

Assessment of water quality and anthropogenic impacts on surface and groundwater in the Zhambyl region using GIS-technology

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Abstract. An integrated hydrochemical and geospatial assessment was performed to assess the water quality of wastewater accumulation basins and adjacent aquatic systems in the Zhambyl region (southern Kazakhstan) under conditions of increasing anthropogenic impact. Monitoring was carried out at eight sampling points (P1-P8) during three seasonal campaigns (September 2025, November 2025, and January 2026). The measured parameters included pH, oxidation-reduction potential (ORP), dissolved oxygen (DO), salinity, total dissolved solids (TDS), electrical conductivity (EC), and chemical oxygen demand (COD).

The results demonstrate pronounced spatial variability in hydrochemical conditions. The highest levels of contamination were recorded at the wastewater treatment facility (P1) and in the upstream accumulation basins (P2-P3), where elevated COD values (up to 126.4 mg/L) and critically low DO concentrations (as low as 0.63 mg/L) were observed. In contrast, the peripheral sites (P7-P8) exhibited comparatively stable and less impacted conditions.

Seasonal analysis revealed a clear increase in organic pollution and oxygen depletion during the winter period, likely associated with reduced dilution capacity and temperature-dependent biochemical processes. The findings indicate that insufficiently treated wastewater represents the primary driver of hydrochemical deterioration in the studied area. These results underscore the necessity for improved wastewater treatment strategies and the implementation of continuous monitoring frameworks. The application of GIS-based modeling further demonstrated its effectiveness as a tool for spatial analysis, environmental assessment, and informed decision-making in sustainable water resource management.

Keywords: hydrochemical analysis; Geographic Information System (GIS); spatial-temporal analysis; wastewater accumulation basins; anthropogenic impact.

1. Introduction

1.1. Water resources and anthropogenic impact in the Zhambyl region

Water resources of the Zhambyl region constitute a strategic component of environmental sustainability and regional socio-economic development. Increasing urbanization and population growth, particularly in Taraz, have led to rising water consumption and wastewater generation, placing increasing stress on both surface and groundwater systems.

Wastewater management in the region remains insufficient. Existing reports indicate systemic challenges in wastewater treatment and disposal, including limited treatment capacity and the accumulation of untreated effluents in storage facilities (Egemen Qazaqstan, 2018). According to recent regional assessments, the ecological condition of the Zhambyl region continues to deteriorate under increasing anthropogenic pressure on water resources (ZhambylNews, 2025). According to available data, only about 30 % of wastewater undergoes treatment prior to discharge, while the remaining volumes are either accumulated or released into the environment (Inbusiness.kz, 2023).

A significant portion of untreated wastewater is stored in accumulation basins located near the Asa and Kostobe settlements, where long-term infiltration into soils and aquifers leads to gradual changes in groundwater chemistry and affects the stability of adjacent river systems (Egemen Qazaqstan, 2018). The expansion of wastewater storage infrastructure over time reflects increasing discharge volumes, while the lack of full-cycle biological and chemical treatment further contributes to environmental degradation (Egemen Qazaqstan, 2018).

Anthropogenic load is further shaped by a combination of agricultural, municipal, and industrial activities. Agricultural return flows from irrigated lands within the Talas and Shu river basins introduce residual fertilizers, pesticides, and dissolved salts into hydrological systems, increasing nutrient loading and mineralization levels (Bekseitova, 2016). Comparable pressures have been documented at the national scale, where irrigation efficiency, return-flow management, and the modernization of water-distribution infrastructure remain among the principal constraints on the sustainable use of agricultural water resources in Kazakhstan (Amalbekova et al., 2026). Municipal wastewater contributes organic matter to receiving water bodies, further altering their hydrochemical composition (Unified Environmental Internet Resource of Kazakhstan, 2024).

Industrial activities represent another significant source of contamination. The Zhambyl region is characterized by phosphorus-processing and chemical enterprises, including "Kazphosphate" LLP and the "New Zhambyl Phosphorus" plant, both of which discharge a range of inorganic pollutants as part of their production processes (Orda.kz, 2022; Seitqaziev & Mustafayev, 2015). Additional contamination originates from phosphogypsum waste and industrial sludge infiltrating groundwater.

The cumulative impact of untreated wastewater, industrial discharge, and agricultural runoff has led to measurable deterioration in the ecological condition of regional rivers, including the Talas, Shu, and Asa ("Zhambyl Oblysynyn Geokologiyalyq Zhagdayy," 2022). Elevated concentrations of nutrients contribute to eutrophication processes, while contamination of aquifers poses a risk to groundwater resources that serve as primary sources of drinking water. Increased mineralization and chemical transformation of water resources may pose risks to agricultural productivity and public health (Ibrayev, 2013; "Zhambyl Oblysynyn Geokologiyalyq Zhagdayy," 2022).

Despite the substantial body of evidence demonstrating hydrochemical degradation in the Zhambyl region (Bekseitova, 2016; Egemen Qazaqstan, 2018; Ibrayev, 2013; Inbusiness.kz, 2023; Orda.kz, 2022; Seitqaziev & Mustafayev, 2015; Unified Environmental Internet Resource of Kazakhstan, 2024; "Zhambyl Oblysynyn Geokologiyalyq Zhagdayy," 2022; ZhambylNews, 2025), the spatial distribution of anthropogenic pressures and their interactions with regional hydrological systems remain insufficiently understood. The complex coexistence of wastewater storage facilities, river networks, irrigated agricultural areas, and groundwater recharge zones necessitates a comprehensive spatial analysis to identify areas of heightened vulnerability and to support informed environmental management strategies.

Comparable challenges have been documented across other Kazakhstani and Central Asian river basins, where seasonal hydrological regimes and anthropogenic loading jointly determine water quality outcomes. Long-term assessments of the Yelek River basin have shown that dissolved oxygen deficits and elevated suspended and dissolved solids intensify during low-flow periods under increasing human influence (Mussina et al., 2025). Similarly, studies of the transboundary Ural-Caspian basin and the Shu River basin have identified wastewater discharge and inadequate treatment infrastructure as principal determinants of aquifer and surface water degradation, reinforcing the relevance of integrated hydrochemical-GIS approaches at the regional scale (Amirgaliev et al., 2022; Tazhiyev et al., 2025).

In this context, the present study aims to provide a detailed hydrochemical characterization of wastewater accumulation basins in the Zhambyl region through the systematic analysis of key water quality parameters, including pH, oxidation–reduction potential, dissolved oxygen, salinity, total dissolved solids, electrical conductivity, and chemical oxygen demand. This analysis is integrated with Geographic Information System (GIS)-based mapping to enable spatial visualization of contamination patterns and to establish a robust scientific basis for continuous monitoring and sustainable management of regional water resources.

1.2. GIS technology in water quality monitoring

Geographic Information Systems (GIS) have become an indispensable tool in contemporary water quality monitoring due to their capacity to integrate, analyze, and visualize spatially referenced environmental data beyond the capabilities of traditional point-based sampling methods. Conventional monitoring approaches are often constrained by spatial and temporal limitations, whereas GIS enables the synthesis of information from multiple sources, including field measurements, remotely sensed imagery, and ancillary geographic datasets, within a unified analytical framework. By combining hydrochemical analysis with spatial data, this integrated approach allows for a more comprehensive assessment of water quality across spatial and temporal scales, facilitating the identification of spatial patterns, trends, and anomalies in hydrochemical parameters that may remain undetected through isolated measurements (Akar et al., 2024).

Beyond simply merging data sources, GIS also acts as a structured information-management platform, storing and organizing layered datasets - hydrological networks, land use patterns, population distribution, and similar variables - so that each can be queried alongside the others. Linking geographic location to these environmental attributes lets researchers examine how spatial relationships and dependencies shape hydrochemical conditions (Ngamile et al., 2025).

One of the principal advantages of GIS lies in its capacity to transform complex environmental datasets into thematic maps that support scientific interpretation and environmental decision-making. By spatially representing hydrochemical indicators such as dissolved oxygen, chemical oxygen demand, salinity, and conductivity, GIS allows researchers to identify areas of elevated contamination and evaluate the spatial extent of anthropogenic impacts on water bodies (Ngamile et al., 2025). Spatial statistical methods extend this capability from visualization to explanation: spatial autocorrelation analysis and geographical detector models applied to chemical oxygen demand emissions have revealed pronounced clustering of discharge loads and quantified the contribution of individual socio-economic and land use drivers to their distribution, demonstrating the value of spatially explicit approaches for pollution source attribution (Zhu et al., 2024). Furthermore, GIS enables multi-temporal analysis through the comparison of datasets collected during different monitoring periods, thereby facilitating the identification of seasonal variations and long-term trends in water quality parameters (Akar et al., 2024).

The analytical capabilities of GIS extend to spatial modeling and interpolation techniques, such as inverse distance weighting and kriging, which enable the generation of continuous water quality surfaces from discrete sampling points and support prediction in areas with limited data (Akar et al., 2024).

GIS-based hydrogeological modeling has also proven effective for characterizing transboundary aquifers and groundwater-surface water interactions in arid and semi-arid basins, providing a methodological basis for identifying vulnerable recharge zones near wastewater accumulation sites (Tazhiyev et al., 2025). Complementing spatial analysis, machine learning-assisted GIS frameworks have recently been applied to optimize pollution source apportionment and reactive media selection in water treatment design, illustrating the growing convergence between spatial analytics and remediation engineering (Kwak et al., 2024). Accurate characterization of the hydraulic and reactive properties of barrier media remains essential for such design frameworks, particularly under variable subsurface conditions (Gray et al., 2024).

The application of GIS in water quality monitoring significantly enhances environmental assessment by enabling integrated spatial-temporal analysis, supporting data-driven decision-making, and providing visual outputs that improve the interpretation and communication of research results. Overall, GIS represents a robust and versatile analytical tool for modern hydrochemical investigations, providing a solid scientific basis for sustainable water resource management (Akar et al., 2024; Khan et al., 2023).

1.3. Permeable reactive barriers as a remediation response

The spatial identification of contamination hotspots is closely linked to the selection of appropriate remediation strategies. Conventional ex-situ approaches, in which contaminated water is extracted and treated at the surface before discharge or reinjection, remain widely applied but are frequently constrained by high capital and operational costs, continuous energy demand, and the need for long-term maintenance of pumping and treatment infrastructure (Chidiac et al., 2024). These constraints are particularly relevant for dispersed contamination sources such as wastewater accumulation basins, where the affected volume is large, and the contaminant plume is diffuse.

Permeable reactive barriers (PRBs) offer an alternative passive in-situ technology in which a reactive medium is emplaced across the flow path of a contaminant plume, allowing groundwater to pass through under natural hydraulic gradients while contaminants are retained or transformed by sorption, precipitation, or reductive degradation. Because no pumping is required, PRB systems substantially reduce operational energy demand relative to pump-and-treat configurations, although their performance depends on the correct selection of reactive media, barrier geometry, and residence time (Budania & Dangayach, 2023). Practical implementation has been documented across the full sequence from laboratory column testing and reactive media screening to field-scale construction, most extensively in the passive treatment of acid mine drainage, where PRB and layered permeable barrier configurations have achieved sustained retention of dissolved metals and neutralization of acidity (Wang et al., 2024).

The applicability of PRB technology extends beyond inorganic contaminants. Recent experimental work has demonstrated effective removal of the pharmaceutical residues acetaminophen and diclofenac from wastewater treatment plant effluents using reactive barrier configurations, indicating the relevance of the approach to municipal discharge scenarios of the type present in the Zhambyl region (Kalmakhanova, Khabashova, et al., 2026). Comparative reviews of reported field and laboratory applications further confirm the capacity of PRB systems to address pharmaceuticals and heavy metals simultaneously in groundwater remediation, while identifying reactive medium longevity, clogging, and passivation as the principal factors limiting long-term efficiency (Kalmakhanova, Reimbayev, et al., 2026). Barrier service life is itself predictable from site-specific parameters: longevity models that incorporate influent contamination level and groundwater velocity have been used to estimate the operational lifetime of reactive media prior to installation (Kwak et al., 2024).

Integrating GIS-based vulnerability mapping with PRB design therefore provides a coherent framework for regional water resource management. Spatial analysis identifies where contaminant loading and aquifer vulnerability coincide, while hydrochemical characterization of those locations supplies the influent composition and flow parameters required for reactive medium selection and

barrier sizing. This combined approach underlies the present study, in which hydrochemical monitoring of wastewater accumulation basins is undertaken both as an assessment of current conditions and as a basis for the subsequent design of targeted remediation measures.

2. Materials and methods

2.1. Wastewater Plant

The study area is located in the Zhambyl Region of southern Kazakhstan and encompasses wastewater treatment and storage facilities situated near the settlements of STP, Bas-01, Bas-02, Bas-03, Bas-04, Bas-05, Shaikoryk, and Kostobe (Figure 1, showing the location of sampling points P1–P8).

The geographical coordinates of the monitoring sites range from 71.223378° to 71.300220° E longitude and from 42.945339° to 42.982306° N latitude. Eight fixed sampling points (P1–P8) were established within the wastewater storage basins and adjacent water bodies associated with the wastewater treatment plant.

Sampling and monitoring were carried out during three observation periods: September 2025, November 2025, and January 2026, enabling a seasonal comparison of hydrochemical conditions.



Figure 1. Study area map, Zhambyl Region, Kazakhstan

2.2. Water sampling procedure

Surface water samples were collected following the international ISO 5667 series, which sets out how water quality monitoring programs should be designed and specifies appropriate sampling methods and handling requirements. These standards establish fundamental principles for obtaining representative samples and preventing alterations in the chemical composition of water between the time of collection and laboratory analysis (ISO 5667-1, 2006).

Prior to sampling, pre-cleaned and sterilized sampling containers were employed, thereby eliminating the risk of secondary contamination. Water samples were collected from representative points of the water body under conditions that prevented resuspension of bottom sediments and intrusion of extraneous substances into the samples (ISO 5667-3, 2018).

Following collection, the samples were hermetically sealed and transported to the laboratory for subsequent analysis. To prevent changes in chemical composition, the samples were stored at reduced temperatures in a refrigerated chamber until analysis. In accordance with the ISO 5667

standards, laboratory measurements were performed as soon as possible after sampling, minimizing potential alterations in the physicochemical properties of the water (ISO 5667-3, 2018).

Key water quality parameters were measured as soon as the samples reached the laboratory, which kept the original sample characteristics intact and made the analytical results more dependable (ISO 5667-1, 2006; ISO 5667-3, 2018).

2.3. Hydrochemical Analysis

The physicochemical characterization of the collected water samples was carried out through in-situ measurements of a comprehensive set of parameters. pH, oxidation–reduction potential (ORP, mV), and dissolved oxygen (DO, mg/L) were determined using a calibrated Bante 9 Series multiparameter water quality meter (Bante Instruments, Shanghai, China). Salinity (‰), total dissolved solids (TDS, mg/L), and electrical conductivity (EC, $\mu\text{S}/\text{cm}$) were measured using a LuminSens LMS-PA100P portable water quality analyzer (Qingdao LuminSens Marine Technology Co., Ltd., Qingdao, China). All instruments were calibrated prior to field deployment in accordance with the manufacturers' specifications, and measurements were performed directly in the field immediately following sample collection to minimize potential alterations in parameter values attributable to transport or storage conditions.

The chemical oxygen demand (COD) of water samples was determined using an Intelligent COD Rapid Tester 5B-3C(V8) (Lianhua Technology Co., Ltd.), based on the standard dichromate oxidation method. Pre-prepared COD digestion vials containing potassium dichromate, sulfuric acid, and silver sulfate catalyst were used for the analysis. Prior to measurement, samples were collected in clean polyethylene containers and, when necessary, filtered to remove suspended particles. Samples with COD values exceeding the measurement range were appropriately diluted with deionized water. A defined volume of the sample was added into the digestion vial, which was then tightly sealed and mixed thoroughly. The vials were placed in the digestion unit of the analyzer and heated at 165 °C for 10 minutes to ensure complete oxidation of organic matter. After digestion, the vials were allowed to cool to room temperature, and the absorbance was measured photometrically by the analyzer at the specified wavelength. The COD values, expressed in mg O₂/L, were automatically calculated using the instrument's pre-calibrated curves. Calibration accuracy was verified using potassium hydrogen phthalate (KHP) standard solutions, and a reagent blank was analyzed to account for background interference. All measurements were performed in triplicate, and the results were reported as mean $\pm$ standard deviation.

The monitoring program was conducted over three distinct seasonal periods: September 2025, November 2025, and January 2026, at eight fixed sampling sites within wastewater accumulation basins and adjacent water bodies. This methodology produced a structured spatio-temporal dataset, enabling the analysis of seasonal variations and spatial heterogeneity in hydrochemical conditions. The resulting dataset provided a solid foundation for subsequent GIS-based integration, spatial analysis, and interpretation of water quality dynamics across the study area.

2.4. GIS data processing and spatial analysis

Hydrochemical data obtained from eight fixed sampling points over three seasonal campaigns (September 2025, November 2025, and January 2026) were structured in a CSV file with UTF-8 encoding. Each record included the following attributes: site identifier, name, geographic coordinates (longitude and latitude in decimal degrees, WGS 84), date of sampling, and measured physicochemical parameters (pH, oxidation-reduction potential, dissolved oxygen, salinity, total dissolved solids, conductivity, and chemical oxygen demand).

Care was taken to ensure the correct formatting of numerical and temporal fields to prevent import errors.

The dataset was imported into QGIS 3.x as a delimited text layer, defining point geometry based on geographic coordinates (EPSG:4326). An OpenStreetMap basemap served as the spatial reference to contextualize the sampling locations. Symbolology was configured to distinguish sampling points

categorically according to site identifiers, while interactive HTML pop-ups were set up to display detailed hydrochemical information for each point, including seasonal measurements.

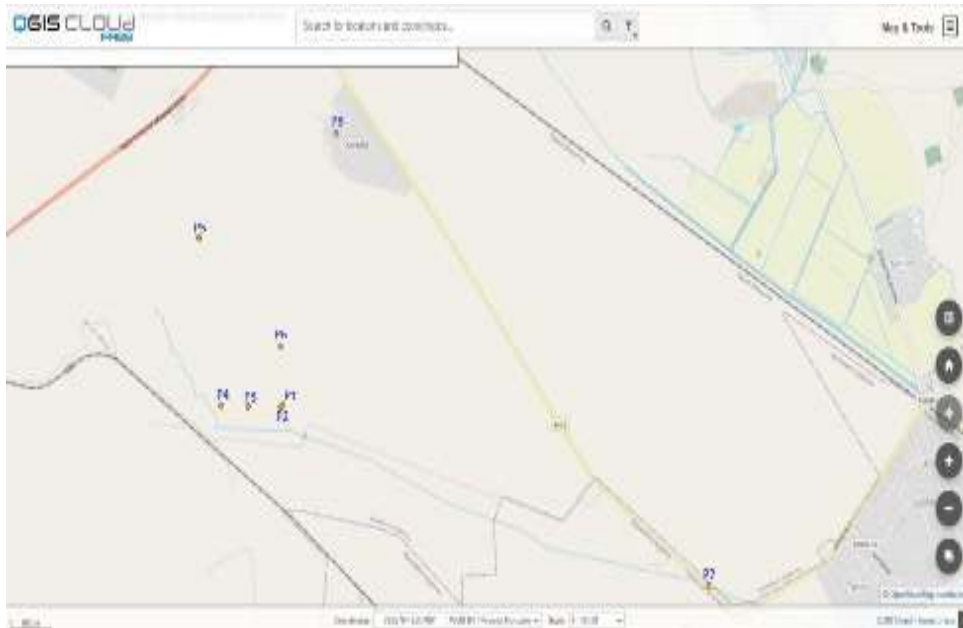


Figure 2. Interactive map of sampling points (P1–P8) in the Zhambyl Region. (Map generated via QGIS Cloud)

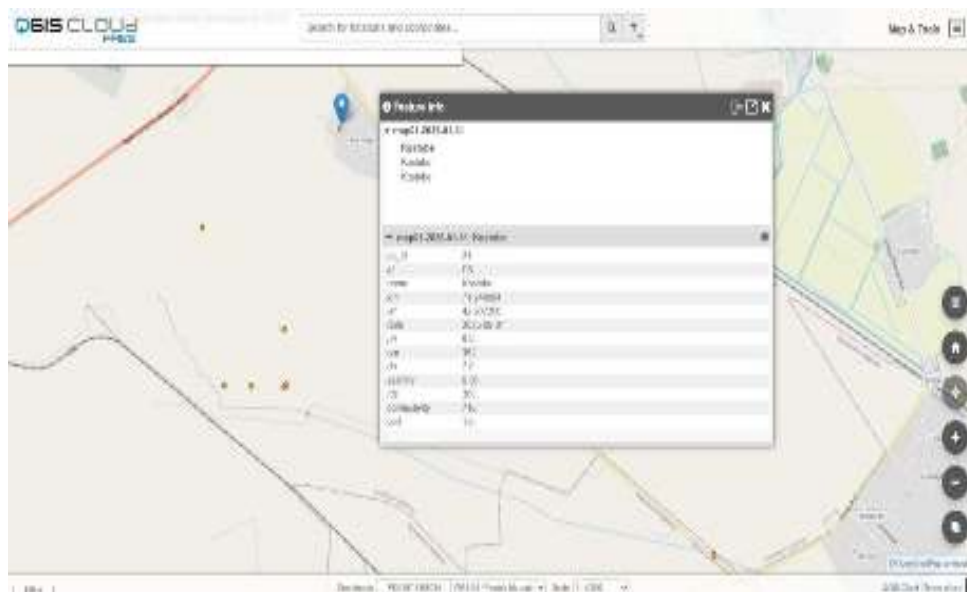


Figure 3. Hydrochemical data at each sampling point (P1–P8) for three seasonal campaigns (September 2025, November 2025, January 2026). (Data accessible by clicking points in QGIS Cloud.)

Temporal visualization was enabled to allow sequential inspection of data across the three observation periods. This approach facilitated the detection of spatio-temporal trends, seasonal variability, and areas potentially affected by elevated contaminant levels. The processed GIS project was subsequently prepared for both static cartographic outputs, suitable for publication, and dynamic web-based visualization using qgis2web, enabling public access and further analysis of water quality dynamics. The locations of all eight fixed sampling points (P1–P8) in the wastewater accumulation

basins and adjacent water bodies are shown in Figure 2 and Figure 3. Each point contains hydrochemical parameters (pH, ORP, DO, salinity, TDS, conductivity, and COD) for three seasonal campaigns (September 2025, November 2025, and January 2026), which can be accessed interactively by clicking on the points in the QGIS Cloud map.

3. Results

3.1. Interpretation of results in GIS environment

Hydrochemical analysis of wastewater accumulation basins and adjacent water bodies in the Zhambyl region revealed significant spatial and temporal variability in water quality parameters over the monitoring period from September 2025 to January 2026, as shown in Table 1.

Table 1. The hydrochemical characterization of the collected water samples

Id	Name	pH (Sep/Nov/ Jan)	ORP (mV) (Sep/Nov/J an)	DO (mg/L) (Sep/Nov/J an)	Saltinity (ppt) (Sep/Nov/J an)	TDS (ppm) (Sep/Nov/J an)	EC (μS/cm) (Sep/Nov/J an)	COD (mg/L) (Sep/Nov/J an)
P1	STP	6.85 7.00 6.90	381.8 277.2 301.2	1.30 0.63 3.16	0.51 0.5 0.57	490 479 515	975 923 1045	51.17 74.14 126.4
P2	Bas-01	6.90 7.10 7.80	363.5 283.2 261.5	7.95 1.20 14.1	0.51 0.51 0.59	483 476 561	938 964 1121	19.13 49.13 103.8
P3	Bas-02	7.10 7.40 7.90	375.0 258.6 257.1	1.50 9.53 15.4	0.75 0.66 0.53	710 563 506	1450 1164 1001	79.70 80.27 90.3
P4	Bas-03	6.90 7.30 7.70	365.3 263.7 270.1	6.41 3.27 1.47	0.74 0.53 0.55	682 485 523	1363 1012 1044	63.54 67.70 102.3
P5	Bas-04	6.70 7.30 7.80	312.6 258.5 26.1	5.64 1.44 7.80	0.57 0.55 0.52	560 531 502	1045 1061 1012	41.83 48.10 90.3
P6	Bas-05	7.20 7.10 7.70	301.5 282.7 271.5	6.45 5.14 3.47	0.6 0.58 0.53	589 567 501	1062 981 1007	49.21 54.73 108.3
P7	Shaikor yk	6.70 7.70 7.70	362.5 225.9 280.9	16.21 11.85 9.80	0.25 0.26 0.36	252 259 356	501 504 700	15.05 18.50 34.61
P8	Kostob e	6.50 7.10 7.80	362.0 258.7 260.6	7.80 8.74 15.5	0.36 0.38 0.29	360 367 285	716 731 574	1.50 5.03 8.59

The pH of the water exhibited minor fluctuations across sites and seasons, ranging from 6.5 at Kostobe (P8) in September 2025 to 7.9 at Bas-02 (P3) in January 2026, reflecting slightly acidic to neutral conditions, as shown in Figure 4. A gradual increase in pH was observed in most locations during the winter sampling period, potentially associated with diminished dilution and reduced microbial activity under low-temperature conditions.

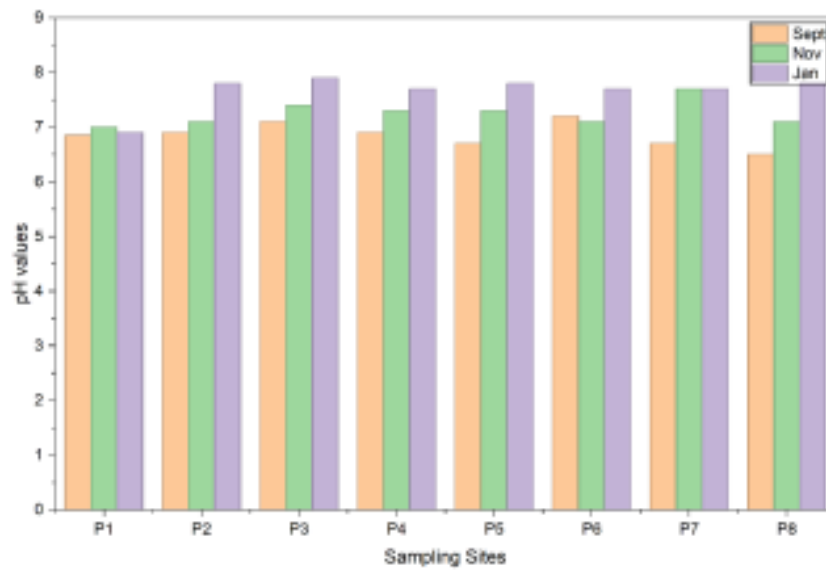


Figure 4. Spatial and temporal variation of pH values at sampling sites

Oxidation-reduction potential (ORP) varied considerably among monitoring points, with the highest values measured at the sewage treatment plant (STP, P1) in September 2025 (381.8 mV), indicative of oxidizing conditions, while the lowest redox potential occurred at Bas-04 (P5) in January 2026 (26.1 mV), suggesting a localized accumulation of reducing agents due to organic matter degradation Figure 5.

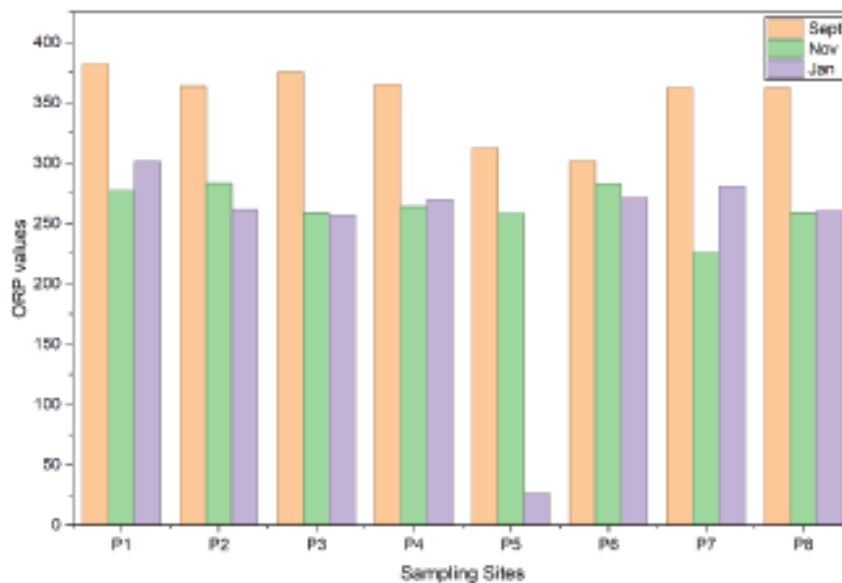


Figure 5. Spatial and temporal variation of oxidation–reduction potential (ORP) at sampling sites

Dissolved oxygen (DO) concentrations were markedly heterogeneous, with the lowest values consistently recorded at P1, where oxygen depletion reached 0.63 mg/L in November 2025, highlighting the pronounced impact of anthropogenic effluents. Conversely, Bas-02 (P3) exhibited elevated DO in January 2026, reaching 15.4 mg/L, likely due to increased aeration and lower organic input relative to upstream discharge points. Peripheral sites such as Shaikoryk (P7) and Kostobe (P8) maintained moderate to high oxygen concentrations throughout the monitoring period, reflecting minimal exposure to direct wastewater inflows Figure 6.

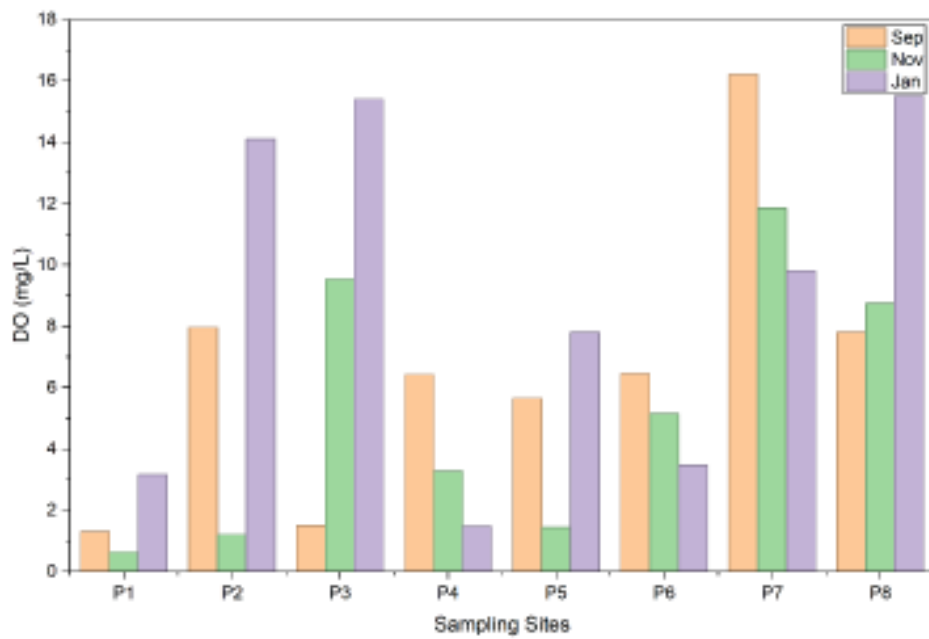


Figure 6. Dissolved oxygen (DO) levels across sampling sites and seasons

Salinity values remained generally low across the study area, ranging from 0.25 ‰ at P7 in September 2025 to 0.75 ‰ at P3 in September 2025, with slight seasonal increases observed in central basins, suggesting minor concentration effects associated with reduced flow and evaporation Figure 7.

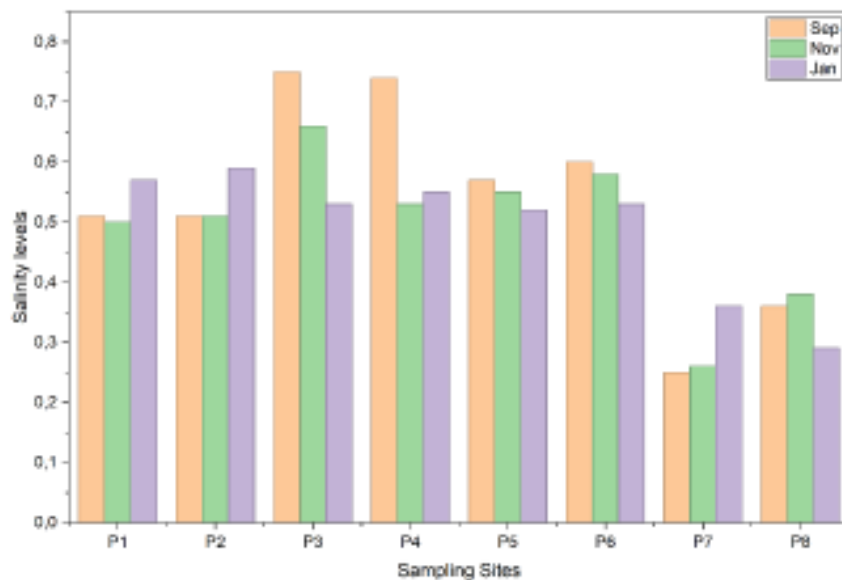
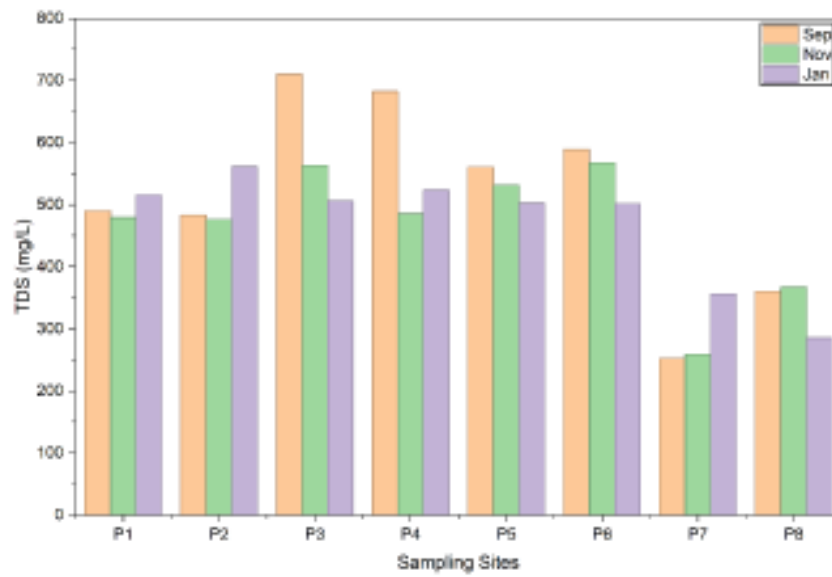
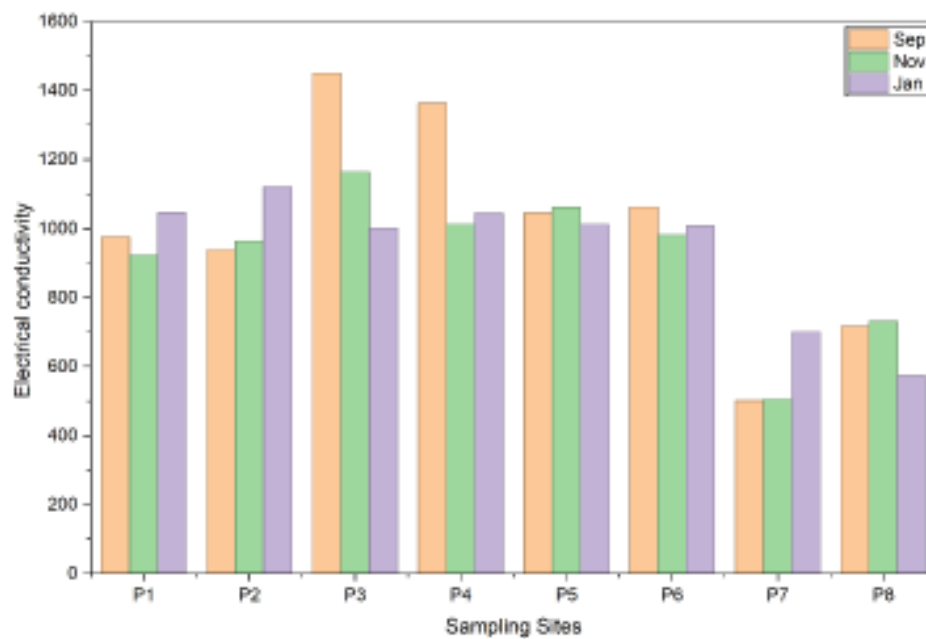


Figure 7. Salinity levels across sampling sites and seasons

Total dissolved solids (TDS) and electrical conductivity mirrored these patterns, with the highest TDS recorded at P2 (561 mg/L) in January 2026 and the lowest at P7 (252 mg/L) in September 2025, confirming the correlation between dissolved ionic content and basin accumulation processes Figure 8.



a)



(b)

Figure 8. Spatial and temporal variation of total dissolved solids (TDS) and electrical conductivity (EC) at sampling sites: (a) TDS, (b) EC

Chemical oxygen demand (COD) demonstrated the most pronounced variability, reflecting spatial differences in organic loading. Maximum COD levels were consistently observed at STP (P1), reaching 126.4 mg O₂/L in January 2026, and were also elevated at Bas-01 (P2) and Bas-02 (P3), emphasizing the influence of wastewater discharge. In contrast, COD values at Shaikoryk (P7) and Kostobe (P8) remained relatively low, ranging from 1.5 mg/L to 34.6 mg/L across the sampling periods, indicating limited anthropogenic impact as shown in Figure 9.

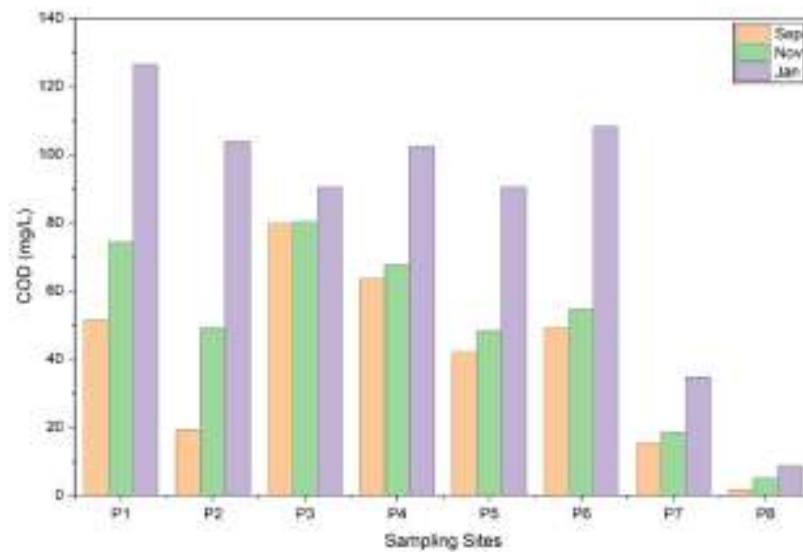


Figure 9. COD levels across sampling sites and seasons

Temporal trends showed progressive accumulation of organic matter from September to January, concomitant with a decline in dissolved oxygen at impacted sites, underscoring the seasonal influence of reduced dilution and temperature-dependent metabolic activity.

4. Discussion

The obtained results provide a coherent picture of hydrochemical processes occurring within wastewater accumulation basins and adjacent water bodies in the Zhambyl region. Rather than isolated variations, the measured parameters reveal interconnected patterns driven by both anthropogenic inputs and natural seasonal dynamics.

A clear relationship is identified between chemical oxygen demand (COD) and dissolved oxygen (DO), particularly at sites directly affected by wastewater discharge (P1-P3). Elevated COD values are systematically accompanied by reduced DO concentrations, indicating intensive oxygen consumption during the biochemical oxidation of organic matter. The critically low DO concentration recorded at P1 (0.63 mg/L) reflects a high organic load and limited self-purification capacity of the aquatic system. This relationship is widely recognized as a key indicator of anthropogenic pollution in wastewater-impacted environments (Zhu et al., 2024).

The distribution of oxidation-reduction potential (ORP) further supports this interpretation. High ORP values observed at P1 during September (381.8 mV) indicate oxidizing conditions associated with active inflow and mixing processes. The markedly low ORP value at P5 in January (26.1 mV) suggests the development of reducing conditions, likely resulting from the accumulation and anaerobic decomposition of organic matter. These localized redox shifts indicate the presence of zones with limited water exchange and enhanced biogeochemical transformation.

Parameters reflecting mineralization processes, including total dissolved solids (TDS), electrical conductivity (EC), and salinity, demonstrate a consistent spatial pattern. Elevated values at central accumulation basins (P2-P4) indicate prolonged retention and concentration of dissolved ions, while lower values at peripheral sites (P7-P8) reflect dilution effects and reduced exposure to wastewater inflows. Seasonal variability plays a significant role in shaping hydrochemical conditions. During the winter period, an increase in COD combined with a decrease in DO is observed across several monitoring sites, which can be attributed to reduced dilution capacity, lower temperatures, and slower oxygen exchange processes. Under such conditions, organic matter accumulates, and oxygen consumption processes dominate, leading to further deterioration of water quality.

The spatial distribution of hydrochemical parameters reveals a clear gradient of anthropogenic influence across the study area. Sites located near wastewater discharge points function as primary

zones of contamination, whereas more distant locations exhibit relatively stable conditions and partial recovery of water quality. These findings confirm that wastewater impact is spatially confined, representing a key factor governing regional hydrochemical dynamics.

These findings are consistent with broader patterns reported for semi-arid river basins of Kazakhstan and Central Asia, where seasonal low-flow periods and insufficient wastewater treatment consistently coincide with the most pronounced water quality deterioration (Mussina et al., 2025; Amirgaliev et al., 2022; Tazhiyev et al., 2025). Similar seasonal declines in dissolved oxygen and increases in mineralization under reduced dilution capacity have also been documented for transboundary basins such as the Ural-Caspian and Shu river systems, supporting the interpretation that reduced winter flow and temperature-dependent biochemical activity are a regional, rather than site-specific, driver of hydrochemical deterioration (Amirgaliev et al., 2022; Tazhiyev et al., 2025).

Given the confirmed role of insufficiently treated wastewater as the principal driver of hydrochemical deterioration at P1-P3, passive treatment technologies such as permeable reactive barriers (PRBs) represent a promising complementary strategy for mitigating contaminant loading before discharge into accumulation basins. Recent reviews highlight the effectiveness of zero-valent iron, activated carbon, and zeolite-based reactive media in reducing organic loading, nutrients, and trace contaminants under low-energy, passive operating conditions (Budania & Dangayach, 2023; Yadav et al., 2026; Kwak et al., 2024). Similarly, engineered PRB media have shown high removal efficiencies for pharmaceutical and emerging organic contaminants in wastewater treatment plant effluents, further supporting the applicability of reactive barrier configurations to organically loaded discharges such as those observed at the STP site (Mansour et al., 2026). The cyclic adsorptive-oxidative configuration of PRB technology, in particular, has demonstrated potential for treating wastewater with variable organic loads similar to those observed at the STP and upstream basins in this study, suggesting a feasible pathway for reducing COD and restoring dissolved oxygen levels at the most heavily impacted sites (Wang et al., 2024; Chidiac et al., 2024).

The integration of hydrochemical data within a GIS framework substantially enhances the interpretation of these patterns. Spatial analysis enables the identification of contamination hotspots and facilitates the assessment of their temporal evolution, which provides a comprehensive understanding of environmental processes compared to conventional point-based monitoring.

5. Conclusion

Integration of hydrochemical measurements within a Geographic Information System (GIS) framework enabled spatially explicit interpretation of water quality dynamics. GIS mapping revealed clear contamination hotspots, particularly at STP (P1) and upstream accumulation basins (P2–P3), characterized by elevated COD and reduced dissolved oxygen. Moderate TDS and salinity levels were confined to central basins, whereas peripheral locations (P7 and P8) retained near-natural water quality. Temporal layering within the GIS environment highlighted seasonal variations, with winter conditions exacerbating organic load accumulation and oxygen depletion, while early autumn exhibited lower pollutant concentrations and more homogeneous hydrochemical conditions. The GIS-based visualization facilitated identification of zones under significant anthropogenic influence and provided a robust platform for correlating hydrochemical parameters with spatial distribution. The combined analysis of hydrochemical data and GIS mapping indicates that wastewater effluents exert the strongest impact on STP and adjacent accumulation basins, while peripheral sites maintain relatively stable water quality. The integration of field measurements with geospatial analysis enhances the interpretive capacity of environmental monitoring programs, allowing targeted management of contaminated zones and informing decision-making processes. The web-based GIS map generated via QGIS Cloud serves as a tool for continuous monitoring and potential public dissemination, offering a transparent and data-driven approach to regional water resource management.

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7. Author Contributions

Conceptualization – K.M.; G.H.; methodology – R.Y.; software – T.Z.; validation – K.M., K.Z., U.A.; formal analysis – B.A.; investigation – R.Y., T.Z.; resources – B.Z.; data curation – R.Y.; writing - original draft preparation – K.Z.; writing - review and editing – G.H., K.M.; visualization – U.A.; supervision – G.H.; project administration – K.M.; funding acquisition – K.M. All authors have read and agreed to the published version of the manuscript.

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11. Conflicts of Interest: The authors declare no conflicts of interest.

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Жамбыл облысындағы беткі және жер асты суларының сапасын және антропогендік әсерлерді ГИС-технологияны қолдану арқылы бағалау

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Аңдатпа. Жамбыл облысында (оңтүстік Қазақстан) антропогендік қысымның күшеюі жағдайында ағынды суларды жинақтау бассейндері мен оларға іргелес су объектілерінің сапасын бағалау мақсатында кешенді гидрохимиялық және геоақпараттық талдау жүргізілді. Зерттеу үш маусымдық кезеңде (2025 жылғы қыркүйек, қараша және 2026 жылғы қаңтар) сегіз бақылау нүктесінде (P1-P8) жүзеге асырылды. Алаңдық өлшеулер барысында негізгі физика-химиялық көрсеткіштер анықталды: рН, тотығу-тотықсыздану потенциалы (ORP), еріген оттегі (DO), тұздылық, жалпы еріген заттар (TDS), электрөткізгіштік (EC) және химиялық оттегіге сұраныс (COD).

Алынған нәтижелер гидрохимиялық көрсеткіштердің айқын кеңістіктік әртүрлілігін көрсетті. Ең жоғары ластану деңгейі ағынды суларды тазарту құрылысы маңында (P1) және ағынның жоғарғы бөлігіндегі жинақтау бассейндерінде (P2-P3) тіркелді, бұл COD мәндерінің жоғары болуымен (126.4 мг/л дейін) және еріген оттегінің төмен деңгейімен (0.63 мг/л дейін) сипатталады. Керісінше, шеткі бақылау нүктелерінде (P7-P8) гидрохимиялық жағдай салыстырмалы түрде тұрақты және аз дәрежеде өзгерген.

Маусымдық талдау қыс мезгілінде органикалық жүктеменің артуы мен еріген оттегінің төмендеу үрдісін көрсетті, бұл сұйылу дәрежесінің азаюымен және температураға тәуелді биохимиялық үдерістермен байланысты. Жалпы алғанда, нәтижелер өңірлік су жүйелерінің гидрохимиялық жағдайының нашарлауында жеткіліксіз тазартылған ағынды сулардың шешуші рөл атқаратынын айқындайды.

Зерттеу нәтижелері ағынды суларды басқару жүйелерін жетілдіру және тұрақты мониторинг жүргізу қажеттілігін негіздейді. GIS-негізіндегі модельдеу кеңістіктік талдау жүргізу, экологиялық бағалау және су ресурстарын тұрақты басқару үшін тиімді құрал ретінде дәлелденді.

Түйін сөздер: гидрохимиялық талдау; Географиялық ақпараттық жүйе (GIS); кеңістіктік-уақыттық талдау; ағынды суларды жинау бассейндері; антропогендік әсер.

Оценка качества поверхностных и подземных вод и антропогенного воздействия в Жамбылской области с использованием ГИС-технологий

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Аннотация. Проведена комплексная гидрохимическая и геопространственная оценка качества воды в бассейнах накопления сточных вод и прилегающих водных объектах Жамбылской области (Южный Казахстан) в условиях возрастающего антропогенного воздействия. Полевые исследования выполнены на восьми мониторинговых точках (P1-P8) в рамках трех сезонных кампаний (сентябрь 2025 г., ноябрь 2025 г. и январь 2026 г.). В ходе мониторинга определялись ключевые физико-химические параметры: pH, окислительно-восстановительный потенциал (ORP), растворенный кислород (DO), солёность, общее содержание растворенных веществ (TDS), электропроводность (EC) и химическое потребление кислорода (COD).

Результаты свидетельствуют о выраженной пространственной неоднородности гидрохимических характеристик. Наиболее высокий уровень загрязнения зафиксирован в районе очистных сооружений (P1) и в верхних накопительных бассейнах (P2-P3), где наблюдаются повышенные значения COD (до 126,4 мг/л) и критически низкие концентрации растворенного кислорода (до 0,63 мг/л). В то же время периферийные участки (P7-P8) характеризуются относительно стабильными и менее нарушенными условиями.

Сезонный анализ показал увеличение органической нагрузки и снижение содержания растворенного кислорода в зимний период, что, вероятно, связано с уменьшением разбавляющей способности водной системы и влиянием температурно-зависимых биохимических процессов. Полученные данные указывают на доминирующую недостаточно очищенных сточных вод в формировании гидрохимического состояния исследуемых водных объектов. Результаты исследования подчеркивают необходимость совершенствования систем очистки вод и внедрения непрерывного мониторинга. Применением GIS-моделирования продемонстрировало высокую эффективность для пространственного анализа, экологической оценки и обоснования решений в области устойчивого управления водными ресурсами.

Ключевые слова: гидрохимический анализ; Географическая информационная система (ГИС); пространственно-временной анализ; бассейны накопления сточных вод; антропогенное воздействие.