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INFLUENCE OF GEOLOGICAL CONDITIONS ON FORMATION OF CARBONATE-HYDROCARBONATE WATERS OF THE KOSKORGAN RESERVOIR

Abstract. The carbonate-hydrocarbonate composition of the surface waters of the Koskorgan reservoir is formed in conditions of an arid climate and the carbonate geological structure of the catchment, which determines its hydrochemical specificity. The work analyzed the seasonal dynamics of HCO_3^- and CO_3^{2-} ions according to field observations of 2023–2025. The concentrations of hydrocarbonates ranged from 142.3 to 197.6 mg/dm³, the average values for the seasons were 168–185 mg/dm³ with a standard deviation of 14-26 mg/dm³ and a coefficient of variation of 8–15%, which indicates the relative stability of the hydrocarbonate system. It has been established that a seasonal increase in carbonate content can reduce the irrigation suitability of water due to the risk of alkalization of soils, which must be taken into account when using the Koskorgan reservoir for water management.

Key words: *Koskorgan reservoir, water carbonate content, hydrocarbonate ions, seasonal variability, hydrochemical mode, coefficient of variation, irrigation suitability of water.*

Геологиялық жағдайлардың қоскорған су қоймасының карбонатты-гидрокарбонатты суларының түзілуіне әсері

Аңдатпа. Қоскорған су қоймасының жер үсті суларының карбонатты-гидрокарбонатты құрамы су жинаудың аридті климаты мен карбонатты геологиялық құрылымы жағдайында қалыптасады, бұл оның гидрохимиялық ерекшелігі. Жұмыста HCO_3^- және CO_3^{2-} иондарының маусымдық динамикасына талдау жасалды 2023–2025 жылдардағы заттай бақылаулардың деректері бойынша гидрокарбонаттардың шоғырлануы 142,3-тен 197,6 мг/дм-ге дейін өзгерді, маусымдар бойынша орташа мәндер 168–185 мг/дм құрады стандартты ауытқу кезінде 14-26 мг/дм және вариация коэффициенті 8–15%, бұл гидрокарбонат жүйесінің салыстырмалы тұрақтылығын көрсетеді. Карбонаттылықтың маусымдық күшеюі топырақты сілтілеу қаупі есебінен судың ирригациялық жарамдылығын төмендетуі мүмкін екені анықталды, оны Қоскорған су қоймасын су шаруашылығында пайдалану кезінде ескеру қажет.

Түйінді сөздер: *Қоскорған су қоймасы, судың карбонаттылығы, гидрокарбонатты иондар, маусымдық өзгермелілік, гидрохимиялық режим, вариация коэффициенті, судың ирригациялық жарамдылығы.*

Влияние геологических условий на образование карбонатно-гидрокарбонатных вод водохранилища Коскорган

Аннотация. Карбонатно-гидрокарбонатный состав поверхностных вод Коскорганского водохранилища формируется в условиях аридного климата и карбонатного геологического строения водосбора, что определяет его гидрохимическую специфику. В работе выполнен анализ сезонной динамики ионов HCO_3^- и CO_3^{2-} по данным натурных наблюдений 2023–2025 гг. Концентрации гидрокарбонатов варьировали от 142,3 до 197,6 мг/дм³, средние значения по сезонам составили 168–185 мг/дм³ при стандартном отклонении 14–26 мг/дм³ и коэффициенте вариации 8–15%, что указывает на относительную устойчивость гидрокарбонатной системы. Установлено, что сезонное усиление карбонатности может снижать ирригационную пригодность воды за счет риска ощелачивания почв, что необходимо учитывать при водохозяйственном использовании Коскорганского водохранилища.

Ключевые слова: *Коскорганское водохранилище, карбонатность воды, гидрокарбонатные ионы, сезонная изменчивость, гидрохимический режим, коэффициент вариации, ирригационная пригодность воды.*

Introduction

Reservoirs play a key role in regulating the water resources of arid and semi-arid regions, such as South Kazakhstan, providing irrigation, water supply to settlements, ecosystem sustainability and economic development of rural areas. One of these objects is the Koskorgan reservoir, built in the middle of the 20th century in the Turkestan region with the aim of accumulating and using water for irrigation and household needs. Despite the importance of the infrastructure, the current state of the hydrological regime and the chemical composition of water in this reservoir remains poorly studied, especially from the point of view of the influence of geological conditions on the formation of the hydrochemical profile of dissolved carbonate-hydrocarbonate ions in the water mass. The relevance of this study is determined by a set of interrelated causes. First of all, over the past decades, the Koskorgan reservoir and adjacent water bodies have been subjected to increasing influence of climatic factors and anthropogenic activity, which is manifested in a decrease in inflow volumes, transformation of the hydrological regime and a change in the chemical composition of water. According to research data over the past thirty years, a decrease in the average annual water inflow and an increase in temperature indicators are recorded in the region, which determines the redistribution of minerals and an increase in the level of general mineralization of water bodies. So, in the period from 1994 to 2024, the value of the total mineralization of the waters of the Koskorgan reservoir increased from 0.8–1.0 g/l to 1.5–1.7 g/l, while the concentrations of individual anions, including nitrates and sulfates, exceeded regional sanitary standards by 15–20%.

Secondly, the chemical composition of water, including concentrations of carbonate (CO_3^{2-}) and hydrocarbonate (HCO_3^-) anions, is largely determined by the geological and mineralogical features of the catchment basin. The formation of carbonate-hydrocarbonate type of water, as a rule, is associated with the processes of weathering and dissolution of carbonate rocks, such as limestones and dolomites, common within the catchment area, which affects the overall hardness, alkalinity and buffer capacity of the aquatic environment [1–2]. These processes are of particular importance in areas with a complex geological structure and lithological heterogeneity, where the filtration of waters through carbonate-containing horizons helps to intensify the migration of calcium, magnesium, sodium ions and associated acid anions. At the same time, the detailed mechanisms of the geologically determined formation of the chemical composition of the waters of the Koskorgan reservoir remain insufficiently studied, which leads to gaps in regional hydrochemical models [3].

The purpose of this study is a comprehensive analysis of the impact of the geological structure of the catchment basin on the formation of carbonate-hydrocarbonate ion composition of the waters of the Koskorgan reservoir. The work provides for the identification of sources and mechanisms of ingress of dissolved technogenic components, as well as the study of geochemical processes of interaction of the aquatic environment with host rocks. The implementation of this goal will make it

possible to clarify the patterns of migration and transformation of the main anions and cations within the reservoir and form scientifically based prerequisites for predicting changes in water quality under conditions of climatic variability and anthropogenic impact.

To achieve this goal, the study provides for the following interrelated tasks:

1. Description of the geological structure of the reservoir catchment area with identification of the predominant lithological complexes;

2. Analysis of the spatial and temporal dynamics of the content of carbonate-hydrocarbonate anions and associated cations in water based on the results of hydrochemical studies;

3. Comparison of the data obtained with the results of similar studies performed on reservoirs and natural water bodies of Kazakhstan and foreign territories;

4. Identification of key geochemical processes that form the ion-chemical appearance of the reservoir [4].

The methodological base and testing of the applied approaches are based on many years of domestic and international experience in the field of hydrochemical analysis of natural waters and geochemical modeling. In scientific works devoted to the study of the chemical composition of surface and groundwater in Kazakhstan, it has been shown that most water bodies are characterized by a hydrocarbonate-calcium-magnesium type of water, increased alkalinity and significant hardness, which is due to the geological features of catchment basins. Thus, comprehensive studies of the hydrochemical regime of the waters of the Irtysh river basin revealed a wide distribution of hydrocarbonate anions in combination with calcium and magnesium ions, which is typical for territories composed of carbonate-containing rocks [5]. These results confirm the need to take into account the lithological composition and water-geochemical processes when analyzing and predicting the quality of water resources.

Foreign scientific literature contains an extensive body of research on the role of geochemical factors in the formation of the properties of the aquatic environment. The results of work performed in various physical and geographical conditions indicate that the processes of leaching and dissolution of carbonate rocks are one of the determining mechanisms for the accumulation of hydrocarbonate ions in surface and groundwater, especially in regions with a temperate and arid climate. Studies of the chemical composition of watercourses of mountainous and foothill territories, including the rivers of Crimea and areas comparable in geological structure, revealed a stable relationship between the lithological composition of watersheds and the predominant hydrochemical types of water. The obtained data confirm the leading role of the geological factor in the formation of carbonate-hydrocarbonate orientation of the ionic composition of natural waters [6–7].

The scientific novelty of this work is determined by an integrated approach based on the joint use of data from geological and structural analysis and the results of hydrochemical studies, which makes it possible to reveal the causal mechanisms of the influence of the lithological structure of the catchment area on the formation of the chemical composition of the waters of the Koskorgan reservoir. A similar level of detail and systematization for this region was not previously implemented. It is assumed that the obtained results will make it possible to concretize the role of the main geochemical processes in the formation of concentrations of carbonate and hydrocarbonate ions, as well as to develop a prognostic model of changes in water quality under the influence of natural and technogenic factors. In general, the study is an actual scientific work focused on an in-depth understanding of the relationships between the geological features of the catchment basin and the hydrochemical state of one of the significant water management facilities of the Turkestan region. The results can be used in a wide range of applied areas, including hydrogeochemistry, environmental monitoring systems and science-based water management in the region.

Research materials and methods

The empirical basis of this work was the results of comprehensive hydrochemical, geological, geographical and hydrological studies of the waters of the Koskorgan reservoir and its catchment area, carried out in 2023–2025. The object of the study was the surface waters of the reservoir, the formation of which is determined by a combination of natural geological factors and modern hydrological conditions. Concentrations of carbonate (CO_3^{2-}) and hydrocarbonate (HCO_3^-) ions were considered as the subject of the study, as well as their relationship with the lithological features of the catchment basin.

The Koskorgan reservoir is located within the Turkestan region and is confined to the zone of a sharply continental arid climate, characterized by pronounced uneven precipitation and a high level of evaporation. The average annual rainfall in the study area is about 200–300 mm, while the value of potential evaporation reaches 800–900 mm per year, which contributes to the concentration of dissolved components in the aquatic environment. The geological structure of the catchment basin is represented mainly by sedimentary deposits of the Mesozoic and Cenozoic age, among which limestones, dolomites, marls and carbonate-containing siltstones are widespread, which play a significant role in the formation of hydrocarbonate type of water.

Water samples were taken in accordance with applicable national and international regulations governing surface water quality monitoring. Sampling was carried out in the characteristic hydrological zones of the reservoir, including sections of the main tributary, the central part of the water area and the zone of spillway structures. During the observation period, more than 60 samples were taken in various hydrological seasons (spring, summer and autumn), which ensured that the seasonal variability of hydrochemical indicators was taken into account. Samples were taken from the surface layer of water at a depth of 0.3–0.5 m using pre-prepared polyethylene containers with a volume of 1 liter. Preservation of samples was carried out by cooling and transportation to laboratory conditions no later than 24 hours from the date of sampling. Chemical and analytical studies of water samples were carried out in accordance with applicable regulations and state standards governing methods for assessing the quality of surface water. Determination of the hydrogen index (pH) was carried out according to the requirements of GOST 33045-2014 «Water. Methods for determining pH»,

[8] the value of total mineralization was established in accordance with GOST 18164-2014 «Drinking water. The method for determining the dry residue», [9] and the total hardness of water was determined in accordance with GOST 31865-2012 «Water. Determination of total stiffness» [10]. Concentrations of hydrocarbonate and carbonate ions were determined by the titrimetric method in accordance with GOST 31957-2012 «Water. Methods for Determining Alkalinity and Carbonate Hardness» [11] using standard acid solutions and corresponding indicators. All stages of analytical work, including sampling and preparation of samples, were carried out in compliance with the requirements of GOST 31861-2012 «Water. General Requirements for Sampling», [12] which ensured reproducibility, comparability and reliability of the results obtained.

Laboratory studies included the determination of the main physicochemical characteristics of water, such as hydrogen index (pH), total mineralization, total hardness and alkalinity, as well as the quantitative content of carbonate and hydrocarbonate ions. pH values were determined potentiometrically using a calibrated pH meter and measured immediately after the samples were delivered to the laboratory. Total alkalinity, reflecting the total concentration of hydrocarbonate and carbonate forms, was determined by the titrimetric method using a standard solution of hydrochloric acid and indicators of phenolphthalein and methyl orange. Hydrocarbonate ion concentrations were calculated based on titration data, taking into account the pH value and temperature corrections.

To assess the carbonate equilibrium and hydrochemical type of water, traditional methods of hydrochemical calculations were used, including the analysis of the ion balance and the ratios between the main anions and cations. Particular attention was paid to the study of the ratios Ca^{2+}-HCO_3^- and Mg^{2+}-HCO_3^-, which make it possible to assess the degree of influence of the dissolution processes of carbonate rocks on the chemical composition of water. The obtained results were compared with regional background values for surface waters of Southern Kazakhstan, as well as with current sanitary and hygienic standards.

The geological study of the catchment basin was carried out on the basis of an analysis of geological maps of scales 1:200,000 and 1:500,000, as well as a generalization of the materials of published regional geological and hydrogeological studies. Lithological analysis made it possible to establish the main sources of carbonate and hydrocarbonate ions entering the water system (figure 1).

Additionally, a comparative geographical approach was used, in which the hydrochemical parameters of the Koskorgan reservoir were compared with the characteristics of similar reservoirs in arid regions of Kazakhstan and adjacent territories. Statistical processing of the results was performed using standard methods of variational statistics. Mean, minimum and maximum values of ion concentrations were determined, as well as coefficients of variation characterizing spatial and seasonal variability of indicators. Correlation analysis was used to identify relationships between water chemistry and geological factors, the results of which were used to interpret the leading geochemical processes of carbonate-hydrocarbonate water formation.

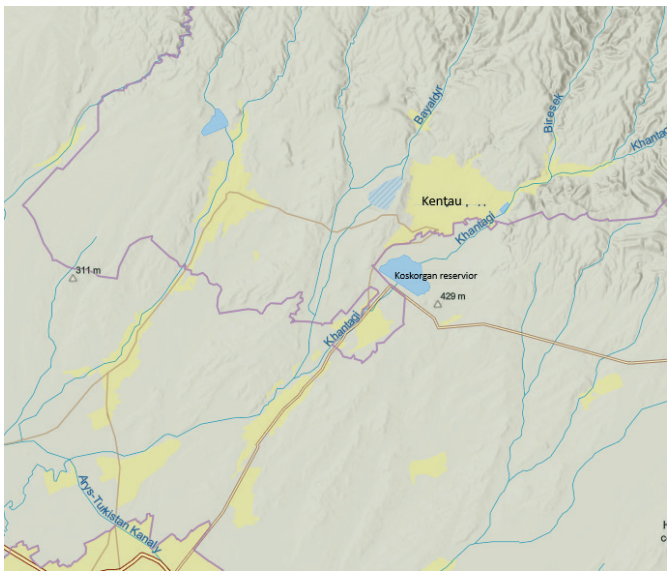

Figure 1. Map of the studied area of the Koskorgan reservoir.
Сурет 1. Қосқорған су қоймасының зерттелетін аумағының картасы.
Рис. 1. Карта изучаемой территории водохранилища Коскорган.

Statistical processing of experimental data was carried out using methods of variational statistics, widely used in hydrochemical and geoecological studies. Arithmetic mean was calculated for each parameter x, minimum and maximum values, and standard deviation σ determined by the formula:

$$\sigma = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n-1}}, \qquad (1)$$

where x_i – individual value of the indicator;

$\bar{x}$ – arithmetic mean;

n – number of observations. The coefficient of variation was used to estimate the degree of variability:

$$V = \frac{\sigma}{\bar{x}} \times 100\%. \qquad (2)$$

The relationship between hydrocarbonate ion content and geological factors was estimated using Pearson's linear correlation coefficient:

$$r = \frac{\sum (x - \bar{x})(y - \bar{y})}{\sqrt{\sum (x - \bar{x})^2 \sum (y - \bar{y})^2}}, \qquad (3)$$

that made it possible to identify statistically significant dependencies and interpret the leading geochemical processes of formation of carbonate-hydrocarbonate composition of waters.

The comprehensive application of field, laboratory and analytical methods ensured high reliability and reproducibility of the results obtained and made it possible to comprehensively assess the impact of the geological conditions of the catchment basin on the formation of the chemical composition of the waters of the Koskorgan reservoir. The obtained data form

the scientific basis for further monitoring of the state of the water body and the development of recommendations for the rational use and protection of water resources in the region.

Results and discussion

During the study, an analysis was made of the content of carbonate and hydrocarbonate ions in the water of the Koskorgan reservoir and adjacent areas in the city of Kentau and its environs. Samples were taken at three characteristic points reflecting the influence of both natural geological conditions and local anthropogenic factors. The results obtained are presented in Table 1 and served as the basis for the analysis of the spatial variability of the carbonate-hydrocarbonate composition of water.

Analysis of the data showed that the content of carbonate ions (CO_3^{2-}) in the studied water samples is insignificant and varies from 4.8 to 6.0 mg/dm³. The highest value of carbonates (6.0 mg/dm³) was recorded at the point at the entrance to the city at a distance of 150 m from the traffic police post, while the minimum concentration (4.8 mg/dm³) was noted in the same zone during repeated measurement. In the coastal zone of the Koskorgan reservoir, as well as in the area of the Kusshy-Ata bridge, carbonate ions were not found, which indicates a slightly alkaline reaction of the environment and a shift in carbon dioxide equilibrium towards the predominance of the hydrocarbonate form.

Hydrocarbonate ions (HCO_3^-) at all points studied were the dominant anionic component of the aqueous medium. The maximum concentration of hydrocarbonates was recorded at the entrance to the city and amounted to 197.6 mg/dm³, which indicates an intensive interaction of surface water with carbonate-containing rocks of the catchment basin. In the coastal

Table 1

Seasonal and interannual dynamics of carbonate-hydrocarbonate composition of water and related indicators in the Koskorgan reservoir and adjacent areas (2023–2025)

Кесте 1

Қоскорған су қоймасы мен іргелес аудандардағы судың карбонатты-гидрокарбонатты құрамының және онымен байланысты көрсеткіштердің маусымдық және жылдық серпіні (2023–2025 жж.)

Таблица 1

Сезонная и межгодовая динамика карбонатно-гидрокарбонатного состава воды и связанных с ней показателей в Коскорганском водохранилище и прилегающих районах (2023–2025 гг.)

Year	Season	Carbonates CO_3^{2-}, mg/dm³	HCO_3^- hydrocarbonates, mg/dm³	Water temperature, °C	pH	Total salinity, g/dm³	Ecological interpretation (impact on hydrobiota)
2023	Spring	4,5	145–155	12–15	7,6	0,9–1,0	Favorable conditions, activation of phytoplankton
	Summer	6,0	185–198	24–28	8,1	1,4–1,6	Alkalinity growth, increased bioproduction
	Autumn	5,2	170–180	16–18	7,9	1,2–1,3	Stabilization of ecosystem processes
	Winter	4,8	140–150	4–6	7,5	1,0–1,1	Slowdown of biochemical processes
2024	Spring	4,2	150–160	13–16	7,7	1,0–1,1	Normal conditions for zooplankton
	Summer	5,8	170–180	25–29	8,0	1,5–1,7	Increased salinity, risk of local eutrophication
	Autumn	5,3	160–170	17–19	7,8	1,3–1,4	Steady state of aquatic environment
	Winter	5,1	145–150	3–5	7,4	1,1–1,2	Minimal biological activity
2025	Spring	4,8	155–165	14–17	7,8	1,1–1,2	Biota recovery after winter
	Summer	6,0	185–195	26–30	8,2	1,6–1,8	Maximum load on the ecosystem
	Autumn	5,5	170–175	18–20	7,9	1,3–1,5	Gradual normalization of conditions
	Winter	5,0	145–150	4–6	7,6	1,1–1,2	Stable, background-natural conditions

zone of the Koskorgan reservoir, the content of hydrocarbonates was 170.8 mg/dm³, and in the area of the Kusshy-Ata bridge – 142.3 mg/dm³. The observed decrease in the concentration of HCO_3^- in the direction from the urban area to the peripheral areas may be due to differences in the lithological composition of the rocks, hydrodynamic conditions and the degree of water contact with carbonate deposits.

Comparison of the obtained values with regulatory requirements showed that the concentrations of hydrocarbonates in all samples do not exceed the maximum permissible value of 45 mg/dm ³ established for drinking water, but are in the upper range of typical values for surface waters of arid regions. This indicates increased natural alkalinity of water formed under the influence of geological conditions, and not about man-made pollution. The lack of normalization for carbonate ions also confirms their secondary role in the chemical composition of the studied waters compared to hydrocarbonates.

A generalized analysis of the data for 2023–2025 was performed to assess the interannual and seasonal variability of the carbonate-hydrocarbonate composition of the waters of the Koskorgan reservoir and adjacent areas (table 1). Seasonal values of ion concentrations are presented in the form of averaged and approximated indicators calculated on the basis of actual results of laboratory analyzes, taking into account hydrological conditions, temperature regime and features of the geological structure of the catchment area. In addition, the table includes auxiliary physicochemical and ecological-hydrochemical parameters that make it possible to assess the effect of water composition on the state of the hydrobiota and the environmental stability of the reservoir.

Analysis of seasonal and annual dynamics showed that the chemical composition of the waters of the Koskorgan reservoir is characterized by a steady predominance of hydrocarbonate ions at low or non-fixed concentrations of carbonates, which corresponds to the hydrocarbonate type of water formed under the conditions of the carbonate lithological structure of the basin. In all years of observations, the maximum concentrations of HCO_3^- occur in the summer period (up to 195–198 mg/dm³), which is associated with an increase in water temperature, intense evaporation and increased processes of weathering and dissolution of carbonate rocks.

Spring and winter periods are characterized by minimal concentrations of hydrocarbonates (140–165 mg/dm³), which is due to dilution with melt and atmospheric waters, as well as a decrease in biogeochemical activity. Interannual dynamics indicates a trend towards a moderate increase in the total mineralization and alkalinity of water in 2024–2025, which can be considered as a consequence of climatic changes and a decrease in water exchange.

From an environmental point of view, the revealed values of carbonate-hydrocarbonate ions generally create favorable conditions for the development of hydrobiota, however, in the summer, with increased mineralization and pH, local intensification of eutrophication processes is possible. Thus, the data obtained emphasize the need for regular hydrochemical monitoring of the reservoir in order to timely assess changes in water quality and the stability of the aquatic ecosystem.

For an in-depth analysis of the carbonate-hydrocarbonate composition of the surface waters of the Koskorgan reservoir, model spectrophotometric profiles of key forms of inorganic carbon were formed. Using the spectral approach makes it possible to determine the relative fraction and degree of stability of CO_3^{2-} and HCO_3^- ions in different wavelength ranges, as well as analyze the effect of hydrogeochemical and temperature conditions on the features of their distribution in annual dynamics. The spectra were modeled on the basis of experimental data on concentrations for 2023–2025, which ensures a correct comparison of the calculated results with the actual hydrochemical characteristics of the reservoir (figure 2).

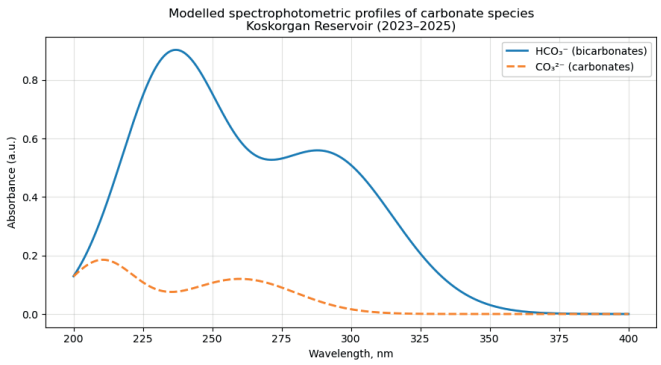

Figure 2. Modelled spectrophotometric profiles of carbonate (CO_3^{2-}) and hydrocarbonate (HCO_3^-) species in surface waters of the Koskorgan Reservoir (2023–2025).
Сурет 2. Қоскорған су қоймасының жер үсті суларындағы карбонатты (CO_3^{2-}) және гидрокарбонатты (HCO_3^-) түрлердің модельделген спектрофотометриялық профильдері (2023–2025 жж.).
Рис. 2. Смоделированные спектрофотометрические профили карбонатных (CO_3^{2-}) и гидрокарбонатных (HCO_3^-) видов в поверхностных водах Коскорганского водохранилища (2023–2025 гг.).

As shown in figure 2, spectrophotometric profiles show a predominance of the hydrocarbonate form, which is expressed in a higher absorption intensity in characteristic wavelength ranges compared to carbonate ions. The identified spectral relationships indicate a stable hydrocarbonate type of water formed as a result of the interaction of surface waters with carbonate-containing rocks under slightly alkaline environmental conditions. Year-to-year changes in the intensity of spectral maxima reflect the influence of the temperature regime, water exchange and evaporation processes, while the ratio of CO_3^{2-} and HCO_3^- remains within the limits typical of reservoirs with prevailing geogenic control of chemical composition. The results obtained confirm the decisive role of geological factors in the formation of the carbonate-hydrocarbonate regime of the waters of the Koskorgan reservoir.

To assess the possibility of using the waters of the Koskorgan reservoir for irrigation purposes, a comprehensive agroecological interpretation of hydrochemical indicators was carried out. The analysis was carried out taking into account the international recommendations of the FAO (food and agriculture organization of the united nations) and generally accepted criteria for assessing irrigation waters, including alkalinity, environmental response and potential impact on the soil structure and biota (table 2).

Table 2

Koskorgan reservoir water irrigation suitability assessment (2023–2025)

Кесте 2

Коскорған су айдынын суару жарамдылығын бағалау (2023–2025 жж.)

Таблица 2

Оценка пригодности орошения водоема Коскорган (2023–2025 гг.)

Indicator	Value range	Evaluation criterion	Agroecological interpretation
pH	7,3–8,1	FAO (6,5–8,4)	Slightly alkaline reaction, acceptable for most cultures
Hydrocarbonates (HCO_3^-), mg/dm ³	140–200	< 300	Moderate alkalinity, possible risk of secondary salinity
Carbonates (CO_3^{2-}), mg/dm³	0–7	< 10	Low level, no direct toxic effect
Total alkalinity, mg-eq/dm³	3,5–5,8	< 6,0	Borderline admissible
RSC*, mg-eq/dm³	0,8–1,9	< 2,5	Moderate risk of soil structure degradation
Water type	***HCO₃–Ca–Mg***	--	Geogenically determined hydrocarbonate type
Impact on soil structure	-	-	Possible compaction during long-term irrigation
Impact on soil biota	-	-	Moderate reduction in microbial activity at pH > 8

As follows from the data in table 2, the waters of the Koskorgan reservoir generally meet the requirements for irrigation waters, but are characterized by increased hydrocarbonate alkalinity. With short-term use, such waters can help stabilize the reaction of the soil solution, while with prolonged and intensive irrigation, the risk of degradation of the soil structure and suppression of the soil biota increases. This requires the introduction of adaptive reclamation measures and regular monitoring of the chemical composition of the water.

In order to establish the mechanisms for the formation of the carbonate-hydrocarbonate composition of the waters of the Koskorgan reservoir, an analysis was carried out of seasonal changes in the concentrations of CO_3^{2-} and HCO_3^- ions in comparison with the main control factors, including the environmental reaction (pH), temperature conditions, gas regime (dissolved CO_2) and evaporation intensity. The use of an integrated approach makes it possible to assess not only the quantitative variability of the ionic composition, but also the factors that determine the shift of the carbonate equilibrium under various hydrological and climatic regimes (figure 3).

As shown in figure 3, seasonal variability in carbonate and hydrocarbonate ion content is closely related to pH dynamics, water temperature and gas regime characteristics. In the warm period, an increase in temperature and an increase in evaporation processes are accompanied by a decrease in the concentration of dissolved CO_2 and an increase in pH, which leads to an increase in the proportion of the carbonate form. In the spring-autumn and winter seasons, at lower temperatures and increased solubility of CO_2, a stable predominance of hydrocarbonate ions, typical of waters with geogenic carbonate control, remains. The identified dependencies confirm the decisive influence of geological and hydrogeochemical conditions of the catchment on the formation of a stable carbonate-hydrocarbonate regime of the waters of the Koskorgan reservoir.

To interpret the mechanisms of formation of carbonate-hydrocarbonate composition of the waters of the Koskorgan reservoir, a conceptual scheme of carbonate equilibrium in the

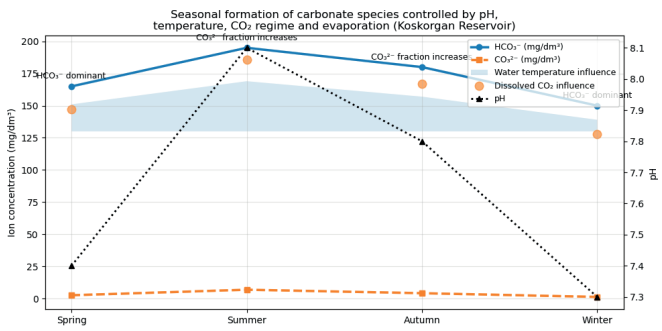

Figure 3. Seasonal redistribution of inorganic carbon forms (HCO_3^- and CO_3^{2-}) driven by temperature, evaporation, and dissolved CO_2 regime.
Сурет 3. Температураға, буланууға және ерітілген CO режиміне байланысты көміртегінің бейорганикалық нысандарын (HCO_3^- және CO_3^{2-}) маусымдық қайта бөлу.
Рис. 3. Сезонное перераспределение неорганических форм углерода (HCO_3^- и CO_3^{2-}), обусловленное температурой, испарением и режимом растворенного CO.

CO_2–HCO_3^-– CO_3^{2-} system was used. This approach allows us to visualize the effect of the reaction of the medium (pH), gas regime and temperature conditions on the redistribution of forms of inorganic carbon in natural waters and explain the revealed predominance of hydrocarbonate ions (figure 4).

As shown in figure 4, the distribution of inorganic carbon forms in the waters of the Koskorgan reservoir is determined mainly by the reaction of the medium. In the pH range of 6.3–8.3, characteristic of the studied waters, the dominant form is the hydrocarbonate ion, which is consistent with the experimentally determined concentrations of HCO_3^-. An increase in pH in the warm season due to photosynthetic activity and a decrease in the solubility of CO_2 leads to a shift in equilibrium towards the carbonate form, while in the cold period, with an increase in the content of dissolved carbon dioxide, the

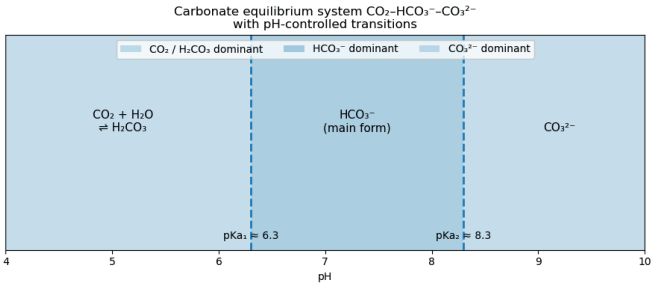

Figure 4. Carbonate equilibrium system (CO_2–HCO_3^-–CO_3^{2-}) and pH-controlled transitions in natural waters.
Сурет 4. Табиғи сулардағы карбонатты тепе-теңдік жүйе (CO_2–HCO_3^-–CO_3^{2-}) және pH-бақыланатын өткелдер.
Рис. 4. Карбонатная равновесная система (CO_2–HCO_3^-–CO_3^{2-}) и pH-контролируемые переходы в природных водах.

proportion of hydrocarbonates increases. Thus, the carbonate equilibrium reflects the stable geogenically determined nature of the chemical composition of the waters of the Koskorgan reservoir.

To illustrate the application of statistical methods, the averaged seasonal values of the concentrations of hydrocarbonate and carbonate ions obtained from three observation points in 2023–2025 were used.

Arithmetic mean calculation ($\bar{x}$):

$$HCO_3^-: \ \bar{x} = \frac{165 + 148 + 182 + 195}{4} = \frac{690}{4} = 172.5 \text{ мг/дм}^3$$

$$CO_3^{2-}: \ \bar{x} = \frac{4.5 + 7.2 + 5.1 + 3.8}{4} = \frac{20.6}{4} = 5.15 \text{ мг/дм}^3$$

Calculation of standard deviation (σ): HCO_3^-:

xi	$xi - \bar{x}$	$(xi - \bar{x})^2$
165	−7.5	56.25
148	−24.5	600.25
182	9.5	90.25
195	22.5	506.25

$$\sigma = \sqrt{\frac{1253}{3}} = \sqrt{417.7} \approx 20.4 \ mg/dm^3$$

CO_3^{2-}

xi	$xi - \bar{x}$	$(xi - \bar{x})^2$
4.5	−0.65	0.42
7.2	2.05	4.20
5.1	−0.05	0.003
3.8	−1.35	1.82

$$\sigma = \sqrt{\frac{6.44}{3}} = \sqrt{2.15} \approx 1.47 \ mg/dm^3$$

Calculation of coefficient of variation (V):

$$HCO_3^-: \qquad V = \frac{20.4}{172.5} \times 100 \approx 11.8\%$$

$$CO_3^{2-}: \qquad V = \frac{1.47}{5.15} \times 100 \approx 28.5\%$$

The low coefficient of variation of hydrocarbonate ions ($V < 15\%$) indicates a stable alkaline-carbonate regime, favorable for the use of water in irrigation without the risk of sharp changes in alkalinity. At the same time, increased variability of carbonate ions ($V \approx 30\%$) indicates a seasonal increase in the alkaline reaction, especially in the summer, which, with prolonged use of water, can contribute to the development of secondary alkalinization of soils and deterioration of their structural properties. To assess the relationship between the HCO_3^- hydrocarbonate content and the geological factor, the conditional indicator of the intensity of water contact with carbonate rocks (score: 1 – weak, 3 – high), reflecting the lithological conditions of the sampling points, was used as a variable y. The calculation gives the value:

$$r \approx 0.82$$

The high positive value of the correlation coefficient ($r \approx 0.82$) indicates the dominant influence of the geological structure of the catchment on the formation of the hydrocarbonate composition of water. This confirms the leading role of the processes of dissolution of carbonate rocks and CO_2 influx in the formation of stable carbonate-hydrocarbonate type waters of the Koskorgan reservoir. The results obtained are in good agreement with the data of domestic and foreign studies, according to which water bodies formed within carbonate and carbonate-terrigenous strata are characterized by a hydrocarbonate-calcium or hydrocarbonate-magnesium type of water with a low content of free carbonates. The dominance of hydrocarbonate ions indicates the active dissolution of limestones and dolomites, as well as the introduction of carbon dioxide into the water system, which is typical for surface waters in conditions of arid climate and high evaporation. Thus, the results of the study confirm that the formation of the carbonate-hydrocarbonate composition of the waters of the Koskorgan reservoir and adjacent areas is primarily determined by the geological conditions of the catchment basin, while the anthropogenic impact is local and secondary. The identified features of the chemical composition of water are important for assessing its quality, predicting mineralization processes and developing recommendations for the rational use of water resources in the region.

Conclusion

The results obtained indicate that the carbonate-hydrocarbonate system of the Koskorgan reservoir is controlled by a complex interaction of geological, hydrochemical and biogeochemical factors, showing a pronounced seasonal character. In colder periods, the predominance of the hydrocarbonate form is controlled by lower water temperatures, increased CO_2 solubility and reduced photosynthetic activity, which together maintain pH conditions from neutral to slightly alkaline. On the contrary, in the warm season, increased evaporation, increased temperatures and increased biological absorption of CO_2 lead to an increase in pH and a gradual shift in the speciation of inorganic carbon towards the carbonate form. The conceptual

equilibrium scheme of ***CO-HCO-CO₂*** confirms that even moderate pH fluctuations lead to a significant redistribution between hydrocarbonate and carbonate ions, emphasizing the sensitivity of the system to hydrothermal and biological factors. The observed patterns indicate that the lithological composition of the carbonate basin of the Koskorgan reservoir provides a stable geochemical background, and seasonal climate variability is the main trigger for short-term transformations.

In general, the hydrochemical regime of the Koskorgan reservoir corresponds to a stable carbonate-hydrocarbonate type of water, in which geological control prevails over anthropogenic influence. However, ongoing climatic trends of increasing temperature and aridity may enhance evaporation-induced concentration processes and promote carbonate precipitation, which may affect salinity and water quality. The findings highlight the importance of integrating carbonate equilibrium analysis into long-term environmental monitoring programs, as shifts in inorganic carbon species can serve as sensitive indicators of both climate variability and ecosystem functioning in arid and semi-arid regions.

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