Seasonal Dynamics of Surface Water Quality and River Water Quality Deterioration in an Urban Area of Mongolia

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Abstract

This research focused on the impacts of environmental policies on the conservation and improvement of urban river water quality in Mongolia. Wastewater contaminated by heavy metal (chromium) from the thriving tanning industry has been recognized as a problem in Ulaanbaatar, the capital of Mongolia, and a facility for pretreatment of chromium-contaminated wastewater was introduced in 2016. To verify the impact of this facility on the water quality of the urban area surrounding the Tuul River, and to assess the current status of potential water pollution, a long-term survey (2014-2018) was conducted using data from 10 monitoring points located upstream and downstream of the wastewater discharge point. Results showed that the concentrations of inorganic nitrogen, phosphorus, and organic matter (biochemical oxygen demand and chemical oxygen demand) were extremely low at points upstream of the point of wastewater discharge from the treatment plant in Ulaanbaatar. Downstream of the point of wastewater discharge, the chromium concentration decreased following commissioning of the pretreatment facility, indicating that the facility is effective. However, concentrations of organic matter, inorganic nitrogen, and phosphorus increased rapidly, indicating inadequate treatment at the plant, especially in winter. Therefore, new treatment measures are necessary and the formulation of appropriate environmental effluent discharge standards and safety standards are required for proper operation of wastewater treatment plants in extremely cold regions.

Keywords: Water quality, Municipal water treatment, Urban area, Cold region, Environmental degradation, Surface water, River

INTRODUCTION

As the human population has grown and industrial activity increased, the condition of the natural environment has deteriorated. Ensuring the quality of natural water bodies, particularly freshwater resources, is recognized as not only a global common issue but also a regional domestic problem. The shortage of freshwater resources has become one of the most urgent environmental problems*, reflecting a situation similar to that of other natural resources. The availability of freshwater and the quality of

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water resources are vital to natural ecosystems, human life, and national socioeconomic development. All elements of every national economy, including industry, agriculture, fisheries, and infrastructure, are supported by water resources. Globally, natural water resources are distributed unevenly and some areas endure water scarcity. The quantity of available water is determined by its natural hydrologic conditions, although human uses of water can make substantial difference. Water quality is also affected by human activities, including point source discharges from municipalities and industry and nonpoint source pollution such as agriculture and runoff from urban areas.2)

Mongolia is located in the basins of three rivers and the territory of the country is landlocked. Its total water resources comprise 98% surface water and 2% groundwater. The water consumed by the country’s socioeconomic activity is derived from rivers and lakes (20%) and from groundwater (80%). Approximately 68% of the surface water flows across the national border. The population and industries are supplied fully by groundwater resources. Households pay for their water use and industries pay water consumption charges and water pollution taxes. The fixed amounts of those fees are relatively small and the total revenue does not cover the costs of the infrastructure of municipal water facilities; therefore, the government maintains such infrastructure using taxes obtained from other sources. In Ulaanbaatar, the capital of Mongolia, groundwater is used for domestic and industrial purposes, and the wastewater is collected, treated at the Central Municipal Wastewater Treatment Plant (CMWWTP), and then discharged as effluent into the Tuul River.

The World Resource Institute reported that Mongolia was one of 36 high-water-risk countries in the world in 2013, and it has been estimated that Mongolia ranked as having medium–high baseline water stress in 2019. The Tuul River basin is crucially important because Ulaanbaatar is supported only by the water resources of this basin. In Mongolia, access to information about water quality and quantity is poor, and local citizens have campaigned for the right to be informed about the fulfillment of laws, national standards, and regulations regarding water issues. For example, residents would not necessarily be aware of whether the water usage fee was being levied in a fair manner. Moreover, there is little information regarding plans for environmental conservation, control of pollution, corrective measures, and remediation of water bodies.

The National Environmental Policy cycle has three main stages: environmental analysis, proposal development, and implementation. Environmental analysis as a first step is insufficient to develop proposals for maintaining environmental conservation in the Tuul River basin. A previous study focused on the contribution of nitrification and denitrification to nitrogen removal in wetland areas along a discontinuous tributary with slow water transport based on one-time sampling and experiment results. Itoh et al. concluded that the common difficulty regarding water quality in developing countries is insufficient wastewater treatment that leads to contamination and eutrophication of natural water bodies. Low temperatures in cold regions can be a problem for biological wastewater treatment processes such as activated sludge; however, experiments performed by Kogure et al. indicated that a concentration of 40 mg/L of NH4-N in wastewater could be reduced to below 1.0 mg/L of NH4-N by nitrification under the condition of average ambient air temperature of 10°C and at a nitrification loading rate of 0.32 kg-N/m3/d.6)

In Mongolia, the yearly variation of water quality is not well known, especially with regard to winter. Therefore, the aim of this study was to reveal the impact of anthropogenic activity on environmental water quality and to determine the major sources of the pollution observed in the Tuul River.

**MATERIALS AND METHODS**

**Locations of discharge and monitoring points**

The elevation of the Tuul River basin ranges from 1,200 to 2,700 m above sea level. The river flows from the east in a
southwestward direction and meanders through the territory of Ulaanbaatar and surrounding areas. The total length of the river is 704 km and it has a catchment area of 49,840 km². The Tuul River basin is the only water source for Ulaanbaatar. Data were collected from 10 monitoring points on the Tuul River located upstream and downstream of the wastewater discharge point of the CMWWTP. The 10 monitoring points were named M1 to M10 from upstream to downstream areas (Fig. 1). To comply with the legal requirements of the Mongolian Law on State and Official Confidentiality (2016)²³, the precise locations of the monitoring points are not disclosed.

To study the impact of point source pollution, results relating to the discharge of effluent between M6 and M7 by the CMWWTP (P1 in Fig. 1) were explored. Additionally, during this analysis, the need to explore another point source of pollution was identified. Thus, the results issued by a third-party testing laboratory regarding the discharge between M7 and M8 by the bioindustry (P2 in Fig. 1) were also examined.

Factors and indicators  In accordance with the guidance of international standard ISO 14031²⁰ and the available data, the results of contaminant concentrations, biochemical oxygen demand (BOD) by 5-day period, chemical oxygen demand (COD) by closed reflux (colorimetric method), inorganic nitrogen (NH₄⁻N (phenate method), NO₂⁻N (colorimetric method), NO₃⁻N (hydrazine reduction method)), and phosphorus (PO₄³⁻P; ascorbic acid method) were determined using standard methods (colorimetric method)²⁵. Additionally, because Ulaanbaatar has a renowned tanning industry that discharges wastewater contaminated with hexavalent chromium (Cr(IV)), the Cr(IV) concentration in the water samples was also analyzed using the standard method (colorimetric method) to assess the water quality²⁶. Dissolved oxygen (DO) in the river water was measured using a portable DO meter (FiveGo, Mettler Toledo, USA). The duration of this analysis of the environmental condition extended from January 2014 to December of 2018, i.e., 60 months. Flow data of the Tuul River (at M4) were supplied by the Information and Research Institute of Meteorology, Hydrology, and Environment (Table 1).

Pearson correlation analysis was performed using Microsoft Excel 2019 run on a Windows 10 platform (Microsoft Corporation, USA).

| Table 1 Average flow rate (m³/sec) of Tuul River at M4 |
|----------------|----------------|----------------|----------------|----------------|
|                | 2014           | 2015           | 2016           | 2017           | 2018           |
| January        | 0.006*¹ 0.008*¹ | Iced*² Iced*²  | Iced*² Iced*²  | Iced*²         |
| February       | Iced*² Iced*²  | Iced*² Iced*²  | Iced*² Iced*²  | Iced*²         |
| March          | 0.13*¹ Iced*²  | 0.003*¹ Iced*² | Iced*² Iced*²  |               |
| April          | 8.68 1.67      | 3.96 0.72*     | 1.96           |               |
| May            | 11.2 22.3      | 31.0 23.8      | 12.1           |               |
| June           | 23.2 14.0      | 33.5 26.0      | 34.6           |               |
| July           | 44.6 11.3      | 40.9 77.6      | 49.3           |               |
| August         | 33.7 24.5      | 16.4 71.5      | 80.2           |               |
| September      | 21.4 12.4      | 11.3 38.7      | 54.5           |               |
| October        | 10.5 6.53      | 6.45 17.5      | 16.0           |               |
| November       | 1.6 1.5        | 2.0 3.5        | 3.4            |               |
| December       | 0.31*¹ 0.018*¹ | 0.13*¹ 0.27*¹  | 0.36*¹         |               |

*¹ Most days were iced.
*² Surface water of the river was iced.
RESULTS AND DISCUSSION

Environmental parameters of original river water and contaminants  Long-term monitoring results were scrutinized to reveal the change in water quality in the Tuul River. Mongolian national standards state that permissible levels of pollutants for safe surface water are 9 mg/L for NO$_2$-N, 0.02 mg/L for NO$_3$-N, 0.5 mg/L for NH$_4$-N, 0.1 mg/L for PO$_4$-P, 3 mg/L for BOD, and 10 mg/L for COD\textsuperscript{10}. Review of the monitoring results showed that the surface water quality at M1–M6 was generally good and in compliance with the related items, pollutants, and permissible values set by the national standard (Figs. 2–4).

Differences were found in environmental parameters of the original surface river water in upstream and downstream parts of the river except water temperature. During the entire study period, NH$_4$-N, NO$_2$-N, NO$_3$-N, and PO$_4$-P concentrations in the monitored river section varied in the range of 0.01

![Fig. 2](image-url) Inorganic nitrogen trends during the study period: (A)–(C) upstream and (D)–(F) downstream. Mongolian national standards (0.02 mg/L for NO$_2$-N and 0.5 mg/L for NH$_4$-N) are indicated by dashed lines. Upstream NO$_2$-N and NO$_3$-N concentrations were not over the standard value of 9 mg/L.
Phosphorus trend during the study period: (A) upstream and (B) downstream. Mongolian national standard (0.1 mg/L for PO_4-P) is indicated by the dashed line.

Organic content trends during the study period: (A)–(C) BOD and (D) and (E) COD (Note the different ranges of all y-axes). Upstream is (A) and (D) and downstream is (B), (C), and (E). Mongolian national standards (3 mg/L for BOD, and 10 mg/L for COD) are indicated by dashed lines.

-44.72, 0.001–1.52, 0.01–15.38, and 0.001–3.588 mg/L, respectively. As shown in Figs. 2 and 3, no apparent change in initial nutrient concentration was observed at upstream points M1–M6, indicating that natural water quality was normal.

At downstream points M7–M10, extremely severe increases in NH_4-N, NO_2-N, and PO_4-P concentrations (maximum amounts detected: 44.72 mg/L in February 2015 at M7, 1.52 mg/L in March 2014 at M9, and 3.588 mg/L in March 2018 at M9, respectively) were observed frequently in the monitoring results of every month. It is tradition in Mongolia that the lunar new year is celebrated in February or January every year. The main site for the production of the meat (mutton and beef) for the celebration is on the outskirts of Ulaanbaatar near M9 on the Tuul River (Fig. 5). Large amounts of residue animal waste derived from the slaughtering process and the temporary market area could explain the maximum amounts of pollutants detected at M9. This finding suggests that point sources of pollutants should be checked and controlled. It can be seen from Figs. 4 and 6 that the BOD, COD, and Cr(VI) concentrations varied in the range of 0.2–1572.0 mg/L, 0.2–320 mg/L, and 1.0–207 µg/L, respectively. Similar tendencies of sharp increases of BOD, COD, and Cr concentrations were observed at M7. These findings suggest that it is important to check the dependent indicator of DO, which is
expended in the biodegradation and oxidation of organic matter. The national standard value for DO is set at \( \geq 6.0 \text{ mg/L} \) during the warm season and \( \geq 4.0 \text{ mg/L} \) during the cold season\(^{12}\). In the cold season, the temperature at the monitoring sites tends to be below 0°C during October–April. During the entire study period, DO concentration in the surface water of upstream–downstream areas varied in the range of 0.05–13.11 mg/L. As shown in Fig. 7, no apparent change in DO concentration was observed at points M1–M6, indicating that the DO content was sufficient enough for the survival of aquatic organisms. However, at points M7–M10, an extremely severe decrease in DO concentration (minimum amount detected: 0.05 mg/L in January 2016, June 2017, and December 2017 at M7) was observed. Because the BOD and COD concentrations were higher at M7–M10 in comparison with M1–M6 (Fig. 4), DO must have been consume for oxidation by microorganisms.

The clear decremental trend of DO and sharp increment of nutrient and pollutant concentrations led us to infer that the river water must have certain point and/or nonpoint sources of pollution.

**Land use nonpoint source pollution** The reason for the seasonal changes in \( \text{NO}_3-N \) concentration between M1 and M6 (Fig. 2(c)) could be attributed to the natural environment of bush and forest and the activities of residents of the ger district. Owing to the presence of high concentrations of oxygen demand and nitrogen and nitrate, the river water tends to show a high level of nutrient pollution.
phosphorus components, it was assumed that the primary pollution sources might be livestock (chicken farms, animal slaughter, pastures, and residents of the ger district), agriculture (crop farming, e.g., rice), or effluent discharged from the wastewater treatment plant (Fig. 5). Because the focus of this study was river contamination, Fig. 5 shows the broad land use adjacent to downstream areas (around monitoring points M6–M10) of the river in the region of Ulaanbaatar and Tov Prefecture.

Although agricultural production is often the first consideration regarding possible sources of pollution for a river, there is no agricultural production, such as the traditional vegetables and fruits, in the Ulaanbaatar area. Moreover, since 2002, livestock husbandry has been restricted by the Government of Mongolia13, and the area of restriction was extended in 2019. Thus, it could not be confirmed that agriculture and livestock contribute as nonpoint sources of pollution to the Tuul River in the Ulaanbaatar urban area.

Following the change in Mongolia from a socialistic centralized society to a democratic and market-based economy, the population and urban functions have become predominantly concentrated in Ulaanbaatar. Urbanization has progressed, and although the population growth and increase in the number of small- and medium-sized factories in the industry sector following the privatization of state-owned property in the capital, are considered symbols of economic growth, the urban development has resulted in environmental problems12. To date, these problems remain unresolved and represent serious challenges in Ulaanbaatar.

Point Source Pollution The CMWWTP in Ulaanbaatar treats domestic and industrial wastewater using a conventional biological wastewater treatment system, and the effluent is discharged into the river between M6 and M7. The national standard permissible levels for BOD and COD in discharged wastewater are 20 and 50 mg/L, respectively. The correlation between the natural water quality at the nearest downstream monitoring point (M7) and that of the effluent water from the CMWWTP was analyzed. Results showed that the NH₄–N concentration had the highest correlation between the river and effluent water ($R^2 = 0.645$); the correlations of COD and BOD were $R^2 = 0.457$ and $R^2 = 0.377$, respectively (Table 2). Given that the maximum concentrations of pollutant compounds and nutrients were observed at M7, effluent discharge by the CMWWTP (P1) was identified as the point source of the pollution. The dates considered for analysis of the concentrations of compounds in the effluent discharged by the CMWWTP were chosen as those nearest the monthly monitoring dates (Fig. 8). As shown in Figs. 2–4, apparent increases in concentrations of COD, BOD, NH₄–N, NO₂–N, and PO₄–P at M7 and M8 were observed in the monthly monitoring tests, indicating effluent discharge by the bioindustry (P2) (Fig. 9). The pollutant load in the Tuul River at M6–M8 clearly indicated that discharge from the CMWWTP affected the quality of river water more, in comparison with that from the bioindustry (Fig. 10).

The efficiency of wastewater treatment by the CMWWTP is highly dependent on the variation of temperature, especially in the cold season. Therefore, in addition to the current conventional treatment process, this study considered the necessity of other technological options that could include combinations of mechanical, biological, and sanitation approaches. Similar problems regarding the potential risk to river environments from wastewater discharge were identified in research conducted by

| Environmental parameter | NH₄–N | NO₂–N | NO₃–N | PO₄–P | BOD | COD | Cr(VI) |
|--------------------------|-------|-------|-------|-------|-----|-----|-------|
| Correlation ($R^2$)      | 0.645 | 0.022 | 0.055 | 0.323 | 0.400 | 0.482 | 0.068 |
Starka et al.\textsuperscript{14}, in which they identified that advanced treatment or technological options are required to remove contaminants shown to cause toxicity to biota, in addition to reducing the environmental risks associated with non-native organic and chemical compounds in wastewater. In the Sustainable Development Report of 2019, the sustainable development goal Index and Dashboards scored that the indicator of wastewater treated in Mongolia was only 3.3\%\textsuperscript{15}. The indicator shows and tracks the proportions of wastewater that flow from households, services, and industrial premises that are treated in compliance with national or local standards. As the CMWWTP must be a
point source, especially with regard to COD, BOD, and NH$_4$-N (Table 2), the treatment of CMWWTP and bioindustry wastewater must be enhanced to include treatment of organic matter and NH$_4$-N oxidation and removal by incorporation of not only a biological treatment system to achieve adequate treatment in cold regions\textsuperscript{8, 16} but also a physicochemical treatment system\textsuperscript{17}. In the case of river pollution, the key factors governing environmental water quality are the concentrations of contaminants in effluent discharged following wastewater treatment and the natural ambient temperature.

**Cr(VI) contamination.** The tanning industry is well developed in Ulaanbaatar and tannery wastewater should undergo pretreatment processes. Tannery effluent contains extremely large contents of compounds of organic pollutants that are not easy to remove using conventional biological treatment methods. The implication that wastewater is poorly treated by the CMWWTP could be verified through assessment of the cycle of water consumption by the tanning industry. For example, pure water obtained from the central municipal water system is used in various tanning processes, and then discharged as wastewater that comprises sheep and bovine animal residues, tanning agents, and chemicals. This wastewater undergoes pretreatment processes of mechanical filtration and chemical precipitation at the pretreatment plant (PTP in Fig. 5), before being released for treatment at the CMWWTP.

Contamination by Cr(VI) in downstream parts of the Tuul River has generally not been evident since mid-2017, which could reflect effective implementation of regulations regarding promotion (restriction) of the use of Cr(III) (Cr(VI)) tanning agents in skin and hide processing factories. Masunaga suggested that decreasing waste output and contamination load by modifying production processes is more efficacious and economical than end-of-pipe wastewater treatment\textsuperscript{18}. Therefore, in-process management of pollutants has major consequences regarding pollution reduction. The solution to the
problem of environmental Cr pollution was to use alternative chemicals, including Cr(III), throughout the tanning process\textsuperscript{19}. The Mongolian Ministry of Industry applied this suggestion to the tannery industry in 2013. Since the second quarter of 2017, Cr(VI) contamination in downstream parts of the Tuul River has not exceeded the standard level (Fig. 6). As a result of the effective implementation of the regulation supporting the use of Cr(III) and other alternative agents in the tanning process, environmental Cr(VI) contamination has been substantially reduced.

**Seasonal variation and cold climate influence.** Mongolia has a subarctic or steppe climate with little precipitation that generally falls between mid-March and the end of September. During May–September, the flow of the Tuul River is generally $>10$ m$^3$/s but in other periods, the flow rate is much reduced, i.e., November–April, and specifically in the iced season (January–February) (Table 1). Contaminant concentrations (BOD, COD, NH$_4$-N, and PO$_4$-P) are generally higher during periods of very low flow or in the iced season than in May–October. Cold temperatures affect biological purification in river water through reduced activity of oxidation, nitrification, and denitrification processes. Examination revealed the variational relationship between low temperatures during October–April and high concentrations of organics and nitrogen compounds in the discharge from the CMWWTP (Fig. 8). It was observed that concentrations of pollutants reached their highest levels (COD: 273 mg/L in January 2016, BOD: 580.52 mg/L in January 2016, and NH$_4$-N: 78.45 mg/L in December 2014) during cold periods, especially in winter. Li et al. revealed that biodegradation in a natural water body is related to water temperature and other factors\textsuperscript{20, 21}. Their studies showed that seasonal variation in microcystin-LR biodegradability of biofilm in a biological treatment facility depends on indigenous degrader abundance, which is associated with water temperature, natural microcystin-LR, and chlorophyll-a concentration. The cold temperatures in Ulaanbaatar during winter cause rivers to become blocked by ice\textsuperscript{22}, and the extreme cold limits the activity of natural biological and chemical reactions for biodegradation, oxidation, and nitrification that are essential for purification of river water and conventional biological wastewater treatment.

In Mongolia, recent population growth, urbanization, and industrial expansion have resulted in environmental problems. The significance of this study is that it expands existing knowledge regarding river environmental pollution, which could support the development of appropriate mitigating strategies by policy makers at national and local government level in developing countries. The findings of this analysis advance understanding regarding environmental protection, and further the development of regional science focused on maintaining natural water bodies and their biological diversity and resolving urgent urbanization-related problems.

**Conclusions**

To investigate the situation regarding the water quality of the Tuul River in the region of Ulaanbaatar, water sampled at 10 monitoring points and the effluent of the CMWWTP were analyzed. Overall, the general situation was revealed as one of deterioration in water quality and the aquatic environment of the river. Results indicated that pollution exists in the aquatic environment in the selected region and that environmental pollution in the river water is also evident. It was established that the source of this pollution was the discharge of poorly treated wastewater from the CMWWTP. There is a developing need to implement certain mitigating measures to ensure conservation of the natural aquatic environment. The results highlight the necessity for rational policy development, proper implementation of water management strategies based on review and improvement of related policies and adjustment technologies in developing countries, and harmonization of environmental standards and regulations. On the basis of this and other related research, implementation of appropriate and economically efficient wastewater treatment systems and technology should be adopted in
developing countries with consideration of their specific climatic conditions.

ACKNOWLEDGMENTS

The authors would like to thank the Project for Human Resource Development Scholarship (JDS) under the Japanese Grant Aid scheme of the Ministry of Foreign Affairs of Japan, the Central Environmental Laboratory of Mongolia, the Laboratory of Municipal Wastewater Treatment Plant of Ulaanbaatar, and the Information and Research Institute of Meteorology, Hydrology, and Environment for supporting this research. We thank James Buxton MSc of Edanz (https://jp.edanz.com/ac) for editing a draft of this manuscript.

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