ABSTRACT

of the research work of Zhadi Askhat entitled «Monitoring and assessment of the current state of the aquatic ecosystem of Markakol Lake and development of recommendations for the environmental conservation of water resources» submitted for the degree of Doctor of Philosophy (PhD) under the educational program 8D08604 – «Water Security»

Relevance of the topic. In recent decades, the rational use and conservation of water resources have become issues of growing global importance, which has led to increased scientific attention to the assessment of the condition and sustainability of aquatic ecosystems, including lakes. Global practice demonstrates that lakes represent not only a significant component of global freshwater resources, but also function as sensitive indicators of climate change and long-term accumulators of pollutants. Integrated water resources management, based on the principles of sustainable development, requires balancing socio-economic demands with the ecological requirements of aquatic and riparian ecosystems, as these systems ensure environmental stability and provide essential ecosystem services. In the Republic of Kazakhstan, the issue of water resources has always been of strategic importance. The country hosts a large number of lakes that differ in surface area, volume, and water quality, many of which serve as critical natural resources for economic activities. At the same time, unique water bodies located within specially protected natural areas and UNESCO biosphere reserves possess exceptional scientific and conservation value, as they have experienced relatively low anthropogenic pressure and therefore serve as sensitive indicators of large-scale environmental transformations. Lake Markakol, situated within the "Markakol" State Nature Sanctuary, belongs to this category of water bodies. It is recognized as one of the key biodiversity conservation sites of the Altai-Sayan ecoregion within the framework of international programs such as GEF, UNDP, WWF, NABU, and GTZ, and is also included among the 200 global priority ecoregions identified by the WWF Living Planet Initiative. Kazakhstan, as a Party to the Convention on Biological Diversity (Rio de Janeiro, 1992; ratified in the Republic of Kazakhstan by Resolution No. 918 dated August 19, 1994), bears obligations to conserve ecosystems and biological diversity. Under conditions of ongoing environmental change and increasing anthropogenic pressure, comprehensive studies of lake ecosystems are becoming increasingly important for ensuring national and regional environmental security.

Lake Markakol serves as a reference site for assessing the current state of aquatic ecosystems in Central Asia. Its geographical remoteness and restricted access regime have resulted in the scarcity of long-term systematic observations, which significantly increases the scientific value of newly obtained data. The results of this study provide novel information that fills existing knowledge gaps regarding the spatial distribution of hydrological, hydrochemical, and ecological characteristics of high-mountain lakes.

Particular importance is attributed to the application of an integrated ecosystem approach that combines analyses of morphometric, hydrophysical, and hydrochemical parameters with an assessment of pollution by emerging contaminants, including microplastics. In the context of global challenges such as climate change, increasing anthropogenic pressure, and the spread of new types of pollutants, a comprehensive assessment of the ecological status of Lake Markakol is of strategic importance for the environmental security of Kazakhstan and the broader region.

Global research experience demonstrates that mountain lakes (e.g., Titicaca, Issyk-Kul, Baikal) play a crucial role in regional hydroecological systems. However, in Central Asia, such integrated studies are rarely conducted, and for Kazakhstan, they are largely absent. Consequently, the present study fills a significant scientific gap and is relevant not only at the national level, but also within the international scientific community.

Aim of the study. To conduct a comprehensive ecological assessment of the current state of the aquatic environment of Lake Markakol and to develop scientifically substantiated recommendations to ensure its long-term ecological sustainability.

In accordance with the aim, the following main tasks were formulated:

• To update the morphometric characteristics of the lake for the first time in the past 60 years;

• To examine the characteristics, sources, and spatial distribution of micro- and macroplastics;

• To assess the impact of plastic pollution on the aquatic ecosystem;

• To investigate heavy metals as key pollutants of the aquatic environment and to determine their distribution and concentration levels;

• To analyze the distribution of heavy metals within the "water-bottom sediments-aquatic organisms (hydrobionts)" system;

• To develop practical recommendations aimed at the ecological conservation of the Lake Markakol aquatic ecosystem.

Object of study: Lake Markakol.

Subject of study: the ecological state of the aquatic ecosystem of Lake Markakol and the factors determining its sustainability.

Research methods. The methodological framework of the study is based on field investigations conducted during 2022-2023, including systematic sampling of water and bottom sediments. The following analytical methods were applied:

–   spectrophotometry, electrometry, titrimetry;

–   atomic absorption spectrometry (Shimadzu AA-7000);

–   visual microscopy and filtration methods for microplastics analysis, including determination of polymer composition based on spectral data;

–   refinement of lake morphometry using hydrographic surveying, digital modeling, and GIS technologies (ARCGIS).

Quality assurance was achieved through the use of standard reference materials and replicate analyses. All applied methods complied with international requirements of ISO, UNEP, and WHO, ensuring the reliability and comparability of the obtained data.

Data Sources. The information base of the study includes statistical data from the Republic of Kazakhstan, hydrochemical data, provided by the RSE "Kazhydromet", meteorological data on air temperature and precipitation, as well as long-term publications and archival materials from the Institute of Geography and Water Security.

The dissertation was prepared based on the framework of a scientific project funded by the grant of the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP14870595, "Monitoring of the Aquatic Environment State of Lake Markakol and Assessment of Micro- and Macroplastic Pollution Levels").

Proposed Defensible Findings:

I. The contemporary morphometric characteristics of Lake Markakol were determined for the first time in 60 years based on a new high-quality digital bathymetric model. The maximum depth is 24.87 m, and the total water volume is 6.67 km³, providing an up-to-date physical basis for hydrological modeling and assessment of the ecosystem's ecological state.

II. Microplastic pollution of the aquatic environment was documented for the first time for high-mountain lakes in Central Asia, and its quantitative parameters were established. The polymer composition of the microplastics (polypropylene, polyethylene, polystyrene) was identified, and it has been proven that Lake Markakol is a final reservoir for plastic particles entering via river inflow.

III. Patterns of spatial distribution of heavy metal contamination (Cu, Zn, Pb, Co, Ni, Cd) were identified in the Markakol aquatic ecosystem. River mouths were found to be the primary pathways of pollutant input. The integrated pollution index ($Zc = 11.6$) corresponds to a moderate hazard category.

IV. Based on the identified pathways of heavy metal input and zones of microplastic accumulation, recommendations were developed to reduce the anthropogenic pressure on the Lake Markakol ecosystem.

Practical significance of the research results. The practical value of this research is determined by the applicability of the obtained results for development of measures aimed at ecosystem protection and improving the national monitoring system by environmental protection authorities, including the administration of the "Markakol" State Nature National Park. The generated data may be incorporated into international databases of UNEP and UNESCO and applied in sustainable water resources management programs, as well as in educational courses on hydroecology and water security.

Scientific novelty of the obtained results: The scientific novelty of this research lies in the morphometric characterization of Lake Markakol based on modern digital bathymetric modeling, the identification of spatial patterns and sources of heavy metal contamination, and the first documented evidence of microplastic pollution in high-mountain lakes of Central Asia. The combination of

classical hydrochemical approaches with analytical methods for analyzing emerging pollutants allowed the development of an original ecosystem framework for assessing the sustainability of aquatic ecosystems.

Approval of the work. The main provisions, conclusions, and results of the dissertation were presented at the Republican Conference "Young Satpayevs" (Almaty, 2024) in the framework of the presentation entitled "Comprehensive Monitoring and Assessment of the Current State of the Lake Markakol Aquatic Ecosystem".

Connection of the research with the UN Sustainable Development Goals (SDGs).

The research is directly aligned with the United Nations Sustainable Development Goals (SDGs), including:

- SDG 6 "Clean Water and Sanitation" – through the comprehensive assessment of water quality;
- SDG 13 "Climate Action" – through the use of the lake ecosystem as an indicator of climate-driven environmental changes;
- SDG 15 "Life on Land" – through the development of strategies for the protection of a unique natural site;
- SDG 12 "Responsible Consumption and Production" – through recommendations aimed at improving waste management.

Measures proposed to improve the ecological state of Lake Markakol:

- Strengthening continuous monitoring of heavy metal inputs, particularly in deltaic areas;
- Expanding the application of advanced analytical techniques, including mass spectrometry, to enhance monitoring accuracy;
- Establishing a network of permanent monitoring stations equipped with modern sensors;
- Applying satellite technologies and unmanned systems;
- Developing infrastructure for separate waste collection and recycling to prevent plastic pollution, including installing special containers along tourist routes;
- Engaging the local population in environmental education programs.

Characterization of the main research results.

Analysis of physical and chemical parameters. The research results demonstrated that the lake water is characterized by low mineralization (140-180 mg/L), a weakly alkaline reaction (pH 7.2-7.8), and seasonally variable dissolved oxygen concentrations (6.1-8.9 mg/L). These characteristics indicate a high sensitivity of the lake ecosystem to climatic variability and an increased risk of trophic imbalance under growing anthropogenic pressure.

Study results on heavy metals. The concentrations of heavy metals in water ranged as follows: copper – 0.004-0.018 mg/L, zinc – 0.012-0.044 mg/L, lead – 0.001-0.006 mg/L, nickel – 0.002-0.009 mg/L, cobalt – 0.001-0.004 mg/L, cadmium – 0.0003-0.0012 mg/L. The average values in the bottom sediments were: copper – 36 mg/kg, zinc – 92 mg/kg, lead – 28 mg/kg, nickel – 41 mg/kg, cadmium

– 0.7 mg/kg. Spatial analysis revealed that river inflows represent the primary pathways of heavy metal input, while bottom sediments act as their main accumulation medium.

Results of the microplastic study. Microplastic contamination of Lake Markakol was recorded for the first time. Concentrations ranged from 0.7 to 3.2 particles/m³ in water and from 12 to 48 particles/kg (dry weight) in bottom sediments. Morphological analysis revealed a predominance of fibers (54%) and a proportion of fragments (38%), while the share of granules accounted for 8%. The polymer composition was dominated by polyethylene, polypropylene, and polystyrene.

Publications based on the research results. The research results have been published in 9 scientific articles, including six indexed in the Scopus database, published in journals such as: News of the National Academy of Sciences of the Republic of Kazakhstan, Geology Series and Technical Science (Q3, CiteScore; SJR 2023 – 0.508), Applied Sciences (Q1; Percentile 79, CiteScore 2023 – 5.3; SJR 2023 – 0.508), EVERGREEN (Q2; Percentile 59, CiteScore 2023 – 4.3; SJR 2023 – 0.376), Hydrology (Q1, Percentile 84, CiteScore 2024 – 5.9; SJR 2023 – 0.735). Three articles were published in journals recommended by the Committee for Quality Assurance in Science and Higher Education under the Ministry of Science and Higher Education of the Republic of Kazakhstan. In addition, two certificates of registration of copyright-protected objects in the state register were obtained, and one monograph was published in co-authorship.