

Article

Plastic Pollution in the Aquatic Ecosystem of the High-Mountain Lake Markakol (Kazakhstan): First Observations and Conclusions

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Abstract: The primary data of micro- and macroplastics in the aquatic environment of Lake Markakol, located in the mountainous area of East Kazakhstan, are presented. The determination of micro- and macroplastics in water is based on sieving, drying, liquid oxidation, density separation and visual sorting using a microscope with a magnification of 40×. The detected plastic fragments in the aquatic environment include fishing line nets, Styrofoam balls, plastic bags, plastic bottles, wrappers, food labels and packages and other types of plastic waste. The sizes of the plastic fragments were >25 mm, 1.0–5.0 mm and 0.315–1.0 mm. The concentration of plastic in Lake Markakol was 837.5 µg/m³ in the tributaries and 482.1 µg/m³ in the lake water. The detected plastic mainly corresponded to sieve mesh sizes of 1.0–5.0 mm and 0.315–1.0 mm. The main sources of plastic pollution are fishing, tourism and the lack of adequate infrastructure for household waste management. These data emphasize the importance of measures to regulate plastic waste management in order to preserve the Lake Markakol ecosystem and maintain human health.

Keywords: environment; aquatic ecosystem; plastic pollution; microplastic; concentration



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1. Introduction

1.1. Microplastics: A Global Environmental Phenomenon

The sensational discovery by the English scientist A. Parkes in 1862 [1–4], presented as a new material called “parkesine” [3], created from cellulose nitrate, did not envision the subsequent catastrophic consequences which would become a global environmental problem half a century later [5,6]. Plastic pollution in the environment, which has become one of the most pressing problems of our time, is a negative source of impact on aquatic ecosystems [4,7–12]. Plastic is durable and almost non-degradable in nature. Its collection is challenging due to the degradation of large plastic products by sunlight, water and wind [13–16] as well as the decomposition of plastic garbage, resulting in smaller plastic particles. Depending on the production and time of plastic deposition, degradation and redeposition in the environment, plastic particles can be found in different sizes (macro- or mesoplastic (>5.00 mm) or coarse microplastic (2.00–5.00 mm)), shapes (fragments, films, filaments and fibers, among others) and colors (white, red, black, brown, blue, silver, transparent, etc.) [17–34]. When small plastic particles, and among them microplastics (MPs), are released into aquatic systems, they can cause serious problems for aquatic

organisms (ichthyofauna and flora) and further down the food chain, affecting human health through the consumption of contaminated food [35–39].

One of the components of this problem is the pollution of surface waters and the world ocean by MPs. Despite the considerable attention paid to this problem in scientific research, the main attention has long been paid to marine ecosystems [40–47].

In recent years, an increasing number of publications has reduced this research gap [47–52]. From these publications, it is known that MP particles can have a complex negative impact on aquatic ecosystems, including mechanisms of physical and chemical impact. Taking this into account, as well as the fact of significant pollution of freshwater ecosystems by MP particles, it is necessary to include MPs in the program of surface water monitoring, including the monitoring of freshwater lakes. Some aspects of the current situation with MPs in the aquatic ecosystems of lakes are described in [47–52].

1.2. Microplastics Research in Kazakhstan and Central Asia

Although microplastics were officially recognized as an ecosystem pollutant at the global level in the early 2000s, they are of growing concern in Kazakhstan currently. MPs are practically not studied in Kazakhstan. The prerequisites for the beginning of the present study were a huge amount of plastic garbage found during previous field studies. With scientific investigations analyzing the degree of pollution by plastic of the world ocean, freshwater ecosystems and the environment as a whole [40–52], we raise for the first time the issues of micro- and macroplastic pollution of the environment in Kazakhstan, with the example of the freshwater Lake Markakol (48°45′ N 85°45′ E). The present study was carried out within the framework of a scientific project under grant funding from the Ministry of Science and Higher Education of the Republic of Kazakhstan (AP14870595) “Monitoring of the state and assessment of the level of pollution by micro- and macroplastics in the aquatic environment of Lake Markakol”.

A literature review demonstrates the relevance of plastic pollution [53–60]. The detection of MPs in water and bottom sediment samples in landlocked countries of Central and East Asia indicates that even less densely populated countries are exposed to MP pollution. It is difficult to understand the severity of MP pollution in these countries because of the limited number of regional MP pollution analyses. Experts claim that among all landlocked countries in Asia, Mongolia has the most studies on MP pollution, while Turkmenistan, Afghanistan, Uzbekistan, Kyrgyzstan, Tajikistan and Kazakhstan have nearly none [61].

Unfortunately, references to studies on plastic in the aquatic environment in Kazakhstan are rather scarce. One of the first references to plastic debris in Kazakhstan was made by Baimukanov M. (2017) in the publication “How to save the Caspian seal (*Pusa caspica*)”. Here, the author noted the visual detection of plastic debris on the Kazakh shores of the Caspian Sea. In 2021, the same author emphasized the need to study the problem of plastic pollution and its impact on the biodiversity of water bodies in Kazakhstan [62,63]. Interesting results were also obtained by a group of scientists led by N. Salikova, who conducted an ecological assessment of MP pollution of solid domestic waste landfills in the Akmola region located in northern Kazakhstan. Thus, the results obtained during the study should serve as both prerequisite and fundamental data for the forthcoming numerical modeling of MP behavior in soil and water [64]. The results of another study on the tributaries of the Syrdarya River conducted by Uzbek colleagues also aroused interest [65]. Thus, according to these authors, they screened the MP content in the surface water and bottom sediments of the Karadarya and Chirchik rivers, the first-order tributaries of the Syrdarya River in Uzbekistan. The average amount of MPs in the Karadarya and Chirchik rivers was 4.28 ± 0.09 and 0.95 ± 0.36 items per m^3 , and in the benthic sediments, it reached 244 ± 28.9 and 333 ± 11.5 items per kg of dry soil, respectively. The MP concentrations in the surface water and bottom sediments of the Karadarya River were significantly higher (p value < 0.01) than those in the Chirchik River. Microfibers were the most widespread there; the proportion of MP fibers in the water of the Karadarya and Chirchik rivers was

89% and 95%, and in the rivers' bottom sediments, it was 86% and 84%, respectively [65]. The prevalence of microfibers may indicate the pathway of entry into the rivers through discharges of domestic wastewater treatment facilities. Polymer microparticles in surface water and bottom sediments of the Karadarya and Chirchik rivers were mainly represented by polyethylene terephthalate (PET), which accounts for half of all MPs found in the Karadarya River. Textile-origin microparticles were particularly abundant in the Karadarya River, where viscose and nylon fibers were detected, indicating the leading role of synthetic textiles in this kind of pollution. The above-mentioned data are the first experimental evidence of MP pollution in the tributaries of the Syrdarya River. But the distribution and circulation of MPs in the surface waters of Central Asia require further comprehensive studies [65].

Such analyses have not been carried out in Lake Markakol or its tributaries until now. Due to the lake's location in the center of a nature protection area, MP pollution was not expected there, like in other strongly protected areas. But plastic garbage was observed by us in the Lake Markakol study area during last year's field campaigns, especially along tourist paths.

Thus, the purpose of this study is detection of macroplastic and microplastic pollution in the water of both Lake Markakol and the main inflowing rivers as well as the one out-flowing river for the first time, in addition to identification of their spatial distribution.

2. Materials and Methodology

2.1. Lake Markakol: Importance of Microplastics Studies

Lake Markakol is a high mountain lake located in the Markakol National Nature Reserve which is known as a unique nature site. The choice of this lake is justified by its geographical location and its status within the UNESCO World Network of Biosphere Reserves [66]. Lake Markakol belongs to the lakes of intra-mountain depressions and is located 1447 m above sea level, being a so-called "background water body" in Kazakhstan because it counts as undisturbed and is relatively less vulnerable to anthropogenic pollution [67,68]. Detection of plastic pollution is a unique and important objective even in Central Asia. It demands both more public attention and resonance and the continuation of research and the fight against plastic pollution.

The mountain ridges around Lake Markakol have heights 2000–3000 m above sea level. The catchment area of the lake is 1180 km², the surface area of the lake is 455 km², and its volume is 6.5 km³. The lake is 38 km long and 19 km wide with a maximum depth of 27 m, while its average depth is 14.3 m [69,70]. The lake is famous for its unique flora and fauna, including rare and endemic fish species such as lenok and grayling. The lake is surrounded by the Markakol Reserve, which was founded to protect and preserve the local ecosystems. The lake's water surface and the adjacent forest and mountain areas provide favorable conditions for many species of birds, mammals and plants.

The lake is a flowing lake as it is fed by several large tributaries (Urunkhaika, Topolevka, Tikhushka, Zhirelka, Elovka and Matabai) and 27 small streams feeding the lake with water from the surrounding mountains, while the Kalzhyr River flows out of it [68,69,71].

Lake Markakol's area is characterized as the coldest region in Kazakhstan, with a minimum temperature of −55 °C and only 162 warm days per year. According to data from the official website of the Republic State Institution "Markakol State Nature Reserve" [69], ice formation on the lake occurs in November–December, and opening and complete clearing of ice occurs by the end of May. According to Kazhydromet's observations, the average long-term air temperature values for January and July were −22.0 °C and 14.5 °C, respectively. Consequently, the choice of time for the field campaign took into account the climatic features and characteristics of Lake Markakol. This is why the summer period was the most suitable time period for the field work.

The water in the lake is fresh. It is an important source of drinking water and a habitat for various species of flora and fauna.

Despite the fact that Lake Markakol is located in a remote, mountainous area, there are several settlements in the vicinity of the lake, including the village of Markakol and small villages in the surrounding areas, like Urunkhaika and Zharma.

Like many natural objects, Lake Markakol faces the impact of anthropogenic activities such as poaching and eco-tourism. Thus, popular tourist trips among nature lovers and an increasing number of tourists during the summer months have led to increased pressure on the ecosystem of the lake, such as through the dumping of solid household waste and food residue in the surrounding lakes and, of course, abandoned poachers' fishing nets.

2.2. Sampling

Based on information on the climate of the Markakol Basin [72], field studies were conducted from 3 July to 13 August 2023.

Sampling for the detection of plastic particles of various size groups in water samples was carried out according to literary sources [4,26,72–81], with the process reflected in the block diagram below (Figure 1).

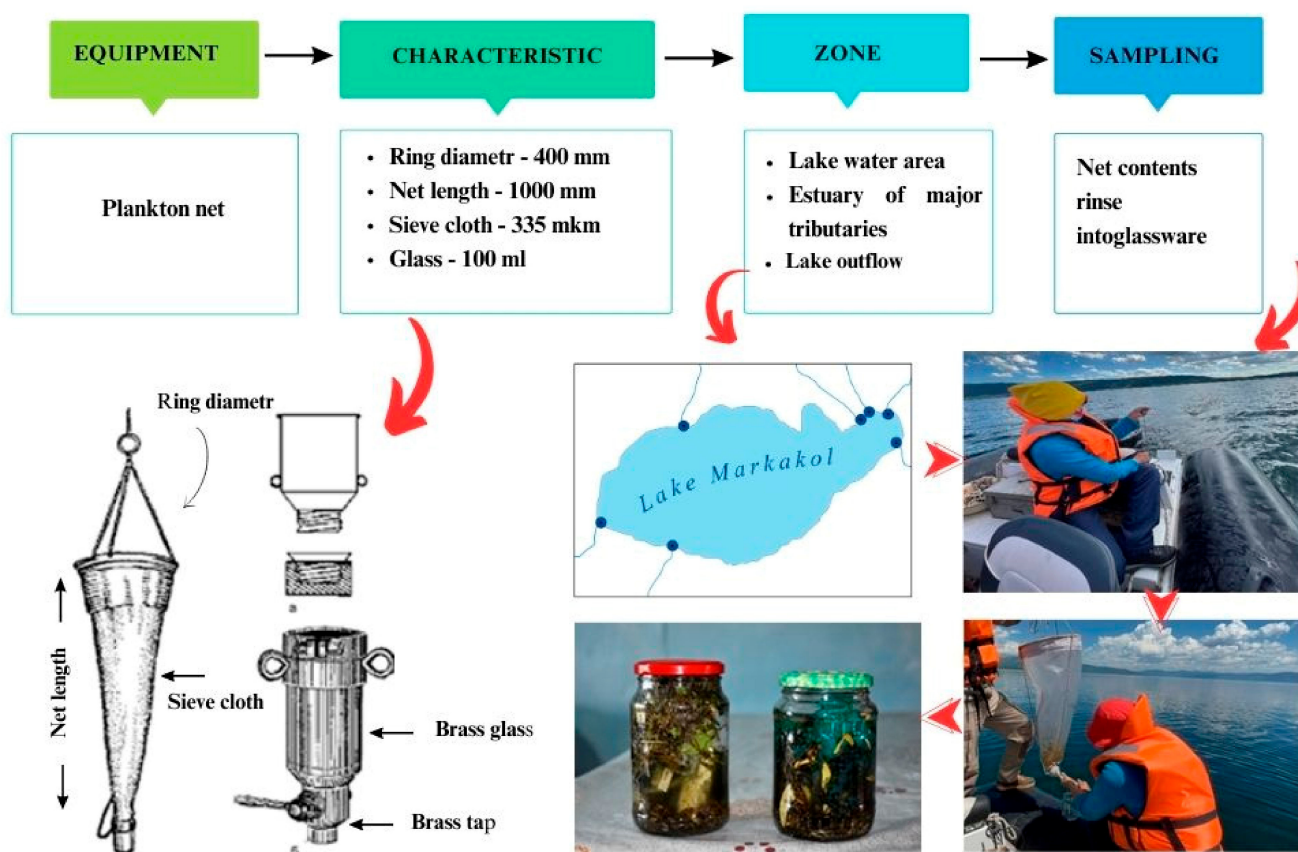


Figure 1. Block diagram of MP sampling conditions in the Lake Markakol and tributaries study area (Kazakhstan).

The main advantage of such nets is the rapid filtration of a large volume of water and the selection of only a concentrated sample [26,81]. They allow representative sampling from a large water surface area, sampling MP particles in the millimeter range [76,77].

For sample collection across the water area, a plankton net was towed along the surface layer at predetermined areas of the lake (Figures 1 and 2) at an average speed of 2.0 knots (1.89–2.43 knots from a PM 550.2 RIB boat) [4,74,79,80,82] with a duration of 15 min on board [4,74,75,79,82,83], making it less susceptible to wave disturbances [78]. The towing time depended on the suspended sediment concentration in the water, as the plankton net was completely clogged in 15 min [4,74,75,79,82,83]. When the net became clogged,

such as in the case of algal blooms or large accumulations of floating debris, the towing time could be reduced [79]. The net contents were washed into glass jars for samples and further laboratory processing [76,77,84]. Due to different surface water inflow conditions for the tributaries and the one outflow by the Kalzhyr River, the lake was divided into five sampling zones (Figure 2), taking into account the influence of the main tributaries and the assessment of potential pollution sources.

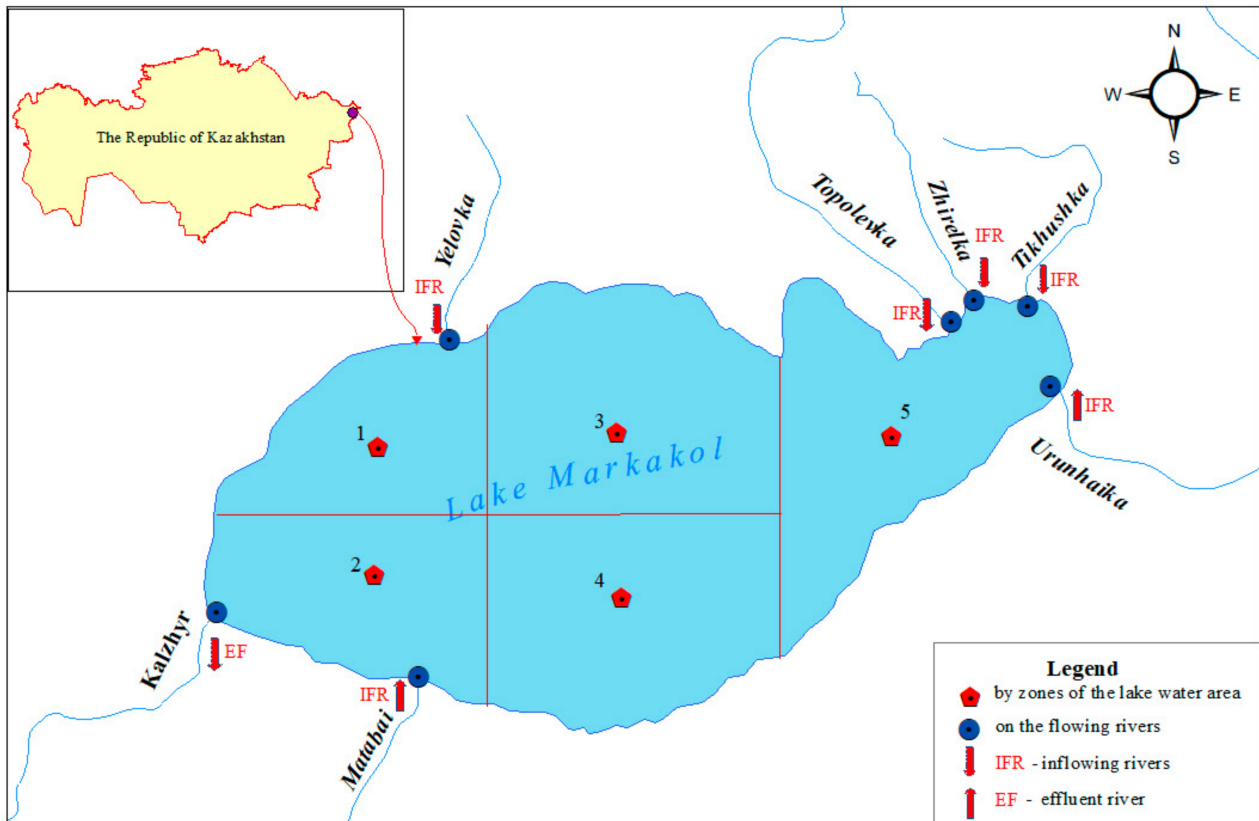


Figure 2. Sampling locations in lake zones of Lake Markakol and inflowing rivers.

2.3. Water Sample Preparation Process

Laboratory water samples from the field were passed through stainless steel sieves 20 cm in diameter and 5 cm deep, each with mesh sizes of 25 mm, 10 mm, 5.0 mm (ISO 3310-2 2000/50) [85], 1.0 mm and 0.315 mm (GOST R 51568-99 200/50) [86] placed one above the other, and washed thoroughly with distilled water to transfer all solid particles to the sieves [26,76,84]. To determine the presence of plastic types, all sieve mesh sizes were considered.

A further sample analysis process started with drying and ended with visual sorting, which served to sequentially prepare and analyze the water samples for micro- and macroplastic detection [84].

2.4. Process for the Determination of Micro- and Macroplastics in Water

After passing the material through a set of sieves [18,26,87–91]. The solids were transferred to a pre-weighed clean beaker and dried at 90 °C for 24 h in a desiccator [22,84,92–94]. After a lapse of time, the mass of the laboratory beaker with dried solids was weighed to obtain the total mass of MPs and natural materials, and 20 mL of iron (II) sulfate catalyst and 20 mL of 30% hydrogen peroxide [95,96] were added to the chemical beaker with the solids. During the removal of organic matter in the prepared solution of iron (II) sulphate, 3 mL of concentrated H₂SO₄ (pH 4) was added. The mixture was left at room temperature for 5 min and then heated to 75 °C while being stirred by a magnetic

stirrer [89,97]. After oxidation, 6 g of sodium chloride [30,79,98] was added for every 20 mL of sample to increase the density of the solution and remove inorganic matter through foam separation, undergoing density separation through flotation using a separator. The solution was transferred to a density separator and left overnight. Then, the precipitate was visually inspected for MP particles, and the residue was passed through a 0.315 mm sieve. The microplastics collected on the sieve were dried and weighed to determine their concentration. The isolated MP particles were visually inspected using a microscope with a $40\times$ magnification [76,84], which allowed the visual identification of plastic particles. The main criteria were luster, brightness and unusual color, which could indicate the presence of plastic, especially if the particles exhibited typical plastic material properties [26,79], as well as elasticity and hardness, which could be determined using tweezers [99]. MP particles larger than 1.0 mm could be visually separated using the following rules [74,79,100–102]: (1) absence of a cellular structure and other organic forms, which helps exclude organic materials, (2) uniform coloration and fiber thickness and (3) a clean and uniform color (i.e., uniform color without inclusions or stains). Color is an important parameter in the visual identification of plastic particles in both marine and freshwater environments because it can provide information about the type and condition of the plastic, as well as its history and environmental impacts [26,102,103]. The visual identification of colors was carried out both by eye and by examination under a microscope.

The described steps provide a systematic and comprehensive analysis of samples for the presence of MPs, from the extraction of particulate matter from a sample to its visual and quantitative analysis [84].

3. Results

The initial survey for plastic pollution in Lake Markakol showed the presence of plastic particles of various sizes, among which fragments of fishing line fibers and food wraps were the most common. Plastic microparticles smaller than 1.0–5.0 mm were found both in the lake itself and in its tributaries. This is an unexpected finding for this unique lake and its isolated location.

The concentrations and sizes of the MPs detected in the water of the lake and in the main tributaries had different spatial distribution patterns (Table 1).

In the eastern part of the lake, large amounts of plastic debris were detected in the Urunhaika River, with concentrations up to $56.8\text{ }\mu\text{g}/\text{m}^3$ for 1.0–5.0 mm particles and $11.5\text{ }\mu\text{g}/\text{m}^3$ for 0.315–1.0 mm particles. The detected litter was mainly of polyethylene origin.

Table 1. Concentrations and sizes of MPs in tributaries and in Lake Markakol (Figures 2 and 3).

Sampling Location	Concentration (mg/m³)					Total (mg/m³)
	0.315–1.0	1.0–5.0	5.0–10	10–25	>25	
Main Tributaries Flowing into Lake Markakol						
Urunhaika River	11.5	56.8	none	none	368.0	850.1
Tikhushka River	30.2	67.7	none	none	none	
Zhirelka River	24.0	43.8	none	none	none	
Topolevka River	26.2	130.9	none	none	none	
Yelovka River	12.6	none	none	none	none	
Matabai River	20.9	57.4	none	none	none	
Kalzhyr River	not found					
Water Area of Lake Markakol						
Zone 1	165.5	121.3	none	none	none	837.5
Zone 2	53.0	147.2	none	none	none	
Zone 3	37.6	4.0	none	none	none	
Zone 4	151.2	6.1	none	none	none	
Zone 5	113.4	38.2	none	none	none	



Figure 3. Concentrations of MPs detected in the water zones of Lake Markakol and its main tributaries.

The northeastern part of the lake, where the Tikhushka, Zhirelka and Topolevka rivers flow into the lake, was also characterized by high concentrations of MPs. The MP concentrations were found for the Topolevka River ($157.2 \mu\text{g}/\text{m}^3$), Tikhushka River ($97.9 \mu\text{g}/\text{m}^3$) and

Zhirelka River ($67.8 \mu\text{g}/\text{m}^3$). The size of the detected MPs in these rivers varied between 1.0 and 5.0 mm and 0.315 and 1.0 mm in the Tikhushka River (sieve mesh: 1.0–5.0 mm, $67.7 \mu\text{g}/\text{m}^3$ and 0.315–1.0 mm, $30.2 \mu\text{g}/\text{m}^3$), Zhirelka River (sieve mesh: 1.0–5.0 mm, $43.8 \mu\text{g}/\text{m}^3$ and 0.315–1.0 mm, $24.0 \mu\text{g}/\text{m}^3$) and Topolevka River (sieve mesh: 1.0–5.0 mm, $130.9 \mu\text{g}/\text{m}^3$ and 0.315–1.0 mm, $26.2 \mu\text{g}/\text{m}^3$). In the Yelovka River, MPs were found for the 0.315–1.0 mm sieve mesh size ($12.6 \mu\text{g}/\text{m}^3$).

The Matabai River flows from the south into the lake, and it had lower MP concentrations compared with the northern tributaries $78.3 \mu\text{g}/\text{m}^3$ (1.0–5.0 mm, $57.4 \mu\text{g}/\text{m}^3$ and 0.315–1.0 mm, $20.9 \mu\text{g}/\text{m}^3$).

The total MP concentrations in the surface layer of the lake were also extremely high, being $316.7 \mu\text{g}/\text{m}^3$ for the 1.0–5.0 mm particles and $520.8 \mu\text{g}/\text{m}^3$ for the 0.315–1.0 mm particles, giving a total water area MP concentration of $837.4 \mu\text{g}/\text{m}^3$. MP particles larger than $5.0 \text{ mg}/\text{m}^3$ were not found in either the inflowing rivers or the lake water. Non-MP particles were found only in the effluent of the Kalzhyr River (Table 1).

Figure 3 shows high concentrations of MPs in the eastern part of the lake (zone 1) for particles in 1.0–5.0 mm size up to $121.3 \mu\text{g}/\text{m}^3$ and for particles 0.315–1.0 mm in size up to $165.5 \mu\text{g}/\text{m}^3$ in the zone of influence for the Urunhaika, Tikhushka, Topolevka and Zhirelka rivers, resulting a total of $391.2 \mu\text{g}/\text{m}^3$ for the polluted effluents. High values of MPs were also characteristic for zone 2 ($200.2 \mu\text{g}/\text{m}^3$), zone 4 ($157.3 \mu\text{g}/\text{m}^3$) and zone 5 ($151.6 \mu\text{g}/\text{m}^3$), which were also influenced by rivers from the northern slopes (Yelovka River (zone 2 and 3)) and from the southern slopes (Matabai River (zone 4)). The lowest MP pollution level was observed in zone 3 (up to $41.6 \mu\text{g}/\text{m}^3$), corresponding to particle sizes of 1.0–5.0 mm ($4.0 \mu\text{g}/\text{m}^3$) and 0.315–1.0 mm ($37.6 \mu\text{g}/\text{m}^3$).

The data on plastic components in the aquatic ecosystem of Lake Markakol indicate serious pollution problems in the lake and its tributaries due to MPs. Fragments of fishing line nets, Styrofoam balls, plastic bags, plastic bottles, wrappers, labels, food packaging and other types of plastic waste predominated the detected plastics (Table 2 and Figure 4). These particles, found to be both mesoplastics (large fragments) and microplastics (microscopic particles), were of different sizes and colors (green, black, red, blue, white, and transparent).

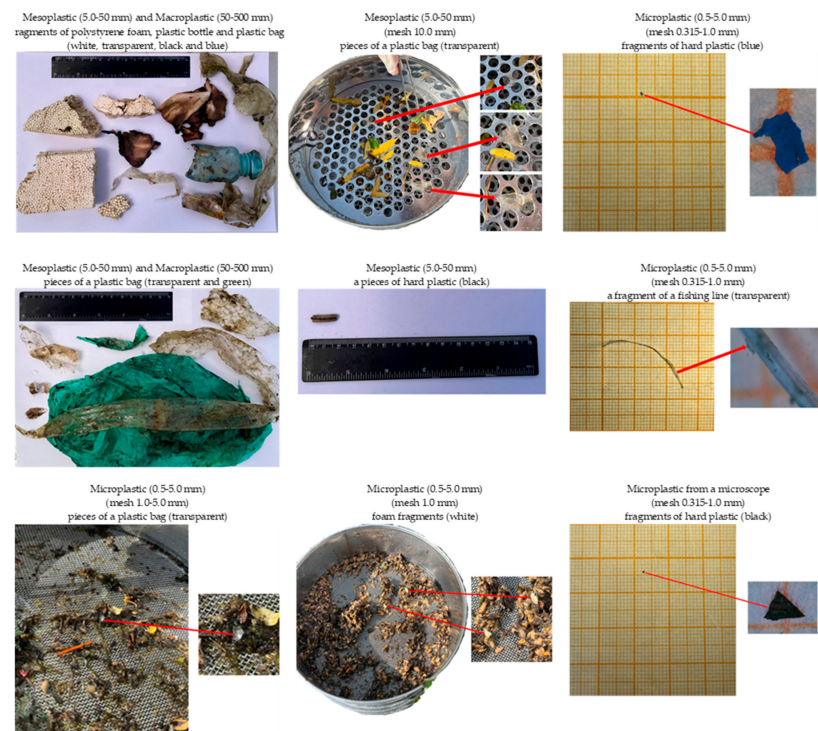


Figure 4. Visual documentation of selected samples from Lake Markakol. Plastic particles of different sizes found in water samples under a microscope with a magnification of $40\times$ (photo credit: A. Madibekova).

Table 2. On-site conditions, observations and counts during plastic sampling at Lake Markakol water area zones and main lake tributary rivers, as well as the effluent of the Kalzhyr River.

Sampling Location	Trawling Time/Distance (min/m)	Weather Conditions	Air Temperature (°C)	Types of Plastic Discovered	Plastic Size (mm)	Quantity of Plastic (Pcs)
The Main Tributaries Flowing into Lake Markakol						
Urunhaika River	15	cloudy	26	Fishing line nets, foam balls, plastic bags, plastic bottles, wrappers, labels, food packaging	0.5–300	125
Tikhushka River		clear, no precipitation	29		0.5–3.8	143
Zhirelka River		clear, no precipitation	29		0.4–3.6	117
Topolevka River		slightly cloudy, no precipitation	26		0.5–4.2	178
Yelovka River		slightly cloudy, no precipitation	26		0.5–3.9	47
Matabai River		slightly cloudy, no precipitation	33		0.4–4.4	121
Kalzhyr River		slightly cloudy, no precipitation	33		not found	
Water Area of Lake Markakol						
Zone 1	15/438	cloudy, no precipitation	26	Fishing line nets, foam balls, plastic bags	0.4–3.1	79
Zone 2	15/841	clear, no precipitation	31		0.5–4.4	53
Zone 3	15/593	clear, no precipitation	30		0.4–3.1	182
Zone 4	15/512	cloudy, no precipitation	33		0.4–4.3	38
Zone 5	15/736	clear, no precipitation	30		0.4–3.7	126

The results (Tables 1 and 2 and Figure 4) indicate a wide variety of plastic pollution in the aquatic ecosystem of Lake Markakol.

4. Discussion

4.1. Discussion of the Lake Markakol MP Analyses

This initial study on plastics, including mesoplastics and microplastics, in the Lake Markakol environment, including the tributary rivers and the only outflow, illustrated both the plastic load of the tributaries and the plastic sink of the lake.

Data on high concentrations of MPs in different areas of Lake Markakol indicate serious pollution problems. For the 0.315–1.0 mm particle size, the highest MP content of the tributaries to the lake was found in the Tishushka River ($30.2 \mu\text{m}/\text{m}^3$), decreasing in the order of the Topolevka River, Zhirelka River, Malaiba River, Yelovka River and Urunhaika River ($11.5 \mu\text{m}/\text{m}^3$). For the 1.0–5.0 mm particle size, the highest MP content of the tributaries to the lake was found in the Topolevka River ($130.9 \mu\text{m}/\text{m}^3$), decreasing in the order of the Tishushka River, Malaiba River, Urunhaika River and Zhirelka River ($43.8 \mu\text{m}/\text{m}^3$) (Figure 3). The highest MP contents within the lake zones for the 0.315–1.0 mm particle size were found in zone 1 ($165.5 \mu\text{m}/\text{m}^3$), decreasing in the order of zone 4, zone 5, zone 2 and zone 3 ($37.6 \mu\text{m}/\text{m}^3$). The corresponding MP contents for the 1.0–5.0 mm particle size for the lake zones were $147.2 \mu\text{m}/\text{m}^3$ in zone 2, followed by zone 1, zone 5, zone 4 and zone 3 ($4.0 \mu\text{m}/\text{m}^3$) (Figure 3). High MP concentrations were found in the northern, northeastern and southern zones (Figure 2 and Tables 1 and 2) of the lake, especially in the confluence areas of the Topolevka, Urunhaika and Matabai rivers, indicating that these areas are active MP pollution hotspots.

The total concentration of macro- and microplastics contributed by the tributaries was $482.1 \mu\text{g}/\text{m}^3$, while the lake water area had a higher concentration of $837.5 \mu\text{g}/\text{m}^3$. These results, together with the non-plastic loaded effluent of the Kazhyr River, indicate that Lake Markakol is a significant MP sink, while the tributaries significantly contribute to the overall pollution pattern.

The indications of possible reasons for the detection of MPs in lake and river areas, such as poaching and unconstructive tourism, emphasize the importance of the anthropogenic

influence on the pollution of aquatic systems. Polyamide fiber nets, monofilament and other plastic materials left behind can create significant pollution and harm to ecosystems, including endemic fish species. According to our observations, the majority of the plastic was associated with local pollution sources, as larger fractions were found in the inflowing rivers of the lake. Also, some of the plastic found in the lake water was of polymer origin, typical of monofilament nets used in fishing activities. These findings suggest that much of the plastic in the lake came from local pollutants and unsustainable fishing practices. At the same time, the transfer of plastic particles from places of unorganized collection of household waste could not be ruled out.

Some of the detected MP particles of the ecosystem of the high-mountain Lake Markakol are probably associated with the increasing tourism in this area. According to oral communication from the heads of community administrations of the surrounding communities, the number of tourists visiting Lake Markakol has increased substantially over the last three decades. Despite the remoteness, inaccessibility, low population and harsh natural and climatic conditions, according to reference data of the “Markakol State Nature Reserve” RSE, the growth of tourists to Lake Markakol over the last 5 years increased from 661 to 892 people per season. Another reason for the large number of mesoplastic particles and MP traces found in our investigations might be the close proximity of the settlement to the lake. Inefficient household waste management, insufficient infrastructure for waste collection and recycling and the widespread use of plastic products in everyday life are obvious reasons for the plastic and MP distribution in the study area. The low specific gravity of plastic particles can cause their widespread distribution in aquatic systems, since they can be transported to various zones of lakes, reservoirs or rivers and deposited in bottom sediments and soils [104–106] under the influence of water flow and air streams.

The used methods were suitable for the first inventory of MP occurrence in the Lake Markakol study area, including the tributaries and the outflow. But using color alone to identify MPs may not be sufficient, especially in cases where the plastic is obscured by a large amount of biological residue. In such situations, additional analyses, such as by microscopy or chemical methods, are required to accurately identify plastic and minimize errors in the MP analysis process. In some cases, it is suggested to disregard transparent and white and black color particles because they interfere with biological material and other substances which can be misidentified as plastic [76,99]. For reliable and rapid identification of large MP particles, it is advisable to use techniques such as pyrolysis-gas chromatography with mass spectrometry (Pyr-GC/MS), Fourier transform infrared spectroscopy (FTIR, μ -FTIR) or Raman spectroscopy (Raman, μ -Raman).

This may pose a problem with water pollution over large areas. In addition, long-range atmospheric transport of small plastic particles is possible [107,108]. This problem also requires further analyses.

4.2. Comparison with Microplastics Studies of Other Water Bodies

Malygina N. et al. [108] conducted a study which dealt with the MP content in the aquatic environment of mountain lakes in Siberia, particularly in Altai and the West Siberian Plain. The authors focused on six lakes: Talmen, Dzhulukul, Teletskoye, Zludyri, Degtyarka and Kuchuk. These lakes are located in the strictly protected Katunsky and Altai areas. These lakes are not affected by industrial activities. They are located in protected areas without permanent populations, and they contained MP particles, the concentrations of which ranged from 4 to 26 particles per liter of water, mainly from various human activities such as fishing, vehicles and waste disposal, especially by tourists. Even in such remote lakes where human activities are limited, high concentrations of MPs were observed. This emphasizes the need for increased attention to waste management and to careful water use in freshwater environments in order to maintain a basic level of environmental and health safety.

Studies conducted in 2011–2013 by the Limnological Institute of the Siberian Branch of the Russian Academy of Sciences [109] and later by Greenpeace on Lake Baikal [110]

revealed significant pollution in the lake from household waste, including plastics. Statistics show that up to 87% of the plastic found on the Lake Baikal coast is single-use plastics. In addition, the concentration of MPs in the lake water and on its shores turned out to be high, according to a study by Moscow State University's (MSU) specialists [111]. For samples taken from the water surface in the coastal zone of the most populated southeastern coast and in the so-called Small Sea near Olkhon Island, in terms of water surface area, the concentration of particles ranged from 19,000 to 75,000 plastic particles per 1 km², with an average value of 42,000 particles per 1 km², which corresponds to a high degree of plastic pollution [111]. Based on chemical composition, the particles were identified to be polyethylene, polypropylene and polystyrene. It is assumed that the MPs detected during this study were decomposition products of various household packaging materials [111].

According to our own long-term observations since 1987 (1988, 2000, 2002, 2003, 2006, 2007, 2009 and 2018) in these case study areas, both in the Altai Mountains (Russian part in West Siberia) and in and around Lake Baikal (East Siberia in Russia), the increasing number of tourists, including unguided and so-called "wild" tourism, is responsible for the huge deposition and distribution of plastic and MPs in these natural lake environments.

Studies conducted by limnologists in the last decade have provided a broader picture of the MP content in lakes around the world and its impact on aquatic ecosystems. About 90 lakes in different regions of Asia, Europe, North and South America and Antarctica were analyzed regarding their plastic pollution [49,112–115]. Chinese scientists processed data from 66 lakes, emphasizing the study of urban influences on MP accumulation in water and sediments [115,116]. Limnologists also found that large lakes have significantly lower MP contents in their mud compared with smaller water bodies. For example, in Lake Victoria, the concentration of MP particles was 6.5 granules per kilogram, while in a small pond in London, this value reached 540 particles per kilogram [114,116]. In the sediments of large lakes, MPs are mainly represented by coarse debris and particles ranging in size from 1 to 5 mm. Light MP fibers easily migrate through the water column, moving upward, downward and horizontally. This allows them to spread over long distances and affect different areas of water bodies [117]. One study [118] was conducted to assess MP pollution in a large, remote mountain lake, namely Hovsgol Lake, located in the mountains of northern Mongolia, which despite its remoteness, protected status and low population density was also prone to MP pollution.

Thus, in the world practice, pollution of water bodies by MPs has no restrictions, whether it is the world ocean, seas, rivers, large or small lakes or regions which are flat or mountainous, densely populated or low in population density or located in specially protected conservation areas or in urbanized areas.

5. Conclusions

This study was the first assessment of micro- and macroplastic pollution in the water area of Lake Markakol and its main tributaries in northeastern Kazakhstan. Lake Markakol is located within the Markakol Reserve, which is included in the UNESCO World Network of Biosphere Reserves, and it was previously considered to be unaffected by anthropogenic impacts.

However, this study showed that Lake Markakol has also been affected by plastic pollution. The main sources of pollution here were recreational and poaching fishing, a lack of organized collection of solid waste as well as a low level of environmental awareness for both tourists and the local population. We identified the main inflowing rivers as sources of plastic and MP inputs into the lake, but non-point plastic and MP inputs were also proven. The comparison of the MP concentrations in the tributary rivers, in just the effluent river and within the lake shows clearly that Lake Markakol is functioning as a MP sink. MP measurements in different zones of the lake showed higher MP concentrations under the influence of the northern lake coast and the Topolevka, Tikhushka, Zhirelka and Yelovka tributary rivers. The corresponding MP concentrations along the south coast of the lake under the influence of the Matabai River tributary and the out-flowing Kazhyr

River were quite lower. This MP content pattern was probably caused by both local inefficient waste management of the rural villages and the increasing number of tourists. Although the total number of plastic-wasting tourists was low in the Lake Markakol study area in comparison with other mountain lakes, despite the remoteness, inaccessibility, low population and harsh natural and climatic conditions, the number of tourists has increased. According to the reference data of the “Markakol State Nature Reserve” RSE, the growth of tourists at Markakol Lake for the last 5 years has increased from 661 to 892 people per season. Therefore, continued monitoring of plastics in aquatic ecosystems is an important step in understanding the extent of the problems and developing effective pollution management strategies.

For analyzing of the MP status of Lake Markakol the first time, the investigation approach, analyzing the MP pollution in both the inflowing rivers and in different lake zones, was suitable. However, to extend the knowledge about the input, storage, including transformation and output situation of MPs, repeated inspections are necessary, both during the same season and during other seasons. Determining the exact sources of origin of plastics will be the subject of future research, including use of the FTIR and Raman spectroscopy methods, which will allow us to more accurately determine the origins of new pollutants.

These observations emphasize the importance of the interaction of the geographical, hydrological and climatic features of a study area for MP analyses in aquatic systems. Additional research may help to understand the processes occurring in Lake Markakol and its catchment area better as well as provide recommendations for managing and reducing plastic pollution in the area.

The results of this study can be used for the development of more large-scale projects on MP problems in lakes. The knowledge about the presence of MPs in water bodies in the Republic of Kazakhstan will improve the understanding of the dimension of MP pollution problems and their impact on the aquatic environment. The study area of Lake Markakol and its tributaries seems to be especially suitable because of their insularity and the closed catchment situation with only one outflow.

Addressing this problem requires comprehensive measures such as raising awareness of waste management, improving waste management, encouraging a shift to alternative materials and actively implementing measures to clean up and restore polluted aquatic ecosystems.

The final results emphasize the need to take measures to prevent pollution of water systems and develop strategies to reduce the use of plastic materials in the region. Combating the MP problem requires a comprehensive approach, including the promotion of environmentally friendly consumption and the use of recyclable and biodegradable materials. Limited production and distribution of plastics, of course, would be the best form of prevention!

There is a need to create and improve systems for collection, recycling and disposal of waste, including plastic garbage. Additionally, it is extremely important to introduce strict laws and regulations on waste management, such as fines for illegal dumping of garbage into water systems.

The implementation of these activities in the future could have a great impact on the development of the system of collection, transportation and recycling of plastic waste, which will have a positive impact on improving the environmental situation in the study area and in all of Kazakhstan. This will contribute to achievement of the goals of the “green” economy. The promotion and support of scientific research on plastic pollution of ecosystems could strengthen the importance of this work in the future and become the basis for further research and practice.

Until there are clear restrictions on the production and use of plastics, we need to preserve our natural heritage. For this purpose, special protection measures are being implemented in the territories of UNESCO sites and other equally important natural areas. But unfortunately, the results of this work show that this has not been sufficient. Therefore,

continued monitoring of plastics in aquatic ecosystems is an important step toward understanding the extent of the problems and developing effective pollution management in combination with prevention strategies.

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