American Journal of Water Resources, 2024, Vol. 12, No. 4, 149-164
Available online at http://pubs.sciepub.com/ajwr/12/4/5
Published by Science and Education Publishing
DOI:10.12691/ajwr-12-4-5

Comprehensive Assessment and Analysis of Drinking Water Quality in the Kathmandu Valley: Implications for Public Health and Policy

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Received October 08, 2024; Revised November 10, 2024; Accepted November 17, 2024

Abstract Drinking water quality reflects both geologic and anthropogenic influences. This study examines drinking water quality in groundwater, municipal supplies, and natural springs of Kathmandu, Nepal. Major ions, trace metals, nutrients, dissolved organic matter, and dissolved silica were analyzed on samples collected twice from ten sites within Kathmandu Valley. Groundwater chemistry is dominated by NaCl, with concentrations Na >> Ca >> Mg > K > NH_4, and Cl >> SO_4 >> NO_3 >> PO_4. This dominance of NaCl in regional groundwater suggests the strong influence of human activities in altering water quality. In natural spring water, Na and Cl were also dominant, but overall concentrations were much lower (346.74 mg/L Cl in groundwater versus 56.10 mg/L in spring water). In municipal tap water, chemical composition is primarily released from natural biogeochemical processes. Trace metals like Al, Ba, Cu, Fe, Mn, V, and Zn were detected in all water systems, while others were below analytical detection limits. Groundwater and natural spring water exceeded WHO guidelines for Na, NO_3, and Fe, while municipal water remained within acceptable limits. Data analysis utilized Bootstrapping with $B = 1000$ iterations and provided 95% confidence interval estimates for chemical parameters comparing with standard values. A Bootstrapped one-way ANOVA was conducted to compare these parameters across the drinking water systems, highlighting policy-related findings. Additionally, we performed correlation and multiple regression analyses among the chemical parameters, generating a range of predictive models. This study highlights the urgent need to improve water management and infrastructure in the Kathmandu Valley and provides recommendations for policy interventions such as protecting water resources, public awareness, minimize pollution, develop and implement strict regulation and community-based approaches to address these issues. Understanding drivers of variability in urban water quality in developing countries is essential to meeting united nation's sustainable development goals and protecting public health.

Keywords: *Major Ions, Drinking Water Quality Assessment, Bootstrapping Estimation and Testing, Predictive Techniques, Trace Elements, Dissolved Organic Carbon (DOC), Water Resources Management*

Cite This Article: Maya P Bhatt, Ganesh B Malla, and William H McDowell, "Comprehensive Assessment and Analysis of Drinking Water Quality in the Kathmandu Valley: Implications for Public Health and Policy." *American Journal of Water Resources*, vol. 12, no. 4 (2024): 149-164. doi: 10.12691/ajwr-12-4-5.

1. Introduction

Water is a precious natural resource essential for the survival of all living organisms. Only 2.4% of the world's water is freshwater of which 69.56% of it in glaciers, ice caps, permanent snow cover and permafrost, making fresh groundwater the second-largest reservoir (30.06%) of the total freshwater [1]. Water demand is increasing due to population growth, but water resources are declining, and quality is deteriorating due to human activities. Over the past century, human water use efficiency has increased at double the rate of population growth, with agriculture accounting for about 70% of total water withdrawal worldwide [2,3].

According to UN estimates, a billion people lack access to safe drinking water, and 2.6 billion people lack acceptable sanitation, leading to millions of water-related illnesses and deaths, particularly in developing countries [2,4]. By 2025, two-thirds of the global population is expected to live in water-stressed countries based on UN. Based on the recent estimate, more than half of the world's population (4.4 billion people) is without safe drinking water across 135 low- and middle-income countries which is more than double the global estimate made in 2020 [5,6,7]. About 1.2 billion people live without safe drinking water in South Asia alone [7]. Rapid population growth, urbanization, pollution, climate change, and rising per capita income are increasing pressure on water resources and exacerbating water scarcity [3,8,9]. In 2020, global water withdrawal reached 4 trillion m³, with 58% in Asia-Pacific countries, 12% in North America, and 7% in Europe [3].

Safe drinking water is a major concern in Nepal, particularly in urban centers like Kathmandu Valley. Despite being rich in surface freshwater resources, its high population density, lack of proper waste management and over-extraction of groundwater have led to a decline in water quality in recent decades. Over-extraction reduces the water table and increases the concentration of chemical species. Additionally, human activities contribute to chemical pollution in urbanized areas, causing subsidence and other issues [2].

Groundwater is a primary source of drinking water in Nepal, providing half of the total water supply in Kathmandu Valley [10,11,12]. Similarly, in the United States, about fifty percent of the population relies on groundwater for drinking and domestic use, with excessive pumping depleting aquifers [2].

Kathmandu Valley faces severe water shortages due to the limited capacity of the municipal water supply agency, Kathmandu Upatyaka Khanepani Limited (KUKL) [13]. Residents rely on untreated sources such as natural springs, wells, tube wells, tanker water, and bottled water. Water contamination from sewage, industry, and agriculture poses serious health threats, especially during the monsoon season [12]. The region's water security issues are worsening by rapid urbanization, ineffective regulations, unplanned waste management, insufficient wastewater treatment, and high migration rates [14].

Human activities such as deforestation, agriculture, construction, and waste disposal significantly impact water chemistry across rural, suburban, and urban catchments [15,16,17,18] [19,20,21,22] [23,24,25,26] [27,28,29]. Urban areas, in particular, carry more pollutants after precipitation, including salts and metals [30,31,32].

Previous studies have reported on surface water chemistry within Kathmandu Valley focusing on nutrients, major ions, trace metals, and dissolved organic carbon (DOC) and total dissolved nitrogen (TDN) in Kathmandu Valley [33,34,35,36] [37,38,39,40,41]. However, there is limited information on the quality of drinking water from various sources such as municipal supplies, natural springs, deep wells, and tube wells [12,42,43,44].

Evaluating chemical parameters in drinking water is crucial for public wellbeing and prosperity, health implications, regulatory compliance, water source protection, and treatment efficiency [45]. Monitoring ensures that drinking water meets safety standards set by agencies such as WHO, US EPA, EU, and other countries set their own standard, preventing health issues like heavy metal poisoning, gastrointestinal diseases, and various other health issues depending on contaminants type. Understanding the chemical composition in drinking water helps in maintaining the legal compliance and public safety ensures the water is safe and pleasant for all consumers. Water quality monitoring is also useful in identifying contaminants, tracing their origins, and managing water resources more effectively. Moreover, analyzing water for chemical parameters helps to evaluate the effectiveness of treatment processes and improve water purification and distribution systems.

The primary objective of this study was to evaluate the complete drinking water quality parameters from various public and private sources in Kathmandu Valley. This includes municipal water systems, natural springs (stone taps/spouts), deep wells, and shallow-deep aquifer tube wells. The study compares and evaluates the chemical species in different drinking water sources, discussing the influence of anthropogenic and natural weathering sources on water quality. This study provides actionable insights for planners and policymakers to sustainably manage water resources and improve drinking water quality in Kathmandu Valley, ensuring the health and safety of over three million residents.

2. Study Area

This research was conducted within the core urban area of Kathmandu Valley, the capital city of Nepal (Figure 1). Water samples were collected from various sources such as groundwater, municipal tap water and natural spring water. Groundwater samples were taken from different depths at sites including Gaurighat near the Bagmati River (KGW-1), along the route to Baneshwor Conference Center, and from a deep well at Lokanthali, Bhaktapur (KGW-7). Municipal tap water sampled from Naya Baneshwor, north-east of Baneshwor Conference Center. Natural spring water samples were collected from Baneshwor Stone Tap at Ratna Rajya High School (KNSW-RR) and Baneshwor Height towards Dhobi Khola (KNSW-BH).

Kathmandu Valley is located in the middle of the Lesser Himalaya at an altitude of 1350 m, covering about 525 km² and the valley is surrounded by forested mountains and the Himalayas, forming a roughly circular basin [40]. The Bagmati River, which flows through the urban center, is a major source of drinking water for approximately 3.1 million residents [46], with a population density of 5905 persons per km². Around 30 million liters of water are tapped daily from the Bagmati and its tributaries, including the Bishnumati [24,47,40].

The population of Kathmandu Valley has grown from 0.6 million in 1973 to 3.1 million in 2021 [40,46,48,]. Despite this rapid growth, sewage treatment infrastructure has not kept pace, leading to inadequate treatment capacity [40].

The valley features two major geological units: a Quaternary unit overlaying the valley's lower portions and a Precambrian to Devonian unit surrounding the valley [49,50]. The Bagmati basin is underlain by metamorphic rocks including gneisses, granites, quartzites, limestones, sandstones, shales, and phyllites [51,52]. The valley's soils range from gray to grayish-brown clay loam to sandy clay loam, supporting fertile agriculture and urban development [40,53].

Sampling sites are within the central groundwater district, composed of thick black clay with some lignite to depths of 200m, underlain by unconsolidated low-permeable coarse sediment and the aquifer in this district contains soluble methane gas, indicating anaerobic conditions [50]. Land use in Kathmandu Valley is primarily residential, followed by agriculture, mixed-use, forest, and business [40,54]. The average temperature ranges from 3ºC in January to 29.5ºC in August, with a mean annual temperature of 19.6ºC and an average annual precipitation of 1556.04 mm [39,46].

3. Materials and Methods

3.1. Sample Collection

Drinking water samples were collected from the Kathmandu water supply system, deep dug wells, groundwater from hand pumps (shallow-deep aquifer tube wells), and public natural drinking water stone taps (Dhunge dhara). Samples were taken twice from ten sites within the core urban area of Kathmandu Valley during April and May 2008 (Figure 1).

In the field, each water sample was filtered through a pre-combusted glass microfiber filter (Whatman GF/F with a pore size of 0.7 µm). Samples for various analyses were collected and analyzed for major ions, dissolved silica, dissolved organic carbon (DOC), total nitrogen (TN) and trace metals. For major ions measurement, 100 mL water samples were taken in acid-washed polyethylene bottles, refrigerated in Kathmandu, and brought frozen to the Water Quality Analysis Laboratory at the University of New Hampshire. Additional 30 mL samples were taken in acid-washed polyethylene bottles, refrigerated in Kathmandu, and sent unfrozen to the University of New Hampshire for dissolved silica analysis. For dissolved organic carbon (DOC) and total dissolved nitrogen (TDN) measurement, 30 mL water samples were collected in glass vials, with 30 µL phosphoric acid added immediately after filtration. Finally, 50 mL filtered water samples were treated with 50 µL of concentrated nitric acid for analysis by ICP-AES.

Figure 1. Sampling locations of drinking water samples from different sources within Kathmandu Valley in central Nepal. All sampling sites are within the core urban area of Kathmandu Valley. KGW indicates Kathmandu Groundwater, KNSW RR indicates Kathmandu Natural Spring Water at Ratna Rajya (Stone Spouts/Tap), KNSW BH indicates Kathmandu Natural Spring Water at Baneshwor Height (Stone Spouts/Tap), KTW indicates Kathmandu Tap Water**.**

3.2. Analytical Methods

Water samples were analyzed for major cations and anions, nutrients, dissolved organic carbon (DOC), total dissolved nitrogen (TDN) and dissolved silica at the New Hampshire Water Resources Research Center, and trace metals at the Environmental Research Group of the University of New Hampshire. The analytical procedures were as follows: Cations (Na^+, K^+, Mg^{2+}, Ca^{2+}) were analyzed using ion chromatography with suppressed conductivity (Dionex ICS-1000, IonPac CS12 column) with a nitric acid/EDTA phase (ASTM 2007 [55]; Bhatt and McDowell 2007 [24]). Anions (Cl^-, NO^{3-}, SO_4^{2-}) were measured using ion chromatography with suppressed conductivity (Dionex ICS-1000, IonPac AS22 column) following US EPA method 300.1 (2007 [56]). Ammonium (NH_4^+) and orthophosphate ($(PO_4^{3-)}$ were analyzed by automated flow injection analysis colorimetry using a SmartChem discrete analyzer. Ammonium was measured using the automated phenate hypochlorite method with sodium nitroprusside enhancement (US EPA method 350.1, 2005 [57]). Orthophosphate was measured using the automated ascorbic acid reduction method (US EPA method 365.1, 2005 [58]). Dissolved Silica (SiO_2)

analyzed as molybdate-reactive silica using a SmartChem discrete analyzer (US EPA method 370.1, 2005 [59]). Dissolved Organic Carbon (DOC) measured as non-purgeable organic carbon with combustion and analysis of end products using a Shimadzu TOCV, following US EPA method 415.1, 2002 [60]. Samples were injected into a 720°C furnace containing a platinum catalyst, where carbon compounds were converted to CO_2 and measured with a Non-Dispersive Infrared Detector (NDIR). Total Dissolved Nitrogen (TDN) measured using a Shimadzu TOCV, where nitrogen compounds were converted to NO and measured using a chemiluminescent N detector, following the method of Merriam et al. 1996 [61]. The technique operates at 680ºC. Dissolved organic nitrogen (DON) was calculated by subtracting inorganic nitrogen (NO_3^--N + NH_4^+-N) from total dissolved nitrogen and data presented in the paper for NO_3^- and NH_4^+ indicates NO_3^--N and NH_4^+-N hereafter. Trace Elements were analyzed using Inductively Coupled Plasma - Atomic Emission Spectroscopy (ICP-AES) following US EPA SW-846 method 6010B**,** 1991 [62] for determining metals in environmental samples. Elements analyzed included Ag, Al, As, Ba, Be, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Sb, Se, Tl, V, and Zn.

4. Results and Discussion

4.1. Measured Chemical Parameters

Water quality in developing countries often faces significant degradation [40], and comprehensive analyses of water quality parameters from drinking water sources such as municipal water supply systems, groundwater, and natural spring water in the Kathmandu Valley has been lacking. While there are detailed reports on the Bagmati River system within Kathmandu Valley [24,27,38,40,41], a thorough assessment of drinking water quality parameters has not been conducted yet within Kathmandu valley. We performed an empirical study analyzing 32 chemical parameters including major ions, dissolved matter, nutrients, dissolved silica and trace elements (Na, K, Mg, Ca, NH_4, Cl, SO_4, NO_3, PO_4, DIN, TDN, DON, DOC, SiO_2, Ag, Al, As, Ba, Be, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Sb, Se, Tl, V, and Zn) in the primary drinking water systems (KGW, KNSW, and KTP) of the Kathmandu Valley, likely for the first time and compared those average data with the previous reported water quality data from Bagmati River system within same basin (Table 1).

The average concentrations of major cations and anions in groundwater were Na >> Ca >> Mg > K > NH_4 and Cl >> SO_4 >> NO_3 >> PO_4, and in natural spring water (stone spouts/taps) were Na > Ca >> K > Mg >> NH_4 and Cl >> NO_3 > SO_4>> $PO_{4.}$ The dominance of NaCl in regional groundwater suggests the strong influence of human activities in altering water quality. The average concentrations of major cations and anions in Kathmandu tap water supplied by the municipality were Na >> Ca >> Mg > K >> NH_4 and Cl > NO_3 >> SO_4 > PO_4. The concentration of trace elements in groundwater samples (shallow and deep dug wells and tube wells) were Fe >> Mn > Ba > Al > Zn >> V > Cu and in natural spring water (feeding stone spouts/taps) were Ba > Al > Zn > V > Fe > Mn > Cu. The concentration of trace elements in municipal drinking water were found in the following order: Zn >> Ba > Mn > Al > Cu > Fe > V. Other trace elements such as Ag, As, Be, Cd, Co, Cr, Ni, Pb, Sb, Se, and Tl were below detection limits for all types of drinking water, except for a deep dug well sample located at Lokinthali, where cadmium was detected at 0.51 µg/L. The measured chemical parameters of drinking water systems in Kathmandu Valley, along with the standard WHO and US EPA guidelines and Bootstrapped (B = 1000) 95% confidence interval estimates are presented in Table 2.

Table 1. Average concentrations of measured chemical parameters in groundwater, natural spring water, tap water in comparison with Bagmati River water with Kathmandu Valley during 2008.

Measured Parameters (mg L^{-1})	KGW	KNSW	KTW	*BR
Na	40.30	41.62	18.20	60.23
K	6.81	13.36	1.61	14.42
Mg	13.16	8.11	2.61	4.70
Ca	26.97	31.77	11.80	11.20
NH_4	3.47	0.05	0.04	20.40
Cl	77.50	48.36	20.58	48.90
NO_3	2.47	15.23	2.03	0.19
SO_4	10.71	12.49	0.63	5.65
PO_4	0.11	0.43	0.01	2.94
SiO_2	7.26	8.02	12.02	17.65
DOC	1.50	1.45	1.18	13.10
TDN	5.63	15.87	2.30	23.85
DIN	5.95	15.28	2.07	20.59
DON	0.56	0.46	0.22	3.27
Al	0.040	0.042	0.038	0.040
Ba	0.063	0.083	0.091	0.144
Mn	0.094	0.000	0.051	0.069
Zn	0.024	0.005	0.340	0.021
Fe	1.494	0.003	0.002	0.048

*BR data from Bhatt and McDowell 2007; and Bhatt et al. 2014. KGW = Kathmandu Groundwater, KNSW = Kathmandu Natural Spring Water, KTP = Kathmandu Tap Water, and BR = Bagmati River.

Table 2. Summary of Bootstrapped (B = 1000) 95% Confidence Interval (CI) Estimates of Major Chemical Parameters in Drinking Water Systems of Kathmandu Valley.

SN	Measured Parameters	Standard Range (mg/L)	95% CI Estimate of KGW (mg/L)	95% CI Estimate of KNSW (mg/L)	95% CI Estimate of KTW (mg/L)
1.	Na	≤20 * ≤ 20 **	< 30.14, 64.68 >	< 37.37, 43.94 >	< 17.09, 19.30 >
2.	K	≤10 *	< 4.53, 9.28 >	< 12.33, 13.88 >	< 1.05, 2.17 >
3.	Mg	≤50 *	< 6.70, 22.78 >	< 6.82, 8.96 >	< 2.27, 2.95 >
4.	Ca	100 to 300 *	< 20.12, 34.84 >	< 31.96, 33.67 >	< 11.17, 12.44 >
5.	Al	≤ 0.2 * 0.05 to 0.20 **	< 0.04, 0.05 >	< 0.04, 0.05 >	< 0.04, 0.05 >
6.	Ba	≤ 0.7 * ≤ 2 **	< 0.04, 0.09 >	< 0.07, 0.09>	< 0.06, 0.12 >
7.	Zn	≤ 5 **	< 0.01, 0.05 >	< 0.01, 0.02 >	< 0.15, 0.53 >
8.	Mn	≤ 0.4 * ≤ 0.05 **	< 0.06, 0.13 >	< 0.00, 0.02 >	< 0.04, 0.06 >
9.	Fe	≤ 0.3 **	< 0.34, 1.65 >	< 0.02, 0.03 >	< 0.01, 0.02 >
10.	Cl	NSVR	< 42.07, 129.32 >	< 41.29, 51.86 >	< 18.78, 22.39 >
11.	NO_3	≤ 50 * ≤ 10 **	< 1.05, 4.25 >	< 14.23, 17.00 >	< 2.01, 2.05 >
12.	SiO_2	≤ 50 **	< 5.79, 8.90 >	< 6.03, 10.15 >	< 6.78, 17.27 >
13.	NH_4	NSVR	< 1.88, 5.86 >	< 0.02, 1.00 >	< 0.01, 0.08 >
14.	SO_4	NSVR	< 5.92, 16.86 >	< 10.66, 13.74 >	< 0.34, 0.93 >
15.	PO_4	NSVR	< 0.01, 0.25 >	< 0.33, 0.50 >	< 0.01, 0.02 >
16.	DOC	NSVR	< 1.17, 2.00 >	< 1.27, 1.79 >	< 0.85, 1.51 >
17.	TDN	NSVR	< 3.68, 7.63 >	< 14.47, 17.22 >	< 2.23, 2.35 >
18.	DIN	NSVR	< 3.99, 8.52 >	< 14.33, 17.04 >	< 2.02, 2.13 >
19.	DON	NSVR	< 0.06, 1.25 >	< 0.18, 0.96 >	< 0.22, 0.23 >

Acronyms: KGW = Kathmandu Ground Water, KNSW = Kathmandu Natural Spring Water, KTW = Kathmandu Tap Water, DOC = Dissolved Organic Carbon, TDN = Total Dissolved Nitrogen, DIN= Dissolved Inorganic Nitrogen, DON = Dissolved Organic Nitrogen, NSVR = No Specific Values Regulated. **Sources of Data:** * = WHO 2017 [63] Guidelines for Drinking-water Quality, **= U.S. Environmental Protection Agency (US EPA, 2024 [64]) Secondary Drinking Water Standards.

NB: The bootstrap results are based on 1000 bootstrap samples.

Interpretation of a 95% Confidence Interval: For instance, a 95% confidence interval of <30.14 mg/L, 64.68 mg/L> for sodium (Na) content in the KGW system suggests that we are 95% confident that the true sample average sodium level lies within this range. This implies that if we were to repeatedly sample from the KGW water system and compute confidence intervals for sodium levels, about 95% of these intervals would contain the true average value of sodium. In this case, the true average value of sodium being estimated falls between 30.14 and 64.68 mg/L, with the specific value being uncertain within this range.

4.2. Bootstrapped (B = 1000) 95% Confidence Interval (CI) Estimates of Major Chemical Parameters in the Main Drinking Water Systems of the Kathmandu Valley

Due to constraints of time and financial resources, we were compelled to work with a limited number of samples. Specifically, to deal with Bootstrapped (B=1000), we used 14 samples for Kathmandu Ground Water (KGW), 4 for Kathmandu Natural Spring Water (KNSW), and 2 for Kathmandu Tap Water (KTW). These limitations necessitated a careful selection of sample sizes that were manageable within our budget and timeframe while still aiming to provide meaningful and reliable results. To ensure the thoroughness of the study and mitigate the impact of the small sample size, we employed Bootstrapping, a statistical method, with B = 1000 iterations. This approach allowed us to generate valid and generalizable insights from the smaller sample sizes.

Bootstrapping is a statistical technique used to estimate the properties of an unknown sample by repeatedly sampling, with replacement, from a small data set to create many simulated samples. This method allows researchers to approximate the distribution of a statistic (like the mean or variance) and assess its reliability without needing a large amount of original data. Essentially, bootstrapping generates multiple "new" samples from the existing data, enabling more accurate and robust conclusions even when the initial sample size is limited.

We computed Bootstrapped (B = 1000) 95% confidence interval estimates for all 19 major chemical parameters in the three main drinking water systems of Kathmandu Valley. These estimates are listed in Table 2 for comparison. The third column of the table provides the permissible standard values for various elements according to the WHO guidelines for drinking water quality (denoted by *) and the U.S. Environmental Protection Agency (US EPA) Secondary Drinking Water Standards (denoted by **). Columns 4, 5, and 6 present the Bootstrapped 95% confidence interval estimates for the KGW system, KNSW system, and KTW system, respectively, corresponding to various elements.

4.2.1. Bootstrapped 95% Confidence Interval Estimates: Key Chemical Parameter Research Findings

Both the KGW and KNSW water systems exceed the sodium (Na) level recommended by the WHO Guidelines but remain within the EPA Standards. However, the KTW system adheres to both standards, with sodium levels falling within acceptable limits. Nitrate (NO_3) levels in all three water systems KGW, KNSW, and KTW are within compliance with WHO Guidelines and exceeding with US EPA Standards in KNWS. Potassium (K) level slightly exceeds the WHO Guidelines only in the KNSW system, while remaining within acceptable limits in the other two systems. Iron (Fe) level is significantly exceeding the WHO guidelines only in the KGW system, while remaining with acceptable limits in the other two systems. The zinc (Zn) EPA standard maximum permissible limit of less than 5 mg/L is still within the 95% confidence interval for the KTW system. All other major chemical parameters (Mg, Ca, Al, Ba, Mn, Zn) regulated by the WHO Guidelines and/or EPA Standards meet the specified limits in all three water systems.

Interestingly, the following table provides a concise overview of how major chemical parameters classified are according to the WHO Guidelines and EPA Standards for drinking water quality.

Table 3. Classification of Major Chemical Parameters in Drinking Water According to WHO 2017 [63] Guidelines and US EPA 2024 [64] Standards.

	Regulated	Not Regulated
WHO Guidelines	Na, K, Mg, Ca, Al, Ba, Mn, NO_3	Zn, Fe, Cl, NH_4, SO_4, PO_4, SiO_2, DOC, TDN, DIN, DON
EPA Standards	Na, Ba, Mn, Fe, Al, Zn, NO_3, SiO_2	K, Mg, Ca, Zn, Cl, NH_4, SO_4, PO_4, DOC, DN, DIN, DON

4.3. Bootstrapped (B = 1000) One-way ANOVA Testing, a Comparative Analysis, of the Major Chemical Parameters in Drinking Water Systems of Kathmandu Valley

To determine if there are statistically significant differences in the concentrations of major chemical parameters among the three water types (groundwater, natural spring water, and tap water), we performed a One-way ANOVA using the Bootstrapping method with B = 1000 iterations. This approach mitigates the effect of the relatively small sample size. The null hypothesis of interest for each parameter is that there is no significant difference in concentrations among the three water types (H_0: $\mu_1 = \mu_2 = \mu_3$), while the alternative hypothesis (H_1) states that at least one group mean is different. Table 4 presents the mean and standard deviation for all 19 major chemical parameters across the three water types in columns 3, 4, and 5. The corresponding F statistic, degrees of freedom (df), and P-value are listed in columns 6, 7, and 8. For parameters showing significant differences (K, Zn, NO_3, PO_4, TDN, and DON), we conducted a Post Hoc Bonferroni Test to identify pairwise significant differences at the 5% significance level. These significant pairs are listed in the last column of the table.

Table 4. Summary of Bootstrapped ANOVA Testing (B = 1000) for Major Chemical Parameters in Drinking Water Systems of Kathmandu Valley.

SN	Parameter	Mean (SD) KGW (mg/L) (1)	Mean (SD) KNSW (mg/L) (2)	Mean (SD) KTW (mg/L) (3)	Statistics			Bonferroni Test Results: Significant Mean Pair(s)
					F	df	P-value	
1.	Na	44.30 (35.84)	41.65 (4.36)	18.20 (1.11)	0.898	2, 19	0.424	None
2.	K	6.81 (4.56)	13.13 (0.91)	1.61 (0.56)	7.621	2, 19	0.004 *	(1) & (2) *, (2) & (3) *
3.	Mg	13.16 (16.47)	7.84 (1.34)	2.61 (0.34)	0.799	2, 19	0.464	None
4.	Ca	26.97 (15.38)	32.73 (1.06)	11.80 (0.64)	2.292	2, 19	0.128	None
5.	Al	0.04 (0.01)	0.04 (0.01)	0.04 (0.01)	2.634	2, 19	0.098	None
6.	Ba	0.06 (.04)	0.08 (0.02)	0.09 (0.02)	0.772	2, 19	0.476	None
7.	Zn	0.03 (0.03)	0.01 (0.01)	0.34 (0.19)	28.938	2, 19	< 0.001*	(1) & (3) *, (2) & (3) *
8.	Mn	0.09 (0.08)	0.01 (0.01)	0.05 (0.08)	3.142	2, 19	0.066	None
9.	Fe	0.90 (1.32)	0.02 (0.01)	0.01 (0.01)	1.470	2, 19	0.255	None
10.	Cl	76.89 (88.80)	46.44 (6.65)	20.58 (1.80)	0.806	2, 19	0.461	None
11.	NO_3	2.47 (3.22)	15.23 (1.78)	2.03 (0.02)	35.565	2, 19	< 0.001*	(1) & (2) *, (2) & (3) *
12.	SiO_2	7.26 (3.12)	7.87 (2.56)	12.02 (5.25)	2.550	2, 19	0.104	None
13.	NH_4	3.47 (4.00)	0.06 (0.05)	0.04 (0.04)	2.366	2, 19	0.121	None
14.	SO_4	10.71 (10.04)	12.12 (1.92)	0.63 (0.30)	1.903	2, 19	0.176	None
15.	PO_4	0.11 (0.24)	0.41 (0.10)	0.01 (0.01)	4.192	2, 19	0.031*	(1) & (2) *
16.	DOC	1.55 (0.84)	1.53 (0.28)	1.18 (0.33)	0.316	2, 19	0.733	None
17.	TDN	5.48 (4.00)	15.63 (1.58)	2.30 (0.05)	16.331	2, 19	< 0.001*	(1) & (2) *, (2) & (3) *
18.	DIN	5.95 (4.71)	15.72 (1.71)	2.08 (0.06)	11.698	2, 19	< 0.001*	(1) & (2) *, (2) & (3) *
19.	DON	0.56 (1.21)	0.58 (0.47)	0.22 (0.01)	0.137	2, 19	0.873	None

* = Statistically significant at 5% significance level

To deepen reader comprehension, we provide below two summary interpretations as illustrative examples for the 19 cases listed in Table 4. We sincerely hope that readers will be able to interpret the remaining results in a similar manner.

Case 1: No significant difference in sodium (Na) concentrations across water sources: The ANOVA test shows no significant difference in sodium concentrations among the water sources.

Case 2: Significant difference in nitrate (NO_3) concentrations across water sources: The ANOVA test reveals significant differences in nitrate concentrations between at least two water sources.

Bootstrapping One-way ANOVA Test for Sodium (Na)

Table 5. Descriptive statistics for Na

Water Types	n	Mean	Standard deviation
Ground water	14	44.30 mg/L	35.84 mg/L
Natural spring water	4	41.65 mg/L	4.36 mg/L
Tap water	2	18.20 mg/L	1.11 mg/L

Table 5 shows the concentration of the sodium across different water types, providing insights into their quality and variability. Based on fourteen groundwater samples, the mean concentration is 44.30 mg/L with a standard deviation of 35.84 mg/L, indicating considerable variability in chemical content. From four natural spring water samples, the mean concentration is 41.65 mg/L with a standard deviation of 4.36 mg/L, showing relatively consistent chemical levels. Among two tap water samples, the mean concentration is 18.20 mg/L with a standard deviation of 1.11 mg/L, suggesting very stable chemical characteristics. Based on the results of the one-way ANOVA conducted to compare the concentrations of sodium (Na) among the three types of water, we fail to reject the null hypothesis (H_0) that states there is no significant difference in the concentrations of sodium among the three water types. The ANOVA produced an F-value of 0.898 with degrees of freedom (2, 19) and a p-value of 0.424. Since the p-value is greater than the significance level of 0.05, we do not have sufficient evidence to conclude that there are statistically significant differences in sodium concentrations among groundwater, natural spring water, and tap water. Thus, the sodium concentrations in these three types of water sources appear to be similar, indicating that the source of the water does not significantly affect the sodium levels within the studied samples. This information could be valuable for water quality management and public health assessments, suggesting that sodium content is consistent across different water sources in the analyzed regions.

Bootstrapping One-way ANOVA Test for Nitrate (NO_3)

To determine if there are statistically significant differences in the concentrations of the trace ion nitrate among the three water types (groundwater, natural spring water, and tap water), we performed an ANOVA using the Bootstrapping method with B = 1000 iterations**.**

Table 6. Descriptive statistics for NO_3.

Water Types	n	Mean	Standard deviation
Ground water	14	2.47 mg/L	3.22 mg/L
Natural spring water	4	15.23 mg/L	1.78 mg/L
Tap water	2	2.03 mg/L	0.02 mg/L

The Table 6 presents the nitrate (NO_3) concentrations across various water sources, highlighting their mean values and variability. From fourteen groundwater samples, the mean NO_3 concentration is 2.47 mg/L with a standard deviation of 3.22 mg/L, indicating significant variability in nitrate levels. Among four natural spring water samples, the mean NO_3 concentration is 15.23 mg/L with a standard deviation of 1.78 mg/L, showing relatively high nitrate levels with moderate consistency. Based on two tap water samples, the mean NO_3 concentration is 2.03 mg/L with a standard deviation of 0.02 mg/L, suggesting very stable and low nitrate levels. Based on the results of the one-way ANOVA conducted to compare the concentrations of the parameter nitrate among the three types of water, we reject the null hypothesis (H_0) that states there is no significant difference in the concentrations of nitrate among the three water types. The ANOVA produced an F-value of 35.565 with degrees of freedom (2, 19) and a p-value less than 0.001. Since the p-value is much smaller than the significance level of 0.05, we have strong evidence to conclude that there are statistically significant differences in nitrate concentrations among groundwater, natural spring water, and tap water.

Post Hoc Analysis, Bonferroni Test Results: To identify pairwise significant differences in nitrate concentrations among the three water types, we performed the Post Hoc Bonferroni Test and found the following results:

There is a significant difference in nitrate concentrations between groundwater and natural spring water, with a p-value less than 0.001 and significant difference in nitrate concentrations between tap water and natural spring water, with a p-value less than 0.001. There is no significant difference in nitrate concentrations between groundwater and tap water, with a p-value of 1.000.

These results indicate that natural spring water has significantly higher nitrate concentrations compared to both groundwater and tap water, while groundwater and tap water do not differ significantly from each other in terms of nitrate levels. This information highlights the unique nitrate profile of natural spring water, which could be critical for water quality assessments and regulatory actions. We anticipate that readers will apply similar interpretations to the other 17 parameter cases presented in the table above.

4.4. Bootstrapped One-Way ANOVA Testing: Key Chemical Parameter Research Findings

There is no statistically significant difference in sodium concentrations among three main sources of water (groundwater, natural spring water, and tap water) in the Kathmandu Valley. Despite the observed differences in mean concentrations, these variations are not large enough to be considered statistically significant given the P-value of 0.424. The test results show a statistically significant difference in potassium concentrations among the three types of drinking water systems (P-value = 0.004). The significant differences in potassium concentrations observed between groundwater and natural spring water, and natural spring water and tap water. Natural spring water has significantly higher potassium levels compared to both groundwater and tap water. Magnesium does not show any significant difference in concentrations among the three main sources of water in the Kathmandu Valley. Despite the observed differences in mean concentrations, these variations are not large enough to be considered statistically significant given the P-value of 0.464.

Calcium does not show any significant difference in concentrations among the three main sources of water in the Kathmandu Valley. Despite the observed differences in mean concentrations, these variations are not large enough to be considered statistically significant given the P-value of 0.128. There is no significant difference in aluminum concentrations among groundwater, natural spring water, and tap water in the Kathmandu Valley. The observed differences in mean concentrations are not statistically significant given the P-value of 0.098, though they are close to the threshold of significance. Barium does not show significant difference in concentrations among three main sources of water in the Kathmandu Valley. Despite the observed differences in mean concentrations, these variations are not large enough to be considered statistically significant given the P-value of 0.476. The zinc concentrations in the three types of drinking water systems in the Kathmandu Valley are significantly different (P-value < 0.001. Specifically, tap water has a significantly higher zinc concentration compared to both groundwater and natural spring water. There is no significant difference between the zinc concentrations in groundwater and natural spring water. There is no significant difference in manganese concentrations among groundwater, natural spring water, and tap water in the Kathmandu Valley. The observed differences in mean concentrations are not statistically significant given the P-value of 0.066, though they are close to the threshold of significance. Iron also does not show significant difference in concentrations among groundwater, natural spring water, and tap water in the Kathmandu Valley. The observed differences in mean concentrations are not statistically significant given the P-value of 0.255.

There is no significant difference in chloride concentrations among three sources of water in the Kathmandu Valley. The observed differences in mean concentrations are not statistically significant given the P-value of 0.461. Nitrate concentrations show statistically significant differences among groundwater, natural spring water, and tap water (P-value 0.001). There is a significant difference in nitrate concentrations between groundwater and natural spring water, with a p-value less than 0.001 and similar significant difference in nitrate concentrations between tap water and natural spring water, with a p-value less than 0.001 but there is no significant difference in nitrate concentrations between groundwater and tap water, with a p-value of 1.000. Sulfate does not show any significant difference in mean concentrations among groundwater, natural spring water, and tap water in the Kathmandu Valley (P-value 0 = 0.176). However, the observed means suggest that natural spring water has the highest concentration of SO_4, followed by groundwater, with tap water having significantly lower SO_4 concentrations. The one-way Bootstrapping ANOVA reveals that there is significant difference in PO_4 concentrations among the three types of drinking water systems in the Kathmandu Valley, with a P-value of 0.031. The post hoc Bonferroni test further identifies that the significant difference exists specifically between groundwater and natural spring water, with natural spring water having a higher mean PO_4 concentration.

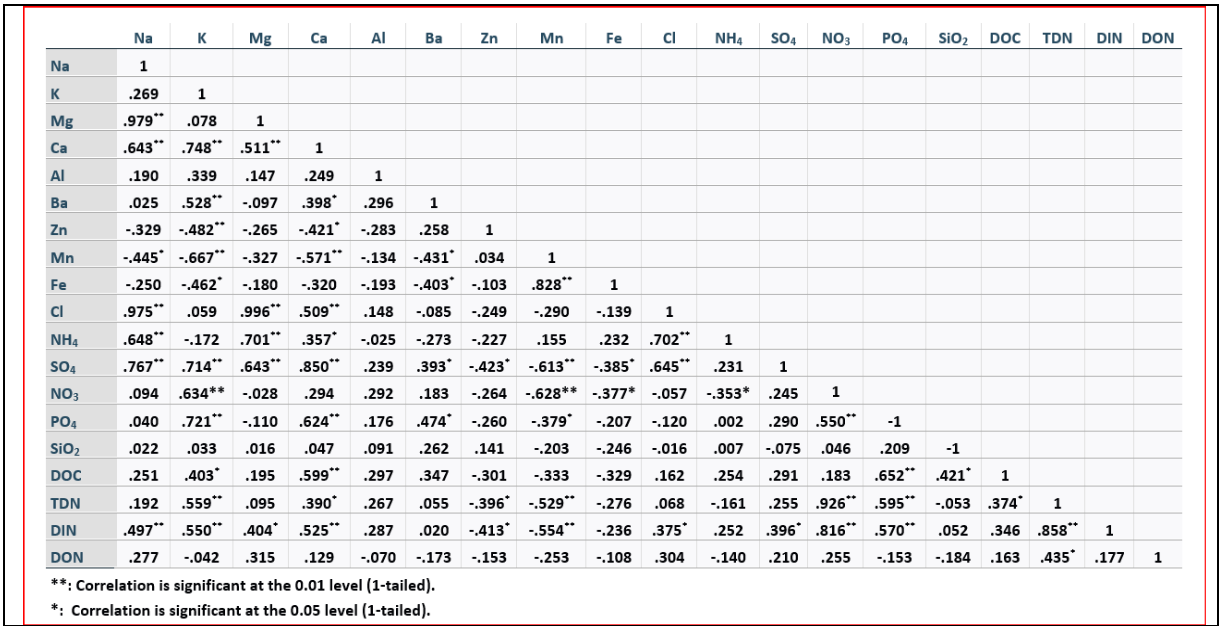
There is no significant evidence to suggest that the mean SiO_2 concentrations differ among groundwater, natural spring water, and tap water in the Kathmandu Valley at the 5% significance level. However, the observed means suggest that tap water has a higher concentration of SiO_2 compared to groundwater and natural spring water. Ammonia does not show significant evidence to suggest that the mean NH_4 concentrations differ among three main sources of water in the Kathmandu Valley at the 5% significance level. However, the observed means suggest that groundwater has a significantly higher concentration of NH_4 compared to natural spring water and tap water.

As P-value of 0.733 is much greater than the conventional significance level ($\alpha = 0.05$), there is no statistically significant difference in mean dissolved organic carbon (DOC) concentrations among groundwater, natural spring water, and tap water in the Kathmandu Valley. The observed means indicate that all three water systems have similar DOC concentrations, with only a slight difference between them. There is significant difference in total dissolved nitrogen (TDN) concentrations among the three types of drinking water systems in the Kathmandu Valley, with a P-value less than 0.001. The post hoc Bonferroni test further identifies those significant differences exist specifically between groundwater and natural spring water, and between natural spring water and tap water. Natural spring water has the highest mean TDN concentration, followed by groundwater and then tap water. Dissolved inorganic nitrogen (DIN) shows significant differences in concentrations among the three types of drinking water systems in the Kathmandu Valley, with a P-value less than 0.001. The post hoc Bonferroni test further identifies those significant differences exist specifically between groundwater and natural spring water, and between natural spring water and tap water. Natural spring water has the highest mean DIN concentration, followed by groundwater and then tap water. Dissolved organic nitrogen (DON) does not show any statistically significant difference in mean concentrations among groundwater, natural spring water, and tap water in the Kathmandu Valley (P-value = 0.873). The observed means indicate that all three water systems have similar DON concentrations, with only slight differences between them.

4.5. Correlation Analysis of Chemical Parameters in Drinking Water of Kathmandu Valley

We performed correlation analyses and calculated the Pearson pairwise correlation coefficients of chemical parameters in drinking water of Kathmandu Valley and observed following observation.

Table 7. Correlation Analysis of Chemical Parameters in Drinking Water of Kathmandu Valley.



	Na	K	Mg	Ca	Al	Ba	Zn	Mn	Fe	Cl	NH_4	SO_4	NO_3	PO_4	SiO_2	DOC	TDN	DIN	DON
Na	1																		
K	.269	1																	
Mg	$.979^{**}$	.078	1																
Ca	$.643^{**}$	$.748^{**}$	$.511^{**}$	1															
Al	.190	.339	.147	.249	1														
Ba	.025	$.528^{**}$	-.097	$.398^{*}$	.296	1													
Zn	-.329	$-.482^{**}$	-.265	$-.421^{*}$	-.283	.258	1												
Mn	$-.445^{*}$	$-.667^{**}$	-.327	$-.571^{**}$	-.134	$-.431^{*}$	.034	1											
Fe	-.250	$-.462^{*}$	-.180	-.320	-.193	$-.403^{*}$	-.103	$.828^{**}$	1										
Cl	$.975^{**}$	.059	$.996^{**}$	$.509^{**}$	.148	-.085	-.249	-.290	-.139	1									
NH_4	$.648^{**}$	-.172	$.701^{**}$	$.357^{*}$	-.025	-.273	-.227	.155	.232	$.702^{**}$	1								
SO_4	$.767^{**}$	$.714^{**}$	$.643^{**}$	$.850^{**}$	.239	$.393^{*}$	$-.423^{*}$	$-.613^{**}$	$-.385^{*}$	$.645^{**}$	.231	1							
NO_3	.094	.634**	-.028	.294	.292	.183	-.264	-.628**	-.377*	-.057	-.353*	.245	1						
PO_4	.040	$.721^{**}$	-.110	$.624^{**}$	.176	$.474^{*}$	-.260	$-.379^{*}$	-.207	-.120	.002	.290	$.550^{**}$	-1					
SiO_2	.022	.033	.016	.047	.091	.262	.141	-.203	-.246	-.016	.007	-.075	.046	.209	-1				
DOC	.251	$.403^{*}$	.195	$.599^{**}$	.297	.347	-.301	-.333	-.329	.162	.254	.291	.183	$.652^{**}$	$.421^{*}$	1			
TDN	.192	$.559^{**}$	.095	$.390^{*}$	.267	.055	$-.396^{*}$	$-.529^{**}$	-.276	.068	-.161	.255	$.926^{**}$	$.595^{**}$	-.053	$.374^{*}$	1		
DIN	$.497^{**}$	$.550^{**}$	$.404^{*}$	$.525^{**}$	.287	.020	$-.413^{*}$	$-.554^{**}$	-.236	$.375^{*}$	.252	$.396^{*}$	$.816^{**}$	$.570^{**}$	.052	.346	$.858^{**}$	1	
DON	.277	-.042	.315	.129	-.070	-.173	-.153	-.253	-.108	.304	-.140	.210	.255	-.153	-.184	.163	$.435^{*}$	.177	1

**: Correlation is significant at the 0.01 level (1-tailed).

*: Correlation is significant at the 0.05 level (1-tailed).

Sodium is significantly correlated at the 5% significance level with Mg, Ca, Mn, Cl, NH_4, SO_4, and DIN. Potassium is significantly correlated at the 5% significance level with Ca, Ba, Zn, Mn, Fe, SO_4, NO_3, PO_4, DOC, TDN, and DIN. Magnesium is significantly correlated at the 5% significance level with Ca, Cl, NH_4, SO_4, and DIN. Calcium is significantly correlated at the 5% significance level with Ba, Zn, Mn, Cl, NH_4, SO_4, PO_4, DOC, TDN, and DIN. Calcium is significantly correlated at the 5% significance level with Ba, Zn, Mn, Cl, NH_4, SO_4, PO_4, DOC, TDN, and DIN. Aluminum is not significantly correlated with any other elements at the 5% significance level. Barium is significantly correlated at the 5% significance level with K, Cl, Mn, Fe, SO_4, and PO_4. Zinc is significantly correlated at the 5% significance level with K, Ca, SO_4, TDN, and DIN. Manganese is significantly correlated at the 5% significance level with Na, K, Ca, Ba, Fe, SO_4, NO_3, PO_4, DOC, TDN, and DIN. Iron is significantly correlated at the 5% significance level with K, Ba, Mn, Cl, SO_4, and NO_3. Chlorine is significantly correlated at the 5% significance level with Na, Mg, NH_4, SO_4, PO_4, and DIN. Ammonium is significantly correlated at the 5% significance level with Na, Mg, Ca, Cl, and SO_4. Sulfate is significantly correlated at the 5% significance level with Na, K, Mg, Ca, Ba, Zn, Mn, Fe, Cl, and DIN. Nitrate is significantly correlated at the 5% significance level with K, Mn, Fe, NH_4, PO_4, TDN, and DIN. Phosphate is significantly correlated at the 5% significance level with K, Ca, Ba, Mn, NO_3, DOC, TDN, and DIN. Silicon dioxide is significantly correlated with only DOC at the 5% significance level. Dissolved organic carbon is significantly correlated at the 5% significance level with K, Ca, PO_4, and SiO_2. Total dissolved nitrogen is significantly correlated at the 5% significance level with K, Ca, Zn, Mn, NO_3, PO_4, DOC, DIN, and DON. Dissolved inorganic nitrogen is significantly correlated at the 5% significance level with Na, K, Mg, Ca, Zn, Mn, Cl, SO_4, NO_3, PO_4, TDN, and DON. Dissolved organic nitrogen with only TDN at the 5% significance level.

4.6. Multivariate Regression Analysis of Chemical Parameters in Drinking Water of Kathmandu Valley

Table 8. Multivariate Predictive Modeling of Chemical Parameters in Drinking Water of Kathmandu Valley.

SN	Chemical Parameter	Predictive Model	R^2 value
1.	Na	$\widehat{\mathbf{Na}}$ = 11.03 + 1.77 Mg + 0.72 SO_4 + 0.45 DIN	99.9%
2.	K	$\widehat{\mathbf{K}}$ = 3.81 + 0.24 Ca – 12.41 Zn + 1.16 NO_3 +5.00 PO_4 - 0.79 TDN - 0.39 DIN	97.7%
3.	Mg	$\widehat{\mathbf{Mg}}$ = - 1.01 + 0.19 Cl	99.6%
4.	Ca	$\widehat{\mathbf{Ca}}$ = 10.00 + 0.76 NH4 + 1.05 SO_4 + 24.25 PO_4	95.7%
5.	Al	$\widehat{\mathbf{Al}}$ = … … …	
6.	Ba	$\widehat{\mathbf{Ba}}$ = 0.06 + 0.01 Cl + 0.01 SO_4	75.1%
7.	Mn	$\widehat{\mathbf{Mn}}$ = 0.10 + 0.006 K - 0.003 Ca + 0.04 Fe – 0.013 NO_3 + 0.004 TDN	95.1%
8.	Zn	$\widehat{\mathbf{Zn}}$ = 0.12 – 0.006 SO_4	42.3%
9.	Fe	$\widehat{\mathbf{Fe}}$ = 1.39 – 0.11 K	46.2%
10.	Cl	$\widehat{\mathbf{Ca}}$ = 5.97 + 5.37 Mg	99.6%
11.	NH_4	$\widehat{\mathbf{NH_4}}$ = - 1.67 + 0.19 Ca + 0.05 Cl – 0.42 SO_4	85.0%
12.	SO_4	$\widehat{\mathbf{SO_4}}$ = - 13.94 + 1.29 Na – 2.25 Mg – 0.52 DIN	97.6%
13.	NO_3	$\widehat{\mathbf{NO_3}}$ = - 1.00 NH_4 + 1.00 DIN	100.0%
14.	PO_4	$\widehat{\mathbf{PO_4}}$ = - 0.43 + 0.03 K + 1.17 Mn + 0.02 NO_3 + 0.17 DOC	87.5%
15.	SiO_2	$\widehat{\mathbf{SiO_2}}$ = 4.90 + 2.11 DOC	42.1%
16.	DOC	$\widehat{\mathbf{DOC}}$ = 0.32 + 0.02 Ca + 1.04 PO_4 + 0.07 SiO_2	76.7%
17.	TDN	$\widehat{\mathbf{TDN}}$ = 3.38 – 0.26 K – 6.58 Zn + 0.63 NO_3 + 7.00 PO_4 + 0.15 DIN +1.37 DON	98.9%
18.	DIN	$\widehat{\mathbf{DIN}}$ = -782 + 0.50 Na – 0.45 K + 0.20 Ca +17.24 Mn – 0.15 Cl – 0.31 SO_4 + 0.58 NO_3 - 3.91 PO_4 + 0.43 TDN – 1.35 DON	99.4%
19.	DON	$\widehat{\mathbf{DON}}$ = - 0.07 + 0.08 TDN	43.5%

Aluminum (Al) is not significantly correlated with any elements; no predictive model exists for it.

Building on the insights gained from the correlation analyses discussed earlier, we conducted Backward-Elimination-Multivariate Regression Analyses to develop multivariate predictive models for several chemical parameters in drinking water of Kathmandu Valley. These models offer valuable predictive capabilities when the values of other significant parameters are known in a given scenario. Additionally, by examining the measures of partial regression coefficients, we can effectively assess the strength of the relationship between the dependent variable and the independent variables. In our analysis, we provide interpretations of select partial regression coefficients to elucidate their significance and meaning in the context of water quality assessment.

Example: Application and Interpretation of Model Coefficients - Case of Sodium

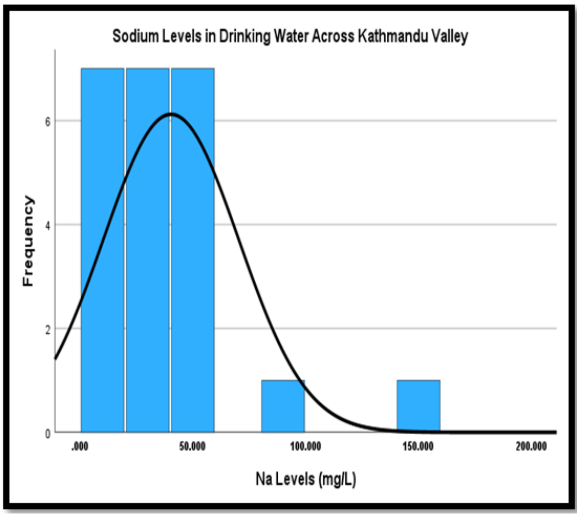
This section illustrates the application of the model and interprets the various coefficients, using Sodium (Na) as an example. A predictive multivariate for Sodium in the drinking water of Kathmandu Valley is

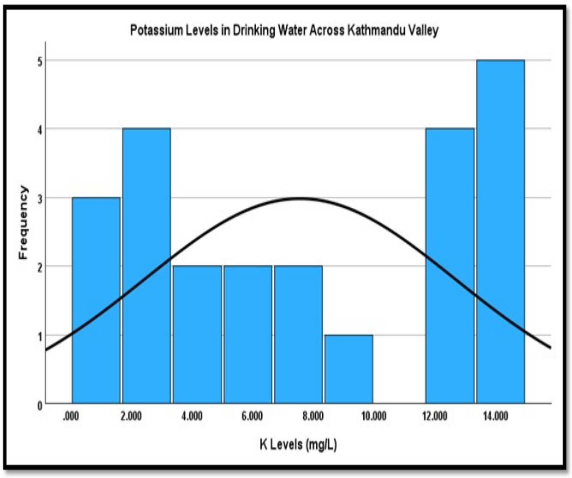
$\widehat{Na}$ = 11.03 + 1.77 Mg + 0.72 SO_4 + 0.45 DIN with R^2 value of 99.9%. Although there are many other elements that are significantly correlated with the sodium level in water, the levels of magnesium, sulfate, and dissolved inorganic nitrogen together are able to predict sodium in almost deterministic way as R^2 value of the model is 99.9%. The R^2 value of 99.9% means that 99.9% variations in sodium is completely explained by these three (Mg, SO_4, and DIN) chemicals together. The partial regression coefficient of sodium with magnesium is 1.77. This means that if the magnesium level in Kathmandu's drinking water increases by 1 mg/L, the sodium level will increase by 1.77 mg/L, assuming all other chemical levels remain constant. The partial regression coefficient of sodium with sulphate is 0.72. This means that if the sulphate level in Kathmandu's drinking water increases by 1 mg/L, the sodium level will increase by 0.72 mg/L, assuming all other chemical levels remain constant. The partial regression coefficient of sodium with dissolved inorganic nitrogen is 0.45. This means that if the dissolved inorganic nitrogen level in Kathmandu's drinking water increases by 1 mg/L, the sodium level will increase by 0.45 mg/L, assuming all other chemical levels remain constant.

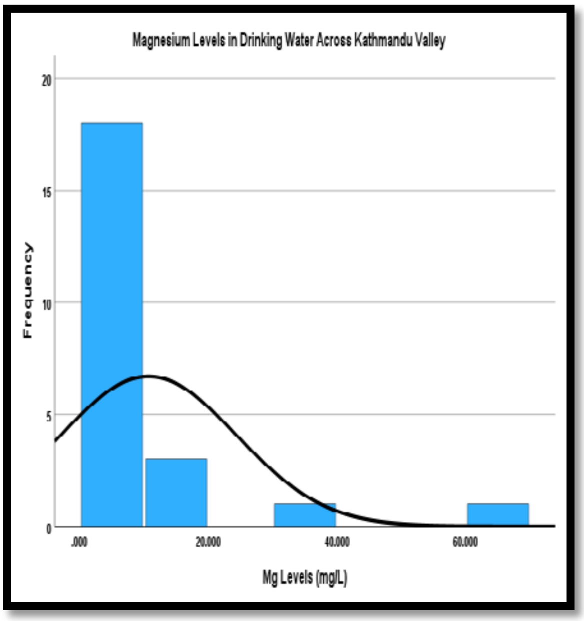
Applications of the model: This model is most effective for predicting the sodium level in Kathmandu Valley's water when the levels of the other three chemicals such as magnesium (Mg), sulfate (SO_4), and dissolved inorganic nitrogen (DIN are known. For instance, if at a given time the levels of Mg, SO_4, and DIN are 10 mg/L, 8 mg/L, and 6 mg/L respectively, the sodium level (Na) can be predicted using the model equation: $\widehat{Na}$ = 11.03 + 1.77 Mg + 0.72 SO_4 + 0.45 DIN**.** Plugging in the values: $\widehat{Na}$ = 11.03 + 1.77(10) + 0.72(8) + 0.45(6) = 37.19 mg/L. Thus, the predicted sodium level is 37.19 mg/L. Furthermore, this mathematical identity can be leveraged for a wide range of analytical and predictive purposes.

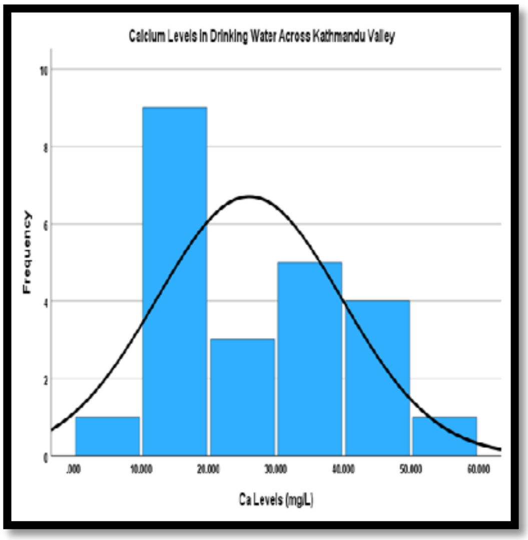
4.7. Visual Representation of the Distribution of the Chemical Parameters in Drinking Water of Kathmandu Valley

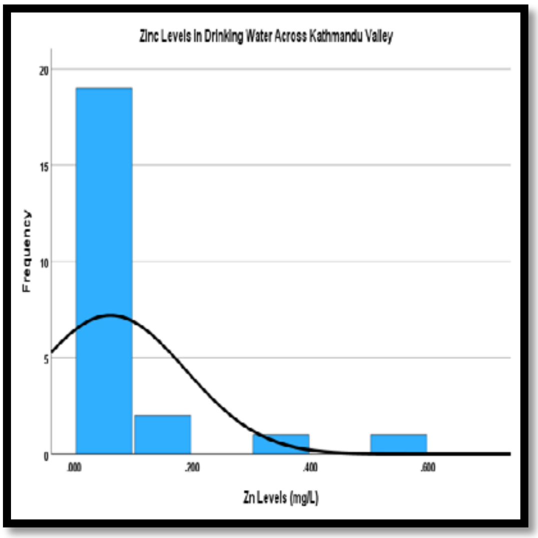
Below, we present 19 histograms, each representing the distribution pattern of a specific chemical parameter in the drinking water of the Kathmandu Valley (Figure 2). These visual aids are designed to be self-explanatory, providing a clear and concise overview of the variations and concentrations of each chemical component in the water samples.

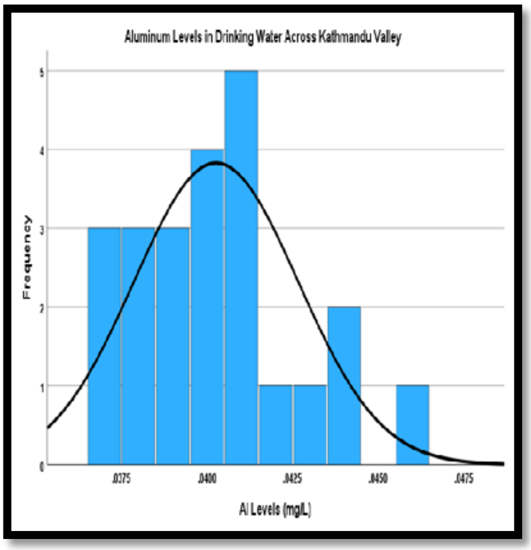


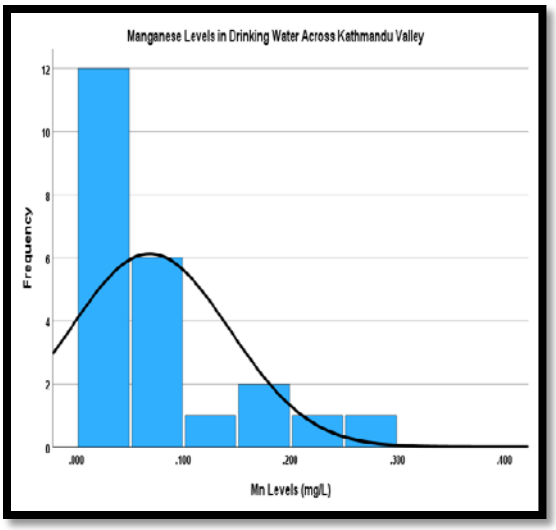


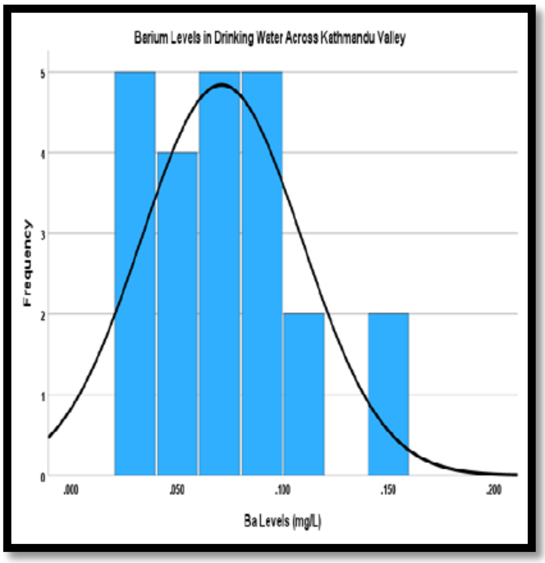


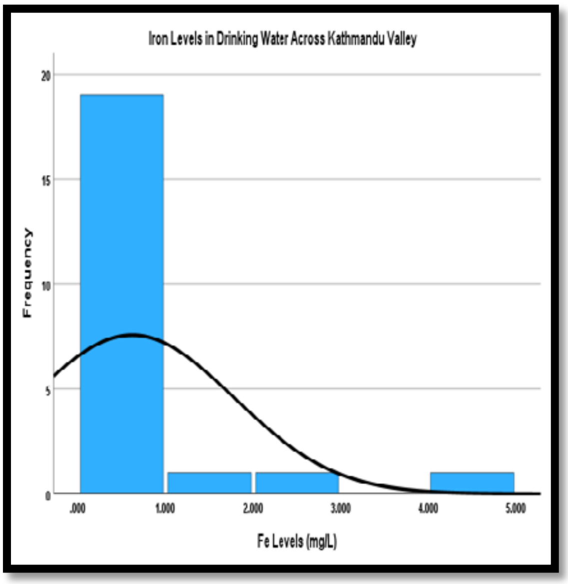

Calcium Levels in Drinking Water Across Kathmandu Valley
Frequency
0
2
4
6
8
10
.000
10.000
20.000
30.000
40.000
50.000
60.000
Ca Levels (mg/L)

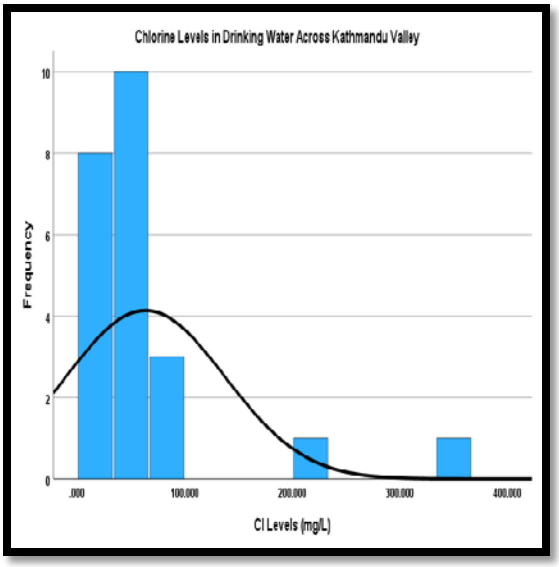

Zinc Levels in Drinking Water Across Kathmandu Valley
Frequency
0
5
10
15
20
.000
.200
.400
.600
Zn Levels (mg/L)

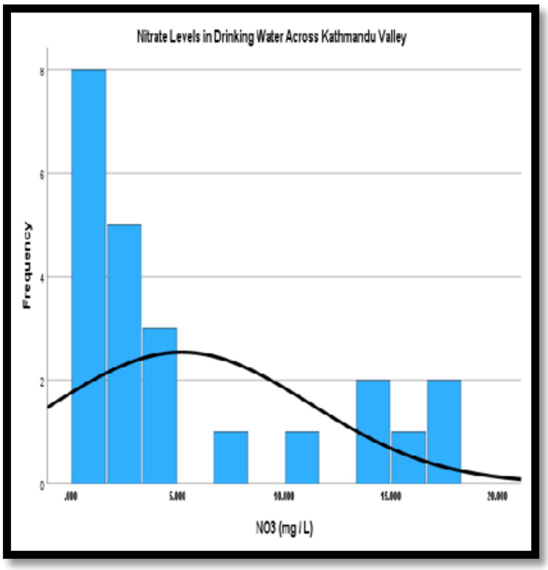

Aluminum Levels in Drinking Water Across Kathmandu Valley
Frequency
0
1
2
3
4
5
.0375
.0400
.0425
.0450
.0475
Al Levels (mg/L)

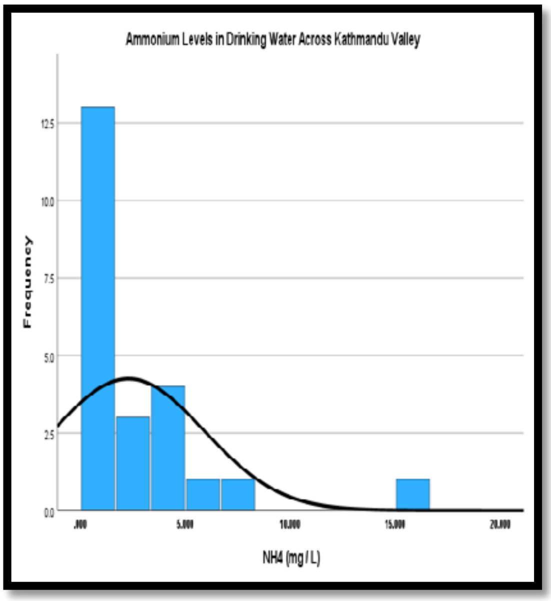

Manganese Levels in Drinking Water Across Kathmandu Valley
Frequency
0
2
4
6
8
10
12
.000
.100
.200
.300
.400
Mn Levels (mg/L)

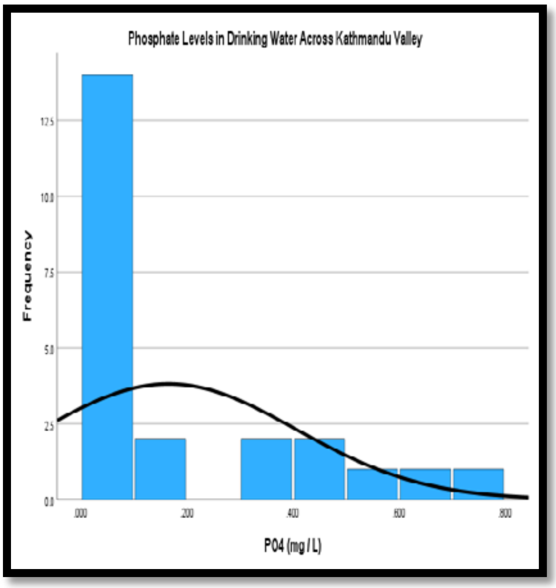

Barium Levels in Drinking Water Across Kathmandu Valley
Frequency
0
1
2
3
4
5
.000
.050
.100
.150
.200
Ba Levels (mg/L)

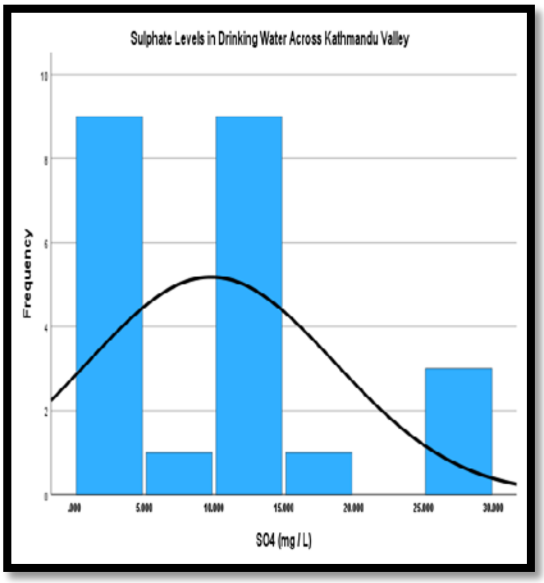

Iron Levels in Drinking Water Across Kathmandu Valley
Frequency
0
5
10
15
20
.000
1.000
2.000
3.000
4.000
5.000
Fe Levels (mg/L)

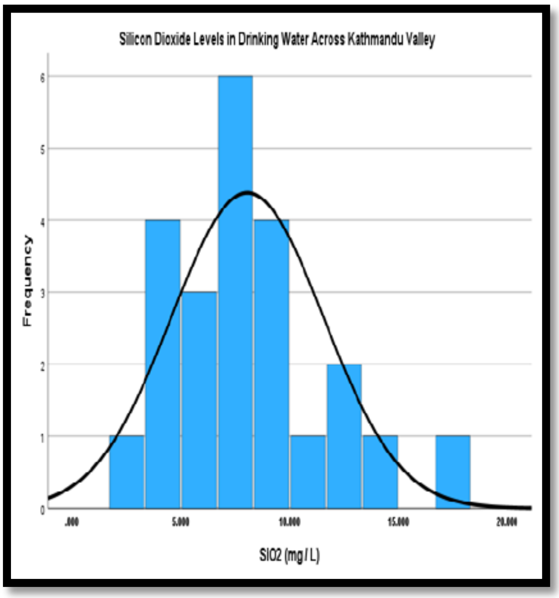

Chlorine Levels in Drinking Water Across Kathmandu Valley
Frequency
10
8
6
4
2
0
.000
100.000
200.000
300.000
400.000
Cl Levels (mg/L)

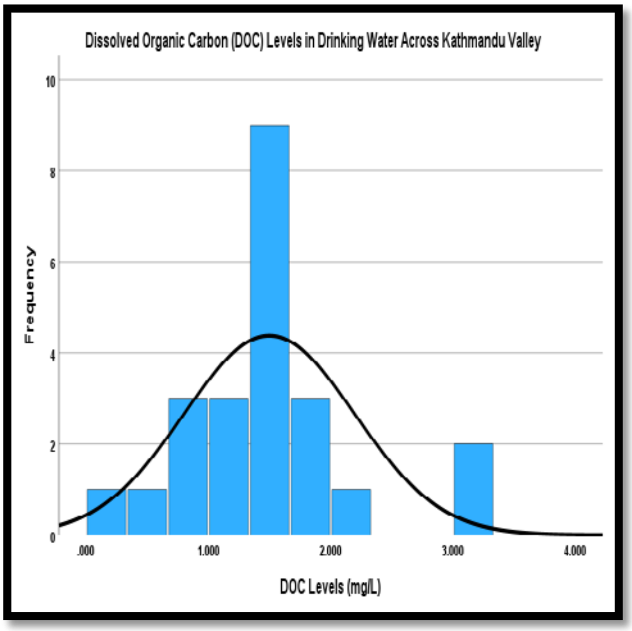

Nitrate Levels in Drinking Water Across Kathmandu Valley
Frequency
8
6
4
2
0
.000
5.000
10.000
15.000
20.000
NO3 (mg / L)

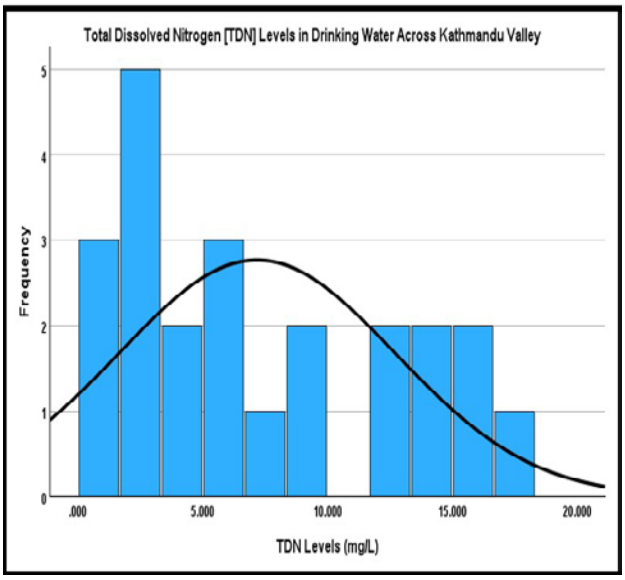

Ammonium Levels in Drinking Water Across Kathmandu Valley
Frequency
12.5
10.0
7.5
5.0
2.5
0.0
.000
5.000
10.000
15.000
20.000
NH4 (mg / L)

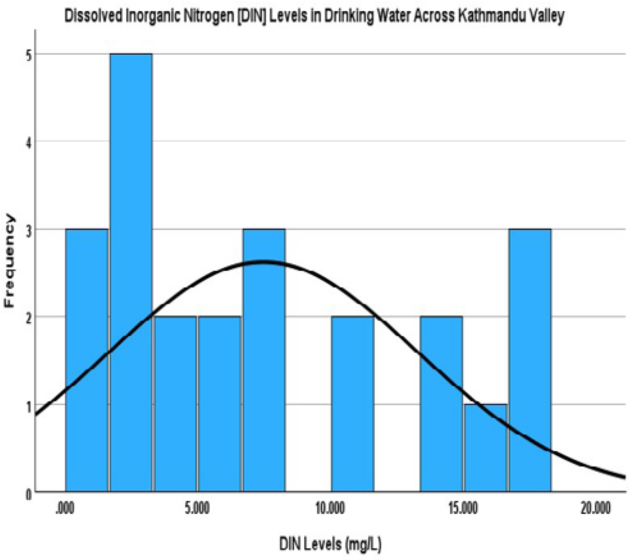

Phosphate Levels in Drinking Water Across Kathmandu Valley
Frequency
12.5
10.0
7.5
5.0
2.5
0.0
.000
.200
.400
.600
.800
P04 (mg / L)


Sulphate Levels in Drinking Water Across Kathmandu Valley
Frequency
10
8
6
4
2
0
.000
5.000
10.000
15.000
20.000
25.000
30.000
SO4 (mg / L)


Silicon Dioxide Levels in Drinking Water Across Kathmandu Valley
Frequency
6
5
4
3
2
1
0
.000
5.000
10.000
15.000
20.000
SIO2 (mg / L)







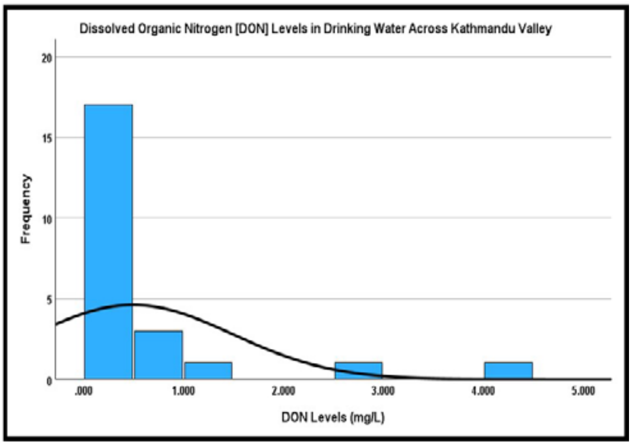


Figure 2. Distribution of Chemical Parameters in Drinking Water of Kathmandu Valley.

5. Conclusions

This research provides a comprehensive analysis of drinking water quality in the Kathmandu Valley, revealing significant variations across different sources. Many water samples exceed permissible limits set by national and international standards, posing serious public health risks. High contamination levels in densely populated areas highlight the impact of anthropogenic activities on water quality. Testing for 19 chemical parameters, including Na, NH_4, NO_3, DOC, and TDN, combined with advanced statistical analyses such as ANOVA, correlation analysis, and predictive modeling, underscores the critical need for enhanced water management practices. The results emphasize the urgency of developing robust infrastructure and implementing effective water quality monitoring systems. Policy interventions and community-based approaches are essential to address the identified water quality issues. Policymakers should prioritize investment in water treatment facilities, enforce stricter regulations on industrial discharges, and promote public awareness about safe water practices. This research contributes to the broader understanding of urban water quality challenges in developing countries. It offers valuable insights for future studies and serves as a foundation for evidence-based policymaking aimed at ensuring safe drinking water access for all residents of the Kathmandu Valley.

Major ion concentrations generally follow the same trend among the three types of samples, except for higher nitrate than sulfate and higher potassium than magnesium in natural spring water. Seven trace metals (Al, Ba, Cu, Fe, Mn, V, and Zn) were detected in all three types of drinking water, while Ag, As, Be, Cd, Co, Cr, Ni, Pb, Sb, Se, and Tl were below detection limits. Sodium, iron, and nitrate levels exceed WHO guidelines in groundwater samples, and potassium slightly exceeds in natural spring water. Natural spring water has significantly higher nitrate concentrations compared to both groundwater and tap water, while groundwater and tap water do not differ significantly from each other in terms of nitrate levels.

Groundwater has a significantly higher concentration of NH_4 compared to natural spring water and tap water. Natural spring water has the highest concentration of SO_4, followed by groundwater, with tap water having significantly lower SO_4 concentrations. Tap water has a higher zinc concentration compared to both groundwater and natural spring water, but there is no significant difference between the zinc concentrations in groundwater and natural spring water.

Overall, while the municipal water supply is acceptable for drinking, groundwater and natural spring water are not suitable for drinking purposes. These findings are crucial for the scientific community and water supply authorities to address water quality issues, public health concerns, and ecosystem conservation within the basin. Human activities contribute to high concentrations of nitrate, sodium, and chloride in groundwater and natural spring water, and the high concentration of iron in deep dug wells is due to anoxic conditions.

Recommendations

Continued Monitoring: It is recommended to regularly monitor the levels of chemical parameters in all three drinking water systems to ensure consistent water quality.

Expanded Study: Conducting a broader study with a larger sample size and additional sampling locations could offer a more comprehensive understanding of the variations in concentration of chemical parameters.

Public Information: Providing information to the public about the levels of chemical parameters in different water sources can assist individuals in making informed decisions about water consumption.

Water Treatment: Consider enhancing water treatment processes to reduce TDN levels, particularly for natural spring water and groundwater, to ensure safe drinking water quality.

Policy and Regulation: Develop and enforce policies aimed at reducing pollutants including nitrogen pollution in water sources.

ACKNOWLEDGEMENTS

The authors express their gratitude to Jeff Merriam, Michelle Daley, Jody Potter, and Scott Greenwood for their assistance in the laboratory. Special thanks are extended to Aaron Parez at the Center for Earth and Environmental Studies of Texas A & M International University for his contribution to producing the image (Figure 1). Additionally, the authors acknowledge the support and provision of valuable information from the Water and Energy Commission Secretariat, Department of Hydrology and Meteorology, Ministry of Forest and Soil Conservation, Department of Survey-Ministry of Land Reform, Department of Mines and Geology, Central Bureau of Statistics, Nepal Water Supply Corporation, and the Government of Nepal. The authors deeply appreciate anonymous reviewers for their thorough review and insightful comments and would also like to thank all members of the editorial office of the journal for their invaluable support.

References

[1] UNEP, "*The Global Environment Outlook 3, past, present and future perspectives*", Earthscan Publications Ltd, London, United Kingdom, 2002, pp. 466.

[2] Cunningham, W. and Cunningham, M., *Environmental Science: A Global Concern*, The McGraw Hill Companies Inc., Fifteenth Edition, Published in 2022, 375 Pages, ISBN10: 1260363821; ISBN13: 9781260363821.

[3] UNEP, "Global resources outlook, UNEP Nairobi, Kenya, 2024, pp. 162. US EPA, United States Environmental Protection Agency, 2024. https:// www.epa.gov/ ground-water -and- drinking-water/national-primary-drinking-waterregulations, Accessed on May 25, 2024.

[4] WM (Water Mission), "Global water crisis, water mission, N. Charleston, SC 29405, USA, 2024. https:// www.watermission.org /about-us/

[5] Greenwood, E.E.,Lauber, T., Hoogen, J.U.D., Donmez, A., Bain, R.E.S., Johnston, R., Crowther, T.W., and Julian, T.R., “Mappin g safe drinking water use in low- and middle-income counties”, *Science* 365 (6710), 784-790, 2024.

[6] Hope, B., “Four billion people lack safe water”, *Science* 385 (6710), 708-709, 2024.

[7] Soliman, A., “Unacceptable: a staggering 4.4 billion people lack safe drinking water, study finds”, *Nature* 632, 964-965, 2024.

[8] Florke, M., Schneider, C., and McDonald, R.I., "Water competition between cities and agriculture driven by climate change and urban growth", *Nature Sustainability* 1, 51-58, 2018.

[9] Intergovernmental Panel on Climate Change (IPCC), *Summary for policymakers. In: Climate Change 2023: Synthesis report. Contribution of working groups I, II, and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,* [Core writing team, Lee H. and Romero J. (eds.)], IPCC, Geneva, Switzerland, 2023, pp. 1-34.

[10] Jha, M.G., Khadka, M.S., Shrestha, M.P., Regmi, S., Bauld, J., Jacobson, G., *The assessment of groundwater pollution in the Kathmandu Valley, Nepal: report on joint Nepal-Australia Project 1995-1996,* Australian Geological Survey Organization, Canberra, 1997. pp. 1-64.

[11] Khatiwada, N.R., Takizawa, S., Tran, T.V.N., Inoue, M., (2002) "Groundwater contamination assessment for sustainable supply in Kathmandu Valley, Nepal", *Water Science and Technology* 46(9), 147-154, 2002.

[12] Warner, N.R., Leavy, J., and Harpp, K., "Drinking water quality in Nepal's Kathmandu Valley: a survey and assessment of selected controlling sites characteristics", *Hydrogeology Journal* 16, 321-334, 2008. https://www.doi.org/10.1007/s10040-007-0238-1

[13] Thapa, B.R., Ishidaira, H., Pandey, V.P., Bhandari, T.M,, and Shakya, N.M., "Evaluation of water security in Kathmandu Valley before and after water transfer from another basin", *MDPI Water* 10, 224, 2018.

[14] Bruijnzeel, A.L., Sun, G., Zhang, J., Tiwari, K.R., and Hao, L., "Forests, water, and livelihood in the Lesser Himalaya" *EOS*, 105, 2024.

[15] McDowell, W.H., Lugo, A.E., James, A., "Export of nutrients and major ions from Caribbean catchments", *J. North American Benthol Soc* 14(1), 12-20, 1995.

[16] Flintrop, C., Hohlmann, B., Jasper, T., Korte, C., Podlaha, O.G., Scheele, S., Veizer, J., "Anatomy of pollution: Rivers of North Rhine Westphalia, Germany", *American J Sci* 296, 59-98, 1996.

[17] Meybeck, M., "Man and river interface: multiple impacts on water and particulate chemistry illustrated in the Seine River basin", *Hydrobiologia* 373/374, 1-20, 1998.

[18] Caraco, N.F, Cole, J.J., "Human Impact on Nitrate Export: An analysis using major world rivers", *Ambio* 28(2), 167-170, 1999.

[19] Gaillardet, J., Dupre, B., Louvat, P., Allegre, C.J.,"Global silicate weathering and CO_2 consumption rates deduced from the chemistry of large rivers", Chem Geol 159(17), 3-30, 1999.

[20] Roy, S., Gaillardet, J., Allegre, C.J., "Geochemistry of dissolved and suspended loads of the Seine River, France: Anthropogenic

impact, carbonate and silicate weathering, *Geochim Cosmochim Acta* 63 (9), 1277-1292, 1999.

[21] Zhang, J., Zhang, Z.F., Liu, S.M., Wu, Y., Xiong, H., Chen, H.T., "Human impacts on the large world rivers: Would the Chanjiang (Yangtze River) be an illustration?", *Global Biogeochemical Cycles* 13 (4), 1099-1105, 1999.

[22] Vörösmarty, C.J., Green, P., Salisburg, J., and Lammers, R.B., "Global water resources: vulnerability from climate change and population growth", *Science* 289, 284-288, 2000.

[23] Hartmann, J., Jansen, N., Kempe, S., Durr, H.H., "Geochemistry of the river Rhine and the upper Danube: Recent trends and lithological influence on baselines", *J Environ Sci Sust Soc* 1, 39-46, 2007.

[24] Bhatt, M.P. and McDowell, W.H., "Evolution of surface water chemistry along the Bagmati drainage within Kathmandu valley", *Water, Air and Soil Pollution*, Vol. 185, 165-176, 2007. https://doi.org/10.1007/s11270-007-9439-4

[25] Daley, M.L., Potter, J.D., and McDowell, W.H., "Salinization of urbanizing New Hampshire streams and groundwater: effects of road salt and hydrologic variability", *J North American Benthol Soc* 28(4), 929-940, 2009.

[26] Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glodden, S., Bunn, S.E., Sullivan, C.A., Liermann, C.R., Davies, P.M., "Global threats to human water security and river biodiversity", *Nature* 467, 555-561, 2010.

[27] Bhatt, M.P., and Gardner, K., "Variation in DOC and trace metal concentration along the heavily urbanized basin in Kathmandu Valley, Nepal", *Environ Geol* 58 (4): 867-876, 2009.

[28] Thom, R., Clair, T.S., Burns, R., Anderson, M., "Adaptive management of large aquatic ecosystem recovery programs in the United States", *Journal of Environmental Management* 183 (Pt 2), 424-430, 2016.

[29] Ding, R., Yu, K., Fan, Z. and Liu, J., "Study and application of urban aquatic ecosystem health evaluation index in River Network Plain Area" *MDPI International Journal of Environmental Research and Public Health*, 19, 16545, 2022.

[30] Kaushal, S.S., Likens, G.E., Pace, M.L., Reimer, J.E., Mass, C.M., Galella, J.G., Utz, R.M., Duan, S., Kryger, J.R., Yaculak, A.M,, Boger, W.L., Baile,y N.W., Haq, S., Wood, K.L., Wessel, B.M., Park, C.E., Collison, D.C., Aisin, B.Y.I., Gedeon, T.M., Chaudhary, S.K., Wildmer. J., Blackwood, C.R., Bolster, C.M., Devilbiss, M.L., Garrison, D.L., Halevi, S., Kese, G.Q., Quach, E.K., Rogelio, C.M.P., Tan, M.L., Wald, H.J.S., Woglo, S.A., (2021) "Freshwater salinization syndrome: from emerging global problem to managing risks", *Biogeochemistry* 154, 255-292, 2021.

[31] Dixon, H.J., Elmarsafy, M., Hannan, N., Gao, V., Wright, C., Khan, L., and Gray, D.K., "The effects of roadways on lakes and ponds: a systematic review and assessment of knowledge gaps", *Environmental Review* 30, 501-523, 2022.

[32] Shattuck, M.D., Fazekas, H.M., Wymore, A.S., Cox, A., McDowell, W.H., "Salinization of stream water and groundwater at daily to decadal scales in a temperate climate", *Limnoloy and Oceanography Letters* 8, 131-140, 2023.

[33] DHM, Department of Hydrology and Meteorology, *Water quality data of rivers of Kathmandu valley 1992-1995*, DHM, Nepal, 1996, pp 69.

[34] ENPHO, Environment and Public Health Organization, *Monitoring and assessment of water quality in Shivapuri Watershed, HMG/FAO*, Kathmandu, Nepal, 1997, pp 1-244.

[35] Karna, S.K,, Harada, H., "Surface water pollution in three urban territories of Nepal, India, and Bangladesh", *Environ Management* 28(4), 483-496, 2001.

[36] ITECO, Nepal (P) Ltd., *Feasibility study and detailed engineering design to update master plan for Bagmati area sewage project*, final report. His Majesty's Government of Nepal, 2003. pp 1-69

[37] Bhatt, M.P., Bhatt, S., and Gaye, B., "Controls of pond water chemistry within Kathmandu Valley, Nepal", *International Journal of Lakes and Rivers* 6(2), 153-172, 2013.

[38] Kannel, P.R,, Lee, S., Kanel, S.R., Khan, S.P., Lee, Y.S., "Spatial-temporal variation and comparative assessment of water qualities of urban river system: a case study of the river Bagmati (Nepal)", *Environ Monit Assess* 129, 433-459, 2007.

[39] DHM, Department of Hydrology and Meteorology, *Water Quality Summary 1992 - 2006*, DHM, Ministry of Environment, Science and Technology, Government of Nepal, Kathmandu, Nepal, 2008.

[40] Bhatt, M.P., McDowell. W.H., Gardner, K., and Hartman, J., "Chemistry of heavily urbanized Bagmati River system within Kathmandu valley, Nepal: Export of organic matter, nutrients and metals", *Environmental Earth Sciences* 7, 911-922, 2014. https://doi.org/10.1007/s12665-013-2494-9

[41] Bhatt, M.P., *Water quality and flux of Bagmati River within Kathmandu valley, Nepal. In: Surface and Sub-surface water in Asia: Issues and Perspectives*, edited by V Subramanian, IOS Press BV, Published in Amsterdam, Netherlands, pp. 243-263, 2015.

[42] Shakya, M.B., Nakamura, T., Kamei, J., Shrestha, S.D., and Nishida, K., "Seasonal groundwater quality status and nitrogen contamination in shallow aquifer system of the Kathmandu Valley, Nepal", *MDPI Water* 11, 2184, 2019.

[43] Sarkar, B., Mitchell, E., Frisbie, S., Grigg, L., Adhikari, S., and Maskey-Byanju, R., "Drinking water quality and public health in the Kathmandu Valley, Nepal: coliform bacteria, chemical contaminants and health status of consumers", *Journal of Environmental and Public Health* 2022, Article ID 3895859, pp. 1-21, 2022.

[44] Shrestha, S., Bista, S., Byanjankar, N., Shrestha, S., Joshi, D.R., and Joshi, T.P.," Groundwater quality evaluation for drinking purpose using water quality index in Kathmandu Valley, Nepal", *Water Science* 37(1), 239-250, 2023.

[45] Gunnarsdottir, M.J., Gardarsson, S.M., St. Jansson, G., Bartram, J., Chemical quality and regulatory compliance of drinking water in Iceland", *International Journal of Hygiene and Environmental Health* 219(8), 724-733, 2016.

[46] CBS, Central Bureau of Statistics, "Statistical Year Book of Nepal. Central Bureau of Statistics" *Government of Nepal*, Kathmandu, Nepal, pp. 618, 2021.

[47] DNPWC, Department of National Parks and Wildlife Conservation, *Shivapuri National Park*, His Majesty's Government, Kathmandu, Nepal, 2003.

[48] NWSC, Nepal Water Supply Corporation, (2001) "*Annual Report*. NWSC, Kathmandu, Nepal, 2001, pp 1-21.

[49] JICA, Japan International Cooperation Agency, *Groundwater management project in the Kathmandu valley*, His Majesty's Government of Nepal, Nepal Water Supply Corporation, 1990, pp A1-F7.

[50] Dixit, A. and Upadhaya, M., "Augumenting groundwater in Kathmandu Valley: Challenges and possibilities", *Nepal Water Conservation Foundatio*, Kathmandu, Nepal, pp. 42, 2005.

[51] Juttner, I., Sharma, S., Dahal, B.M., Ormerod, S.J., Chimonides, P.J., Cox, E.J., "Diatoms as indicators of stream quality in the Kathmandu valley and middle hills of Nepal and India", *Freshwater Biol* 48, 2065-2084, 2003.

[52] Shrestha, O.M., Koirala, A., Karmacharya, S.L., Pradhanga, U.B., Pradhan, P.M., Karmacharya, R., Hanisch, J., Kerntke, M., Joshi, P.R., Stiner, L., Busch, K., Jnawali, B.M., Maske, N.D., Tuladhar, G.B., Kaphle, K.P., "*Engineering and Environmental Geology Map of the Kathmandu Valley*", Department of Mines and Geology, His Majesty's Government, Kathmandu, Nepal, 1998.

[53] IDRS, Integrated Development and Research Services (P) Lts, *Final Report for the Bagmati River Basin Study Impact of Reservoirs and Diversion*, Department of Hydrology and Meteorology, His Majesty's Government, Kathmandu, Nepal, 2001. pp 45.

[54] K.M.C., Kathmandu Metropolitan City, "Information System Center, Kathmandu Metropolitan City", Kathmandu, Nepal, 2001.

[55] ASTM, American Society for Testing and Materials, Analytical methods for cations, *ASTM D 6919-03*, West Conshohocken, PA, 2007.

[56] US EPA, United States Environmental Protection Agency, "Method for the determination of Anions, *US EPA no. 300.1*, 2007.

[57] US EPA, United States Environmental Protection Agency, "Method for the determination of Ammonium", *US EPA no. 350.1*, 2005.

[58] US EPA, United States Environmental Protection Agency, "Method for the determination of Phosphate, *US EPA no. 365.1*, 2005.

[59] US EPA, United States Environmental Protection Agency, "Method for the determination of Silica", *US EPA no. 370.1*, 2005.

[60] US EPA, United States Environmental Protection Agency, "Method for the determination of dissolved organic carbon, *US EPA no. 415.1*, 2002.

[61] Merriam, J., McDowell, W.H., Currie, W.S.,"A high temperature catalytic technique for determining total dissolved nitrogen", *Soil Sci Soc American J* 60, 1050-1055, 1996.

[62] US EPA, United States Environmental Protection Agency, 1991. "Method for the determination of metals in Environmental samples", EPA/600/4-91/010, Office of Research and Development, Washington, DC, 1991.

[63] WHO, World Health Organization, "Guideline for drinking water quality", Fourth Edition incorporating the first addendum, 2017, p. 541. ISBN 978-92-4-154995-0.

[64] US EPA, United States Environmental Protection Agency, 2024. https://www.epa.gov/ground-water-and -drinking-water/national-primary-drinking-water regulations, Accessed on May 25, 2024.