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Drinking Water Quality Assessment in Central to Far West Terai Region of Nepal: Insight from Water Quality Index (WQI) and Bootstrap Approach

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Abstract

Periodic assessment of drinking water quality is essential for protecting public health and supporting sustainable water resource management. This study evaluated the chemical quality of drinking water from the Central-Far Western Terai region of Nepal using physicochemical characteristics, nutrients, major ions, selected trace elements, and an integrated Water Quality Index (WQI). Eleven drinking water samples were collected during May 2025 and analyzed for twenty-two water quality parameters. Descriptive statistics were complemented with 10,000 bootstrap resamples to estimate robust 95% confidence intervals for parameter means despite the limited sample size. Spearman's rank correlation analysis was used to examine associations among the measured variables. Overall chemical water quality at each sampling site was evaluated using a weighted arithmetic WQI based on parameters with established drinking-water guideline values from the World Health Organization (WHO) and the Nepal Drinking Water Quality Standards (NDWQS). Most measured parameters complied with the applicable guideline values. Significant positive correlations were observed between electrical conductivity and total dissolved solids ($\rho = 0.964$), chloride and bromide ($\rho = 0.856$), sodium and magnesium ($\rho = 0.864$), and sodium and sodium adsorption ratio ($\rho = 0.936$). Strong correlations among dissolved nitrogen fractions were interpreted cautiously because some variables are mathematically related. WQI values ranged from 7.28 to 26.12 (mean = 14.02 ± 5.43), and all sampling sites were classified as *Excellent* (WQI < 50), indicating favorable chemical water quality based on the measured parameters included in the index. However, these findings should be interpreted as a baseline chemical assessment because microbiological quality, seasonal variability, and broader regional representativeness were beyond the scope of this study. The results provide useful baseline information for future groundwater monitoring and drinking water management in the Central-Far Western Terai region of Nepal.

Keywords

Drinking Water Quality, Water Quality Index (WQI), Bootstrap Confidence Intervals, Hydrochemical Assessment, Terai Groundwater

1. Introduction

Groundwater represents planet's second-largest freshwater reservoir c. 30.1% after glaciers and ice caps c. 69%, accounting for approximately 99% of all liquid freshwater on Earth and is the source of about 25 percent of all water used by humans [1]. Water quality varies dynamically across landscapes based on regional infiltration rates, the zone of aeration, the zone of saturation, and localized water table depths [2] [3]. Rapid increase in global population escalating water demand has triggered a crisis, with groundwater being withdrawn much faster than recharge rates can sustain in different parts of the world [4], including Nepal and South Asia in recent years. In a similar way, massive population migration from mountainous areas to Nepal's lowland Terai region has triggered rapid urbanization and heavy aquifer pumping to fulfill demand and agricultural irrigation from groundwater of all our sampling sites in central to far-west Terai region. Plunging water tables not only risk depleting entire aquifer but also increase the concentration of hazardous naturally occurring chemical contaminants like arsenic, antimony, selenium, cadmium, etc. because of this over-extraction of groundwater.

Agriculture accounts for approximately 70% of total water withdrawal worldwide as global water use efficiency has increased at double the rate of population increase [3] [5] [6]. Groundwater is a crucial natural resource which constitutes nearly 30.1% of the global freshwater, supplying nearly half of all drinking water and 43% of the water used for irrigation. Historically, this resource has been protected by natural filtration processes, but aquifers are now facing increasing stress from climate extremes and human activities [7]-[9]. The lowland Terai region of Nepal serves as a food bank of the nation that fulfills domestic demands, support food deficit remote hills mountain areas and drives agricultural trade with neighboring countries [10]. The lowland Terai region of Nepal accounts for over 55% of the total cropped area and generates nearly 60% of the country's crop yield despite comprising less than a quarter of the country's total land area [10] [11]. The extremely high food productivity in the region could be driven by enormous alluvial deposits of partially weathered materials rich in organic matter and nutrients transported down by major Himalayan rivers; for example, the Langtang-Narayani river system in the Terai region at Narayanghat shows a high extent of chemical weathering [12]. Such continuous influx of sediment indicates highly intensive chemical weathering, consequently producing deeply fertile, nutrient-rich soils perfectly suited for the extensive cultivation of essential staples like rice paddy, maize and wheat [12] [13]. The low-elevation Terai's long-term agricultural viability and fragile ecosystem face escalating modern threats from rapid urbanization, widespread deforestation, and severe climate volatility despite its foundational role in ensuring national food security [10]. The escalating demand for freshwater is severely exacerbating global water scarcity due to global climate change, rising socioeconomic prosperity, and rapid urbanization due to migration or population growth [14]-[16]. Securing safe drinking water remains a critical challenge, particularly within the densely populated urban centers and urbanizing southern Terai lowland region of Nepal [16] [17]. Water quantity and quality have drastically declined in recent years, primarily sparked by increasing population densities, inadequate waste management systems, and uncontrolled over-extraction of local groundwater resources [16] [18]. Regional water tables lowered and consequently altered aquifer hydrochemistry with various mechanisms, elevating the concentration of hazardous geogenic and anthropogenically induced chemical species for example high arsenic concentration affecting human health in the region due to excessive pumping of groundwater [19]. Such widespread chemical pollution in groundwater aquifers not only risks chronic public poisoning but also threatens local environmental stability by triggering physical hazards like land depression [3] [6].

Higher arsenic concentration than WHO guidelines reported from groundwater of lowland Tearai region of Nepal which is primarily released from quaternary alluvium sediments [20]-[23]. Only about 90% of the tubewells from Terai region are found to have permissible-level arsenic based on the comprehensive data from more than 0.7 million groundwater samples [17]. Some of the Terai districts such as Bara, Kapilvastu, Nawalparasi, Parsa, Rautahat, and Rupendehi are found affected by arsenic in groundwater, showing severe effects of arsenicosis problems although whole area of Tearai exhibit increased arsenic in groundwater depending on locations [23]-[25]. Arsenic is released primarily from (geogenic origin) chemical weathering of sulfide-bearing minerals, for example pyrite in the Himalayan basin [25]. Pyrite oxidation coupled with carbonate dissolution appeared as a dominant geochemical process within the Himalayan landscape and which has been earlier documented by various studies [26] [27]. Coal burning and use of pesticides may have contributed to arsenic contamination in the region, although no documented reports are available. The variation in concentrations of these trace elements depends on landscape position, hydrolysis condition, climate, dissolved oxygen content, and availability of organic matter, for example dissolved organic carbon (DOC), which controls the trace metals concentration due to complexation [28]. Iron assisted biosand filters and Kanchan filters are effective options which have been used to remove arsenic from drinking groundwater in some of the Terai districts [19] [23] [29].

Alternatively, some of the recent desalination technology can also be used to remove chemical contaminants including arsenic and pathogens.

The prime objective of this research is to address these pressing dynamics, systematically evaluating key physicochemical drinking water quality parameters across public and private groundwater systems, specifically targeting deep wells and shallow-deep tube wells distributed throughout the region, such as Chitwan in central region to Kanchanpur in far west region of Nepal. Despite the lack of physical samples from southeastern sub-region, the resulting data serves as a vital framework for the Government of Nepal to engineer targeted water management interventions, mitigate critical environmental health issues, and safeguard the wellbeing of people of the southern Terai plain, which sustain over 50% of the nation's total population.

2. Study Area

The present study covers various districts in central to far west Terai region of Nepal, a lowland area situated directly below the Chure region that spans an elevation range of 63 m to 330 m above sea level [30] [31]. Widely considered a highly fertile region, the specific study area extends approximately 555 km from Narayanghat in the Chitwan district to the Kanchanpur district (**Figure 1**). Over the past few decades, much of this landscape has been covered with subtropical forests dominated by hardwood tree species, primarily Sal (*Shorea robusta*) and Saj (*Terminalia tomentosa*) [32]. Today, the region retains a high percentage of forest cover and numerous wetlands, both of which serve as vital habitats for diverse aquatic and terrestrial wildlife, including elephants, rhinoceroses, Bengal tigers, leopards, swamp deer, and crocodiles. The central to far west Tarai region of Nepal, extending from Narayanghat to Mahendranagar, is characterized primarily by geologically young, fertile alluvial soils. Formed from the active sedimentary deposits of the Siwalik Hills and the broader Himalayan weathering system, these soils exhibit varied textures ranging from sandy loam to heavy clay, with a pH spectrum stretching from highly acidic (4.5) to slightly alkaline (8.0) [30] [33] [34]. Under the USDA/FAO taxonomic systems, the region's diverse soil profiles are formally classified as Ustorthents, Ustifluvents, Ustochrepts, Haplustolls, and waterlogged Gleysols [30] [31] [35].

From a mineralogical perspective, the Indo-Gangetic plains and the low-lying Terai region of Nepal are highly dominated by mica (illite), alongside lesser fractions of smectite and vermiculite [34] [36]. However, continuous rice-based cropping combined with heavy machinery use and minimal organic inputs frequently degrades this native illite, leading to structural compaction and nutrient mining [34]. This soil degradation occurs within a sub-tropical to tropical climate characterized by a mean annual air temperature (MAAT) of 27˚C with summer temperatures exceeding 37˚C and winter minimums dropping to 8˚C and a mean annual precipitation of approximately 1450 mm in the studied area region; however, it slightly varies from Narayanghat to Mahendranagar [37].

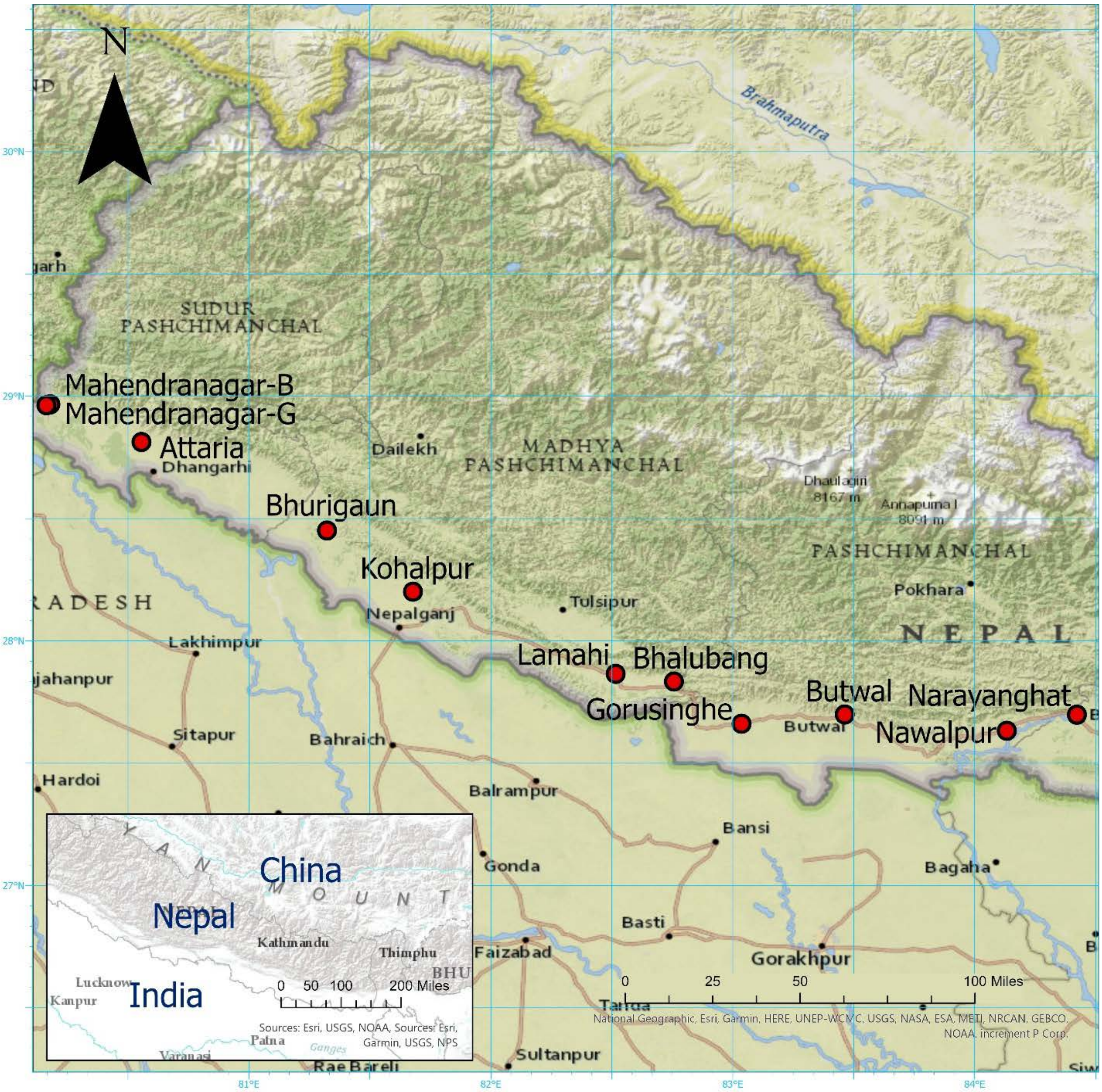

Figure 1. Sampling locations in central to far west Terai region of Nepal.

3. Materials and Methods

3.1. Sample Collection

Groundwater samples were collected from ten major towns (eleven samples because 2 from Mahendranagar) in the central to far west Terai region of Nepal during May 2025 (**Figure 1**). We decided to take one sample from each town of this region and from Mahendranagar we took two samples such as Mahendranagar-B representing an urban center and Mahendranagar-G representing an agricultural field to see urban influence or agricultural influence for comparison. The exact construction date was not available but based on migration data those hand pumps might be installed sometime between three to four decades before. People use water for domestic use, including drinking without any treatment. More detailed sample description with some physical parameters is given in Table 1. Physical parameters, including water temperature, pH, electrical conductivity (EC), and total dissolved solids (TDS), were measured on-site using a Hanna Instruments handheld multimeter.

Table 1. Description of sampling sites with physical parameters of groundwater along central to far west region of Terai in Nepal.

Sampling Station	Site Details	Collection Date	Latitude	Longitude	Depth (m)	Type	Elevation (m)	WT (˚C)	pH	EC (μS/cm)	TDS (mg/L)
Narayanghat	Just after bridge	28-May-25	27.698611	84.422598	12.2	Public Hand Pump	169	30	7.2	692	nd
Nawalpur	Kawaswoti-roadside	28-May-25	27.632901	84.132381	nd	Public Hand Pump	130	32	6.9	795	nd
Butwal	Butwal bazar	28-May-25	27.699369	83.463058	12.8	Public Tube Well	nd	29	6.9	817	nd
Gorusinghe	Roadside hotel	28-May-25	27.661136	83.03634	15.2	Public Hand Pump	99	28.2	7.1	672	333
Bhalubang	Armed Police Station	28-May-25	27.833675	82.756934	~50	Public Tube Well	nd	27.9	6.8	853	426
Lamahi	Roadside hotel	28-May-25	27.865637	82.515961	15	Public Hand Pump	260	28.5	6.9	1596	800
Kohalpur	Roadside house	28-May-25	28.20099	81.678459	18.3	Private Hand Pump	166	28.3	7.1	1586	814
Bhurigaun	Roadside hotel	28-May-25	28.450972	81.322929	11.3	Public Tube Well	nd	27.4	6.8	1244	686
Attaria	Nepal Police Station	28-May-25	28.813429	80.555876	~30.5	Private Tube Well	171	27.3	6.9	844	403
Mahendranagar-B	Urban center	29-May-25	28.967430	80.179275	12.2	Public Hand Pump	199	27.8	6.6	940	620
Mahendranagar-G	Agricultural field	29-May-25	28.963644	80.162706	7.3	Private Hand Pump	198	26.7	6.7	655	327

For major solute and nutrient analyses, samples were collected in 125 mL acid-washed polyethylene bottles, filtered through 0.7 μm precombusted (5+ hours at 450˚C) Whatman GF/F glass microfiber filters, and refrigerated locally before being shipped on ice to the New Hampshire Water Resources Research Center at the University of New Hampshire (Durham, NH, USA). This suite of analyses included major base cations (Na^+, K^+, Mg^{2+}, Ca^{2+}), ammonium (NH_4^+), major anions (Cl^-, NO_3^-, SO_4^{2-}, HCO_3^-, PO_4^{3-}), dissolved organic carbon (DOC), total dissolved nitrogen (TDN), sodium adsorption ratio (SAR), and boron. For trace element analysis, separate groundwater samples were filtered through 0.45 μm polycarbonate membrane filters, acidified with nitric acid and shipped to Carroll College (Helena, MT, USA) to quantify arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), nickel (Ni), lead (Pb), antimony (Sb), selenium (Se), and zinc (Zn).

3.2. Analytical Methods

Water samples were analyzed for major cations, major anions, nutrients, dissolved organic carbon (DOC), total dissolved nitrogen (TDN), and trace metals. Major cations (Na^+, K^+, Mg^{2+} and Ca^{2+}), and major anions (Cl^-, Br^-, NO_3^-, and SO_4^{2-}), were measured via ion chromatography with suppressed conductivity using a Metrohm 940 Professional IC Vario. Cation analysis utilized an oxalic acid mobile phase in accordance with ASTM (2007) [38] guidelines, while anion analysis followed US EPA (2007) Method 300.1 [39]. Nutrients were analyzed by automated colorimetry using a SmartChem discrete analyzer; ammonium was determined via the automated phenate hypochlorite method with sodium nitroprusside enhancement (US EPA 2005, Method 350.1) [40], and orthophosphate (PO_4^{3-}) was determined via the automated ascorbic acid reduction method (US EPA 2005, Method 365.1) [41]. Dissolved organic carbon was analyzed as non-purgeable organic carbon using a Shimadzu TOC-L analyzer following US EPA (2002) Method 415.1 [42], where samples were injected into a 720˚C furnace with a platinum catalyst on silica beads to convert carbon compounds into CO_2 for quantification via a non-dispersive infrared detector (NDIR). Total dissolved nitrogen was quantified using a Shimadzu TOC-L system following the method of Merriam *et al.* (1996) [43], which converts nitrogen compounds to NO at 680˚C for detection by a chemiluminescent nitrogen detector. Finally, dissolved organic nitrogen (DON) was calculated by subtracting inorganic nitrogen ($NO_3^-\text{-N} + NH_4^+\text{-N}$) from the total dissolved nitrogen concentration.

Water samples were analyzed at the New Hampshire Water Resources Research Center following strict quality assurance and quality control (QA/QC) protocols for major ions, nutrients, and dissolved carbon. To ensure data reliability, instrument calibration models were constructed using 4-to-7-point curves, and Method Detection Limits (MDLs) were defined at the 99% confidence threshold. This yielded target analyte detection limits of 0.08 mg/L for Cl^-, 0.004 mg/L for NO_3^-, 0.06 mg/L for SO_4^{2-}, 3.4 μg/L for PO_4^{3-}, 5 μg/L for NH_4^+, 0.03 mg/L for Na^+, 0.003 mg/L for K^+, 0.05 mg/L for Mg^{2+}, 0.16 mg/L for Ca^{2+}, 0.05 mg/L for DOC, and 0.20 mg/L for TDN. Analytical accuracy was systematically monitored via certified Quality Control Samples (QCS; Ultra Scientific or SPEX Certiprep) analyzed at a frequency of approximately every 10 - 15 samples within each analytical batch. Across all measured parameters, the laboratory enforced a uniform acceptable precision limit of ±15% for laboratory duplicates and an accuracy recovery limit of ±15% for quality control standards.

Trace elements (As, Cd, Co, Cr, Cu, Fe, Ni, Pb, Sb, Se, and Zn) were analyzed using an inductively coupled plasma-optical emission spectrometer (ICP-OES; PerkinElmer Avio 200) according to standard methods for determining metals in environmental samples (US EPA 1991) [44]. The instrument was operated under standard conditions utilizing argon plasma, auxiliary, and nebulizer gas flows, with measurements collected in axial view. Quantification was achieved via external calibration curves prepared from multi-element ICP standards, all of which exhibited excellent linearity ($R^2 \geq 0.995$). To ensure analytical accuracy and instrument stability, procedural blanks and calibration verification standards were analyzed periodically. The instrument detection limits (mg/L) for the target elements were 0.025 for As, 0.001 for Cd, 0.002 for Co, 0.001 for Cr, 0.009 for Cu, 0.001 for Fe, 0.002 for Ni, 0.002 for Pb, 0.015 for Sb, 0.030 for Se, and 0.002 for Zn.

3.3. Calculation of the Water Quality Index (WQI)

To provide an integrated assessment of drinking water suitability across sampling sites, a Weighted Arithmetic Water Quality Index (WQI) was calculated using selected physicochemical parameters and trace elements that have established drinking-water guideline values. The WQI converts multiple water quality measurements into a single dimensionless score that facilitates comparison among sites and provides an overall indication of drinking water quality. Parameters were selected based on their relevance to drinking-water safety and availability of guideline values from the World Health Organization (WHO 2022) [45] and Nepal Drinking Water Quality Standards (NDWQS 2025) [46]. Variables without established health-based drinking standards were excluded to avoid disproportionate influence and preserve interpretability of the index.

Relative weights were assigned to reflect the relative importance of each parameter to drinking-water quality and potential human health impacts. Higher weights were assigned to parameters with stronger health implications, particularly toxic trace elements. The WQI was calculated using the weighted arithmetic approach according to the following equations.

First, the relative weight for each parameter was computed as:

$$RW_i = \frac{w_i}{\sum_1^n w_i},$$

where RW_i is the relative weight assigned to parameter i, w_i is the assigned importance weight, and n is the total number of included variables.

The quality rating for each parameter was then calculated as:

$$Q_i = \frac{C_i}{S_i} \times 100$$

where Q_i is the quality rating, C_i is the measured concentration of parameter i, and S_i is the corresponding drinking-water standard.

For pH, quality rating was calculated relative to the ideal value of 7.0:

$$Q_{pH} = \frac{C_i - 7.0}{S_i - 7.0} \times 100 .$$

The sub-index for each parameter was estimated as:

$$SI_i = RW_i \times Q_i .$$

Finally, the overall water quality index for each site was computed as:

$$WQI = \sum_1^n SI_i .$$

Lower WQI values indicate better drinking water quality.

4. Results and Discussion

4.1. Physicochemical Characteristics of Drinking Water

Table 2 summarizes the physicochemical characteristics, nutrient concentrations,

Table 2. Descriptive statistics and bootstrap 95% confidence intervals for physicochemical parameters, nutrients, major ions, and trace elements in drinking water samples from the Central-Far Western Terai region of Nepal.

Parameters	n	Min	Max	Mean	SD	Bootstrap 95% CI		WHO 2022 [45] Threshold	NDWQS 2025 [46]
						LL	UL		
pH	11	6.6	7.2	6.900	0.179	6.780	7.020	6.5 - 8.5	6.5 - 8.5
EC	11	655	1596	972.18	345.857	739.83	1204.53	NG	1500
TDS	11	327	814	507.27	187.863	381.06	633.48	NG	1000
DOC	11	0.05	1.02	0.420	0.315	0.208	0.632	NG	NS
TDN	11	0.24	13.25	2.778	3.704	0.289	5.266	NG	NS
TIN	11	0.068	9.676	2.194	2.816	0.303	4.087	NG	NS
DON	11	0.017	3.578	0.583	1.059	0.145	1.284	NG	NS
Cl	11	1.720	210.090	35.890	60.605	10.761	74.582	250	250
NO_3	11	0.000	9.669	2.114	2.872	0.185	4.043	50	50
SO_4	11	0.040	22.450	5.741	6.466	1.397	10.085	500	250
PO_4	11	0.005	0.038	0.013	0.012	0.005	0.021	NG	NS
Br	11	0.000	0.180	0.069	0.045	0.038	0.099	NG	NS
Na	11	3.740	72.670	25.422	20.828	11.430	39.414	200	NS
K	11	0.940	5.970	2.435	1.804	1.222	3.647	NG	NS
Mg	11	0.030	61.380	19.315	15.776	8.718	29.914	NG	NS
Ca	11	8.660	23.050	14.083	5.799	10.193	17.972	NG	200
NH_4	11	0.002	0.451	0.080	0.138	0.000	0.173	NG	1.5
SAR	11	0.132	1.350	0.777	0.422	0.494	1.061	NG	NS
Fe	11	0.003	0.048	0.032	0.015	0.021	0.042	0.30	0.30
Zn	11	0.002	0.506	0.058	0.149	0.000	0.158	3.0	3.0
Cu	11	0.008	0.012	0.010	0.001	0.010	0.011	2.0	1.0
Ni	11	0.001	0.003	0.002	0.001	0.0017	0.0030	0.020	NS

NB: Units for all elements are reported in mg/L, except EC (μS/cm); pH and SAR are unitless. NG = No health-based guideline established; NS = Not specified in NDWQS; NA = Not available. NDWQS = Nepal Drinking Water Quality Standards. WHO = World Health Organization.

major ions, and selected trace elements measured in eleven drinking water samples collected during May 2025 from the Central-Far Western Terai region of Nepal. For each parameter, the table reports the sample size (n), minimum and maximum values, arithmetic mean, standard deviation (SD), bootstrap-based 95% confidence interval (CI) for the mean, and the corresponding drinking-water guideline values established by the World Health Organization (WHO, 2022) [45] and the Nepal Drinking Water Quality Standards (NDWQS, 2025) [46].

The sampled waters exhibited near-neutral pH, ranging from 6.6 to 7.2 with a mean of 6.90 ± 0.18, well within the acceptable limits established by both WHO and NDWQS (6.5 - 8.5). The narrow bootstrap confidence interval (6.78 - 7.02) indicates little variation in pH among the sampling sites. Electrical conductivity (EC) ranged from 655 to 1596 μS/cm (mean = 972 μS/cm), whereas total dissolved solids (TDS) varied from 327 to 814 mg/L with a mean of 507 mg/L. The mean TDS was well below the NDWQS guideline value of 1000 mg/L, indicating acceptable levels of dissolved minerals. However, EC exceeded the NDWQS guideline (1500 μS/cm) at two locations (Lamahi and Kohalpur), suggesting localized increases in dissolved ionic constituents that warrant continued monitoring.

Nitrogen species showed greater spatial variability than the general physicochemical parameters. Dissolved organic carbon (DOC) remained low (mean = 0.42 mg/L), whereas total dissolved nitrogen (TDN) displayed the greatest variability (mean = 2.78 ± 3.70 mg/L), reflecting elevated concentrations at only a few sampling sites. Total inorganic nitrogen (TIN) constituted the major fraction of dissolved nitrogen (mean = 2.19 mg/L), while dissolved organic nitrogen (DON) contributed a smaller proportion (mean = 0.58 mg/L). The relatively wide bootstrap confidence intervals for TDN and TIN further indicate spatial heterogeneity in nitrogen concentrations across the study area.

The major anions occurred at concentrations well below drinking-water guideline values. Chloride ranged from 1.72 to 210.09 mg/L (mean = 35.89 mg/L), remaining below the WHO and NDWQS limit of 250 mg/L. Sulfate concentrations were also low (mean = 5.74 mg/L), and nitrate averaged only 2.11 mg/L, far below the drinking-water standard of 50 mg/L. Phosphate and bromide concentrations were similarly low throughout the study area, indicating no evidence of widespread contamination from major inorganic anions during the sampling period.

Among the major cations, sodium showed the greatest variation (3.74 - 72.67 mg/L; mean = 25.42 ± 20.83 mg/L), although all observed concentrations remained well below the WHO advisory value of 200 mg/L. Potassium concentrations were consistently low (mean = 2.44 mg/L), whereas magnesium exhibited considerable spatial variation (mean = 19.32 ± 15.78 mg/L), likely reflecting differences in local geology and groundwater-rock interactions. Calcium averaged 14.08 mg/L, substantially below the NDWQS guideline value of 200 mg/L.

Ammonium concentrations were uniformly low (mean = 0.08 mg/L), well below the NDWQS guideline value of 1.5 mg/L. The sodium adsorption ratio (SAR) ranged from 0.132 to 1.350, with a mean of 0.78, indicating a very low sodium hazard. Although SAR is commonly used to assess irrigation suitability rather than drinking water quality, these values suggest that the sampled waters would also be suitable for agricultural use.

The selected trace elements (Fe, Zn, Cu, and Ni) were detected at low concentrations and complied with the applicable drinking-water guideline values. Iron averaged 0.032 mg/L, approximately one-tenth of the WHO and NDWQS guideline value (0.30 mg/L). Zinc, copper, and nickel also remained well below their respective guideline values in all samples, indicating no evidence of trace-metal contamination in the analyzed drinking water.

Because only eleven water samples were available, conventional large-sample confidence interval methods may produce unstable estimates and rely on distributional assumptions that are difficult to verify. To obtain more reliable interval estimates, bootstrap resampling with 10,000 replications was used to construct 95% confidence intervals for the samples mean. Bootstrap methods estimate the sampling distribution empirically through repeated resampling with replacement and are well suited for small environmental datasets. Using 10,000 replications reduces Monte Carlo error and provides stable confidence interval estimates without requiring strict normality assumptions.

4.2. Significant Spearman Rank Correlations among Drinking Water Quality Variables

Because only eleven water samples were available and several variables were not normally distributed, relationships among water-quality variables were evaluated using Spearman's rank correlation coefficient (ρ), a non-parametric measure of monotonic association that is less sensitive to small sample size and distributional assumptions than Pearson's correlation. To improve clarity, only statistically significant correlations ($p < 0.05$) are presented. Correlations among mathematically derived nitrogen variables (TDN, TIN, DON, and NO_3) are omitted from interpretation because these variables are not statistically independent and their strong associations largely reflect their computational relationships rather than independent hydrochemical processes.

The correlation analysis identified several statistically significant associations that are consistent with the hydrochemical characteristics of the sampled groundwater (Table 3). The strongest relationship was observed between electrical conductivity (EC) and total dissolved solids (TDS) ($\rho = 0.964$, $p < 0.001$), confirming that dissolved ionic constituents were the primary contributors to water conductivity which is obvious. Electrical conductivity was also positively associated with magnesium ($\rho = 0.618$), indicating that dissolved alkaline-earth ions contributed substantially to the overall mineralization of the groundwater.

Strong positive correlations were also observed among several major ions. Chloride exhibited a strong association with bromide ($\rho = 0.856$), while sodium was highly correlated with magnesium ($\rho = 0.864$) and the sodium adsorption ratio (SAR) ($\rho = 0.936$). These relationships suggest common geochemical controls,

Table 3. Statistically significant Spearman rank correlations among selected drinking water quality variables in the Central-Far Western Terai region of Nepal.

Variable 1	Variable 2	ρ	p
EC	TDS	0.964	<0.001
DOC	Cl	0.609	0.047
DOC	Br	0.687	0.020
DOC	NH_4	0.624	0.040
DOC	SAR	0.764	0.006
DOC	As	−0.627	0.039
DOC	Sb	−0.691	0.019
Cl	Br	0.856	<0.001
EC	Mg	0.618	0.043
Na	Mg	0.864	<0.001
Na	SAR	0.936	<0.001
K	Mg	0.636	0.035
K	Cu	−0.861	<0.001
Mg	SAR	0.700	0.016
Mg	Cu	−0.729	0.011
SO_4	Ca	0.636	0.035
SO_4	PO_4	−0.622	0.041
SO_4	Co	−0.630	0.038
SO_4	Se	−0.724	0.012
pH	Cr	−0.715	0.013
pH	Ni	−0.686	0.020
Fe	Ni	−0.765	0.006
Cd	Cr	0.695	0.018

including mineral dissolution and groundwater-rock interaction, which influence the ionic composition of the water.

Among variables, dissolved organic carbon (DOC) showed positive correlations with chloride ($\rho = 0.609$), bromide ($\rho = 0.687$), ammonium ($\rho = 0.624$), and SAR ($\rho = 0.764$). In contrast, DOC exhibited negative correlations with arsenic ($\rho = -0.627$) and antimony ($\rho = -0.691$). These associations may reflect differences in geochemical conditions controlling the occurrence and mobility of organic matter and trace elements within the groundwater system.

Sulfate was positively associated with calcium ($\rho = 0.636$), supporting the influence of mineral weathering, but negatively correlated with phosphate ($\rho = -0.622$), cobalt ($\rho = -0.630$), and selenium ($\rho = -0.724$). In addition, pH showed significant negative correlations with chromium (ρ = −0.715) and nickel (ρ = −0.686), suggesting reduced mobility of these metals under less acidic conditions. Several significant relationships were also identified among trace elements. Iron and nickel were also strongly negatively correlated (ρ = −0.765), whereas cadmium and chromium exhibited a positive association (ρ = 0.695).

Correlations involving mathematically derived nitrogen variables (TDN, TIN, DON, and NO_3^-) were not interpreted because these variables are not statistically independent. Their strong correlations primarily reflect their computational relationships and serve as a check on the internal consistency of the analytical measurements rather than providing evidence of independent hydrochemical processes.

4.3. Drinking Water Quality Index (WQI) Assessment

To provide an integrated evaluation of drinking water quality, a Weighted Arithmetic Water Quality Index (WQI) was calculated for each sampling site using physicochemical parameters and trace elements with established drinking-water guideline values. Only parameters with recognized standards from the World Health Organization (WHO, 2022) [45] or the Nepal Drinking Water Quality Standards (NDWQS, 2025) [46] were included in the index calculation. Following data verification, only reliably quantified parameters were retained, whereas variables without established drinking-water standards or excluded during quality assurance were omitted. The WQI was computed using the relative parameter weights, quality ratings, and sub-index values described in Sub-Section 3.3. Parameters with greater public health significance, such as nitrate and nickel, were assigned higher weights than general indicator parameters (**Table 4(a)**). Lower WQI values indicate better overall drinking water quality.

Table 4(b) summarizes the WQI values for the eleven sampling sites together with the overall summary statistics. WQI values ranged from 7.28 to 26.12, with a mean of 14.02 ± 5.43 and a coefficient of variation of 38.7%. According to the adopted classification scheme, all sampling sites were classified as Excellent (WQI < 50), indicating favorable chemical water quality based on the physicochemical parameters and selected trace elements included in the WQI calculation. Because WQI is based only on the measured chemical parameters, it should not be interpreted as a comprehensive assessment of drinking-water safety, particularly since microbiological quality and other potential contaminants were not evaluated spatially and seasonally from the region.

Among the sampling locations, *Mahendranagar-G* recorded the lowest WQI (7.28), representing the best overall water quality, whereas *Lamahi* had the highest WQI (26.12). Although some spatial variation was observed among sampling sites, even the highest WQI remained well below the threshold for the Excellent category. The WQI results are consistent with the descriptive statistics presented in **Table 2**. The relatively higher WQI values observed at a few locations were primarily associated with elevated electrical conductivity, total dissolved solids,

Table 4. (a). Parameters, assigned weights, relative weights, drinking-water standards, reference sources, and justification used for Water Quality Index (WQI) calculation; (b) Water Quality Index (WQI) values, drinking water quality classification, and summary statistics for sampling sites in the Central-Far Western Terai region of Nepal.

(a)

Parameters	Unit	Weight (w_i)	Relative Weight (RW_i)	Standard (S_i)	Reference Standard	Justification
pH	-	4	0.098	8.5*	WHO/NDWQS	Affects solubility and acceptability
EC	μS/cm	3	0.073	1500	NDWQS	Indicator of dissolved ionic content
TDS	mg/L	3	0.073	1000	NDWQS	General water quality
Cl	mg/L	3	0.073	250	WHO/NDWQS	Salinity indicator
NO_3	mg/L	5	0.122	50	WHO/NDWQS	Human health concern
SO_4	mg/L	3	0.073	500	NDWQS	Taste and gastrointestinal concern
Na	mg/L	3	0.073	200	WHO	Sodium exposure
Ca	mg/L	2	0.049	200	NDWQS	Water hardness
NH_4	mg/L	3	0.073	1.5†	NDWQS	Indicator of contamination
Fe	mg/L	2	0.049	0.30	WHO/NDWQS	Aesthetic quality
Zn	mg/L	2	0.049	3.0	WHO/NDWQS	Aesthetic quality
Cu	mg/L	3	0.073	2.0	WHO	Health and aesthetic significance
Ni	mg/L	5	0.122	0.02	WHO	Toxin trace element
Total		$\sum w_i = 41$	$\sum RW_i = 1$			

(b)

No.	Sampling Site	WQI	WQI classification
1	Narayanghat	13.13	Excellent
2	Kawaswoti-Nawalpur	9.43	Excellent
3	Butwal bazar	18.66	Excellent
4	Gorusinghe	10.70	Excellent
5	Bhalubang	11.78	Excellent
6	Lamahi	26.12	Excellent
7	Kohalpur	17.00	Excellent
8	Bhurigaun	14.58	Excellent
9	Attaria	11.55	Excellent
10	Mahendranagar-B	13.98	Excellent
11	Mahendranagar-G	7.28	Excellent

Note: Water Quality Index (WQI) classification: <50 = Excellent; 50 - 100 = Good; 100 - 200 = Poor; 200 - 300 = Very Poor; >300 = Unsuitable for drinking.

and major ion concentrations rather than exceedances of health-based drinking-water standards. Overall, the WQI assessment confirms that the drinking water sources sampled in the Central-Far Western Terai region during May 2025 were of excellent quality and suitable for human consumption based on measured chemical parameters.

4.4. Visual Assessment of Selected Drinking Water Quality Parameters across Sampling Sites

To complement the statistical analyses presented above, boxplots were prepared for six representative drinking water quality indicators: electrical conductivity (EC), nitrate (NO_3^-), sodium (Na), magnesium (Mg), nickel (Ni), and the Water Quality Index (WQI). These variables were selected because they represent overall mineralization, nutrient status, major ion chemistry, a regulated trace element of public health relevance, and the overall quality of drinking water. The boxplots provide a visual comparison of the distributions, variability, and potential outlying observations among the eleven sampling sites.

Figure 2 illustrates the variability of the selected water quality indicators across the study area. The WQI exhibited the smallest spread, with all values well below the threshold for the *Excellent* category (WQI < 50). This observation is consistent with the results presented in Table 4(a) and Table 4(b) and confirms that drinking water quality was uniformly good across all sampling locations based on the measured chemical parameters. Nickel concentrations showed only a narrow range of variation among the samples and remained well below the WHO guideline value of 0.020 mg/L. The absence of unusually high values indicates that nickel contamination was not a concern in the sampled drinking water sources during the study period.

Nitrate concentrations displayed moderate variability, with most samples containing relatively low concentrations and a few sites exhibiting slightly higher values. However, all nitrate concentrations remained substantially below the WHO and NDWQS drinking water standard of 50 mg/L, indicating no evidence of widespread nitrate contamination. Among the major physicochemical indicators, EC, sodium, and magnesium exhibited greater variability than the other measured parameters, reflecting differences in dissolved mineral content among sampling locations or effect of human activities primarily from hotel waste as most of the sites are from town center. Despite this variation, the observed concentrations generally remained within the applicable drinking water guideline values.

Overall, the boxplots complement the descriptive statistics by showing that, although some spatial variation exists among the sampling sites, the measured water quality parameters remained within acceptable limits. The consistently low WQI values further support the conclusion that the drinking water sources sampled during May 2025 were of excellent quality and suitable for human consumption based on the measured chemical parameters.

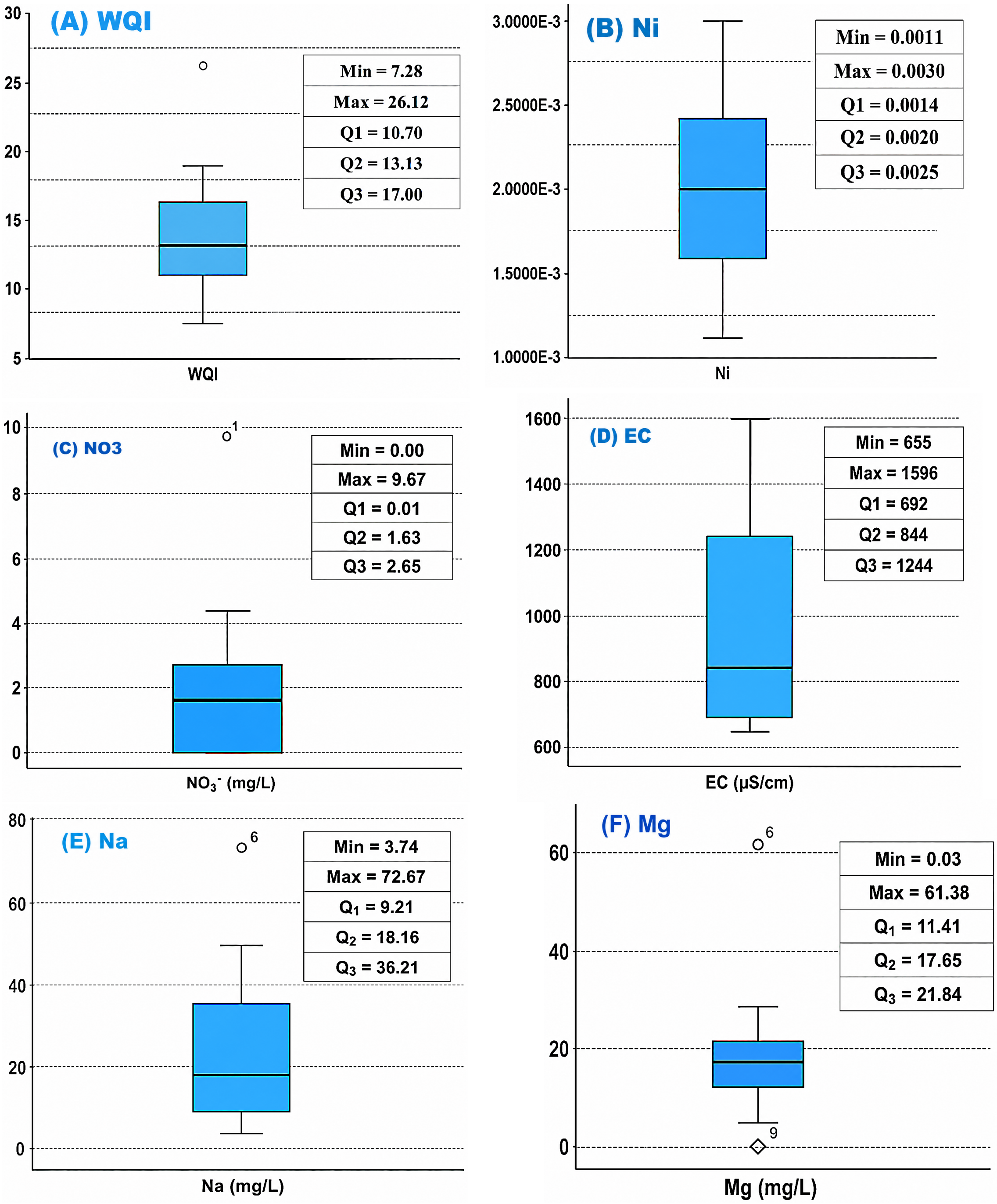

Figure 2. Boxplots of selected drinking water quality parameters across sampling sites in the Central-Far Western Terai region of Nepal.

5. Conclusions

This study provides a baseline assessment of the chemical quality of drinking water collected from eleven sampling sites in the Central-Far Western Terai region of Nepal during May 2025. Descriptive statistics, bootstrap confidence intervals (10,000 replications), correlation analysis, and a Weighted Arithmetic Water Quality Index (WQI) were used to characterize the measured physicochemical properties, nutrients, major ions, and selected trace elements.

Most measured chemical parameters complied with the guideline values recommended by the World Health Organization (WHO, 2022) [45] and the Nepal Drinking Water Quality Standards (NDWQS, 2025) [46]. The sampled waters were generally characterized by near-neutral pH, moderate mineralization, and relatively low concentrations of nitrate, ammonium, and the measured trace elements. Electrical conductivity exceeded the NDWQS guideline at two locations, indicating localized increases in dissolved ionic constituents that warrant continued monitoring. The WQI values ranged from 7.28 to 26.12 (mean = 14.02 ± 5.43), and all sampling sites were classified as *Excellent* according to the adopted classification scheme. These results indicate that, based on the measured chemical parameters included in the WQI, the sampled drinking water exhibited generally good chemical quality during the study period. Correlation analysis identified several strong relationships among physicochemical variables reflecting common hydrogeochemical controls on groundwater chemistry. These statistical relationships provide insight into the processes influencing groundwater composition but should be interpreted cautiously because of the limited sample size and lack of wider representation.

Overall, this study provides useful baseline information on the chemical characteristics of drinking water in the Central-Far Western Terai region. The findings should be interpreted as representing conditions observed during a single sampling campaign and should not be generalized to all groundwater sources or seasons in the region. Furthermore, because microbial water quality and several potential contaminants were beyond the scope of this investigation, the results should not be interpreted as a comprehensive assessment of drinking water safety.

6. Future Research and Limitations

This investigation represents a baseline assessment of groundwater chemistry based on eleven samples collected during a single sampling campaign in May 2025. Although the selected sites provide broad geographic coverage across the Central-Far Western Terai region (c. 555 km), the limited number of samples and the absence of seasonal observations restrict the extent to which the findings can be generalized to the region as a whole. Consequently, the results should be interpreted as a preliminary assessment of chemical water quality rather than a comprehensive regional evaluation.

The present study evaluated only the chemical characteristics of drinking water. Microbial indicators, including *Escherichia coli* and other pathogenic microorganisms, were not analyzed. Therefore, although the measured chemical parameters generally complied with existing drinking-water guidelines, the overall safety of the water for human consumption cannot be fully established without microbiological assessment.

Future studies should include repeated seasonal sampling over multiple years to evaluate temporal variability in groundwater quality. Increasing the number of sampling sites and expanding geographic coverage would improve the representativeness of regional assessments and strengthen statistical inference. Additional investigations should also incorporate a broader range of contaminants, including microbial indicators, emerging pollutants, and other trace constituents where appropriate.

The integration of Geographic Information Systems (GIS), geostatistical methods, and spatial mapping techniques would provide a clearer understanding of the spatial distribution of groundwater quality and potential contamination hotspots. Such approaches would support evidence-based groundwater management and help identify areas requiring targeted monitoring or mitigation. Continued long-term monitoring is recommended.

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Authors Contributions

GBM conducted statistical analyses, including bootstrap methods and correlation analyses, and contributed to manuscript preparation, review, and editing. MPB designed and implemented the research project, coordinated sampling activities, conducted chemical data analyses, and contributed to manuscript writing, review, and editing. Both authors reviewed and approved the final version of the manuscript.

Statement on English Language Editing Tool

The authors used ChatGPT to polish the grammar of the manuscript. No AI tool was used to generate research content, the idea, argument, analyze data, interpret results or prepare references, and intellectual contribution of the paper are entirely original. The authors revised where necessary and approved of any AI-assisted language suggestions and took full responsibility for the final manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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