also clearly illustrated in Figure 1, where treated municipal water forms a compact cluster characterized by high ORP and near-neutral pH, whereas groundwater occupies a broader domain with lower ORP and wider pH variation, consistent with chlorinated treated water and untreated groundwater.

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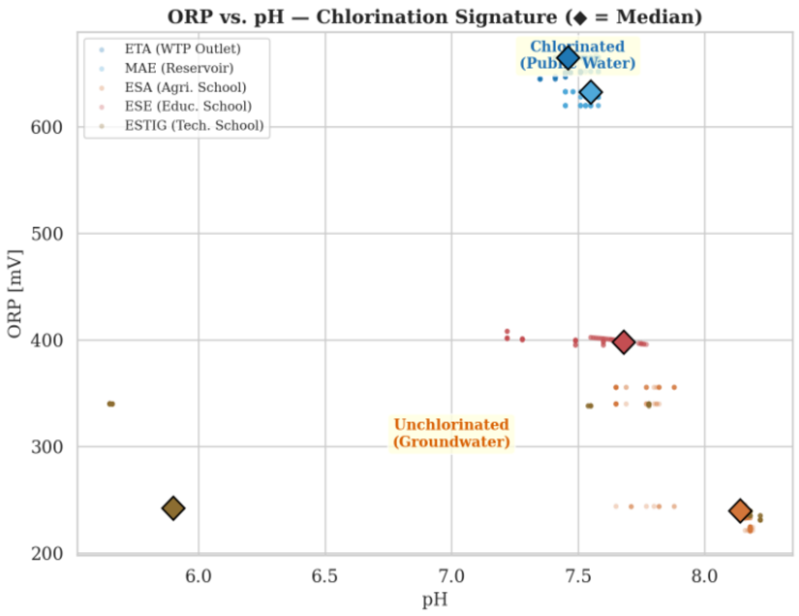

Figure 1. Scatter plot of pH versus ORP for treated municipal water and groundwater, showing the compact clustering of treated water at higher ORP and near-neutral pH, and the broader distribution of groundwater with lower ORP and greater pH variability.

Microbiological analyses were performed only on groundwater samples collected in March 2026. The results complied with [5], with no fecal indicator microorganisms detected in 100 mL samples. However, these results should be interpreted cautiously, as microbiological monitoring was not carried out continuously throughout the study period.

3.2. Statistical Comparison, Temporal Variability, and Correlation Patterns

The statistical analysis confirmed significant differences between treated municipal water and groundwater for all monitored parameters ($p < 0.05$), with the strongest contrasts observed for EC, TDS, and ORP. Groundwater also showed greater dispersion, reflected in higher standard deviations and coefficients of variation, whereas treated municipal water was characterized by a narrower range of values and greater temporal consistency. These results indicate lower temporal stability in the decentralized groundwater source and greater predictability in the treated municipal water, which is consistent with the contrast between a controlled treatment and distribution system and a naturally variable subsurface source. In this sense, the distinction between the two supply models was not limited to differences in central tendency but also involved differences in temporal stability. Correlation analysis provided additional insight into the internal structure of the dataset, as evidenced by the Spearman correlation matrices shown in Figure 2.

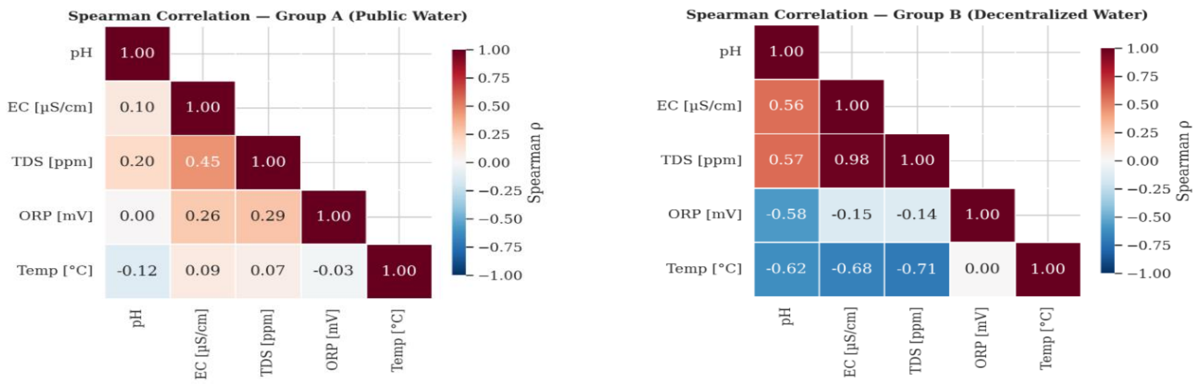

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Figure 2. Spearman correlation matrices for treated municipal water (group A) and groundwater (group B), showing the strength and direction of monotonic relationships among the monitored physicochemical parameters.

Strong positive associations between EC and TDS were observed in both supply types, reinforcing the internal consistency of the monitoring results. In groundwater, correlation patterns were generally more heterogeneous, which is consistent with the broader physicochemical variability observed across sampling points. In this respect, the results are consistent with [16,17], who noted that repeated measurements are particularly valuable when the objective is not only to compare average conditions, but also to examine short-term variability and temporal stability. Although each campaign covered a relatively short period, the present design generated repeated short-interval observations that were analytically more informative than single punctual readings and were therefore suitable for the comparative assessment of short-term variability.

From a hydrochemical perspective, the higher EC and TDS values observed in groundwater are consistent with stronger lithological control and longer water–rock interaction, as commonly described for groundwater systems [1,2,24]. The wider pH range observed in groundwater, including values below the lower parametric value of 6.5 established by Portuguese legislation, further highlights the greater heterogeneity of the decentralized source. Variability among ESA, ESE, and ESTIG also suggests local differences in groundwater circulation, abstraction conditions, or source-specific hydrochemical controls. In contrast, treated municipal water showed a weakly mineralized and more homogeneous profile, consistent with its origin and with the operational control associated with the public supply system.

This greater heterogeneity is also evident in Figure 3, where the groundwater sampling points display broader and, in some cases, more irregular distributions of pH, EC, TDS, and ORP.

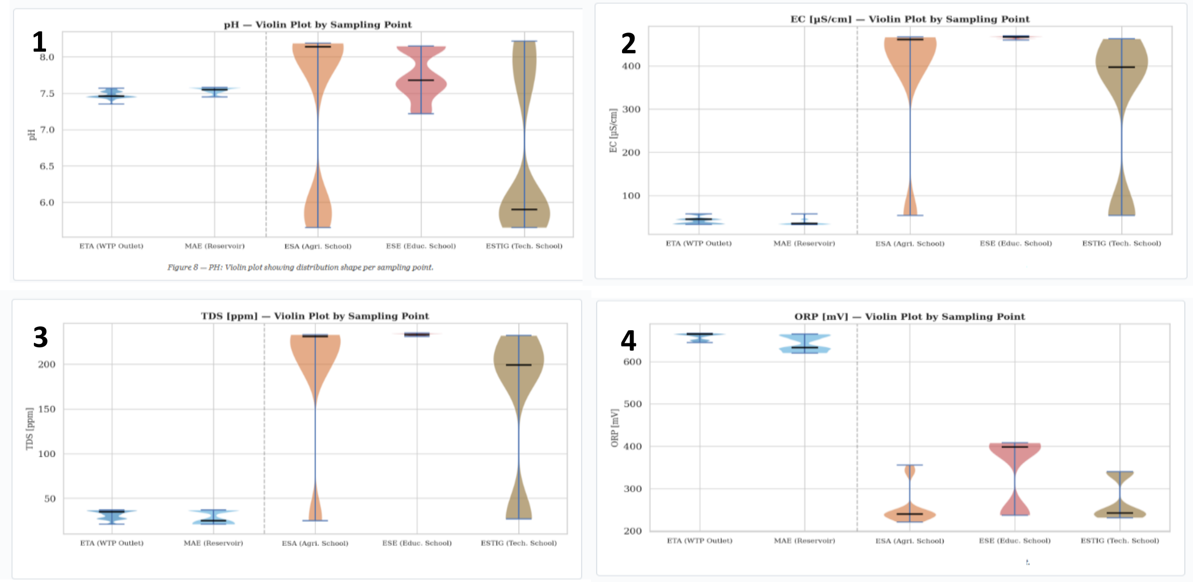

Figure 3. Violin plots of (1) pH, (2) EC, (3) TDS, and (4) ORP by sampling point, showing the broader distributions and greater heterogeneity of groundwater relative to treated municipal water.

Temporal median values by campaign reinforced these differences, with treated-water points showing limited inter-campaign variation and groundwater displaying larger shifts between campaigns and among sampling points, as shown in Figure 4. This pattern suggests that treated municipal water remained under relatively stable operational control throughout the monitoring period, whereas groundwater was more responsive to local and short-term influences, including site-specific hydrogeochemical conditions and external environmental variability, as also reported in studies of groundwater wells and drinking-water systems [3]. In this respect, the present results are consistent with previous studies showing that repeated measurements are particularly valuable for identifying dynamic behavior, short-term variability, and temporal instability that may be overlooked by discrete sampling alone, including in groundwater systems [16–18].

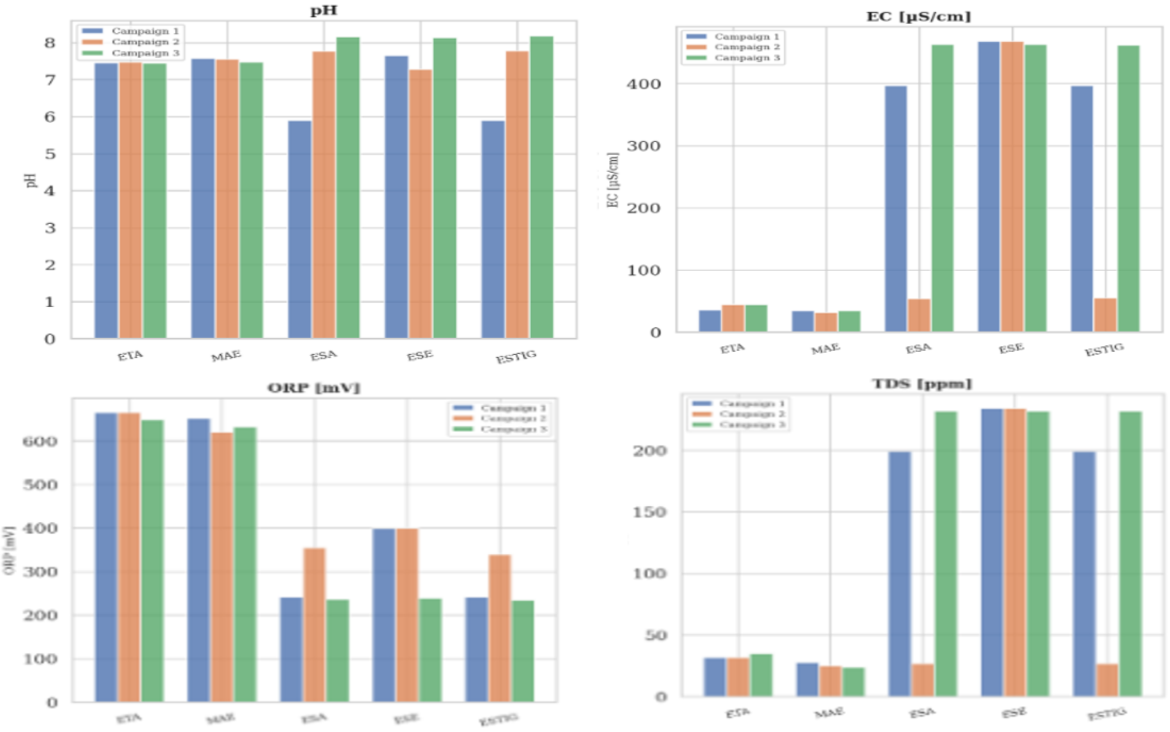

Figure 4. Median values of pH, EC, ORP and TDS by campaign and sampling point, showing the lower inter-campaign variability of treated water and the greater temporal fluctuation of groundwater.

4. Conclusions

The present research compared treated municipal water and decentralized groundwater in Bragança, Portugal, using a high-frequency IoT-based monitoring approach and revealed clear physicochemical differences between the two supply contexts. Treated municipal water showed greater stability, lower temporal variability, and a more consistent oxidizing profile, whereas groundwater exhibited higher mineralization, greater spatial heterogeneity, and more pronounced short-term fluctuations. These contrasts reflect the difference between a controlled treatment and distribution system and an untreated groundwater source influenced by local hydrochemical conditions. A main contribution of the study was the application of a common monitoring framework to both systems, allowing direct comparison under the same local conditions. The repeated short-interval measurements provided more informative insight into variability, stability, and parameter relationships than single punctual readings alone, supporting this approach as a complementary tool for comparative assessment and routine screening. This study should nevertheless be regarded as an initial assessment, since the monitoring period was limited and broader long-term behavior could not be evaluated. Future research should extend the monitoring period and combine high-frequency measurements with periodic laboratory analyses, including microbiological and more detailed hydrochemical assessment. Overall, the results support the value of comparative monitoring under real-use conditions and contribute to more informed management of decentralized groundwater sources.

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review and editing, J.S., A.M.A.G., and C.S.; visualization, J.S., A.M.A.G., and C.S.; supervision, A.M.A.G. and C.S.; project administration, J.S. and A.M.A.G.; funding acquisition, J.S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: “The authors declare no conflicts of interest.”.

Appendix A

Appendix A.1

Table A1. Descriptive statistics by sampling point.

Point	Parameter	N	Mean ± Std	Median	Range	IQR	CV (%)
ETA (WTP Outlet)	pH	594	7.476 ± 0.053	7.460	[7.35, 7.57]	[7.450, 7.520]	0.7
ETA (WTP Outlet)	EC [µS/cm]	594	41.929 ± 8.034	45.000	[33.00, 57.00]	[35.000, 45.000]	19.2
ETA (WTP Outlet)	TDS [ppm]	594	31.864 ± 5.248	35.000	[21.00, 37.00]	[28.000, 37.000]	16.5
ETA (WTP Outlet)	ORP [mV]	594	658.921 ± 7.374	665.000	[645.00, 667.00]	[651.000, 665.000]	1.1
ETA (WTP Outlet)	Temp [°C]	594	20.250 ± 0.838	20.010	[19.20, 22.10]	[19.500, 21.100]	4.1
MAE (Reservoir)	pH	594	7.539 ± 0.047	7.550	[7.45, 7.58]	[7.510, 7.580]	0.6
MAE (Reservoir)	EC [µS/cm]	594	36.328 ± 6.104	35.000	[32.00, 57.00]	[32.000, 35.000]	16.8
MAE (Reservoir)	TDS [ppm]	594	28.955 ± 6.810	25.000	[21.00, 37.00]	[21.000, 37.000]	23.5
MAE (Reservoir)	ORP [mV]	594	641.912 ± 17.431	633.000	[620.00, 665.00]	[628.000, 61.000]	2.7
MAE (Reservoir)	Temp [°C]	594	20.055 ± 1.014	20.500	[18.50, 22.10]	[18.500, 20.500]	5.1
ESA (Agri. School)	pH	573	7.314 ± 1.083	8.140	[5.65, 8.19]	[5.900, 8.160]	14.8
ESA (Agri. School)	EC [µS/cm]	573	373.871 ± 149.917	461.000	[54.00, 467.00]	[397.000, 64.000]	40.1
ESA (Agri. School)	TDS [ppm]	573	187.019 ± 74.984	231.000	[25.00, 233.00]	[199.000, 32.000]	40.1
ESA (Agri. School)	ORP [mV]	573	255.432 ± 41.868	239.900	[220.60, 355.50]	[235.800, 43.900]	16.4
ESA (Agri. School)	Temp [°C]	573	17.965 ± 3.436	16.420	[13.61, 23.28]	[16.260, 23.140]	19.1

ESE (Educ. School)	pH	219	7.755 ± 0.326	7.680	[7.22, 8.15]	[7.560, 8.140]	4.2
ESE (Educ. School)	EC [µS/cm]	219	466.023 ± 2.361	467.000	[460.00, 470.00]	[463.000, 68.000]	0.5
ESE (Educ. School)	TDS [ppm]	219	233.050 ± 1.178	233.000	[231.00, 235.00]	[232.000, 34.000]	0.5
ESE (Educ. School)	ORP [mV]	219	341.239 ± 77.385	398.100	[237.00, 408.10]	[239.900, 00.500]	22.7
ESE (Educ. School)	Temp [°C]	219	14.252 ± 1.549	13.500	[12.74, 16.27]	[12.875, 16.260]	10.9
ESTIG (Tech. School)	pH	319	6.635 ± 1.038	5.900	[5.65, 8.22]	[5.900, 7.780]	15.6
ESTIG (Tech. School)	EC [µS/cm]	319	302.119 ± 169.406	397.000	[54.00, 463.00]	[55.000, 398.000]	56.1
ESTIG (Tech. School)	TDS [ppm]	319	151.304 ± 84.996	199.000	[27.00, 232.00]	[27.000, 199.000]	56.2
ESTIG (Tech. School)	ORP [mV]	319	274.010 ± 47.595	242.100	[231.00, 340.10]	[239.700, 39.500]	17.4
ESTIG (Tech. School)	Temp [°C]	319	20.017 ± 3.188	17.370	[16.25, 23.28]	[17.200, 23.210]	15.9

*N: sample size; Mean: mean; Std: standard deviation; Median: median; IQR: interquartile range; CV: coefficient of variation.

Appendix A.2

Table A2. Direct comparison of descriptive statistics between treated surface water and decentralized groundwater.

Parameter	N	N	Mean	Mean	Median	Median	Std	Std	Min	Min	Max	Max	CV	CV
	Group A	Group B	Group A	Group B	Group A	Group B	Group A	Group B	Group A	Group B	Group A	Group B	Group A	Group B
EC [µS/cm]	1188.000	1111.000	39.129	371.434	35.000	461.000	7.662	151.505	32.000	54.000	57.000	470.000	19.582	40.789
ORP [mV]	1188.000	1111.000	650.417	277.681	652.000	241.400	15.854	61.521	620.000	220.600	667.000	408.100	2.438	22.155
TDS [ppm]	1188.000	1111.000	30.409	185.838	32.000	231.000	6.249	75.833	21.000	25.000	37.000	235.000	20.549	40.806
Temp [°C]	1188.000	1111.000	20.152	17.822	20.500	16.420	0.935	3.658	18.500	12.740	22.100	23.280	4.639	20.522
pH	1188.000	1111.000	7.508	7.206	7.520	7.690	0.059	1.046	7.350	5.650	7.580	8.220	0.789	14.509

Note: Group A = treated surface water from the public supply system; Group B = decentralized groundwater.

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