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CLIMATE CHANGE IMPACTS ON CENTRAL ASIAN HIGH-MOUNTAIN LAKES: THE CASE OF LAKE MARKAKOL (KAZAKHSTAN)

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Abstract. This study examines the long-term impact of climate change on the hydroecological state of Lake Markakol, located in Eastern Kazakhstan. A comprehensive analysis was conducted of air temperature, atmospheric precipitation, ice phenomena, water level, and hydrochemical characteristics. Based on long-term hydrometeorological data (1984–2020), significant trends and patterns in water level, temperature, salinity, and ice regime were identified. Precipitation exhibited pronounced cyclicity with two distinct humidification cycles. The water level of the lake demonstrated periodic fluctuations: a decline was observed between 1943 and 1979, followed by an increase beginning in 2006. The ice regime, serving as a sensitive indicator of climate change, was strongly influenced by variations in temperature and precipitation. Hydrochemical analysis revealed the presence of organic and biogenic substances, as well as elevated concentrations of ammonium and nitrite nitrogen, indicating anthropogenic pollution. The dynamics of organic and biogenic compounds confirmed the intensification of anthropogenic pressure on the lake ecosystem. Despite the relative stability of the main hydrochemical parameters, exceedances of permissible standards for certain compounds were recorded, suggesting potential ecological risks. Results of the Mann–Kendall test showed a statistically significant increase in air temperature (Z = 3.30) at the 99% confidence level. The findings emphasize the importance of continuous hydrological and hydrochemical monitoring to ensure effective water management and sustainable ecosystem development under changing climatic conditions. The study confirms the transformation of the hydrological regime of Lake Markakol under the influence of modern climate change and contributes both to the advancement of scientific knowledge and to the practice of natural resource management.

Key words: lake, climate change, hydrometeorology, atmospheric precipitation, ice cover

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КЛИМАТ ӨЗГЕРУІНІҢ ОРТАЛЫҚ АЗИЯ БИІК ТАУЛЫ КӨЛДЕРІНЕ ӘСЕРІ: МАРҚАКӨЛ КӨЛІНІҢ МЫСАЛЫНДА (ҚАЗАҚСТАН)

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Аннотация. Бұл зерттеуде климаттық өзгерістердің Шығыс Қазақстанда орналасқан Марқакөл көліне гидроэкологиялық әсері көпжылдық мәліметтер негізінде қарастырылды. Ауа температурасы, атмосфералық жауын-шашын, мұздық құбылыстар, су деңгейі мен гидрохимиялық көрсеткіштер талданды. 1984-2020 жылдар аралығындағы көпжылдық гидрометеорологиялық деректерді талдау нәтижесінде су деңгейі, температура, минерализация және мұздық режимінің маңызды үрдістері мен заңдылықтары анықталды. Жауын-шашын айқын циклдік сипатқа ие болып, екі ылғалдану циклі байқалды. Көлдің су деңгейі кезеңдік түрде өзгерді: 1943-1979 жылдары төмендеу, ал 2006 жылдан бастап көтерілу байқалды. Климаттық өзгерістердің сезімтал көрсеткіші болып табылатын мұздық режим температура мен жауын-шашынның ауытқуына байланысты болды. Гидрохимиялық талдау нәтижесінде суда органикалық және биогендік заттардың, сондай-ақ аммоний мен нитрит азотының жоғары деңгейлері анықталды, бұл антропогендік ластануды көрсетті. Сонымен қатар, биогенді және органикалық заттардың көпжылдық динамикасы су экожүйесіне антропогендік қысымының күшейгенін көрсетті. Негізгі көрсеткіштердің салыстырмалы тұрақтылығына қарамастан, жекелеген қосылыстар бойынша нормативтен асу жағдайлары экологиялық қатердің бар екенін аңғартады. Манн-Кендалл тестінің нәтижелері зерттеу аймағында ауа температурасының өсуін (Z=3,30) 99 % сенімділік деңгейінде айқындайды. Зерттеу нәтижелері климаттың өзгеруі жағдайында тиімді су ресурстарын басқару мен экожүйенің тұрақты дамуы үшін гидрологиялық және гидрохимиялық мониторингті үздіксіз жүргізудің маңыздылығын айқындайды. Марқакөл көлі бойынша алынған нәтижелер аймақтық климаттың өзгеруіне байланысты гидрологиялық режимнің трансформациясын дәлелдейді. Бұл жұмыс ғылыми түсінікті дамытуға да, табиғи ресурстарды басқарудың тәжірибелік қолданылуына да айтарлықтай үлес қосады.

Түйін сөздер: көл, климаттың өзгеруі, гидрометеорология, атмосфералық жауын-шашын, мұз жамылғысы

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ВОЗДЕЙСТВИЕ ИЗМЕНЕНИЯ КЛИМАТА НА ВЫСОКОГОРНЫЕ ОЗЕРА ЦЕНТРАЛЬНОЙ АЗИИ: НА ПРИМЕРЕ ОЗЕРА МАРКАКОЛЬ (КАЗАХСТАН)

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Аннотация. В данном исследовании рассматривается влияние изменений климата на гидроэкологическое состояние озера Маркаколь, расположенного в Восточном Казахстане, в многолетнем аспекте. Проведён анализ температуры воздуха, атмосферных осадков, ледовых явлений, уровня воды и гидрохимических характеристик. На основе анализа многолетних гидрометеорологических данных (1984–2020 гг.) выявлены значимые тенденции и закономерности изменения уровня воды, температуры, солёности и ледового режима. Осадки проявили выраженную цикличность с двумя отчётливыми циклами увлажнения. Уровень воды в озере колебался периодически: с 1943 по 1979 гг. наблюдалось снижение, а с 2006 года — повышение. Ледовый режим, являющийся чувствительным индикатором климатических изменений, находился под влиянием колебаний температуры и количества осадков. Гидрохимический анализ показал наличие органических и биогенных веществ, а также повышенные концентрации аммонийного и нитритного азота, что свидетельствует о воздействии антропогенного загрязнения. Анализ выявил признаки усиления антропогенной нагрузки, влияющей на гидрохимический режим и экологическое равновесие озера. Несмотря на относительную стабильность основных показателей, зафиксированы превышения нормативов по отдельным соединениям, что указывает на потенциальные экологические риски. Результаты теста Манна–Кендалла по температуре воздуха в районе озера показали повышение температуры ($Z=3,30$) с уровнем достоверности 99%. Результаты исследования подчёркивают важность непрерывного гидрологического и гидрохимического мониторинга для эффективного водопользования и устойчивого развития экосистемы в условиях изменения климата. Проведённая работа вносит вклад как в развитие научных представлений о воздействии климатических изменений, так и в совершенствование практики управления природными ресурсами.

Ключевые слова: озеро, изменение климата, гидрометеорология, атмосферные осадки, ледовый покров

Introduction. Lakes are important components of the global hydrosphere, having a significant impact on local ecosystems, climate and human economic activity. The hydrological regime of lakes, including changes in water level, temperature, salinity and other parameters, is determined by a complex of natural and anthropogenic factors.

The hydrological regime of lakes is characterized by several key factors. Firstly, seasonal fluctuations significantly impact water levels. Secondly, water temperature varies seasonally, affecting water mass mixing processes. Long-term climatic changes, particularly global warming, can induce substantial alterations in lake hydrological regimes. These changes manifest in water level fluctuations, precipitation patterns, and temperature conditions. A notable example of such long-term impacts is the shrinking of the Aral Sea due to increased irrigation in its basin (Duan et al, 2024, Wang et al, 2024). Anthropogenic activities, such as water withdrawal for economic purposes, dam construction, and water pollution, can significantly disrupt natural hydrological cycles. Lake Chad, for instance, has experienced a decline in size due to intensive water extraction and climatic factors (Akuma et al, 2024, Sultonov et al, 2024). Lastly, physiographic factors, including geological features like soil type and topography, influence infiltration and surface runoff processes. Vegetation within the lake basin plays a crucial role in water retention and evaporation reduction.

The hydrological regime of natural water bodies, including lakes, serves as a crucial indicator of their functional characteristics. This regime is influenced by both zonal and azonal factors. Among the zonal factors, climate emerges as a primary driver, affecting the water and thermal regimes of lakes. Azonal factors, such as the lake basin's morphometry and morphology, also play a significant role (Shiklomanov, et al, 2013). The hydrological regime of rivers is crucial for various human activities. Consequently, the study of river hydrological regimes, their formation processes, and their variations is a global endeavor. Numerous issues, including surface-groundwater interactions, climate change impacts, water body level regimes, and the effects of environmental problems and anthropogenic factors, are closely linked to changes in water body hydrological regimes (Zhang et al, 2016, Dutta et al 2015).

In recent decades, global climate change, characterized by rising air temperatures, has had a pronounced impact on water body regimes. These changes occur both globally and regionally (Israel et al, 2001). One notable consequence of global warming is the transformation of river hydrological regimes. Therefore, understanding how climate change manifests in lake hydrological regimes is of paramount importance. It is evident that the hydrological regime of lakes is the product of complex interactions between natural and anthropogenic factors. The study of this regime is essential for effective water resource management, mitigation of hydrological disasters, and sustainable development of lake-dependent regions. Modern monitoring and modeling techniques offer valuable tools for comprehending and forecasting changes in lake hydrological regimes, enabling informed decision-making in water use and environmental protection.

Determining hydrological characteristics under varying conditions is a critical practical task in design work, addressed in both normative literature and scientific research. This article examines the changes in the hydrological characteristics of Markakol Lake, selected as the study site.

Materials and Methods. Markakol Lake, situated in the mountainous region of Eastern Kazakhstan, is a freshwater lake occupying an asymmetrical intermontane basin. Remnants of ancient, now-drained lakes can be found in the surrounding mountains. The lake's basin is characterized by steep slopes to the south and an accumulative shoreline to the north. Its formation is linked to tectonic uplift, which created a barrier, leading to water accumulation in the depression. Initially, the Kalzhyr River flowed through the basin, but subsequent tectonic activity submerged the riverbed, forming the lake. The region experiences harsh winters with average temperatures plummeting to −20°C or lower, leading to prolonged ice cover formation. Winter snow cover further influences the lake's thermal regime and ice formation processes. Markakol Lake is located at an altitude of approximately 1449 meters above sea level. It covers an area of around 455 km2, with a length of 38 km, a width of up to 19 km, an average depth of 14.3 m, and a maximum depth of 24 m.

Ice cover typically forms on the lake in early winter (October-November) and persists until spring (April-May). The duration and thickness of the ice cover are influenced by annual temperature fluctuations and precipitation. On average, ice thickness can reach 1-1.5 m. The ice cover significantly impacts aquatic ecosystems by limiting light penetration and photosynthesis during winter, affecting vegetation and aquatic organisms. Ad-ditionally, alterations in the oxygen regime beneath the ice can lead to changes in the species composition of aquatic organisms.

The study utilizes hydrometeorological observation data obtained from the weather station of the National Meteorological Hydrological Service RSE 'Kazhydromet' (Figure 1). The analysis incorporates data on average monthly air and water temperatures, monthly precipitation totals, ice thickness values, and the onset and cessation dates of ice phenomena. Static analysis methods were employed in the research. Trends were calculated using the least squares method, and their statistical significance was assessed through the Student and Fisher criteria. Difference integral curves were utilized to identify spatial and temporal patterns in the long-term fluctuations of hydrometeorological indicators.

Figure 1. Location map of Markakol Lake weather station.

Results and discussion. Change in air temperature

A prominent characteristic of long-term climate change in the region is a warming trend observed in the latter half of the 20th century and the early 21st century. Figure 2 illustrates the multi-year variations in mean air temperature in the Markakol Lake region from 1983 to 2022. The results clearly indicate a pronounced upward trend in temperatures throughout the year. The average annual air temperature (Figure 2f) exhibits a steady gradient of +0.05 °C/year during the 1983-2022 period.

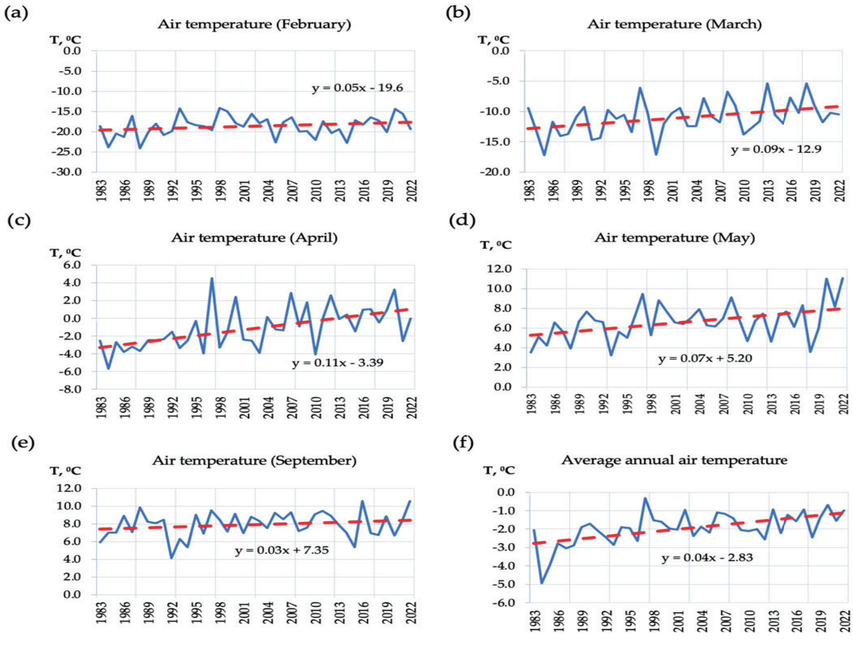

Figure 2 Multiyear variations of mean air temperature in the area of Markakol Lake for the 1983−2022 period. (a) February, (b) March, (c) April, (d) May, (e) September, and (f) Annual average

Changes in atmospheric precipitation

Table 1 shows the values of the intra-annual distribution of atmospheric precipitation in the Markakol Lake area. According to long-term data from 1983 to 2020, annual precipitation in the Markakol Lake region ranges from 404 mm (1986) to 724 mm (2016), with an average of 564 mm. Over half of the annual precipitation (51.8%) occurs between May and September, with the summer season contributing an average of 32.4% to the annual total (Table 1). Winter is the driest season, accounting for only 18.1% of the annual precipitation. Autumn and spring contribute 28.4% and 20.9%, respectively.

Overall, the analyzed meteorological stations in Almaty Region show a trend of air temperature change by 0.2–0.3°C per decade between 1937 and 2024.

The study of long-term precipitation changes is one of the key issues. Precipitation undergoes spatial and temporal variations influenced by atmospheric circulation patterns, physical-geographical conditions, and seasonal factors. These factors interact closely, shaping the spatial and temporal distribution of precipitation both throughout the year and from year to year.

The precipitation regime across different regions of Kazakhstan is highly diverse. Except for high mountain areas, Kazakhstan is classified as a region with insufficient precipitation. In desert zones, precipitation levels are extremely low. Therefore, a defining characteristic of Kazakhstan's steppe climate is pronounced aridity, primarily due to its location in the center of Eurasia.

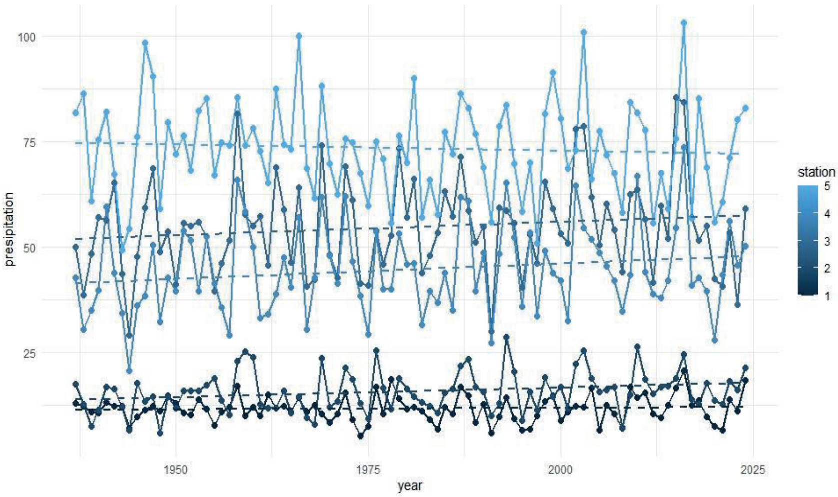

Figure 3. Dynamics of precipitation changes in Almaty region (1937–2024)
*1 - Kuygan, 2 - Zharkent, 3 - Almaty, 4 - Kogaly, 5 – Mynzhylky

Figure 3 presents the distribution of annual average precipitation dynamics for the studied locations. The highest precipitation levels are recorded at the Mynzhylky station, while the lowest levels are observed at the Kuigan and Zharkent meteorological stations. Over the study period, precipitation at Mynzhylky showed a decreasing trend of 0.5 mm per decade, whereas in Almaty, Zharkent, and Kogaly, precipitation increased by 0.4–0.8 mm per decade. At the Kuigan station, no significant trend was observed. Topography plays a crucial role in precipitation distribution. Due to the influence of mountain slopes, precipitation tends to increase in mountainous areas while decreasing at lower elevations.

During the second half of the 20th century, precipitation trends across Kazakhstan were influenced by synoptic processes within the general warming trend. However, it was found that precipitation increased during the cold season while decreasing during the warm season (Muratova, et al, 2014). In 2021, the average annual air temperature anomaly in Kazakhstan was recorded at +1.6°C above the 1961–1990 average (5.4°C), which was 0.3°C lower than in 2020. Since the 1960s, each subsequent decade in Kazakhstan has been warmer than the previous one. During the most recent decade (2012–2021), the average annual air temperature was recorded at +6.6°C, exceeding the climate norm by 1.2°C, marking the highest decadal anomaly on record. The previous warmest decade was 2001–2010, with an anomaly of +1.1°C.

The most recent five-year period (2017–2021) was also the warmest on record, with an average annual air temperature of +6.7°C, which was 1.3°C above the climate norm.

Table 2. Warmest years in observation history and corresponding averaged annual air temperature anomalies (°C)

№	Global (since 1850)	Kazakhstan	Almaty region (1941–202)	Average annual air temperature anomaly averaged across Kazakhstan (jan.-dec.)	Average annual air temperature anomaly averaged across Almaty region (jan.-dec.) (1937-2021)
1	2020	2020	2016	1,9	2,0
2	2016	2013	2013; 2019	1,9	1,9
3	2019	1983	2002	1,8	1,8
4	2017	2015	2006; 2007	1,6	1,8
5	2015	2021	2021	1,6	1,7
6	2021	2002	2015	1,6	1,6
7	2018	2004	2008	1,5	1,6
8	2014	2019	2004	1,5	1,6
9	2010	2016	1997; 1941	1,5	1,6
10	2005	2007	2017	1,5	1,5

Table 2 presents the ranked series of annual mean temperature anomalies for the selected meteorological stations in the Almaty region from 1937 to 2021. On a global scale, all ten of the warmest decades have occurred in the last century. According to the 2021 report by the World Meteorological Organization, 2021 was one of the seven warmest years on record. The global average air temperature in 2021 was approximately 1.1°C higher than the 1850–1900 baseline period.

The following tables (Tables 2 and 3) provide data on temperature and precipitation deviations for different decades in the Almaty region from 1937 to 2024.

Table 3. Air temperature variations in different periods

Station	Air temperature variations in different periods, °C								
	1937-1946	1947-1956	1957-1966	1967-1976	1977-1986	1987-1996	1997-2006	2007-2016	2017-2024
Kuigan	-0,3	-0,8	-0,5	-1,0	-0,2	0,3	1,1	1,0	2,4
Zharkent	-0,7	-1,2	-0,3	-0,7	0,3	0,40	1,1	0,9	2,3
Almaty	-0,3	-0,8	-0,5	-0,8	-0,2	0,0	1,0	1,1	2,2
Kogaly	-0,2	-0,5	-0,4	-0,6	0,2	0,2	0,6	0,6	1,1
Mynzhylky	-0,6	-0,6	-0,5	-0,6	0,2	0,0	0,8	0,8	1,3

According to Table 3, the warmest decades in the Almaty region from 1937 to 2021 were observed in the last 30 years, with air temperature increases ranging from 0.6°C to 1.5°C. The most significant warming was recorded at the Almaty station (1–1.5°C), which can be explained by its urban location. The increase in greenhouse gas emissions from vehicles and thermal power plants contributes to additional heat accumulation.

Table 1**.** Intra-annual distribution of atmospheric precipitation in the area of Markakol Lake

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
Precipitation, mm	29	27	28	36	54	53	68	62	55	51	54	46	564
% of annual amount	5.14	4.79	4.96	6.38	9.57	9.40	12.1	11.0	9.75	9.04	9.57	8.16	100

Multi-year variations in total annual precipitation, as depicted in Figure 3, indicate a decreasing trend for the months of May, August, and December. However, this trend is not evident in the graph of total annual precipitation values (Figure 3d).

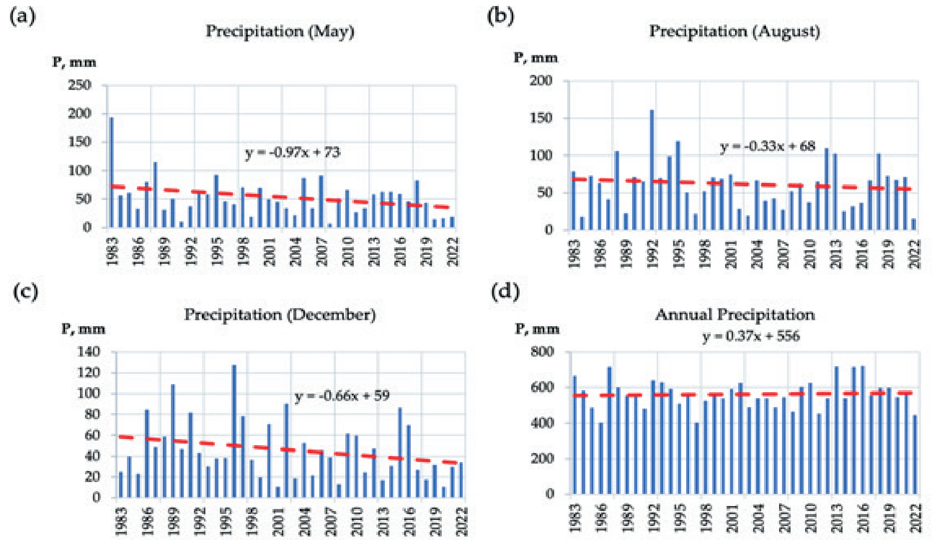

Figure 4. Multiyear changes in atmospheric precipitation in the Markakol Lake for the 1983−2022 period. (a) May, (b) August), (c) December), and (d) Annual total

In addition to unidirectional trends, multi-year changes in atmospheric precipitation in the Markakol Lake region exhibit cyclical patterns. The difference integral curve (Figure 4) allows for the identification of phases of decreased (below-normal precipitation) and increased (above-normal precipitation) moisture content (Table 2).

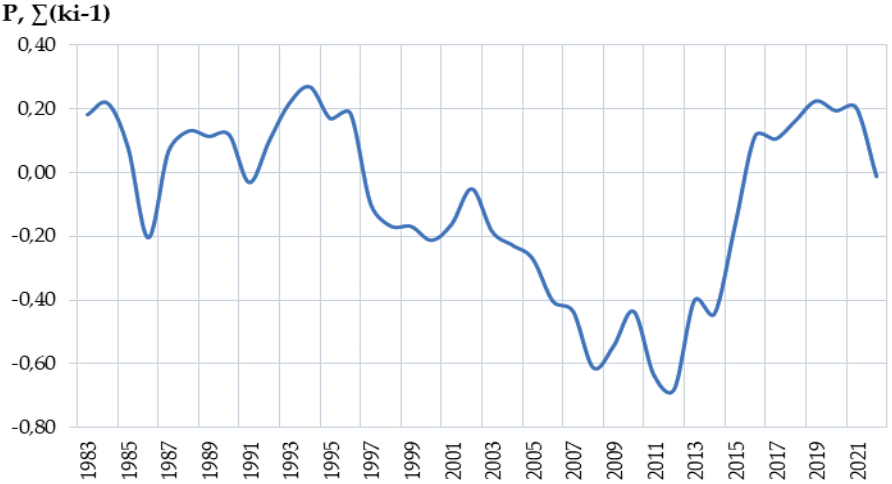

Figure 5. Difference integral curve of annual precipitation totals in the area of Markakol Lake

Table 2. Phases of low and high moisture content

Phase of low moisture content			Phase of high moisture content			Full cycle (years)	Mean annual precipitation for the full cycle (mm)
Period	Cycle (years)	Average precipitation, mm	Period	Cycle (years)	Average precipitation, mm		
1984-1986	3	491	1987-1990	4	610	7	559
1991-1992	2	559	1993-1996	4	576	6	570
1997-2000	4	508	2001-2002	2	609	6	542
2003-2008	6	511	2009-2010	2	614	8	537
2011-2012	2	495	2013-2019	7	637	9	605
2020-2022	3	520					

Analysis of Table 2 reveals two complete cycles: 1984-2002 and 2003-2019, spanning 19 and 17 years, respectively. Phases of low moisture content (lasting 2 to 6 years) alternate with phases of high moisture content (lasting 2 to 7 years). The complete cycles range from 6 to 9 years in duration.

Climate change impact on the hydrological regime of Markakol Lake

Water level fluctuations in lakes are influenced by the balance between inflow and outflow components of the water balance: precipitation, evaporation, surface runoff, and groundwater exchange. Unlike rivers, which respond rapidly to changes in climatic conditions, lakes exhibit significant hydrological inertia. While river water levels are primarily determined by current inflow, lake water levels are influenced by the inflow-outflow balance of the current year as well as the climatic conditions of the preceding season (Danilovich, 2005, Madibekov, et al, 2024).

Climatic factors, such as atmospheric precipitation and air temperature, significantly impact river and lake water supply. The inflow to Markakol Lake is dominated by river runoff, with 27 small rivers and streams, including the Karabulak, Matabai, and Zhiren Baital rivers, feeding the lake. The Kalzhyr River is the primary outflow. However, due to the absence of hydrological stations on the inflowing rivers, it was not possible to quantify the inflow into the lake. Data on runoff is available only for the outflowing Kalzhyr River.

We utilized air temperature and precipitation data from three meteorological stations near Markakol Lake, provided by RSE 'Kazhydromet': Markakol Reserve (1983-2020), Terekty (1972-2020), and Orlovsky settlement (1940-1997). These stations have consistent observation records.

To assess the impact of climate change on Markakol Lake's hydrological regime, we employed statistical methods, including the linear trend coefficient and the non-parametric Mann-Kendall test. The Mann-Kendall test is a widely used non-parametric statistical test for trend analysis in time series. In recent years, this method has been applied to evaluate trends in hydrological and meteorological data, such as precipitation, river flow, and air temperature. The advantages of this test include its non-parametric nature, which does not require normally distributed data, and its low sensitivity to abrupt discontinuities in time series. Non-detected data points were assigned a common value below the smallest measured value in the dataset.

The null hypothesis (H0) of the Mann-Kendall (Z) test assumes no trend, while the alternative hypothesis (H1) suggests a trend. A positive Z value indicates an increasing trend, while a negative Z value indicates a de-creasing trend. Significant trends at the 0.1, 0.05, and 0.01 significance levels correspond to |Z| values greater than 1.64, 1.96, and 2.58, respectively. In this study, we applied 90%, 95%, and 99% confidence levels to analyze the hypotheses.

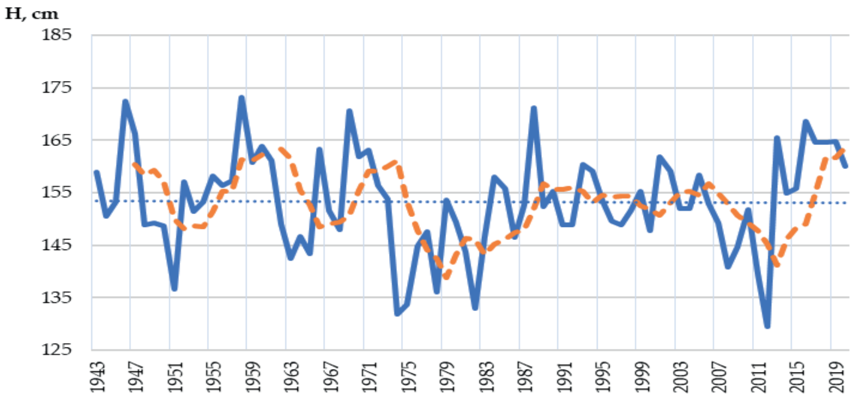

Figure 6. Time course of Markakol Lake level.

Analysis of water level fluctuations in the lake reveals a cyclical pattern characterized by alternating phases of increasing and decreasing water content. However, these cycles exhibit varying durations, resulting in a complex overlapping pattern. A rolling five-year analysis of the long-term water level course indicates a gradual decline from 1943 to 1979, followed by a gradual increase until 2006. A slight decrease was observed from 2007 to 2013, but in recent years, the water level has been gradually rising.

While a slight downward trend is evident in the long-term water level course, dividing the period into two segments (1943-1973 and 1974-2020) due to modern climate change reveals a significant positive trend ($Z \geq 2.58$) at a 95% confidence level for the period 1974-2020, as determined by the Mann-Kendall test (Table 3).

Table 3. Mann-Kendall test results (Z-statistics).

Months	**Periods**	**Test Z (lake level)**	**Test Z (precipitation)**	**Test Z (temperature)**
1	**1943-1973**	**0.43**	**0.70**	**0.83**
2		**0.39**	**-0.80**	**-0.41**
3		**0.15**	**0.12**	**1.48**
4		**0.03**	**-0.44**	**0.02**
5		**0.65**	**0.61**	**-0.88**
6		**0.49**	**0.51**	**-0.09**
7		**0.02**	**1.29**	**-0.82**
8		**0.41**	**0.48**	**-1.02**
9		**0.51**	**0.26**	**-0.75**
10		**0.56**	**0.65**	**-0.12**
11		**0.43**	**-0.92**	**2.14**
12		**0.54**	**-0.54**	**0.99**
year		**0.44**	**1.09**	**1.16**
1	**1974-2020**	**2.63****	**0.48**	**0.10**
2		**2.57***	**-0.02**	**1.26**
3		**2.92****	**2.15***	**3.02****
4		**3.69*****	**0.88**	**3.15****
5		**3.10****	**0.08**	**1.49**
6		**1.89**	**1.39**	**1.94**
7		**2.19***	**2.86****	**1.46**
8		**2.51***	**1.06**	**2.35***
9		**2.52***	**1.12**	**0.27**
10		**2.59****	**1.67**	**1.16**
11		**2.25***	**0.98**	**0.77**
12		**2.46***	**-0.32**	**1.27**
year		**3.12****	**2.75****	**3.30*****

Validated significance levels: 0.001 (***), 0.01 (**) and 0.05 (*)

Additionally, the considered meteorological stations exhibit a positive trend in annual precipitation amounts ($Z = 2.75$) for the modern period (1974-2020). The

Mann-Kendall test results for air temperature in the lake area indicate a significant increase in air temperature (Z = 3.30) at the 99% confidence level.

Analysis of the difference integral curves of water level and precipitation reveals synchronization in their courses (Figure 6). However, the precipitation course exhibits a phase shift, with the onset of maximum and minimum precipitation occurring earlier than the peak water level.

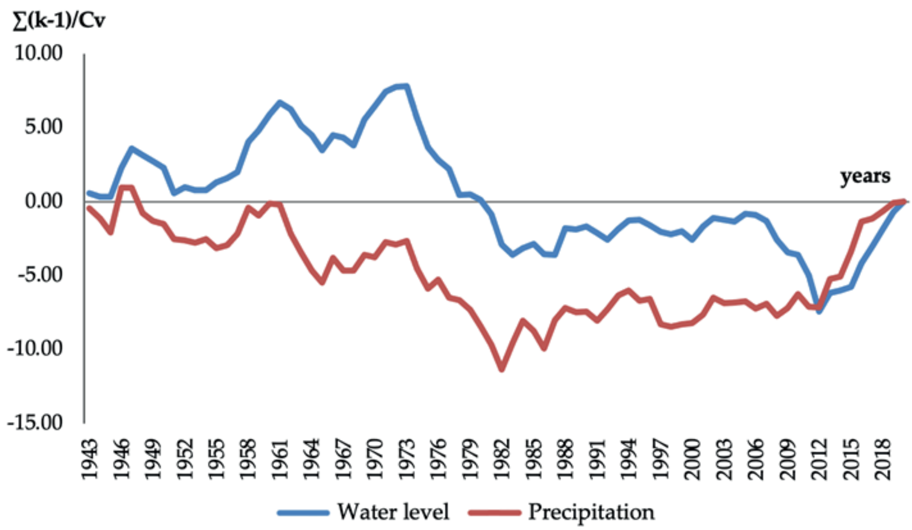

Figure 7. Difference integral curve of precipitation and water level of Lake Markakol.

Assessment of the impact of climate change on Markakol Lake's hydrological regime and the study of its ice regime are of significant scientific and practical importance. The ice regime of lakes serves as a crucial indicator of climate change. Variations in ice cover duration can reflect changes in temperature and other climatic parameters, enabling the monitoring and forecasting of climatic trends (Table 4).

Furthermore, ice cover plays a vital role in lake hydrological processes, including water exchange, water level, and water quality. These processes are essential for water management and the maintenance of lake eco-systems. Changes in the ice regime can lead to alterations in biodiversity and ecosystem dynamics.

The socio-economic implications of lake ice regimes are also noteworthy. Ice cover is essential for various human activities, such as fisheries, transportation, and recreation. Changes in the ice regime can impact the economies of regions reliant on these activities.

Therefore, studying lake ice regimes is crucial for understanding and predicting natural and anthropogenic processes, as well as for developing strategies to adapt to changing climatic conditions.

Table 4. Ice phenomena on water bodies with stable ice cover, Lake Markakol - Urunkhay village.

Characteristic	Date					
	onset of autumn ice phenomena	start of the autumn ice drift	ice outbreak	onset of ice breakup	ice-out	deicing
Average	01.11	82 %	21.11	23.04	18.05	26.05
Early (highest)	04.10	-	06.11	19.03	04.05	14.05
Year (% cases)	1982	-	1943	1944	1947	1978,1981
Late (lowest)	19.11	-	04.12	17.05	07.06	08.06
Year (% cases)	1973	-	1955	1977	1975	1975

CharacteristiC	*Duration, 24 hours*					
	autumn ice phenomena	*autumn ice drift*	*ice outbreak*	*spring ice events*	*spring ice drift*	*ice-free period*
Mean	*19*	*-*	*180*	*32*	*9*	*159*
Early (highest)	*47*	*11 (11)*	*205*	*73*	*20*	*182*
Year (% cases)	*1982*	*1944, 1947*	*1974-1975*	*1944*	*1947*	*1978*
Late (lowest)	*8*	*0*	*160*	*16*	*0*	*128*
Year (% cases)	*1973, 1988*	*78 %*	*1955-1956*	*1952*	*24 %*	*1966*

The study of ice phenomena on water bodies with stable ice cover, such as Markakol Lake, is vital for understanding climatic processes, hydrological regimes, ecological consequences, and socio-economic impacts. This paper presents an analysis of the ice regime of these water bodies, encompassing climatic conditions, physical characteristics, temporal parameters of ice cover, and its influence on the environment and human activities.

To ensure safety and efficient resource utilization, regular monitoring of ice cover is crucial, including measurements of ice thickness, temperature changes, and weather conditions. Modern technologies, such as satellite monitoring and ice sensors, enable the acquisition of accurate data and timely responses to changes in ice conditions. The study of ice phenomena on Markakol Lake demonstrates that stable ice formation in the water body significantly impacts the ecosystem, climate research, socio-economic development, and the safety of the local population. Regular monitoring and analysis of ice phenomena are essential for adapting to changing climatic conditions and optimizing the use of water resources.

Physico-chemical parameters of the lake in multiyear aspect

The dynamics of long-term hydrochemical parameters of Markakol Lake were analyzed based on obser-vational data from the 'Markakol' hydrological post of RSE 'Kazhydromet' for the period 1982-2020 (Madibekov et al, 2018).

Under changing air and water temperature regimes, the pH value remained relatively stable between 7.5 and 8.1, indicating a consistently weak alkaline environment over the 38-year period.

Concentrations of organic substances in the lake water fluctuated significantly, ranging from 4.0 to 24.0 mg/l. High values, such as 24.0 mg/l in 1986 and 23.0 mg/l in 1995, were likely associated with plant residue decomposition processes, as evidenced by elevated nitrate nitrogen levels up to 5.50 mg/l (Figure 7). The oxidizability of lake water remained relatively stable between 4.0 and 5.9 mg/l from 2000 to 2013.

No significant changes were observed in the concentrations of nutrients in the lake water. However, exceedances of fishery standards were noted for ammonium and nitrite nitrogen. Ammonium nitrogen concentrations fluctuated between 0.01 and 2.93 mg/l, with exceedances of up to 7.5 times the fishery standard in 2010 and up to 1.2 and 1.7 times in subsequent years, indicating the presence of organic matter decomposition products in the lake water. Nitrite nitrogen concentrations ranged from 0.0 to 0.10 mg/l, consistently exceeding or reaching the fishery standard in most years. Nitrate nitrogen concentrations varied widely from 0.0 to 2.4 mg/l but remained below normative levels. The presence, quantity, and ratio of nitrogen-containing compounds in the water provide insights into the degree and age of water pollution by organic matter.

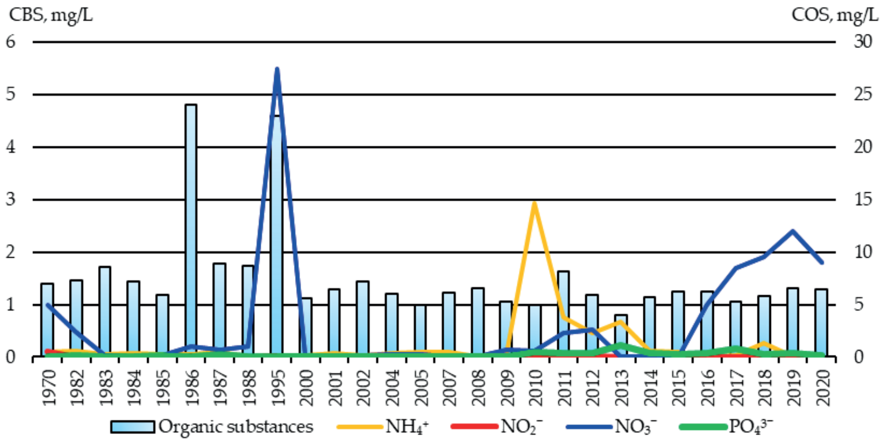

Figure 8. Concentrations of nutrients and organic matter in the water of Markakol Lake over a multi-year period.

Lake water is characterized by low concentrations of dissolved phosphorus, ranging from 0.014 to 0.214 mg/l, which does not exceed MACfishery standards.

Dissolved oxygen concentrations range from 6.53 to 12.8 mg/l, averaging 89% saturation (Figure 8), providing favorable conditions for aquatic life.

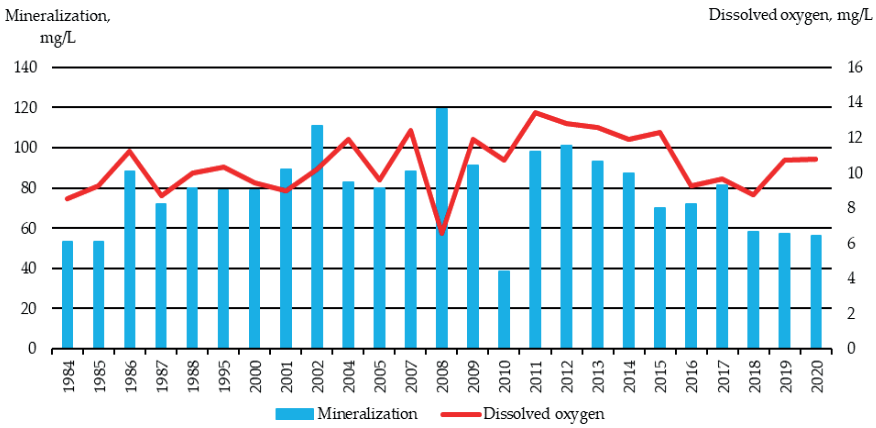

Figure 9. Water mineralization and dissolved oxygen concentration over a multi-year period.

Relatively high values of lake water mineralization, reaching 111 and 119 mg/l in 2002 and 2008, respectively (Figure 8), were observed. However, overall, the lake water mineralization ranges from 38.0 to 93.0 mg/l, classifying it as fresh water. Based on its ionic composition, Markakol Lake water belongs to the hydrocarbonate class of the calcium group.

Since the 1970s, a gradual increase in water mineralization has been observed, ranging from 53.0 to 96.0 mg/l on average (Table 1). An exception is 2010, when mineralization was low at 38.0 mg/l, potentially due to abundant precipitation leading to increased lake water volume.

Regarding the toxicological status of the lake, analysis of literature, scientific, and project data indicates that the lake ecosystem has been subjected to various stressors in recent decades, including pollution from animal waste and chemical and toxicological contamination of water and soil (Rakybaeva et al, 2011).

Analysis of monitoring data from RSE 'Kazhydromet' (18-25) for the period 1970 to 2002 revealed that the average long-term content of copper (up to 3.8 μg/l) and zinc (up to 7.4 μg/l) in the water exceeded established standards (2.2 and 3.8 MACfishery, respectively). The maximum copper concentration, reaching 7.0 μg/l in 2002, exceeded the standard by 7.0 times (Figure 9). High zinc concentrations were observed in two periods: 1984-1988 (up to 12.2 μg/l) and 2001-2004 (up to 12.3 μg/l). The maximum zinc concentration for the entire period was recorded in 1986, reaching 20.0 μg/l.

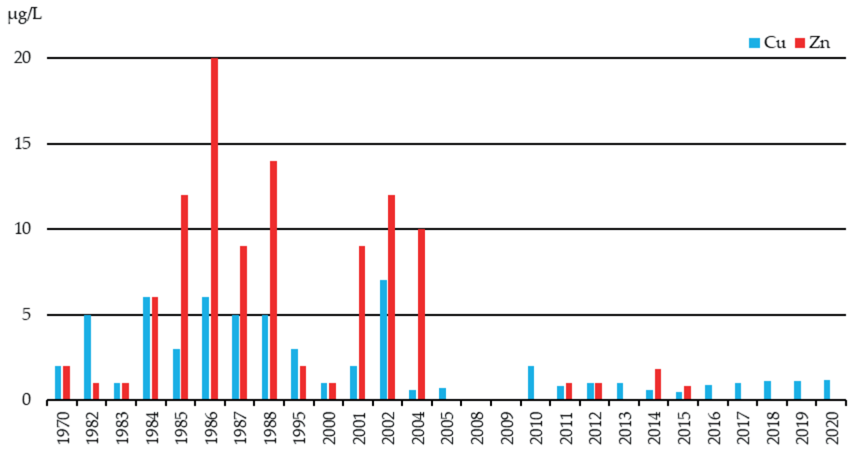

Figure 10. Heavy metals in water of Markakol Lake.

Cadmium concentrations were significantly below the fishery standard in recent years. However, the lack of long-term data precludes a comprehensive assessment of long-term trends in cadmium levels in the lake water.

The toxicological burden on the lake's aquatic ecosystem is further supported by studies conducted by the Institute of Hydrobiology and Ecology (Amirgaliev, et al, 2019), which reported elevated concentrations of zinc, copper, and lead. According to data from 1992-1993, zinc concentrations in water ranged from 0.005 to 0.061 mg/l, averaging 0.022 mg/l.

Zinc accumulation in higher aquatic plants was found to be between 0.5 and 80.0 g/t, with an average of 8.67 g/t (Madibekov et al, 2024, Ismukhanova et al, 2024).

Conclusions. The hydrological regime analysis of Lake Markakol yields several key findings. Cyclical patterns are evident in the multi-year variation of atmospheric precipitation in the region. Two distinct cycles are identified: from 1984 to 2002 and from 2003 to 2019, lasting 19 and 17 years respectively. Periods of low humidity, ranging from 2 to 6 years, alternate with phases of higher humidity, which last between 2 to 7 years. These complete cycles span between 6 and 9 years.

Similarly, the lake's water level regime follows a cyclical pattern, influenced by the variability in atmospheric precipitation. Analyzing the fluctuations reveals alternating phases of rising and falling water levels, with complex overlapping cycles of varying duration. A notable decline in the water level was observed from 1943 to 1979, followed by a gradual increase until 2006. From 2007 to 2013, a slight decrease occurred, but recent years have seen a gradual rise. Over the long term, there is a minor downward trend in water level. However, when divided into two periods (1943–1973 and 1974–2020) to account for modern climate change, the Mann-Kendall test for the 1974–2020 period reveals a significant positive trend ($Z \geq 2.58$) at a 95% confidence level.

During the modern period (1974–2020), meteorological stations in the area also show a positive trend in annual precipitation, with a significant result (Z = 2.75). Furthermore, air temperature analysis using the Mann-Kendall test demonstrates a statistically significant increase (Z=3.30) with 99% confidence.

Synchronization between water levels and precipitation patterns is observed through difference integral curves. However, a shift in the timing of precipitation extremes is noted, with maxima and minima in precipitation occurring earlier than those in the lake's water level.

The long-term dynamics of biogenic and organic substances in the lake indicate the presence of organic decay products, which adversely affect the hydrochemical regime. While the lake's water is classified as oligo-trophic based on key physical and chemical parameters, indicators such as dissolved oxygen and nutrient levels suggest the potential for increased aquatic vegetation. This could lead to pollution and disturbance of the lake's biological balance, potentially triggering eutrophication and algal blooms.

Additionally, the content and ratio of nitrogen compounds in the water reflect the degree and age of pollution from organic sources. The anthropogenic impact on the lake's aquatic ecosystem is further exacerbated by the presence of heavy metals, which pose a threat to the aquatic biota.

To ensure the long-term sustainability of Lake Markakol's hydrological and ecological systems, a comprehensive approach is needed. Key actions include continuous monitoring of hydrological cycles and water quality, alongside the development of climate change adaptation strategies. Addressing potential eutrophication requires stricter pollution control, particularly targeting nutrient and organic inputs, while efforts to reduce heavy metal contamination through remediation and source identification are essential. Conservation of biodiversity through protected zones and habitat restoration, coupled with community engagement in sustainable practices, will help maintain the ecological balance. Additionally, fostering collaboration and further research will enhance understanding of the lake's complex dynamics and support innovative restoration and management efforts.

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