NATIONAL ASSESSMENT REPORT FOR MONGOLIA

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CHAPTER 1. BASIC INFORMATION ON NATIONAL MONITORING ACTIVITIES

1.1 Outline of activities on acid deposition and air pollution in National Monitoring Plan

Mongolia is a landlocked country in Central Asia, located between Russia and China, with a total area of approximately 1.56 million km². The country is characterized by vast highlands, mountain ranges, steppe landscapes, and the Gobi Desert. Major geographical regions include the Altai, Khangai, and Khentii Mountains, the eastern steppe, and the Gobi region.

Mongolia has a strongly continental climate, with long, cold, and dry winters and short, warm summers. Annual precipitation is generally low and varies considerably across the country, with higher amounts in the northern and mountainous regions and much lower amounts in the Gobi. Mongolia is also vulnerable to climate-related hazards such as droughts, dzuds, strong winds, dust storms, and severe winter conditions.

The country has diverse natural zones ranging from mountain taiga and forest-steppe to grassland, desert-steppe, and desert. These ecosystems support extensive pastoral livestock production, which is a major form of land use.

Mongolia has a low and uneven population density. The population is highly concentrated in Ulaanbaatar and other urban centers, while large areas of the countryside remain sparsely populated. Rapid rural-to-urban migration has increased urbanization, particularly around Ulaanbaatar.

Overall, Mongolia is characterized by its vast territory, sparse population, extreme continental climate, extensive grasslands, and strong dependence on pastoral land use. These geographical and climatic characteristics are important for understanding environmental issues such as air quality, land degradation, pasture conditions, soil carbon, water resources, and climate change.

The Central Laboratory of Environment and Metrology (CLEM) serves as Mongolia's national center within the East Asia Network on Acid Deposition (EANET). In accordance with the EANET monitoring programme, CLEM conducts monitoring of wet and dry deposition, ambient air quality, inland aquatic environments, soils, and vegetation.

1.2 Monitoring program

Wet deposition monitoring at both sites is conducted each year from May to October. Monitoring is suspended during the coldest part of the year because the wet-only sampling equipment cannot operate reliably under extremely low-temperature conditions.

Dry deposition monitoring is conducted throughout the entire year at both Ulaanbaatar and Terelj, allowing the seasonal variation of atmospheric gaseous and particulate components, including the pronounced wintertime increases, to be evaluated. The monitoring programs are shown in Table 1.

Table 1. The monitoring programs

Items	Monitoring site	Monitoring period	Monitoring interval	Monitoring parameters
Wet deposition	Terelj Ulaanbaatar	2021–2025	Daily (May to October)	pH, EC, SO_4^{2-}, NO_3^-, Cl^-, NH_4^+, Na^+, K^+, Ca^{2+}, Mg^{2+}
Dry deposition	Terelj Ulaanbaatar	2021–2025	Biweekly Weekly	Gases: SO_2, HNO_3, HCl, NH_3 Aerosol: SO_4^{2-}, NO_3^-, Cl^-, NH_4^+, Na^+, K^+, Ca^{2+}, Mg^{2+}
Air quality monitoring	UB04	2016–2025	Continuous monitoring at 15-minute intervals	SO_2, NO_2, PM_{10}, $PM_{2.5}$, O_3, Meteorological parameters
Inland aquatic environment	Terelj River	2021–2025	Six times per year	pH, EC, alkalinity, SO_4^{2-}, NO_3^-, Cl^-, NH_4^+, Na^+, K^+, Ca^{2+}, Mg^{2+}
Soil	Ulaanbaatar	2021–2025	Every 3–5 years	pH (H_2O), pH (KCl) Exchangeable acidity

1.3 Monitoring sites

1.3.1 Urban site

Ulaanbaatar, the capital of Mongolia, is located in the central part of the country, in the Tuul River valley and among the mountain ranges of the Khentii Mountains. The city lies at an elevation of approximately 1,300–1,350 m above sea level and is geographically situated within the forest-steppe zone of the Khentii Mountain region. Its terrain is characterized by a combination of mountains, intermontane valleys, and river valleys. Ulaanbaatar has a strongly continental climate, with long and very cold winters and short, relatively warm summers. The surrounding mountains, including Bogd Khan, Chingeltei, and Songino Khairkhan, together with the Tuul River valley, strongly influence the city's local climatic and atmospheric conditions.

The Ulaanbaatar acid-deposition monitoring site had been located on the rooftop of the NAMEM building since 1998. Due to construction of an extension to the NAMEM building, the monitoring equipment was relocated on 15 June 2020, prior to the present assessment period. The wet-deposition sampler was moved to the meteorological observation field within the CLEM premises, while the filter-pack sampler used for dry-deposition monitoring was relocated to the UB01 air-quality monitoring station, also located within the CLEM premises (Figure 1).

The CLEM (or Khan-Uul) site is located 3.60 km from NAMEM. The UB04 (or Bayanzurkh) site is located 1.95 km from NAMEM and 4.85 km from CLEM.



Figure 1. Locations of the urban monitoring sites relative to NAMEM

Rooftop of NAMEM (MNA 001)
47°55’13”N, 106°54”E



Khan-Uul (MNA 004)
47°53'39"N 106°52'57"E



Figure 2. Wet deposition and filter pack sampling site in Ulaanbaatar

1.3.2 Remote site

The Terelj monitoring site is located in the Gorkhi-Terelj National Park, northeast of Ulaanbaatar. In terms of physical geography, the site lies within the forest-steppe zone of the Khentii Mountain Range and is characterized by a mountainous terrain with valleys and intermontane depressions. The area has a relatively cool and humid climate, with forest and grassland ecosystems forming the dominant natural landscape.

At the Terelj site, the monitoring station was relocated twice due to changes in the electricity supply. It was finally relocated to the Terelj meteorological observation site in May 2023. Furthermore, considering the increasing human settlement in the Terelj area and the proximity of the new site to the main road, the Network Center has proposed reclassifying the site from “remote” to “rural.”



Figure 3. Locations of the Terelj monitoring sites relative to initial site location

Initial location	Temporary location	Existing location
47°58'59"N 107°27'4"E	47°59'7"N 107°27'30"E	47°59'19"N 107°27'24"E



Figure 4. Wet deposition and filter pack sampling site in Terelj (MNA 002)

1.3.3 Air quality monitoring station

The automatic air quality monitoring network in Ulaanbaatar was established in 2010. Currently, the network comprises 19 fully automated monitoring stations operating continuously across the city, with air quality data made publicly available through the official website, www.agaar.gov.mn. As part of Mongolia's cooperation with EANET, air quality monitoring data from the UB04 station, located in Bayanzurkh District, are submitted annually to the EANET Network Center. The UB04 station is equipped with monitoring instruments manufactured by the French company ENVEA.

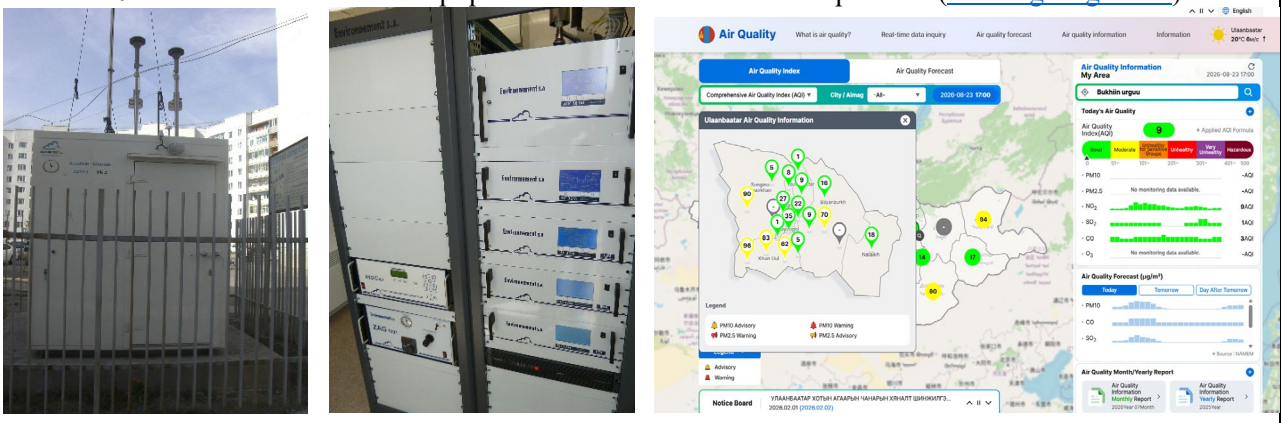


Figure 5. UB04 air quality monitoring station (Bayanzurkh-MNA 003)

1.3.4 Inland aquatic monitoring site

The Terelj River originates in the southern part of the Khentii Mountains and is one of the important tributaries of the Tuul River. It flows through the Gorkhi-Terelj National Park, an ecologically important protected area located approximately 60 km east of Ulaanbaatar.



Figure 6. Inland aquatic sampling site at Terelj River

The Terelj River is characterized by relatively clean water, particularly in its upper reaches. Water quality studies have generally classified the river as **"**very clean to clean" (Class I–II), with nutrient-related pollutants such as ammonium, nitrite, and phosphate generally within acceptable limits.

1.4 Sampling and Measurement

The The wet-only precipitation sampler manufactured by Ogasawara Co., Ltd. has a 357 mm collection opening and is used for daily precipitation sampling during the warm season. Because it cannot operate reliably under extremely low winter temperatures, it is removed before freezing conditions and reinstalled the following spring. During winter, bulk snow samples are collected at the Terelj site using a 395 mm diameter plastic basket. The wet-deposition results in Section 2.2 include only samples collected from May to October and exclude winter bulk-snow samples.

Dry deposition is monitored using an MB-01T four-stage filter-pack sampler (Tokyo Dylec Co., Ltd.). The filters collect particulate matter and gaseous SO_2, HCl, HNO_3, and NH_3, allowing simultaneous monitoring of particulate and gaseous components.

At Terelj, wet and dry deposition samples are collected by local staff and transported to the Central Laboratory of Environment and Metrology (CLEM) twice per month for analysis. At the Ulaanbaatar site, sampling and analysis are conducted directly by CLEM personnel.

Annual arithmetic mean pH and EC were calculated from available wet-deposition samples collected during May–October.

Table 2. Analytical method and equipment

Items	Monitoring parameters	Measuring method	Equipment

Wet deposition	pH	pH-meter	HANNA, edge
	EC	EC-meter	DS-12, Horiba
	SO_4^{2-}, NO_3^-, Cl^-, NH_4^+, Na^+, K^+, Ca^{2+}, Mg^{2+}	Ion chromatography	ICS-1600, Dionex
Dry deposition	Gases: SO_2, HNO_3, HCl, NH_3	Ion chromatography	ICS-1600, Dionex
	Aerosols: SO_4^{2-}, NO_3^-, Cl^-, NH_4^+, Na^+, K^+, Ca^{2+}, Mg^{2+}		
Air quality monitoring	SO_2, NO_2, PM_{10}, $PM_{2.5}$, O_3, Meteorological parameters	Automatic air quality monitoring station	AF22e, AC32e, MP101M, O342e, Vaisala WXT520
Inland aquatic environment	pH	pH-meter	HANNA, edge
	EC	EC-meter	DS-12, Horiba
	SO_4^{2-}, NO_3^-, Cl^-, NH_4^+, Na^+, K^+, Ca^{2+}, Mg^{2+}	Ion chromatography	ICS-1600, Dionex
	Alkalinity	Titration	Titration with 0.02 N H_2SO_4

CHAPTER 2. STATE OF ACID DEPOSITION IN MONGOLIA

2.1 State of dry deposition

Across the 2021–2025 monitoring period, a pronounced urban–remote contrast was observed between Ulaanbaatar and Terelj. Both sites exhibited clear seasonal variation, with higher sulfur concentrations during the cold season and lower concentrations during summer. However, concentrations at the Ulaanbaatar urban site were consistently substantially higher than those measured at the remote Terelj site.

The strong winter enhancement in Ulaanbaatar is likely associated with increased emissions from residential heating, power generation, traffic, and other combustion-related urban sources, together with unfavorable winter dispersion conditions. In contrast, the much lower concentrations at Terelj indicate relatively clean regional background conditions, although the repeated winter increase suggests some influence from regional transport and seasonal atmospheric processes.

The error bars represent the minimum and maximum concentrations measured during 2021–2025 and therefore indicate the observed concentration range rather than statistical uncertainty around the mean. Sampling was conducted weekly at Ulaanbaatar and biweekly at Terelj. The substantially larger ranges observed in Ulaanbaatar, particularly during winter, indicate pronounced temporal variability in urban atmospheric sulfur concentrations; however, direct quantitative comparison of variability between the two sites should be made with caution because of the different sampling frequencies.

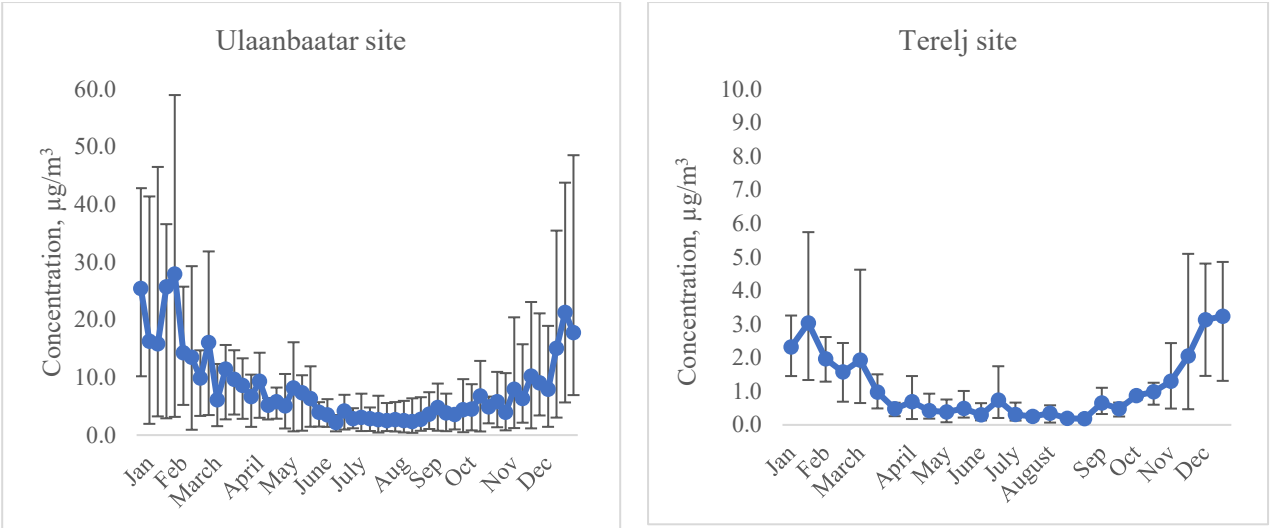


Figure 7. Sulfur dioxide concentration at sampling sites. Error bars indicate the minimum and maximum measured concentrations during the monitoring period.

NH_3 exhibited a pronounced warm-season maximum at both the Ulaanbaatar urban site and the Terelj site. Concentrations increased progressively from spring, reached their highest levels during June–August, and declined toward autumn and winter. The seasonal pattern was substantially more pronounced in Ulaanbaatar, where summer concentrations approached approximately 9–10 µg/m³, compared with approximately 2–2.5 µg/m³ at Terelj.

The warm-season enhancement at both sites is consistent with increased temperature-dependent volatilization of ammonia from soils, livestock excreta, waste, and other nitrogen-containing surfaces. The consistently higher concentrations in Ulaanbaatar indicate additional contributions from urban and peri-urban anthropogenic sources. The greater variability observed in Ulaanbaatar during summer also suggests substantial short-term variability in emission intensity and meteorological conditions. Although NH_3 concentrations at Terelj were considerably lower, the recurring summer enhancement indicates the influence of regional biogenic, livestock-related, and potentially transported ammonia sources.

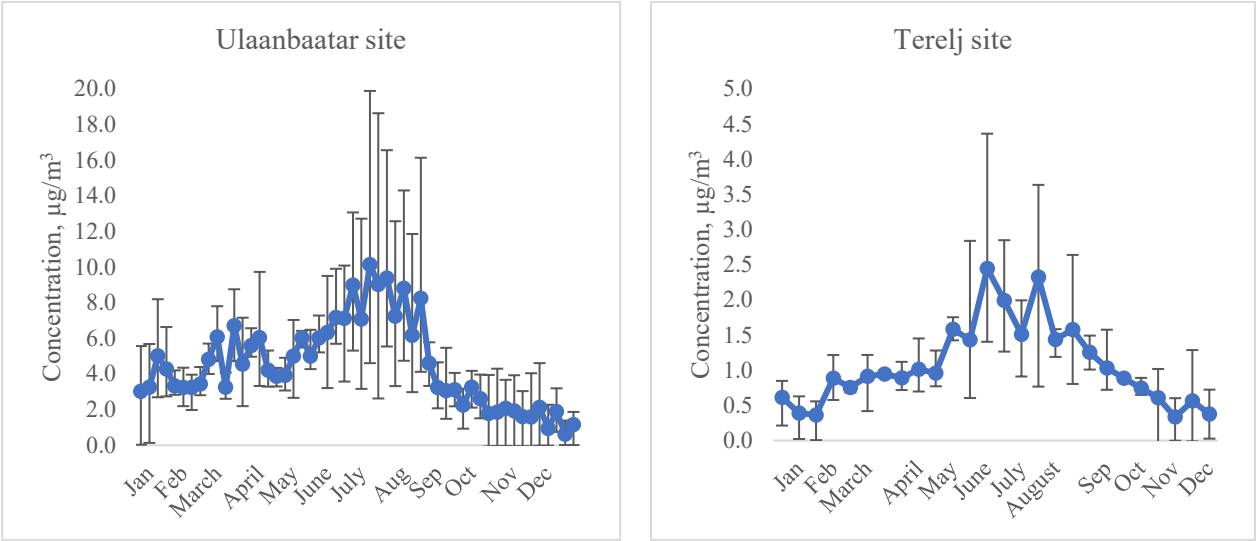


Figure 8. Ammonia concentration at sampling sites. Error bars indicate the minimum and maximum measured concentrations during the monitoring period.

HNO_3 concentrations were substantially higher at the Ulaanbaatar urban site than at the Terelj site. Unlike the strong winter maximum observed for SO_2 and the summer maximum of NH_3, HNO_3 exhibited a relatively weak and irregular seasonal pattern, with episodic increases occurring during different seasons.

The higher concentrations and greater variability observed in Ulaanbaatar are consistent with the influence of urban NO_x emissions and subsequent atmospheric oxidation and formation of nitric acid. At Terelj, HNO_3 concentrations remained close to regional background levels for most of the year, although modest increases during winter and early summer suggest possible influences of regional transport and photochemical production of oxidized nitrogen.

Variability represented by the error bars reflects repeated weekly sampling at Ulaanbaatar and biweekly sampling at Terelj during 2021–2025. Therefore, direct comparison of variability between the two sites should take the different sampling frequencies into account.

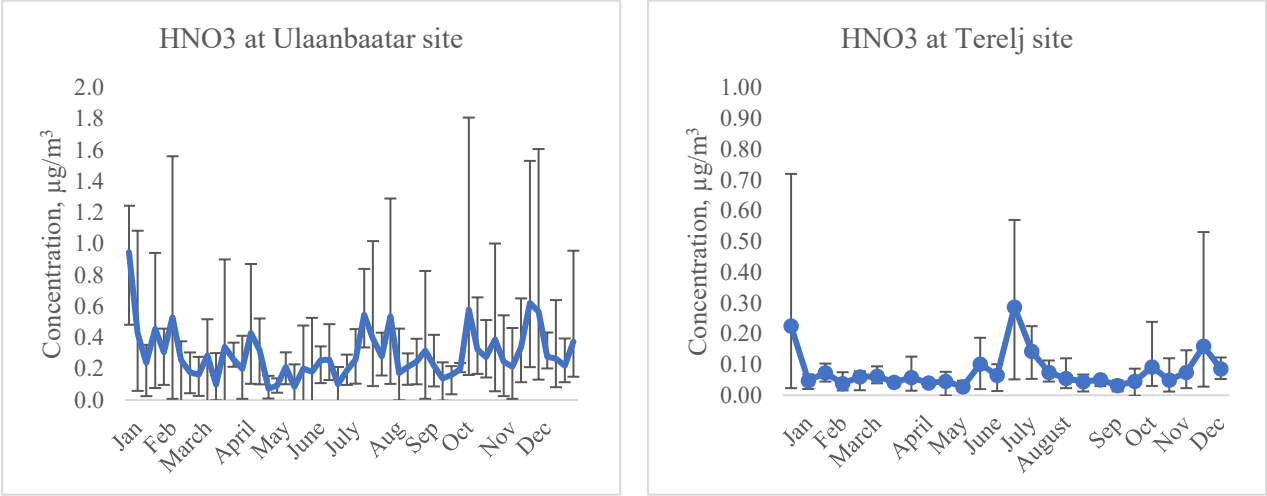


Figure 9. Nitric acid concentration at sampling sites. Error bars indicate the minimum and maximum measured concentrations during the monitoring period.

HCl-related concentrations were consistently higher at the Ulaanbaatar urban site than at the remote Terelj site, indicating a pronounced urban–remote gradient in atmospheric chloride. Ulaanbaatar concentrations remained relatively elevated throughout the year, with a moderate increase during late spring and summer, whereas Terelj exhibited much lower concentrations and a gradual warm-season maximum extending into early autumn. The substantially higher levels in Ulaanbaatar suggest contributions from urban combustion sources, chloride-containing particulate matter, and secondary atmospheric processing. In contrast, the seasonal increase observed at Terelj may reflect regional transport, mineral or saline dust aerosols, and temperature-dependent atmospheric transformations of chloride-containing particles. The markedly greater variability at Ulaanbaatar, based on weekly measurements, further indicates strong short-term fluctuations in urban atmospheric chloride loading. Because Terelj was sampled biweekly, differences in the magnitude of variability between the two sites should be interpreted cautiously.

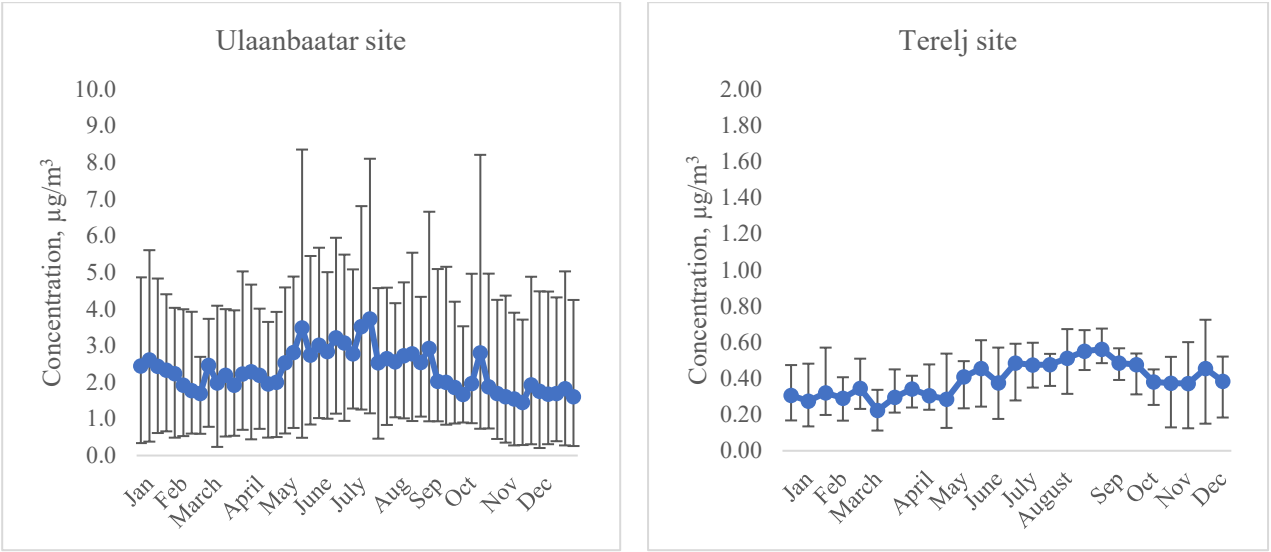


Figure 10. Hydrochloric acid concentration at sampling sites. Error bars indicate the minimum and maximum measured concentrations during the monitoring period.

Across 2021–2025, all four gaseous components presented here showed consistently higher concentrations at the Ulaanbaatar urban site than at the Terelj remote site, confirming a strong urban–remote gradient. However, their seasonal patterns differed, indicating different dominant sources and atmospheric processes.

Table 3.

Component	Ulaanbaatar urban site	Terelj remote site	Main interpretation
SO_2 / sulfur species	Strong winter maximum; highest concentrations and very large variability	Much lower, but also increases in winter	Urban fuel combustion, heating-season emissions, and poor winter dispersion; possible regional transport to Terelj
NH_3 / reduced nitrogen	Strong summer maximum, reaching the highest levels in June–August	Lower concentrations but similar summer enhancement	Temperature-dependent volatilization from soils, manure, waste, livestock, and other nitrogen sources
HNO_3 / nitrate species	Relatively low but highly variable; episodic peaks throughout the year	Very low background levels with small winter and early-summer increases	Secondary formation from NO_x, photochemical reactions, aerosol chemistry, and regional transport
HCl / chloride species	Elevated throughout the year with a moderate warm-season increase	Much lower, with a gradual summer–early autumn maximum	Urban combustion, chloride-containing particles, dust, secondary atmospheric chemistry, and transport

Atmospheric gaseous components measured by the filter-pack method showed a clear urban–regional gradient, with substantially higher concentrations in Ulaanbaatar than at Terelj. SO_2 showed a pronounced winter maximum associated with combustion and heating-season emissions, whereas NH_3 exhibited a strong summer maximum related to temperature-dependent volatilization. HNO_3 showed weaker and more episodic seasonal behavior consistent with secondary atmospheric formation, while HCl exhibited moderate warm-season enhancement potentially associated with

chloride-containing aerosols, dust, combustion, and secondary chemistry. Overall, the filter-pack measurements indicate distinct seasonal source and transformation processes, with stronger anthropogenic influence in Ulaanbaatar and lower regional-background concentrations at Terelj.

Across the 2021–2025 monitoring period, the particulate major-ion composition measured by the filter-pack method at both Ulaanbaatar and Terelj was characterized by a strong contribution of sulfate (SO_4^{2-}), which accounted for approximately 29% of the total major-ion composition at both sites. The similar relative contribution of sulfate at the two sites suggests that sulfur-containing pollutants were influenced by both regional atmospheric transport and secondary atmospheric transformation, in addition to local emission sources. However, the similarity in relative contribution does not necessarily indicate that the absolute sulfate concentrations were comparable between the two sites.

Clear differences were observed in the contributions of the other major ions. The most pronounced difference was found for Ca^{2+}, which contributed approximately 20% at Ulaanbaatar compared with 10% at Terelj. The substantially higher Ca^{2+} contribution at Ulaanbaatar indicates a stronger influence of crustal and mineral materials, particularly resuspended road dust, construction activities, exposed soil, and other urban dust sources. In dry deposition, these particles can be directly deposited onto surfaces under conditions of low precipitation. The relatively high contribution of Ca^{2+} therefore reflects the stronger influence of local urban dust and mineral aerosol sources at the Ulaanbaatar site.

In contrast, the relative contributions of NH_4^+ and NO_3^- were higher at Terelj. NH_4^+ accounted for approximately 19% at Terelj compared with 15% at Ulaanbaatar, while NO_3^- represented about 14% and 11%, respectively. These ions are commonly associated with secondary inorganic aerosol formation through atmospheric reactions involving gaseous precursors such as ammonia and nitrogen oxides. Their relatively higher contributions at Terelj may indicate a greater influence of regional atmospheric transport and secondary aerosol formation, particularly because the Terelj site is less directly affected by dense urban emissions. Nevertheless, higher relative contributions do not necessarily imply higher absolute concentrations.

Similarly, Cl^- contributed approximately 16% at Terelj compared with 13% at Ulaanbaatar. The relatively higher contribution at Terelj may be associated with the influence of transported aerosol particles and regional atmospheric sources. Chloride in dry deposition may originate from mineral particles, saline or chloride-containing aerosols, and other regional sources. The contribution of Cl^- should therefore be interpreted together with meteorological conditions, aerosol transport pathways, and the chemical characteristics of the surrounding environment.

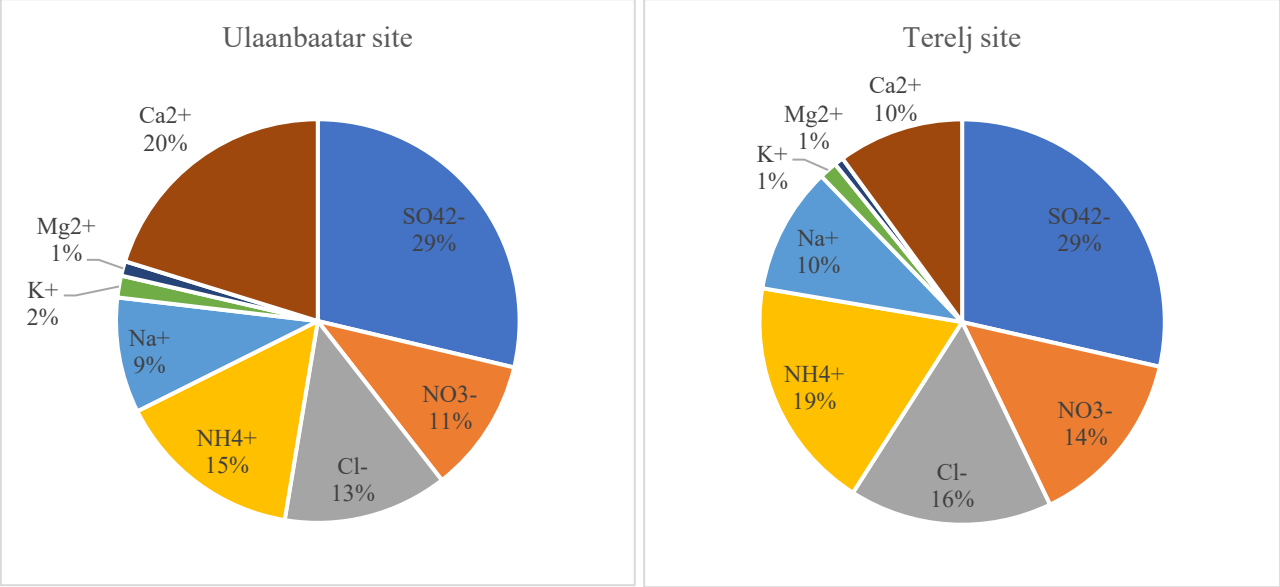


Figure 11. Relative composition of particulate major ions measured by the filter-pack method at Ulaanbaatar and Terelj, 2021–2025

Overall, the particulate major-ion composition measured at Ulaanbaatar was characterized by a relatively larger contribution of Ca^{2+}, reflecting the stronger influence of urban mineral dust, resuspended road dust, construction activities, and exposed soil. In contrast, Terelj showed relatively greater contributions of NH_4^+, NO_3^-, and Cl^-, which may reflect the influence of regional atmospheric transport and atmospheric chemical transformation. The similar sulfate contribution at both sites further suggests a potential regional component in sulfur deposition. However, relative ionic composition alone is insufficient to determine source contributions or to directly compare absolute concentrations between the two sites.

2.2 State of wet deposition

During the May–October monitoring periods from 2021 to 2025, the arithmetic mean pH of precipitation at both Ulaanbaatar and Terelj generally increased toward the later years, with the lowest mean values observed in 2022 and the highest in 2025. Precipitation amount was highest in 2024, but pH did not vary directly with precipitation, indicating that precipitation amount alone does not explain the observed variation in rainwater acidity. Ulaanbaatar generally showed slightly higher pH than Terelj despite stronger urban atmospheric pollution, which may partly reflect neutralization by alkaline components, particularly Ca^{2+} associated with mineral and resuspended dust, together with NH_4^+. Overall, precipitation pH reflects the combined effects of atmospheric chemical loading, precipitation characteristics, and neutralization processes.

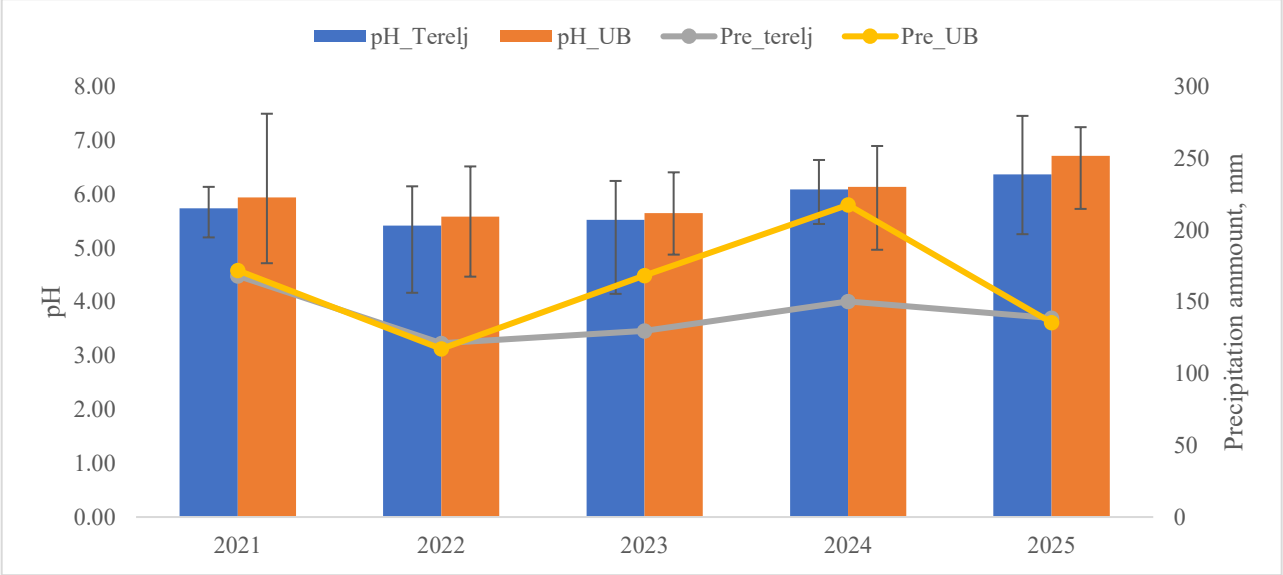


Figure 12. Arithmetic mean pH and total precipitation amount at the Ulaanbaatar and Terelj sites during the May–October monitoring periods, 2021–2025. Error bars indicate the minimum and maximum measured pH values.

Table 4. Frequency distribution of pH values in rain samples, 2021–2025

Sampling site	pH	2021	2022	2023	2024	2025
Terelj	<4.50	0	3	1	0	0
	4.51-5.00	0	3	2	0	0
	5.01-5.50	7	7	9	1	1
	5.51-6.00	24	13	18	4	11
	6.01-6.50	3	3	3	18	15
	6.51-7.00	0	0	0	3	10
	>7.00	0	0	0	0	4
	pH	2021	2022	2023	2024	2025
Ulaanbaatar	<4.50	0	1	0	0	0
	4.51-5.00	1	4	1	1	0
	5.01-5.50	3	3	9	1	0
	5.51-6.00	14	9	10	7	1
	6.01-6.50	7	3	6	12	5
	6.51-7.00	4	1	0	5	16
	>7.00	1	0	0	0	4

During the May–October monitoring periods from 2021 to 2025, precipitation EC exhibited substantial interannual variability at both Ulaanbaatar and Terelj, with relatively high values in 2022 and substantially lower values during 2023–2024. The generally lower EC during the wetter years, particularly in 2024, suggests that precipitation amount exerts an important dilution effect on dissolved atmospheric ions. Conversely, relatively low precipitation in 2022 coincided with elevated EC at both sites, indicating more concentrated ionic loading. Nevertheless, the relationship between precipitation and EC was not strictly inverse, demonstrating that variations in aerosol loading, mineral dust, anthropogenic emissions, atmospheric transport, and individual precipitation-event chemistry also influenced rainwater mineralization. When considered together with pH, the results indicate that

changes in total ionic concentration do not directly correspond to changes in acidity, because alkaline species such as Ca^{2+} and NH_4^+ can substantially neutralize sulfate- and nitrate-derived acidity.

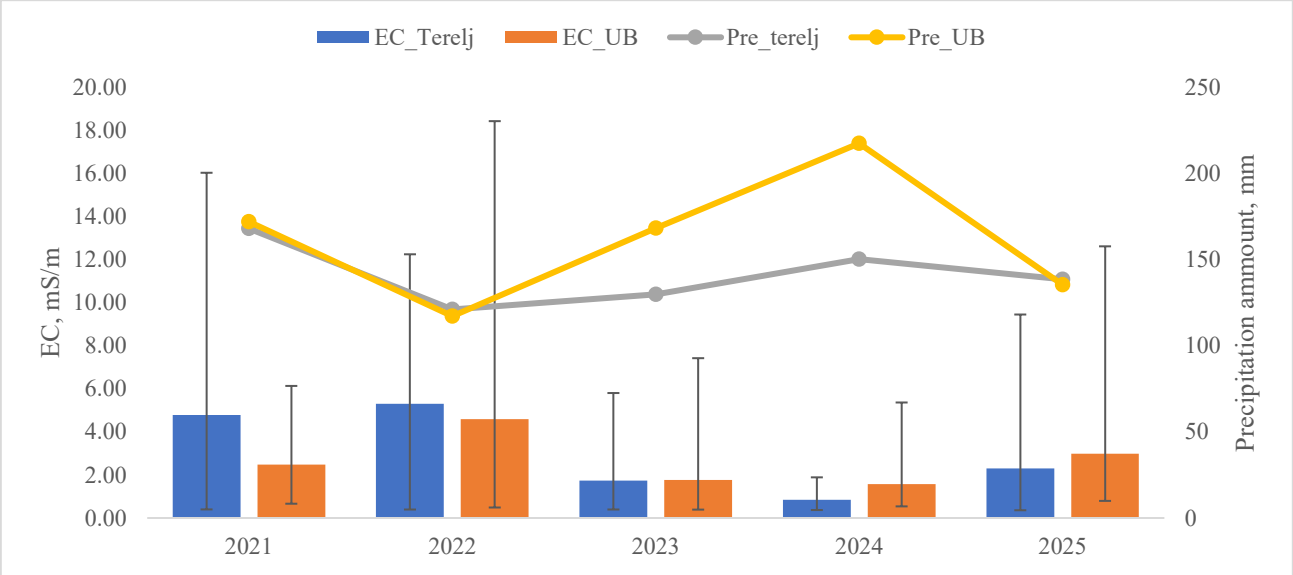


Figure 13. Arithmetic mean electrical conductivity (EC) and precipitation amount at the Ulaanbaatar and Terelj sites during the May–October monitoring periods, 2021–2025. Error bars indicate the minimum and maximum measured EC values.

The ionic composition of precipitation differed clearly between the remote Terelj site and the urban Ulaanbaatar site. At Terelj, Na^+ was the dominant ion, accounting for 40% of the total ionic composition, followed by SO_4^{2-} (31%), NH_4^+ (10%), NO_3^- (7%), and Ca^{2+} (7%). In contrast, precipitation in Ulaanbaatar was characterized by a more balanced contribution of major ions, with SO_4^{2-} representing 28%, followed by Na^+ (22%), Ca^{2+} (17%), NH_4^+ (15%), and NO_3^- (13%). Cl^- contributed approximately 2% at both sites, while K^+, Mg^{2+}, and H^+ each accounted for only about 1%.

The substantially higher relative contribution of Ca^{2+} in Ulaanbaatar (17% versus 7% at Terelj) is consistent with a stronger influence of mineral dust and alkaline particulate matter in the urban environment. Ulaanbaatar also showed higher relative contributions of NO_3^- and NH_4^+, which may reflect greater influence from urban emissions and secondary inorganic aerosol formation. In contrast, the Terelj site was distinguished by a particularly high proportion of Na^+, which dominated the cationic composition. The relatively similar sulfate contribution at the two sites—31% at Terelj and 28% in Ulaanbaatar—indicates that sulfate is an important component of wet deposition at both locations and is consistent with contributions from regional atmospheric transport and secondary atmospheric transformation, in addition to local sources.

Importantly, because these figures show relative percentages, they should not be used by themselves to conclude that the absolute concentration of an ion was higher at one site. Comparison of actual mean concentrations in μmol L^{-1} is required for that conclusion.

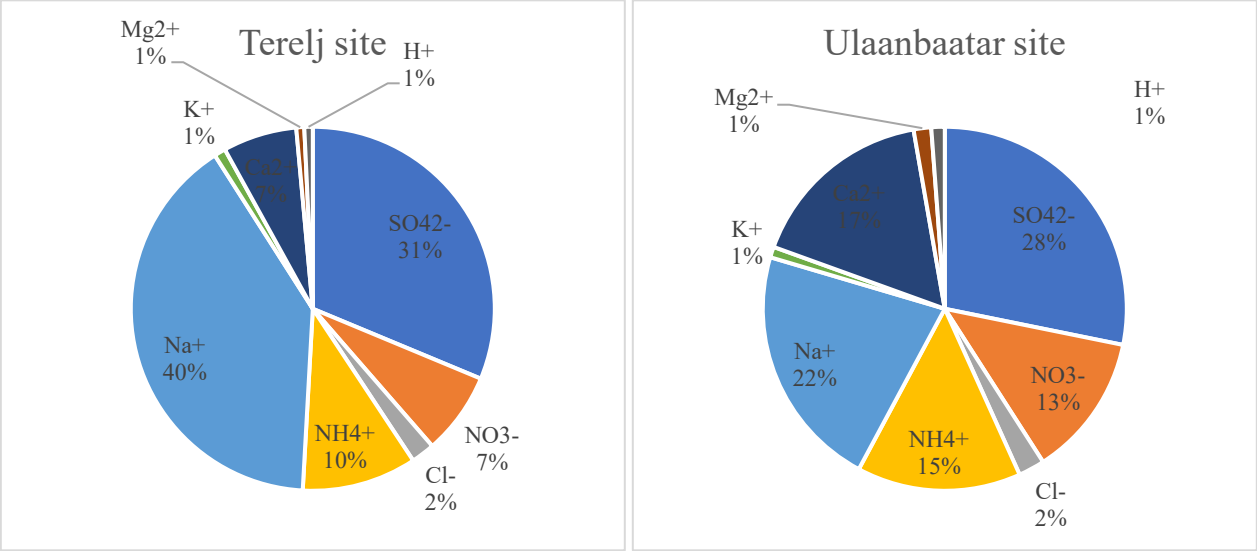


Figure 14. Relative composition of major ions in wet-deposition samples collected during May–October at Terelj and Ulaanbaatar, 2021–2025, calculated from mean ion concentrations expressed in µmol L^{-1}.

At the Terelj site, total anion concentrations were relatively high in 2021, at approximately 370 µmol L^{-1}, while total cation concentrations were around 250 µmol L^{-1}. In 2022, cation concentrations increased sharply to more than 600 µmol L^{-1}, whereas total anions were approximately 280 µmol L^{-1}. This coincided with the highest wet-deposition flux during the monitoring period, approximately 111 mmol m^{-2}. After 2022, both ionic concentrations and wet-deposition flux decreased substantially. Deposition declined to approximately 22 mmol m^{-2} in 2023 and 15 mmol m^{-2} in 2024, before increasing to approximately 28 mmol m^{-2} in 2025. The increase in cation concentration in 2025 relative to 2023–2024 is particularly noticeable.

A broadly similar temporal pattern occurred in Ulaanbaatar, although the magnitude was generally lower than at Terelj during 2021–2022. Total anion and cation concentrations in 2021 were approximately 200 and 165 µmol L^{-1}, respectively, with wet-deposition flux of approximately 49 mmol m^{-2}. In 2022, total cation concentration increased markedly to approximately 300 µmol L^{-1}, while anion concentration remained near 190 µmol L^{-1}. Wet-deposition flux reached its maximum of approximately 57 mmol m^{-2}. A sharp decline occurred in 2023, followed by an increase in 2024 and a slightly lower value in 2025, while total cation concentrations continued to increase.

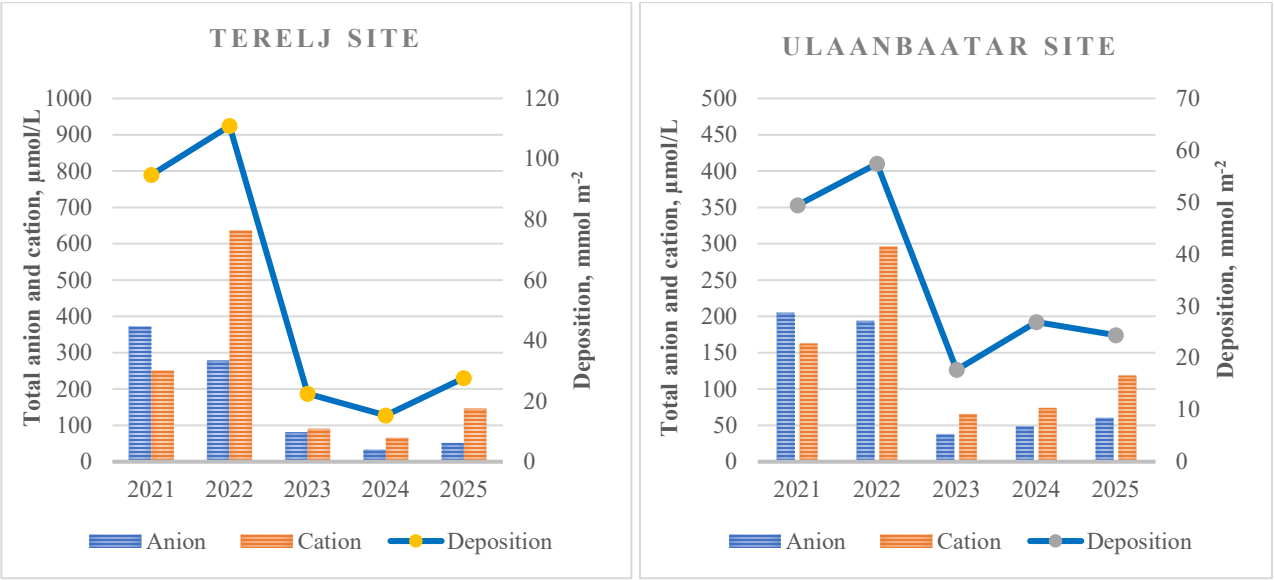


Figure 15. Interannual variation in total anion and cation concentrations and wet-deposition flux at Terelj and Ulaanbaatar during the May–October monitoring periods, 2021–2025.

The most pronounced difference between the sites occurred in 2021–2022, when wet-deposition flux during the May–October monitoring period was considerably higher at Terelj than in Ulaanbaatar. In 2022, for example, the deposition flux at Terelj was nearly twice that observed in Ulaanbaatar. This indicates that lower atmospheric concentrations at a regional site do not necessarily correspond to lower wet-deposition flux, because wet deposition is influenced by precipitation amount, atmospheric chemical loading, air-mass transport, and precipitation scavenging processes.

From 2023 onward, the difference between the two sites became considerably smaller. Both sites showed substantially lower total ionic concentrations than in 2021–2022, while wet-deposition fluxes were generally within approximately 15–30 mmol m^{-2}. The broadly similar temporal variation at the two sites suggests that meteorological conditions and regional atmospheric processes may contribute to the interannual variability observed in wet deposition.

Wet-deposition flux should not be interpreted from concentration alone. Relatively low ionic concentrations may still produce substantial deposition when precipitation is high, whereas high concentrations during relatively dry conditions may not necessarily result in proportionally high deposition. Wet-deposition flux should therefore be interpreted together with precipitation amount during the corresponding May–October monitoring period.

2.3 State of air quality in Bayanzurkh, Ulaanbaatar city

The air-quality monitoring data for Ulaanbaatar show strong seasonal, diurnal, and interannual variability, with particulate matter and combustion-related gaseous pollutants exhibiting the clearest wintertime enhancement. Among the monitored pollutants, PM_{10} had the highest overall mean concentration (92.4 µg m^{-3}), followed by NO_2 (52.9 µg m^{-3}), $PM_{2.5}$ (34.9 µg m^{-3}), SO_2 (27.8 µg m^{-3}),

and O_3 (20.2 μg m^{-3}). The distributions are strongly right-skewed, particularly for particulate matter and SO_2, indicating that relatively moderate background conditions are interrupted by short periods of extremely high pollution**.**

Table 5. Summary of air-quality concentrations (μg m^{-3}) at the UB04 station, 2016–2025

Pollutant	Mean	Median	95th percentile	Main pattern
PM_{10}	92.4	68	247	Very high in winter; strong episodic peaks
NO_2	52.9	50	104	Elevated in winter and at night
$PM_{2.5}$	34.9	19	122	Strong winter maximum
SO_2	27.8	12	99	Extremely strong winter seasonality
O_3	20.2	17	54	Opposite pattern: higher in warm/sunny periods

Over the 2016–2025 period, PM_{10} and $PM_{2.5}$ displayed pronounced recurring winter peaks, while concentrations decreased markedly during the warmer months. PM_{10} had a median value of approximately 68 μg m^{-3} and a 95th percentile of about 247 μg m^{-3}, with individual extreme values reaching more than 2600 μg m^{-3}. $PM_{2.5}$ showed a mean of approximately 34.9 μg m^{-3}, a median near 19 μg m^{-3}, and a 95th percentile around 122 μg m^{-3}. These large differences between mean, median, and upper-percentile values indicate that particulate pollution in Ulaanbaatar is strongly influenced by episodic high-pollution events, particularly during the cold season.

Sulfur dioxide shows one of the strongest seasonal signals. Its median concentration was relatively low, around 12 μg m^{-3}, compared with a mean of approximately 27.8 μg m^{-3}, while the 95th percentile approached 99 μg m^{-3}. Several very large winter peaks are evident in the time series, demonstrating the importance of episodic sulfur dioxide accumulation. Such a pattern is consistent with enhanced cold-season combustion emissions together with unfavorable atmospheric dispersion. However, the magnitude of sulfur dioxide peaks appears to vary substantially among years, suggesting changes in emission intensity, fuel use, meteorological conditions, or emission-control measures during the monitoring period.

Nitrogen dioxide concentrations were comparatively persistent throughout the year, with a mean of approximately 52.9 μg m^{-3} and median near 50 μg m^{-3}. Nevertheless, a clear seasonal cycle remains evident, with concentrations increasing during the colder months and decreasing during summer. This pattern is consistent with the combined influence of traffic emissions, stationary combustion sources, enhanced winter fuel consumption, and reduced atmospheric mixing. The persistence of relatively high nitrogen dioxide also indicates that nitrogen oxide emissions represent an important component of Ulaanbaatar's urban atmospheric chemistry.

In contrast to the primary pollutants, ozone exhibits an opposite seasonal behavior. Ozone concentrations tend to increase during the warmer and sunnier parts of the year and decrease during winter. The mean ozone concentration was approximately 20.2 μg m^{-3}, with a median near 17 μg m^{-3} and a 95th percentile of about 54 μg m^{-3}. This seasonal pattern is typical of a secondary photochemical pollutant because ozone formation depends on sunlight and reactions involving NO_x and volatile organic compounds. Consequently, periods of relatively low wintertime ozone occur simultaneously with high NO_2 and particulate concentrations, whereas ozone becomes more important under warmer and more photochemically active conditions.

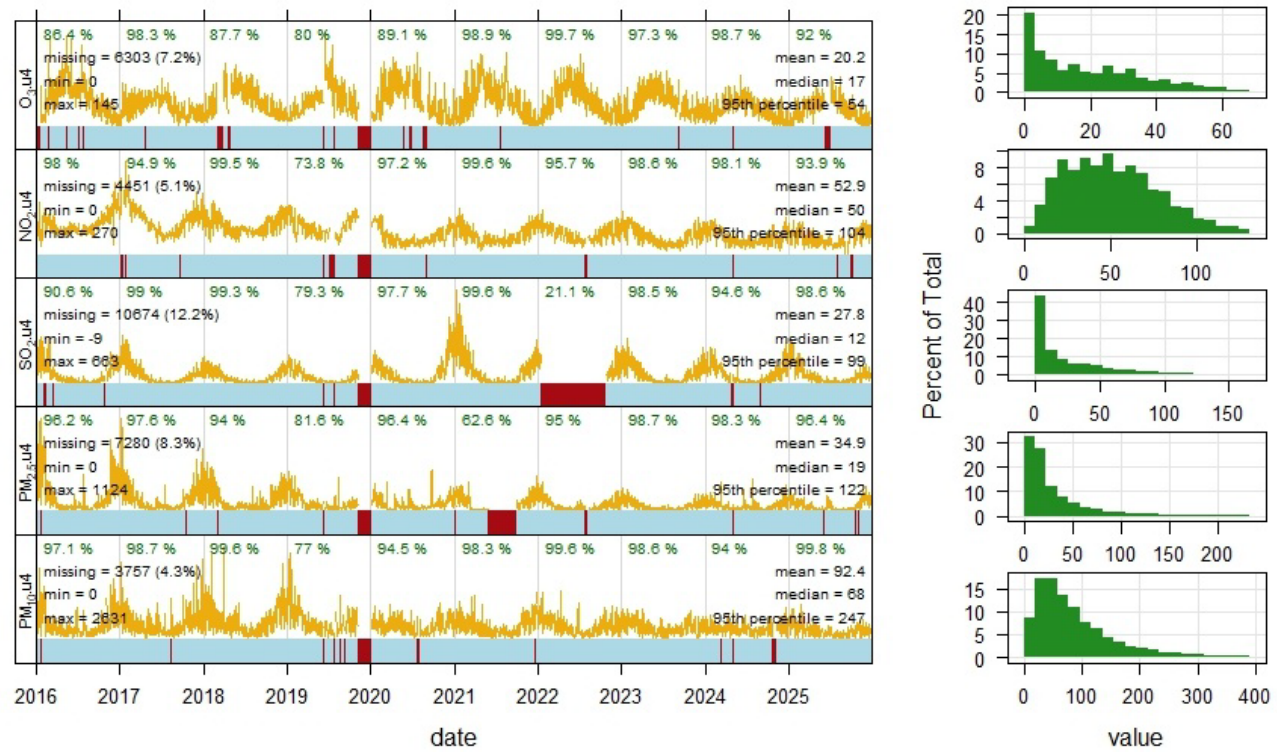


Figure 16. Time variation of air quality monitoring data at UB04 station

Diurnal variation. The hourly patterns demonstrate a distinct daily pollution cycle. PM_{10} is highest during the nighttime and early morning**,** decreases strongly after sunrise, shows a smaller secondary increase around midday, and then rises again during the late evening. $PM_{2.5}$ follows a broadly similar pattern, although its daily variation is less pronounced.

The reduction in particulate concentrations during daytime hours is likely associated with the development of a deeper atmospheric mixing layer, which enhances pollutant dispersion. In contrast, nighttime cooling and atmospheric stability favor pollutant accumulation near the surface.

Nitrogen dioxide also decreases from nighttime toward the middle of the day and rises again during the evening, reflecting both changes in emissions and boundary-layer conditions. This late-evening increase is consistent with the combined influence of traffic, residential combustion, and a shallower atmospheric boundary layer.

Ozone displays the opposite diurnal cycle: concentrations are relatively low during the night and early morning but increase during daylight hours, reaching their highest levels during the afternoon before decreasing again in the evening. The inverse relationship between O_3 and NO_2 is consistent with their closely linked photochemical chemistry.

Monthly variation. The monthly averages reveal perhaps the clearest feature of Ulaanbaatar air pollution: a very strong winter–summer contrast**.**

Concentrations of PM_{10}, $PM_{2.5}$, SO_2, and NO_2 are highest from approximately November to February, with particularly high values in December and January. Concentrations then decrease rapidly through spring and reach their lowest levels during summer, particularly from June to August. From September onward, concentrations begin increasing again as temperatures decrease.

This pattern strongly indicates the importance of cold-season emissions and meteorological conditions. During winter, increased combustion for heating coincides with strong atmospheric stability, shallow boundary layers, and frequent temperature inversions, allowing pollutants to accumulate close to the surface. During summer, reduced heating emissions and stronger vertical atmospheric mixing substantially improve pollutant dispersion.

The seasonal pattern of sulfur dioxide is especially pronounced, with very low summer concentrations compared with large wintertime values, indicating its close association with seasonal combustion sources.

Ozone again behaves differently, increasing from winter toward spring and early summer as solar radiation and photochemical activity increase, before decreasing later in the year.

Day-of-week variation. Compared with the seasonal and hourly cycles, weekday differences are relatively small**.** PM_{10}, $PM_{2.5}$, SO_2, and NO_2 remain at broadly similar levels from Monday through Sunday. There is some indication of slightly lower particulate and nitrogen dioxide concentrations toward the weekend, but the magnitude of this change is modest.

This limited weekday–weekend contrast suggests that continuous emission sources, particularly residential and stationary heating, are important contributors to Ulaanbaatar pollution rather than pollution being controlled exclusively by weekday traffic or industrial activity.

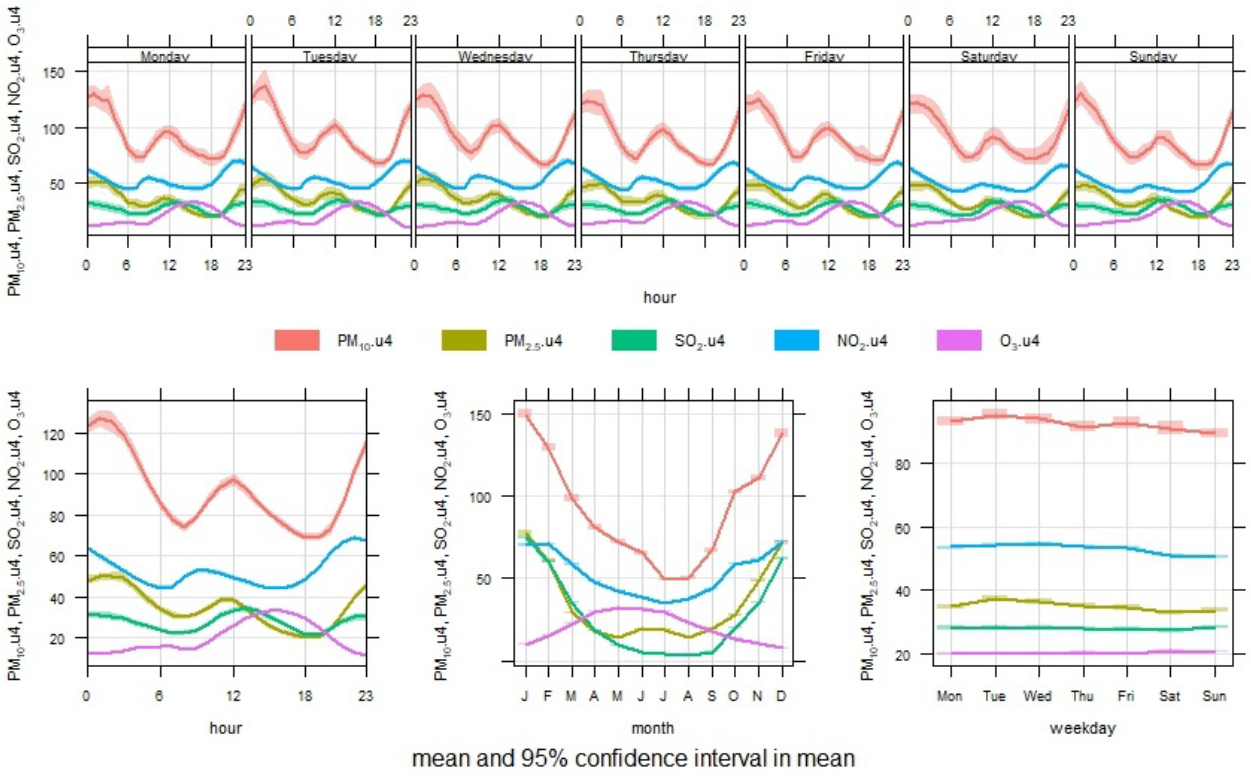


Figure 17. Diurnal, monthly, and day-of-week variation in air-quality parameters at the UB04 station. Lines represent mean concentrations and shaded areas indicate 95% confidence intervals

Overall, the 2016–2025 observations indicate that Ulaanbaatar's air pollution is dominated by a strong cold-season pollution regime. Particulate matter, SO_2, and NO_2 increase sharply during winter, while their concentrations decline substantially during the warmer months. The occurrence of very high maximum and 95th-percentile concentrations demonstrates that extreme pollution episodes remain a major feature of urban air quality, even when annual or long-term mean concentrations are much lower.

The combined seasonal and diurnal patterns indicate that Ulaanbaatar air quality is controlled by an interaction between emission intensity and meteorological conditions. Wintertime combustion, traffic and other urban sources provide the pollutants, while stable atmospheric conditions and shallow mixing layers favor their accumulation. Conversely, stronger atmospheric mixing during summer reduces primary pollutant concentrations.

Although the measurements were obtained from different urban monitoring locations, the UB04 air-quality observations provide useful contextual information for interpreting the wet-deposition chemistry observed in Ulaanbaatar. Atmospheric SO_2 and NO_2 are important precursors of sulfate (SO_4^{2-}) and nitrate (NO_3^-) in aerosols and precipitation. Therefore, the substantial presence of sulfate in rainwater may partly reflect atmospheric oxidation and subsequent scavenging of sulfur-containing compounds. However, the similar sulfate contribution observed at Ulaanbaatar and the remote Terelj site suggests that regional transport and secondary atmospheric transformation are also important, rather than sulfate being controlled entirely by local Ulaanbaatar emissions. At the same time, the high Ca^{2+} contribution in Ulaanbaatar wet deposition indicates that mineral dust can provide substantial alkaline neutralization of acidic sulfate and nitrate species**.**

The decade-long observations show that Ulaanbaatar experiences a highly seasonal air-pollution regime characterized by severe wintertime PM_{10}, $PM_{2.5}$, SO_2, and NO_2 pollution, strong episodic peaks, and much cleaner summer conditions, whereas O_3 follows the opposite photochemical seasonal cycle. Together with precipitation chemistry, these patterns indicate that air quality and deposition in central Mongolia are governed by a combination of urban emissions, mineral dust, atmospheric chemistry, meteorological conditions, and regional pollutant transport.

2.4 State of inland aquatic environment

During the 2021–2025 monitoring period, the water quality of the Terelj River showed moderate interannual variability in pH, electrical conductivity (EC), and alkalinity. Overall, the river remained generally near-neutral, ranging from slightly acidic conditions during 2021–2023 to slightly alkaline conditions during 2024–2025, while EC values remained relatively low, indicating generally low concentrations of dissolved ionic constituents.

The mean pH remained relatively stable between 2021 and 2023, ranging from approximately 6.3 to 6.5. The lowest value was observed in 2023, after which pH increased markedly to about 7.5 in 2024 and remained relatively high at approximately 7.3–7.4 in 2025. This shift indicates that the Terelj River became more alkaline during the final two years of the monitoring period.

Electrical conductivity (EC) varied from approximately 3.8 to 5.2 mS/m. EC increased from about 4.1 mS/m in 2021 to 4.6 mS/m in 2022, followed by a decline to its lowest level of approximately 3.8 mS/m in 2023. It subsequently increased to around 4.4 mS/m in 2024 and reached its highest value of approximately 5.1 mS/m in 2025. Despite this increase, the overall EC values remained relatively low, suggesting that the Terelj River generally contains a low concentration of dissolved salts and mineral ions.

Alkalinity also displayed noticeable year-to-year variability. It was approximately 0.32 meq L^{-1} in 2021, increased to its highest level of around 0.38 meq L^{-1} in 2022, and then decreased substantially to approximately 0.26 meq L^{-1} in 2023. Alkalinity recovered to about 0.34 meq L^{-1} in 2024 and increased slightly further to approximately 0.35 meq L^{-1} in 2025. The higher alkalinity observed in 2022 and 2024–2025 indicates a greater capacity of the river water to neutralize acidic inputs during these years.

Overall, the results show that 2023 was characterized by comparatively low pH, EC, and alkalinity, whereas 2024–2025 showed a shift toward higher pH, increasing electrical conductivity, and relatively high alkalinity. The simultaneous increase in pH and alkalinity during the later years may reflect greater contributions of alkaline and mineral-derived ions to the river water. The relatively large error bars, particularly for alkalinity and EC, indicate substantial variability among individual samples within each year, which may be associated with seasonal hydrological conditions, precipitation, snowmelt, groundwater contribution, and variations in river discharge. Nevertheless, the consistently low EC and generally near-neutral pH indicate that the Terelj River maintained relatively stable water-quality conditions during the monitoring period.

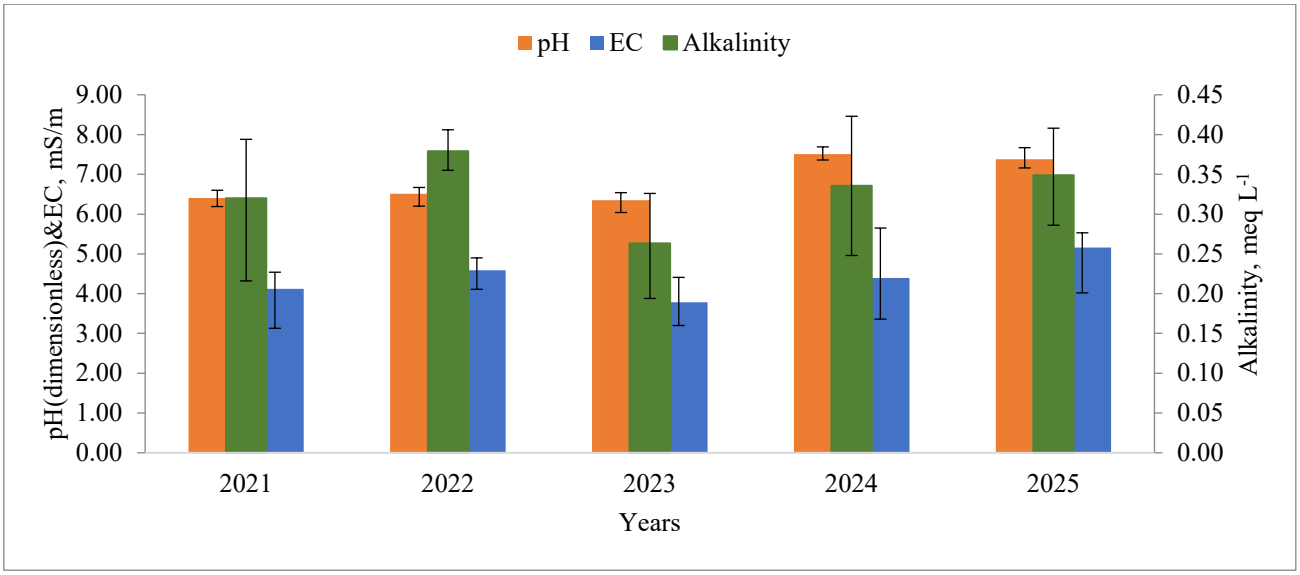


Figure 18. Interannual variability in pH, electrical conductivity (EC), and alkalinity. Error bars indicate the minimum and maximum measured values within each monitoring year.

The major-ion composition of the Terelj River showed clear seasonal and interannual variability during the 2021–2025 monitoring period. The measured ions included SO_4^{2-}, NO_3^-, Cl^-, NH_4^+, Na^+, K^+, Ca^{2+}, and Mg^{2+}. Among these, Ca^{2+} was consistently the dominant ion, indicating a strong influence of natural mineral weathering and water–rock interactions within the river catchment.

In 2021, total major-ion concentrations were generally lower than in the later monitoring years. Concentrations were particularly low in May and increased during the summer and autumn months. Ca^{2+} accounted for the largest proportion of the ionic composition, while SO_4^{2-}, Na^+, Cl^-, and K^+ made smaller contributions. The relatively low total ionic concentrations suggest comparatively dilute river-water conditions during this period.

Complete ion measurements were not available for 2022 because of a malfunction of the analytical equipment. Therefore, 2022 data were excluded from the interannual comparison of major-ion composition. This data gap should be considered when interpreting temporal trends across the full 2021–2025 monitoring period.

In 2023, overall ionic concentrations were generally higher than in 2021, with several samples reaching approximately 15–16 mg L^{-1} in total measured ions. Ca^{2+} remained dominant, while the contribution of SO_4^{2-} became more pronounced. Na^+, K^+, Cl^-, and NO_3^- showed noticeable seasonal fluctuations, suggesting that both hydrological conditions and seasonal inputs influenced river-water chemistry.

During 2024, the ionic composition continued to be dominated by Ca^{2+} and SO_4^{2-}. Total concentrations varied considerably between sampling dates, with the highest values occurring in autumn. Sulfate concentrations were generally higher than those observed in 2021, while Ca^{2+} continued to contribute a substantial proportion of the total ionic load. The temporal variability indicates changes in dilution, runoff, groundwater contribution, and mineral dissolution throughout the season.

In 2025, the Terelj River generally exhibited the highest major-ion concentrations of the monitoring period. Most samples showed total measured-ion concentrations of approximately 14–19 mg L^{-1}. Ca^{2+} remained the principal cation, while SO_4^{2-} was the most prominent measured anion. Several 2025 samples also showed relatively higher NO_3^- concentrations compared with earlier years, although NO_3^- remained substantially lower than Ca^{2+} and SO_4^{2-}.



Figure 19. Major-ion concentrations in the Terelj River in 2021 and 2023–2025; complete ion measurements were unavailable for 2022.

Overall, the available data indicate a general increase in major-ion concentrations from 2021 toward 2023–2025, although considerable seasonal variability occurred within individual years. The persistent dominance of Ca^{2+} is consistent with a substantial influence of natural geochemical processes, particularly mineral weathering and groundwater–surface water interactions. At the same time, variations in SO_4^{2-}, NO_3^-, Cl^-, Na^+, and K^+ may reflect seasonal differences in precipitation, snowmelt, surface runoff, biological processes, and atmospheric or catchment-derived inputs. Because reliable measurements were unavailable for 2022, the observed interannual pattern should be interpreted as a comparison of 2021, 2023, 2024, and 2025, rather than as a continuous annual trend.

2.5 State of soil and vegetation

No new soil or vegetation monitoring data were available for the present assessment period. Therefore, no temporal assessment of changes in soil or vegetation condition was conducted for 2021–

2025. Continued periodic monitoring is recommended to maintain long-term comparability and to assess possible ecosystem responses to atmospheric deposition.

2.6 Overall analysis

The integrated monitoring results for 2021–2025 demonstrate that atmospheric and aquatic environmental conditions in central Mongolia are controlled by the combined effects of urban emissions, mineral dust, regional atmospheric transport, secondary atmospheric transformation, precipitation variability, and local environmental conditions. The comparison between Ulaanbaatar and Terelj reveals a clear spatial contrast in atmospheric concentrations, while the deposition and precipitation-chemistry results indicate that regional and meteorological processes also play an important role in determining environmental exposure.

Filter-pack measurements showed a pronounced urban–regional gradient in atmospheric gaseous components. Concentrations of SO_2, NH_3, HNO_3, and HCl were consistently higher in Ulaanbaatar than at Terelj, reflecting the stronger influence of residential heating, power generation, traffic, and other urban emission sources. The seasonal behavior of these components further indicates differences in dominant processes. SO_2 showed a strong winter maximum, corresponding with the pronounced cold-season increases in PM_{10}, $PM_{2.5}$, and NO_2 observed at the UB04 air-quality station. This pattern is consistent with increased combustion emissions combined with stable atmospheric conditions, shallow boundary layers, and reduced dispersion during winter. In contrast, NH_3 exhibited a warm-season maximum at both sites, consistent with enhanced temperature-dependent volatilization from soils, livestock-related sources, waste, and other nitrogen-containing surfaces.

The particulate major-ion composition measured by the filter-pack method showed a different spatial pattern from the gaseous concentrations. SO_4^{2-} accounted for approximately 29% of the major-ion composition at both Ulaanbaatar and Terelj, suggesting that secondary atmospheric transformation and regional transport contribute to sulfate occurrence in addition to local sources. In contrast, the substantially greater relative contribution of Ca^{2+} in Ulaanbaatar is consistent with a stronger influence of mineral and resuspended dust from roads, construction activities, exposed surfaces, and surrounding dry landscapes. Terelj showed relatively larger contributions of NH_4^+, NO_3^-, and Cl^-, which may reflect regional transport and secondary atmospheric processes. However, these differences represent relative composition and should not be interpreted as direct evidence of differences in absolute atmospheric loading or deposition flux.

Wet-deposition chemistry provides additional evidence that urban–regional differences are modified by precipitation processes. Rainwater pH generally increased during the later years of the assessment period, while electrical conductivity and total ionic concentrations showed substantial interannual variability. Precipitation amount alone did not explain these changes. During the May–October monitoring period, relatively low precipitation in 2022 coincided with high ionic concentrations and the highest wet-deposition flux at both monitoring sites, whereas greater precipitation in 2024 was associated with much lower ionic concentrations and deposition. This

indicates that wet deposition is determined by the interaction between precipitation amount and atmospheric chemical loading, rather than by rainfall amount alone.

The ionic composition of precipitation also differed between sites. Terelj was characterized by a particularly high relative contribution of Na^+, whereas Ulaanbaatar showed greater relative contributions of Ca^{2+}, NH_4^+, and NO_3^-. The higher Ca^{2+} contribution in Ulaanbaatar is consistent with greater mineral-dust influence and may contribute to neutralization of acidic sulfate and nitrate species. At the same time, SO_4^{2-} represented a substantial and relatively similar proportion of wet-deposition chemistry at both locations, supporting the interpretation that regional atmospheric transport and secondary transformation contribute to precipitation chemistry in addition to local emission influences.

Marked interannual variability was observed in wet-deposition flux. Both sites showed their highest May–October wet-deposition fluxes in 2022, followed by a substantial decrease in 2023 and generally lower values during 2024–2025. The broadly synchronous pattern at Ulaanbaatar and Terelj suggests an important influence of year-to-year meteorological conditions and regional atmospheric processes. Nevertheless, interpretation of changes at Terelj across 2022–2023 should consider the relocation of the monitoring station to the Terelj meteorological observation site in May 2023. Changes in local surroundings, road proximity, and increasing settlement may have contributed to part of the observed variability.

The long-term UB04 air-quality observations provide important context for interpreting the deposition measurements. The strong winter maxima of PM_{10}, $PM_{2.5}$, SO_2, and NO_2 demonstrate the importance of cold-season urban pollution, while O_3 follows an opposite warm-season photochemical cycle. The presence of atmospheric SO_2 and NO_2 provides precursor compounds for sulfate and nitrate formation, respectively. However, the similarity in relative sulfate contributions between Ulaanbaatar and Terelj indicates that precipitation chemistry cannot be explained solely by local Ulaanbaatar emissions and is consistent with additional regional transport and atmospheric transformation processes.

The Terelj River results indicate that the aquatic environment remained generally near-neutral and relatively low in dissolved mineral content during the monitoring period. Ca^{2+} consistently dominated the major-ion composition, which is consistent with a substantial influence of natural mineral weathering, groundwater contribution, and water–rock interactions within the catchment. The increase in several major-ion concentrations during 2023–2025 may reflect changes in hydrological conditions, mineral dissolution, surface runoff, or other catchment processes. Because complete major-ion measurements were unavailable for 2022, these differences should be interpreted using the available monitoring years rather than as a continuous five-year trend.

Overall, the results demonstrate that environmental conditions in central Mongolia cannot be attributed to a single pollution source or process. Urban emissions exert the strongest influence on atmospheric concentrations in Ulaanbaatar, particularly during winter, whereas mineral dust, regional

atmospheric transport, secondary chemical transformation, and meteorological variability influence atmospheric and precipitation chemistry at both Ulaanbaatar and Terelj. The aquatic results further demonstrate the importance of natural catchment and hydrological controls. Continued integration of atmospheric composition, precipitation chemistry, ambient air quality, and ecosystem monitoring is therefore essential for distinguishing local anthropogenic impacts from regional transport and natural environmental variability, and for evaluating future changes associated with emission-control measures and climate variability.

CHAPTER 3. REVIEW OF NATIONAL AIR QUALITY MANAGEMENT INCLUDING ACID DEPOSITION

Under Mongolia's long-term development policy, Vision–2050, improving air quality in urban and settlement areas is addressed through an integrated approach covering energy and heating systems, urban development, transport, green infrastructure, waste management, and environmental monitoring. Key measures include improving the efficiency and reliability of heating systems, expanding access to cleaner and renewable energy technologies, improving living conditions in ger areas through redevelopment and infrastructure development, promoting sustainable urban planning, reducing excessive population concentration in Ulaanbaatar, developing environmentally friendly public transport, and expanding urban green spaces and waste-management systems.

Building on these long-term policy directions, Government Resolution No. 133, adopted on 19 March 2025, introduced more specific measures to reduce air pollution in Ulaanbaatar by accelerating the transition of household heating systems in designated air-quality improvement zones from traditional solid fuels to electricity, gaseous fuels, and other cleaner technologies. The resolution provides a more targeted framework for implementing cleaner-heating measures at the household level.

Key measures under the resolution include expanding access to preferential green loans for households to improve building insulation and adopt electric, gas, or other cleaner heating technologies; incorporating energy-efficient housing and passive-building standards into national budget planning; and providing accessible financing mechanisms to support household insulation. The resolution also promotes measures to reduce population concentration in Ulaanbaatar and supports voluntary relocation to rural areas.

In addition, the government is considering tax incentives and other financial mechanisms to encourage households to adopt cleaner heating technologies. Public awareness and safety campaigns are to be strengthened, particularly regarding the safe use of electric and gas heating systems, energy-efficient housing, and advanced heating technologies. Training and certification systems are also planned for professionals responsible for the installation and maintenance of gas facilities and equipment. Furthermore, the necessary standards, regulations, and technical requirements for the transition to gas- and electricity-based heating are to be developed and enforced, while facilitating the introduction of advanced technologies.

Together, Vision–2050 and Government Resolution No. 133 provide a policy framework for reducing emissions from residential heating and improving urban air quality in Ulaanbaatar. These measures are particularly relevant to the air-quality patterns identified in the present assessment, as residential and stationary heating are major contributors to wintertime PM, SO_2, and NO_2 pollution in the city. Continued long-term monitoring of ambient air quality, wet and dry deposition, and related atmospheric parameters will therefore be important for evaluating whether the transition toward

cleaner heating technologies results in measurable reductions in pollutant concentrations and atmospheric deposition.

CHAPTER 4. SUMMARY AND CONCLUSIONS

4.1 Summary

This national assessment summarizes the results of atmospheric deposition, ambient air quality, precipitation chemistry, and inland aquatic monitoring in Mongolia, with particular emphasis on the Ulaanbaatar urban site and the Terelj site during the 2021–2025 assessment period.

Filter-pack measurements showed a clear spatial contrast between Ulaanbaatar and Terelj. Concentrations of the monitored gaseous atmospheric components were substantially higher in Ulaanbaatar, reflecting the stronger influence of urban and anthropogenic emission sources. SO_2 showed a pronounced winter maximum, consistent with increased cold-season combustion emissions and unfavorable dispersion conditions. In contrast, NH_3 exhibited a clear warm-season maximum at both sites, while HNO_3 showed weaker and more episodic seasonal variation. HCl concentrations were also consistently higher in Ulaanbaatar than at Terelj. Overall, these observations indicate a strong urban–regional concentration gradient, modified by seasonal meteorological conditions and atmospheric transformation processes.

The particulate major-ion composition measured by the filter-pack method also differed between the two sites. SO_4^{2-} represented approximately 29% of the major-ion composition at both Ulaanbaatar and Terelj. Ulaanbaatar showed a substantially higher relative contribution of Ca^{2+}, approximately 20% compared with 10% at Terelj, which is consistent with a stronger influence of mineral and resuspended dust. In contrast, Terelj showed relatively greater contributions of NH_4^+, NO_3^-, and Cl^-, which may reflect the influence of regional atmospheric transport and secondary atmospheric transformation. These relative percentages, however, should not be interpreted as direct evidence of differences in absolute concentrations or deposition fluxes.

Wet-deposition chemistry during the May–October monitoring periods showed substantial interannual and spatial variability. Rainwater pH generally increased during the later years of the monitoring period, with the lowest mean values occurring in 2022 and the highest values in 2025. The increase in pH did not correspond directly to precipitation amount, indicating that rainwater acidity was controlled by the combined effects of atmospheric pollutant loading, dilution by precipitation, and neutralization by alkaline constituents such as Ca^{2+} and NH_4^+.

The relative ionic composition of precipitation differed clearly between the two sites. At Terelj, Na^+ was the dominant ion, accounting for approximately 40% of the total major-ion composition, followed by SO_4^{2-} at 31%. In Ulaanbaatar, SO_4^{2-} accounted for approximately 28%, followed by Na^+ at 22%, Ca^{2+} at 17%, NH_4^+ at 15%, and NO_3^- at 13%. The greater relative contributions of Ca^{2+}, NH_4^+, and NO_3^- in Ulaanbaatar are consistent with stronger urban, mineral-dust, and secondary inorganic aerosol influences, whereas the similar sulfate contribution at both sites is consistent with a contribution from regional atmospheric transport and secondary atmospheric transformation in addition to local sources.

Wet-deposition flux and total ionic concentrations during the May–October monitoring periods showed marked interannual variability. The highest values occurred in 2022 at both sites, particularly at Terelj, where total cation concentrations exceeded 600 μmol L^{-1} and wet-deposition flux reached approximately 111 mmol m^{-2} during the May–October monitoring period. Ulaanbaatar showed a corresponding maximum of approximately 57 mmol m^{-2}. Concentrations and deposition decreased sharply in 2023 and remained substantially lower during 2024–2025. The contrast between high ionic concentrations and relatively low precipitation in 2022, and greater precipitation but lower ionic concentrations in 2024, demonstrates that wet-deposition flux is determined by the combined effects of precipitation amount and precipitation chemistry rather than by precipitation amount alone. Interpretation of temporal changes at Terelj should also consider the relocation of the monitoring site in May 2023.

Long-term air-quality monitoring at the UB04 station during 2016–2025 showed a pronounced cold-season pollution regime in Ulaanbaatar. PM_{10}, $PM_{2.5}$, SO_2, and NO_2 concentrations increased strongly during winter and declined substantially during summer. Extreme concentration episodes were particularly evident for particulate matter and SO_2. O_3 showed the opposite seasonal behavior, with relatively higher concentrations during warmer and sunnier periods. The observed seasonal and diurnal patterns are consistent with the combined influence of emission intensity, atmospheric stability, boundary-layer development, and photochemical processes.

The Terelj River generally maintained near-neutral and relatively low-mineralization conditions during the monitoring period. River-water pH shifted from slightly acidic conditions during 2021–2023 to slightly alkaline conditions during 2024–2025, while electrical conductivity remained relatively low. Ca^{2+} was consistently the dominant major ion, which is consistent with a substantial influence of natural mineral weathering and water–rock interactions. Major-ion concentrations showed considerable seasonal and interannual variability and were generally higher during 2023–2025 than in 2021. Because complete major-ion measurements were unavailable for 2022 due to analytical equipment malfunction, these differences should be interpreted using the available monitoring years rather than as a continuous five-year trend.

Overall, the monitoring results demonstrate that atmospheric deposition and environmental quality in central Mongolia are governed by interacting local and regional processes. Urban emissions strongly influence atmospheric concentrations in Ulaanbaatar, while mineral dust, secondary atmospheric chemistry, meteorological variability, precipitation processes, and regional atmospheric transport influence deposition chemistry at both sites. The integration of atmospheric, precipitation, air-quality, and inland-water monitoring therefore provides an important basis for distinguishing local anthropogenic influences from broader regional environmental processes.

4.2 Conclusions

The main conclusions of the assessment are as follows:

1. A clear urban–regional contrast was observed in atmospheric concentrations. Ulaanbaatar showed substantially higher concentrations of SO_2, NH_3, HNO_3, and HCl than Terelj, reflecting the stronger influence of urban and anthropogenic emission sources.
2. Seasonality is a major characteristic of atmospheric pollution. SO_2 and major urban air pollutants, including PM_{10}, $PM_{2.5}$, and NO_2, showed pronounced winter enhancement, while NH_3 exhibited a warm-season maximum and O_3 showed higher concentrations during warmer and sunnier periods.
3. Particulate major-ion composition reflects both anthropogenic and natural influences. SO_4^{2-} represented approximately 29% of the major-ion composition at both sites, while the larger relative contribution of Ca^{2+} in Ulaanbaatar is consistent with a stronger influence of mineral and resuspended dust. The relatively higher contributions of NH_4^+, NO_3^-, and Cl^- at Terelj may reflect regional atmospheric transport and secondary transformation processes.
4. Wet-deposition chemistry differed substantially between Ulaanbaatar and Terelj. Terelj was characterized by a high relative contribution of Na^+, whereas Ulaanbaatar showed greater relative contributions of Ca^{2+}, NH_4^+, and NO_3^-. The similar contribution of SO_4^{2-} at the two sites is consistent with regional atmospheric transport and secondary atmospheric transformation in addition to local influences.
5. Wet-deposition flux during the May–October monitoring periods showed pronounced interannual variability. The highest ionic concentrations and deposition fluxes occurred in 2022 at both sites, followed by substantially lower values from 2023 onward. The results indicate that wet deposition reflects the combined effects of precipitation amount and atmospheric chemical loading rather than precipitation amount alone.
6. Precipitation did not show a progressive increase in acidity during the May–October monitoring periods from 2021 to 2025. Instead, arithmetic mean pH generally increased during 2024–2025. This pattern is consistent with the combined effects of atmospheric loading, precipitation characteristics, and neutralization by alkaline constituents such as Ca^{2+} and NH_4^+.
7. Ulaanbaatar continues to experience a pronounced cold-season air-pollution regime. PM_{10}, $PM_{2.5}$, SO_2, and NO_2 reached their highest concentrations during winter, while extreme concentration episodes remained an important feature of the long-term record. Continued monitoring will be essential for evaluating the effectiveness of national measures aimed at reducing wintertime emissions.
8. The Terelj River remained generally near-neutral and relatively low in dissolved mineral content. Its major-ion composition was dominated by Ca^{2+}, consistent with an important influence of natural catchment processes and water–rock interactions. Continued monitoring is needed to determine whether the higher major-ion concentrations observed during the later monitoring years represent natural hydrological variability or broader environmental change.
9. Monitoring-site changes and data gaps must be considered in long-term interpretation. In particular, the relocation of the Terelj monitoring station in May 2023 may have influenced observed interannual variability, while the absence of complete river major-ion data for 2022 limits continuous trend assessment.

10. Long-term integrated monitoring remains essential. Continued and methodologically consistent monitoring of atmospheric composition, wet and dry deposition, ambient air quality, precipitation chemistry, soil and vegetation, and inland aquatic environments is needed to distinguish local emission effects from regional transport and natural variability. Maintaining continuous datasets, minimizing analytical and sampling gaps, and documenting monitoring-site changes will strengthen future assessments and provide a more robust scientific basis for air-quality and environmental management in Mongolia.