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Spatiotemporal assessment of water quality and geochemical evolution of Ugii Lake

***CORRESPONDING AUTHOR**
Uuriintuya Gantsetseg
uuriintuya_g@mas.ac.mn
ORCID
0000-0002-4694-9129

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Uuriintuya Gantsetseg[1,*], Odsuren Batdelger[1], Narangerel Serdyanjiv[1], Batnyam Tseveengerel[1], Odbaatar Enkhjargal[1], Purevsuren Munkhtur[1], Davaagatan Tuyagerel[1], Chao Han[2], Cheng Liu[2], Zhaode Wang[2]

[1]*Institute of Geography and Geoecology, Mongolian Academy of Sciences, Ulaanbaatar, 15170, Mongolia*
[2]*Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, China*

ABSTRACT

Ugii Lake, a shallow freshwater body in Mongolia's semi-arid steppe zone, plays an important ecological and socioeconomic role. However, its water quality is increasingly influenced by both natural variability and human-induced pressures. This study investigates the seasonal and spatial dynamics of water chemistry in Ugii Lake by analyzing samples collected during three key periods November 2023 (late autumn), June 2024 (summer), and January 2025 (winter). A total of 24 samples were analyzed for major ions, nitrogen compounds, and supporting physicochemical indicators. To understand the processes shaping the lake's hydrochemistry, we employed a combination of Piper diagram, ion ratio-based mixing, scatter plots, and multivariate statistical tools, including hierarchical cluster analysis (HCA) and decision tree modeling. The findings revealed that Ugii Lake water predominantly belongs to the Ca–Mg–HCO_3 type, consistent with carbonate and silicate mineral weathering. Notably, fluoride concentrations in several samples exceeded WHO drinking water guidelines, indicating possible natural geogenic enrichment. Ammonium levels were also elevated in certain areas, suggesting localized organic input or anthropogenic sources. Cluster analysis grouped water samples primarily by season, highlighting strong temporal patterns in water chemistry rather than spatial ones. Meanwhile, the decision tree analysis identified magnesium, fluoride, and ammonium as key predictors of total nitrogen concentrations, underscoring their geochemical and possibly anthropogenic origin.

KEYWORDS

Ugii Lake, Water quality, Geochemical processes, Decision tree, Nitrogen pollution

1. INTRODUCTION

Freshwater lakes are among the most vital natural ecosystems on the planet. They play a crucial role in maintaining ecological balance, supporting biodiversity, and sustaining the livelihoods of communities that depend on them. Yet, these fragile systems are increasingly under threat. The combined pressures of climate change and human activity such as land conversion, intensive farming, waste discharge, and expanding tourism, are steadily degrading water quality [1], [2]. These pressures alter runoff patterns, increase nutrient loading, and mobilize harmful trace elements, placing both aquatic life and dependent populations at risk [3], [4].

Ugii Lake, a shallow freshwater lake situated in the semi-arid steppes of Arkhangai Province in central Mongolia, is one such ecosystem facing these challenges. Recognized for its ecological importance, it is listed as a wetland of international significance under the Ramsar Convention. The lake not only serves as critical habitat for migratory birds and local biodiversity but also provides water for household use and supports a growing tourism sector. However, mounting human-induced stressors including overgrazing, seasonal tourism camps, and the broader impacts of climate variability, such as rising temperatures and diminished tributary inflows, have begun to compromise the lake's ecological integrity [5].

To date, most research on Ugii Lake has centered around its physical and biological characteristics [6]. Detailed scientific assessments of its seasonal water chemistry, pollution dynamics, and geochemical interactions have been sparse. Yet such insights are crucial, especially in arid and semi-arid regions where water bodies are highly sensitive to even small changes in hydrology [7]. This study aims to bridge that gap. Specifically, we examine how Ugii Lake's water quality changes across space and seasons, identify the geochemical processes at work, and assess its pollution. By combining major ion chemistry, diagnostic geochemical tools (Piper diagram), and multivariate statistical techniques such as cluster analysis, the study seeks to unravel the natural and human factors shaping the lake's water chemistry. Importantly, this research establishes a valuable baseline for future environmental monitoring in the region. It also sheds light on the resilience and vulnerabilities of Mongolian lake systems in the face of a changing climate and evolving land-use patterns. The findings are intended to support the development of informed water management policies, not just for Ugii Lake, but for similar freshwater ecosystems across Central Asia.

2. RESEARCH METHODS

2.1. Field sampling and in-situ measurements

Water sampling was conducted throughout three different campaigns: November 2023 (late autumn), June 2024 (summer season), and January 2025 (winter season), thus covering seasonal fluctuation. A total of 24 surface water samples were collected from Ugii Lake using pre-cleaned polyethylene bottles. Sampling points were geo-referenced through a handheld GPS receiver (Garmin eTrex), in addition to recording field conditions such as weather and lake level.

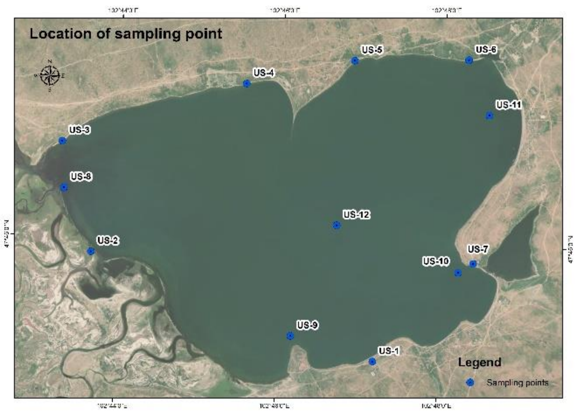

Figure 1. Location of sampling points

At all locations where sampling was marked, in situ water temperature (°C), pH, electrical conductivity (EC, µS/cm), and total dissolved solids (TDS, mg/L) were determined using a portable multiparameter probe (Hanna Instruments HI98194). The samples were passed through 0.45 µm membrane filters and subsequently kept at 4°C in an ice-cooled box until being taken to the laboratory for analysis.

2.2. Laboratory analysis

In the laboratory, samples were tested for:

Major ions: Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, HCO_3^{-}, CO_3^{2-}, F^{-}

Nitrogen components: NH_4^{+}, NO_2^{-}, NO_3^{-}, Total Nitrogen (TN)

The following analytical procedures were applied: The titrimetric method was used for alkalinity, total hardness (TH), and chloride (Cl^{-}) as per APHA (2017) standard methods [8]. Spectrophotometry (UV-Vis) was used to measure NO_3^-, NH_4^+, SO_4^{2-}, and F^- in a Hach DR6000 apparatus. Calibration was performed using multi-element standards made in ultrapure deionized water (18.2 MΩ·cm resistivity). All reagents used were of analytical grade. QA/QC methods included blank sample analysis, duplicate analysis, and recovery of standard reference material (SRM).

2.3. Data analysis and water quality assessment

Descriptive statistics (standard deviation, mean, minimum, and maximum values) were computed to describe water chemistry variation between seasons. Graphical plots (Piper diagram, ion-ratio based mixing, and Scatter diagram) were made using OriginPro 2025b. Hierarchical Cluster Analysis (HCA) was performed to group similar water quality sampling sites based on water quality parameters using Orange 3.35.0 software. Euclidean distance and Ward's linkage method were employed to form the dendrogram. Decision Tree Modeling selected the most essential variables through recursive binary splitting, helping to reveal patterns and thresholds that relate to nitrogen pollution.

3. RESULT AND DISCUSSION

3.1. Physicochemical characteristics of Ugii Lake water

Descriptive statistics of key physicochemical indicators for Ugii Lake are shown in Table 1. The lake displayed a moderately alkaline to alkaline pH, with pH values ranging from 8.13 to 9.37 and an average of 8.56. This is typical for lakes in semi-arid regions, where carbonate-rich soils and bedrock influence water chemistry [9]. The variation in pH may be driven by natural CO_2 fluctuations and biological activity, such as photosynthesis. Electrical conductivity (EC) ranged from 472 to 794 µS/cm (mean: 632 µS/cm), which suggests moderate levels of dissolved salts in the water. Similarly, total dissolved solids (TDS) were between 260 and 439 mg/L, falling within the "slightly mineralized" category [10]. The higher EC values recorded during colder months likely reflect less dilution from inflow and stronger evaporation conditions typical of closed-basin lakes in Mongolia's dry season [11].

Among the major cations, calcium (Ca^{2+}) and magnesium (Mg^{2+}) were dominant, averaging 24.2 mg/L and 35.45 mg/L, respectively. These, along with bicarbonate (HCO_3^-), confirm the Ca–Mg–HCO_3 water type, commonly associated with the weathering of limestone and dolomite rocks.

Bicarbonate levels ranged from 274.5 to 408.7 mg/L, while carbonate (CO_3^{2-}) varied more widely (12–36 mg/L), which may relate to seasonal changes in temperature and pH that shift carbonate equilibria [12].

Sodium and potassium ($Na^+ + K^+$) concentrations were slightly elevated (69.9–104.2 mg/L), indicating potential input from feldspar weathering or human sources such as detergents or wastewater runoff [13]. Chloride (Cl^-) and sulfate (SO_4^{2-}) levels were relatively stable and within natural ranges (mean Cl^-: 25.9 mg/L; SO_4^{2-}: 52.25 mg/L), pointing to minimal external contamination during the study period.

Fluoride (F^-) levels stood out as a concern, ranging from 0.4 to 3.48 mg/L with an average of 2.51 mg/L well above the World Health Organization's guideline of 1.5 mg/L [14]. This suggests the fluoride may come from natural geologic sources such as fluorite or apatite-bearing rocks in the watershed, which is consistent with findings in other parts of Mongolia [15].

The lake water was moderately hard (mean TH: 4.29 mg/L), falling into the "soft to moderately hard" category. The oxidation of permanganate (CODmn), which serves as a rough estimate of organic matter in water, ranged widely from 0.64 to 9.44 mg/L. This variation hints at seasonal inputs of organic material possibly from decomposing plants or runoff from nearby grazing areas.

Ammonium (NH_4^+) levels varied between 0.01 and 0.68 mg/L, averaging 0.13 mg/L. Some samples slightly exceeded Mongolian standards (MNS 4586:2024), indicating a need for closer monitoring in zones of intensive human activity [16]. Nitrite (NO_2^-) concentrations were mostly low (mean: 0.09 mg/L) but peaked at 0.97 mg/L in a few samples, which could be tied to microbial processes or decaying organic matter under low oxygen conditions. Nitrate (NO_3^-) ranged from 0.16 to 1.94 mg/L (mean: 0.28 mg/L). These values suggest active nitrification, and their fluctuations are likely influenced by temperature, oxygen levels, and biological uptake, factors known to drive nitrogen cycling in shallow lakes [17].

3.2. Geochemical processes: Understanding water–rock interactions through the Piper diagram

Table 1. Descriptive statistics of the physicochemical parameters of the Ugii Lake water

Parameters	Unit	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD
		Late Autumn season				Summer season				Winter season			
pH		8.45	9.37	9.04	0.32	8.41	8.69	8.61	0.08	8.13	8.20	8.16	0.03
EC	µS/cm	671	732	685	18.6	472	644	611	42.3	647	794	672	53
TDS	mg/L	369	439	377	22.31	260	354	337	23.2	356	437	370	29.2
Ca^{2+}	mg/L	24.2	27.7	24.4	1.4	19.8	29.9	23.6	2.58	24.0	27.7	24.6	1.39
$Na^{+}+K^{+}$	mg/L	70.8	85.2	73.2	4.7	69.9	88.7	79.6	4.60	81.6	104.2	86.8	8.06
Cl^{-}	mg/L	23.4	25.2	25.2	0.6	23.8	27.7	25.9	0.9	28.0	32.0	28.4	1.5
HCO_3^{-}	mg/L	280.6	317.2	305.0	11.2	274.5	338.6	292.8	16.6	329.4	408.7	353.8	28.0
CO_3^{2-}	mg/L	24.0	36.0	36.0	5.42	12.0	30.0	21.0	6.0	12.0	18.0	18.0	2.40
SO_4^{2-}	mg/L	40.0	82.0	45.0	13.6	43.0	59.3	53.5	4.1	51.0	60.3	52.2	3.4
Mg^{2+}	mg/L	36.5	43.8	38.5	2.5	31.3	36.5	33.0	1.5	36.7	43.4	39.8	2.4
F^{-}	mg/L	5.92	6.39	6.10	0.15	0.40	2.66	2.56	0.66	1.68	2.17	1.77	0.17
TH	mg/L	4.26	4.98	4.39	0.23	3.75	4.40	3.87	0.21	4.33	4.95	4.42	0.23
COD mn	mg/L	4.16	7.68	4.80	1.19	4.32	9.44	7.52	1.48	0.64	1.12	0.96	0.19
TN	mg/L	0.09	0.65	0.31	0.19	0.08	0.51	0.29	0.14	0.34	0.76	0.56	0.14
NH_4^{+}	mg/L	0.07	0.76	0.34	0.24	0.00	0.44	0.16	0.12	0.04	0.13	0.06	0.03
NO_2^{-}	mg/L	0.01	0.01	0.01	0.00	0.01	0.74	0.14	0.22	0.01	0.97	0.38	0.33
NO_3^{-}	mg/L	0.16	0.32	0.22	0.05	0.19	1.69	0.28	0.40	1.32	1.94	1.67	0.22

Piper diagram was used to visualize the major ion composition across different seasons to understand better the chemical behavior of Ugii Lake's water and its interaction with the surrounding geology (Figure 2).

The results show a clear and consistent pattern: in all three sampling periods November 2023, June 2024, and January 2025 the lake waterfalls within the calcium–magnesium–bicarbonate (Ca–Mg-HCO_3) zone. This strongly suggests that the water chemistry is primarily shaped by natural processes, especially the weathering of carbonate-rich rocks like limestone and dolomite [18].

Looking closer at the diagram, most points in the cation triangle cluster near the calcium (Ca^{2+}) corner, with smaller contributions from sodium and potassium. On the anion side, the dominance of bicarbonate (HCO_3^{-}) is unmistakable. This combination is typical of lakes in semi-arid steppe environments, where minerals from soil and bedrock slowly dissolve into the water through natural geochemical processes [19].

What's particularly notable is that the overall water type didn't change much despite covering three distinct seasons. This points to a geochemically stable system that is largely buffered against short-term changes. In other words, natural weathering is the dominant force shaping the lake's chemistry, more so than seasonal variation or direct human activity.

Piper diagram results indicate that the lake's hydrochemistry is strongly governed by geological factors, yet it also reflects seasonal variations and human influences, especially in areas with concentrated land use or surface runoff.

The current study provides a comprehensive analysis of Ugii Lake's water quality, building upon and extending the findings of prior research. Our results confirm the dominance of a Ca–Mg–HCO_3-type hydrochemical facies, consistent with the observations of Navaandorj et al. [20], who attributed this composition to carbonate and silicate weathering processes.

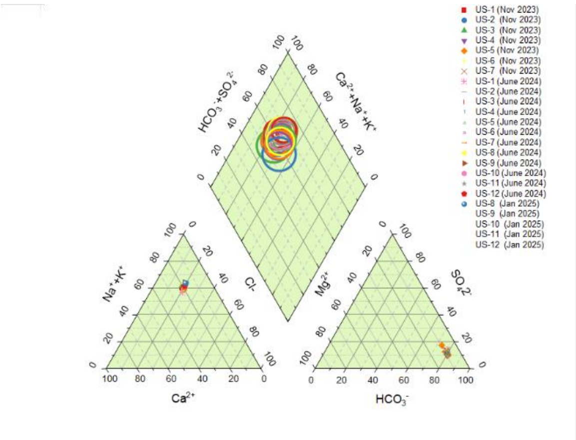

Figure 2. Hydrochemical facies based on a Piper diagram

3.3. Geochemical processes: Insights from mixing diagrams

To complement the Piper diagram analyses, two ion ratio-based mixing diagrams were constructed using the molar ratios of Ca^{2+}/Na^{+} vs HCO_3^{-}/Na^{+} and Ca^{2+}/Na^{+} vs Mg^{2+}/Na^{+} (Figure 3). These diagrams help us understand the relative influence of three dominant weathering and geochemical regimes: carbonate dissolution, silicate weathering, and evaporite inputs [21], [22].

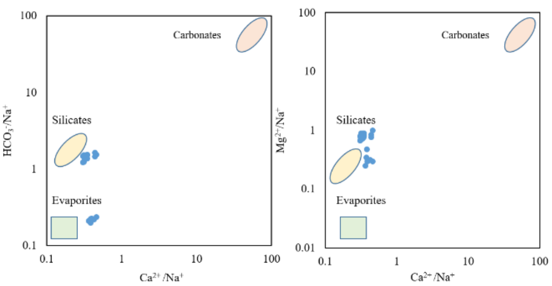

Figure 3. Mixing diagram molar ratios of Ca^{2+}/Na^{+} vs HCO_3^{-}/Na^{+} and Ca^{2+}/Na^{+} vs Mg^{2+}/Na^{+}

The majority of the water samples clustered toward the "silicate weathering" field, suggesting that the chemical makeup of Ugii Lake is largely influenced by the breakdown of aluminosilicate minerals, such as feldspar and mica, likely sourced from surrounding granitic and metamorphic bedrock.

Interestingly, a distinct group of samples plotted within or near the "evaporation dominance" zone, specifically those collected in January 2025. This pattern suggests that evaporative concentration played a much larger role during the winter sampling period, likely due to reduced inflow, minimal precipitation, and ice-cover conditions that limit water exchange.

In contrast, none of the samples approached the "carbonate" endmember zone, even though the Piper diagram classified the lake water as Ca–HCO_3 type. This apparent discrepancy may be due to the co-influence of silicate sources or because more complex hydrological and mineral interactions dilute carbonate weathering. The mixing diagram confirms that Ugii Lake's chemistry is governed by a combination of silicate weathering and seasonal evaporation, with carbonate dissolution playing a secondary role. The seasonal shift of 2025 winter samples toward the evaporative corner is a strong indication of this shallow lake system's climatic sensitivity.

3.4. Ion balance and water chemistry relationships

To examine ionic relationships and charge balance in Ugii Lake water, scatter plots of equivalent concentrations (meq/L) were constructed for the major cations and anions (Figure 4, panels a–d). These diagrams help evaluate geochemical equilibrium, dominant ion contributions, and potential exchange processes [23], [24].

Figure 3a compares the total cation concentration ($Ca^{2+} + Mg^{2+}$) to the total cation charge (Tz^{+}). The points fall slightly below the 1:1 line, suggesting a modest anion excess potentially due to additional unmeasured anions or bicarbonate buffering beyond the measured constituents. Figure 3b, showing $Na^{+} + K^{+}$ versus Tz^{+}, indicates that sodium and potassium contribute a smaller fraction to the total cationic load, consistent with earlier findings from the Piper diagram. This pattern supports the conclusion that alkali metals play a minor role, and divalent cations dominate the water chemistry. In Figure 3c, a strong linear correlation is observed between $Ca^{2+} + Mg^{2+}$ and $HCO_3^{-} + SO_4^{2-}$, suggesting that these cations are balanced primarily by bicarbonate and sulfate anions, and that their source is likely rock weathering, both carbonate and silicate-derived [25]. Figure 3d compares HCO_3^{-} to $HCO_3^{-} + SO_4^{2-}$ and shows a tight fit near the 1:1 line, implying that bicarbonate is the dominant anion, further confirming the Ca–HCO_3 type water classification.

These diagrams reinforce the interpretation that Ugii Lake's water chemistry is geochemically balanced and dominantly shaped by natural mineral weathering, with only minor deviations from ideal charge neutrality. The near-linear relationships suggest minimal anthropogenic interference and a system governed primarily by geogenic inputs and ionic equilibrium.

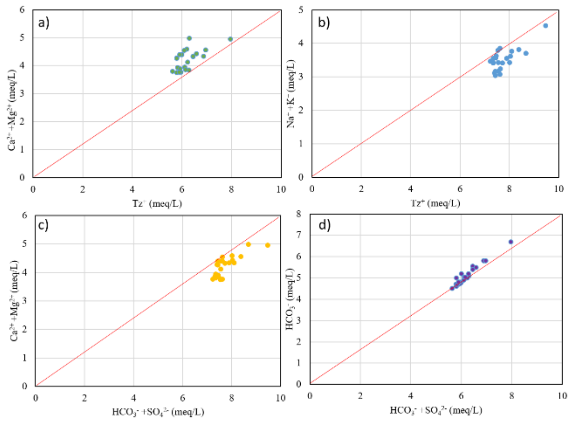

Figure 4. Scatter diagram (a-d)

3.5. Cluster analysis of water quality parameters

To explore seasonal and spatial patterns in water quality, hierarchical cluster analysis (HCA) was performed using Ward's linkage method and Euclidean distance metrics in Orange software. Based on their physicochemical similarity, the resulting dendrogram (Figure 5) grouped the 24 water samples into three distinct clusters (C1–C3).

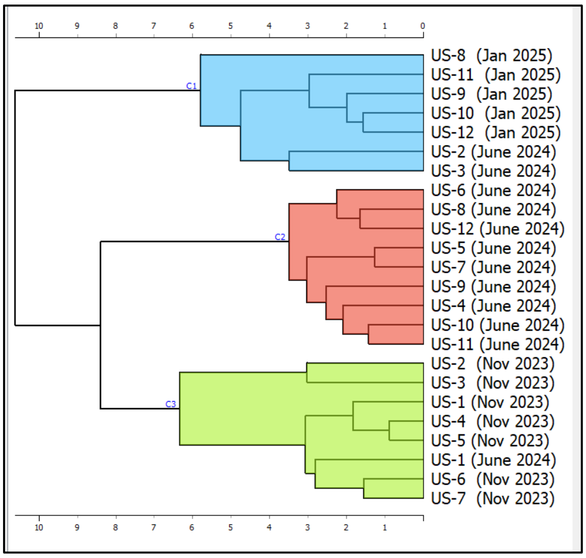

Figure 5. Hierarchical cluster analysis (HCA)

Cluster C1 primarily consists of samples collected during January 2025 (winter), including US-8, US-9, US-10, US-11, and US-12. These samples show tight internal similarity, reflecting the concentration of dissolved ions due to low inflow and enhanced evaporation under ice-covered, low-temperature conditions. This is a typical feature of shallow lakes in semi-arid zones during winter [26]. US-2 and US-3 shared multiple hydrochemical features with January samples, including high Na^{+}+K^{+} concentrations, elevated EC and TDS, and increased Mg^{2+} and SO_4^{2-} levels. These parameters reflect similar environmental conditions such as limited inflow, localized evaporation, and ion accumulation, particularly in the swampy region. In combination with their TN values, these similarities explain their clustering into the winter group (C1), despite being sampled in summer. Cluster C2 comprises mainly June 2024 (summer) samples. This group reflects the influence of increased river inflow and surface runoff during the rainy season. This may have led to a relative dilution of solute concentrations and greater variability in specific indicators. Cluster C3 includes mainly November 2023 (late autumn) samples. The group shows moderate separation, suggesting a transitional chemical profile influenced by reduced flow and the first rainfall events over dry soils, which often carry accumulated ions into the lake [27]. Although US-1 was collected during the summer (June), it showed an unusual hydrochemical profile. The sample had relatively low overall mineralization (TDS = 341 mg/L), yet notably elevated concentrations of calcium (Ca^{2+} = 28.1 mg/L) and magnesium (Mg^{2+} = 36.5 mg/L) compared to other summer sites. This combination suggests that US-1 may have been influenced by distinct geochemical processes, such as enhanced water–rock interactions, localized solute accumulation, or the early flushing of ions from dry soils following initial rainfall. These factors resulted in a chemical signature more similar to transitional or autumn conditions rather than typical summer dilution patterns likely contributing to its placement within cluster C3.

What's especially revealing is how the clusters are aligned with sampling seasons rather than spatial location. This strongly indicates that temporal variation driven by climate, hydrology, and land use is a dominant factor shaping the hydrochemistry of Ugii Lake. In other words, the lake's water quality is not static but fluctuates meaningfully with environmental and seasonal dynamics.

While Nomindari et al. [28] emphasize spatial differences, our hierarchical cluster analysis suggests that seasonal variation actually plays a much more significant role in shaping water quality parameters. During winter, increased evaporation leads to higher concentrations of major ions, whereas summer inflows result in dilution. These findings highlight the critical importance of accounting for seasonal dynamics when assessing water quality, rather than focusing solely on spatial heterogeneity.

3.6. Decision tree analysis: Identifying factors influencing total nitrogen (TN)

A decision tree model was developed using Orange data mining software to understand which water quality parameters most strongly influence total nitrogen (TN) concentrations in Ugii Lake. The model selected the most essential variables through recursive binary splitting, helping to reveal patterns and thresholds that relate to nitrogen pollution.

At the top of the tree, magnesium (Mg^{2+}) emerged as the most decisive variable. TN levels tended to be higher when Mg^{2+} exceeded 37.1 mg/L, indicating an indirect geochemical link between Mg-bearing minerals and nutrient enrichment, possibly driven by catchment geology or groundwater inputs [29].

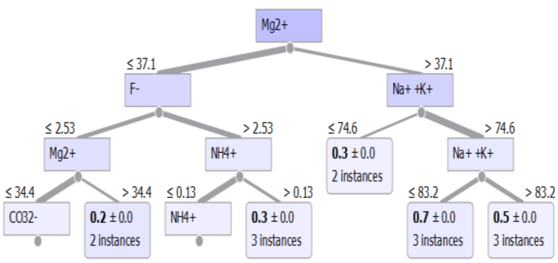

Figure 6. Decision tree analysis

The second split involved fluoride (F^-), where TN levels were further elevated if F^- was greater than 2.53 mg/L. This co-occurrence suggests that fluoride and nitrogen may share common pathways, such as groundwater movement or zones of anthropogenic influence like settlements or grazing lands [30].

Further down the tree, additional splitting variables included $Na^+ + K^+$ (alkali metals), whose higher concentrations were linked to higher TN, possibly due to wastewater inputs or increased ionic strength; NH_4^+ (ammonium), which directly represents reactive nitrogen forms from organic contamination or livestock activity; and CO_3^{2-} (carbonate), which may reflect pH-buffering conditions that influence nitrogen cycling in the lake. The terminal leaf nodes of the tree represent water sample groups with different TN averages (e.g., 0.2, 0.3, 0.5, 0.7 mg/L). This shows that TN concentrations are not determined by a single variable but by the interaction of multiple geochemical and anthropogenic factors.

Overall, the decision tree reveals a non-linear, rule-based relationship between TN and other water chemistry indicators, highlighting the complexity of nutrient pollution in closed-basin lakes like Ugii. Such insights are crucial for designing targeted mitigation and management strategies.

Navaandorj et al. [20] primarily highlighted the roles of climate change and anthropogenic activity in shaping water quality. In contrast, our findings point to magnesium (Mg^{2+}), fluoride (F^-), and ammonium (NH_4^+) as significant predictors of total nitrogen (TN) concentrations. This indicates a more intricate interplay between natural geochemical processes and human influences than previously recognized.

4. CONCLUSION

This study offered a detailed and multi-faceted assessment of Ugii Lake's water chemistry across three distinct seasons. The results reveal that the lake's hydrochemistry is largely shaped by natural mineral weathering, particularly from silicate and carbonate rocks, with seasonal evaporation acting as a secondary but consistent influence. While the overall water quality remains within acceptable ecological limits, notable hotspots of fluoride and ammonium enrichment were observed, suggesting the need for continued monitoring, especially in areas affected by land use or groundwater inflow.

Diagnostic diagrams, such as piper and ion mixing plots, confirmed that Ugii lake water is predominantly of the bicarbonate type, influenced by both geological and hydrological processes. Cluster analysis clearly grouped water samples by season, underscoring the strong role of temporal dynamics over spatial variation in controlling water chemistry. Furthermore, decision tree modeling identified magnesium, fluoride, and ammonium as the most influential variables governing total nitrogen levels, reflecting the complex interplay between geochemical conditions and potential anthropogenic sources.

Together, these findings generate new knowledge that enhances our understanding of Lake Ecosystem behavior under seasonal and environmental stressors. Beyond scientific interpretation, the insights derived from this study offer practical guidance for long-term monitoring, adaptive resource planning, and policy-making in fragile freshwater systems. In the case of Ugii Lake, this integrated approach demonstrates how combining geochemical tools with machine learning can support evidence-based management in response to climate variability and human pressures across central Asia.

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