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# Integrated environmental monitoring and assessment of anthropogenic impacts on the Ilek River ecosystem, Kazakhstan

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## ABSTRACT
Ilek River, one of the most polluted water bodies in the Ural–Caspian Basin, experiences significant anthropogenic pressure. The primary sources of pollution include heavy metals (Cr, Pb, Fe, and Mn), boron, petroleum hydrocarbons, and organic contaminants such as surfactants, chemical oxygen demand (COD), and biochemical oxygen demand ($BOD_5$). The aim of this study was to conduct a comprehensive bioindication-based assessment of organic pollution in the river channel. The saprobity index of macrophyte communities was applied alongside instrumental analysis of the physicochemical properties of water. Additionally, the study evaluated the phytoremediation potential of six macrophyte species, namely *Ceratophyllum demersum*, *Lemna minor*, *Eichhornia crassipes*, *Pistia stratiotes*, *Typha latifolia*, and *Phragmites australis*, for removing priority pollutants from the aquatic environment. The research was further supported by a systematic review of scientific publications indexed in Scopus from 2018 to 2025, which provided a broader scientific context for assessing macrophyte-based remediation efficiency and ecological monitoring of contaminated river ecosystems.

**Keywords:** Anthropogenic pressure, Environmental monitoring, Macrophytes, River ecosystem, Sustainable management.
**Article type:** Research Article.

## INTRODUCTION
Kazakhstan, as a key country in Central Asia, is increasingly facing the degradation of freshwater ecosystems driven by a combination of historical and contemporary factors related to unsustainable water resource management (Karatayev *et al.* 2017; Musirmonov *et al.* 2023; Atakhanova *et al.* 2024). The cumulative effects of long-term anthropogenic pressures are manifested in the deterioration of water quality, particularly in industrially developed regions, where the ecological integrity of river systems directly affects both human health and ecosystem stability. Since the mid-20$^{th}$ century, many countries, including Kazakhstan, have experienced persistent anthropogenic alterations of river hydrological regimes. These changes are most critical for small and medium-sized rivers, which serve as sensitive indicators of ecological conditions (Wang *et al.* 2017; Liu *et al.* 2020; Xue *et al.* 2021). In Kazakhstan, the primary sources of anthropogenic pressure remain industrial discharges from mining and metallurgical enterprises, inefficient agricultural water use, channel transformation, and insufficient treatment of municipal wastewater (Thompson *et al.* 2021; Seraya *et al.* 2025).

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**Historical sources of pollution in the Ilek River Basin**

Ilek River, a transboundary tributary of the Ural, has been subjected to long-term contamination originating from both Kazakhstan and Russia (Dyachenko *et al.* 2021; Wu *et al.* 2024). Historically, the key sources of anthropogenic pressure were tailing ponds and sludge storage facilities of mining and metallurgical enterprises, particularly those associated with the processing of chromium- and boron-bearing ores (Tursunova *et al.* 2022; Gupta & Mishra 2023). Since the 1960s–1980s, accumulated wastes have increasingly migrated into the hydrological system through infiltration flows and erosion processes (Lovinskaya *et al.* 2019; Salikova *et al.* 2021; Safarov *et al.* 2022; Berdesheva *et al.* 2024). Elevated concentrations of heavy metals (Cr, Pb, and Zn), petroleum hydrocarbons, and boron compounds have been recorded along the river channel and floodplain zones, as confirmed by comprehensive hydrochemical surveys (Zholmuratova *et al.* 2020; Egbueri *et al.* 2023; Severinenko *et al.* 2023). The impact is further exacerbated by agricultural drainage inputs containing nitrogen compounds and pesticides (Bytyçi *et al.* 2022; Xu *et al.* 2022). The combined influence of these factors has created a complex chemical and biological background that necessitates an integrated monitoring approach, incorporating both physicochemical and bioindication methods (Ali *et al.* 2013; Milke *et al.* 2020). In the past, pollution in the Ilek River basin was primarily associated with industrial discharges from mining and metallurgical enterprises, which caused significant heavy metal contamination and long-term ecological risks. In contrast, present-day challenges are largely linked to municipal wastewater discharges, agricultural non-point source pollution, urban runoff, and the cumulative impacts of transboundary pressures. This separation of historical and current pollution drivers provides a clearer understanding of the temporal dynamics of anthropogenic impacts on the river ecosystem.

**Rationale for the use of macrophytes and bioindication in Ilek River**

Under the conditions of multi-component pollution characteristic of the Ilek River basin, traditional physicochemical monitoring provides information only on individual substances and therefore does not fully reflect the ecological condition of the aquatic ecosystem (Lovinskaya *et al.* 2019; Salikova *et al.* 2021; Safarov *et al.* 2022; Severinenko *et al.* 2023; Egbueri *et al.* 2023; Gupta & Mishra 2023; Г.А. *et al.* 2024). Recent decades have thus seen increasing interest in bioindication approaches, which allow the evaluation of cumulative anthropogenic pressure through the structure and condition of aquatic communities (Ali *et al.* 2013; Ma *et al.* 2016; Milke *et al.* 2020; Ramakrishnan *et al.* 2021; Gataulina *et al.* 2025; Gulzira *et al.* 2025). Macrophytes—higher aquatic plants—represent a promising tool for both bioindication and bioremediation, as they are capable of accumulating a wide range of pollutants, including heavy metals, boron compounds, petroleum hydrocarbons, and organic toxicants (Milke *et al.* 2020; Gulzira *et al.* 2025). Their morphological and physiological plasticity allows them to adapt to variable hydrochemical conditions, which is particularly important under the fluctuating hydrological regime of Ilek River (Ramakrishnan *et al.* 2021). Several species, including *Eichhornia crassipes*, *Pistia stratiotes*, *Ceratophyllum demersum*, *Lemna minor*, *Typha latifolia* and *Phragmites australis*, have demonstrated high efficiency in the accumulation of heavy metals and in supporting microbial consortia involved in petroleum hydrocarbon degradation (Vymazal 2014). The use of mixed phyto-associations enables simultaneous reduction of different classes of pollutants, making these species particularly relevant for integrated ecological monitoring and water-quality management in transboundary rivers (Varol *et al.* 2012; Ma *et al.* 2016).

**Pollution challenges of Ilek River and the relevance of macrophyte selection**

Ilek River, a transboundary tributary of the Ural, is exposed to considerable anthropogenic pressure from mining, metallurgical and petrochemical activities in Kazakhstan and Russia (Safarov *et al.* 2022; Г.А. *et al.* 2024). Recent hydrochemical assessments have recorded exceedances of maximum permissible concentrations (MPCs) for heavy metals (Cr, Pb, Fe, and Mn), boron compounds, petroleum hydrocarbons and organic matter reflected in elevated COD and $BOD_5$ values (Tyagi *et al.* 2013). In certain sections, petroleum hydrocarbons reach up to 0.4 mg $L^{-1}$, indicating persistent pollution inputs and limited natural self-purification capacity (Vymazal 2014; Rizzo *et al.* 2016). Conventional water treatment measures in flowing river systems are often economically costly and technically difficult to apply under field conditions (Vymazal 2014; Rizzo *et al.* 2016 Ramakrishnan *et al.* 2021). Consequently, increasing attention is being directed toward nature-based solutions, particularly phytoremediation, where aquatic vegetation operates as a living filter and sorbent (Schneider, 2007; Urbanič, 2011). The combined use of macrophyte species from different ecological niches—floating, submerged and emergent wetland plants—has shown promise for multi-tier pollutant removal and ecosystem stabilization in contaminated rivers (Reyjol *et al.* 2014; Küpper & Andresen 2016; Sharma *et al.* 2023).

**Mechanisms of Action and Rationale for Macrophyte Selection**

The effectiveness of phytoremediation is determined by the physiological and morphological traits of plants, as well as by the structure of microbial communities inhabiting their rhizospheres (Vymazal 2014; Kasimov *et al.* 2020; Ramakrishnan et al. 2021). Floating species such as *Eichhornia crassipes* and *Pistia stratiotes* possess extensive root systems capable of absorbing dissolved heavy metals, petroleum hydrocarbons and other organic pollutants. Their rhizospheres also support diverse microbial consortia that enhance the degradation of hydrocarbons and surfactants (Environmental Protection Agency Hazardous Waste Management System Standards Applicable to Transporters of Hazardous Waste 1980; Vymazal, 2014). Submerged species such as *Ceratophyllum demersum* play an important role in purifying bottom water layers and stabilizing sediments. Laboratory studies show that this species can remove up to 84% of Cr and 95% of Pb within 12 days, although reported efficiency varies depending on environmental conditions (Ali *et al.* 2013; Ma *et al.* 2016). In addition, *C. demersum* contributes to nitrogen conversion processes and reduces ammonium and nitrite concentrations, thereby improving biochemical oxygen demand ($BOD_5$) values (Vymazal 2014; Rizzo *et al.* 2016). Emergent wetland species such as *Typha latifolia* and *Phragmites australis* form reducing zones within their rhizospheres that facilitate heavy-metal precipitation and denitrification processes. *P. australis* also demonstrates enzymatic capability to degrade phenols and organic compounds and can reduce Cr (VI) to less toxic form. Thus, forming mixed macrophyte communities that represent different ecological niches—floating (*Eichhornia, Pistia*), submerged (*Ceratophyllum, Lemna*), and emergent wetland species (*Typha, Phragmites*)—supports multi-level pollutant removal and strengthens ecosystem resilience to recurrent contamination (Sharma *et al.* 2023).

**Enviromental incidents of 2025 and associated bio-risks**

Between June and August 2025, acute ecological incidents were recorded in the Ilek River basin, including mass mortality of aquatic organisms—such as turtles and fish during the spawning period—and episodes of intense algal “green water’’ blooms accompanied by hypoxia. These events indicate persistent organic loading and suggest a high risk of toxicological impact on the ecosystem. The vulnerability of rare and fragmented populations of the European pond turtle (*Emys orbicularis*) in the tributaries Or, Uil, and Emba is further exacerbated by the temporal overlap of their breeding season (April–June) with peaks of anthropogenic pressure (Vymazal 2014). The cumulative toxic background associated with boron and Cr (VI) poses potential reproductive and teratogenic risks, as evidenced by experimental studies in animals and epidemiological observations (Bolt *et al.* 2012; Dujsebayeva *et al.* 2025).

**Transboundary context, sources, and hydrochemical profile**

The technogenic history of the Ilek River basin has been shaped by peak discharges since 1957 following the launch of the AZKhS plant, with subsequent infiltration of toxicants into groundwater. Additional hotspots have existed since the 1940s due to the activities of the Alga Chemical Plant, as well as from landfills, car wash facilities, livestock farms, and abandoned wells in the Aktobe region. According to international classifications, water quality in certain sections is rated as “very dirty” or “extremely dirty” (Ali *et al.* 2013; Ma *et al.* 2016). Concentrations of boron and chromium remain persistently high, primarily linked to tailing ponds of former chemical industries and the inflow of contaminated groundwater. Comprehensive assessments across the basin, including the integrated toxicity index, confirm the technogenic nature of contamination and highlight the associated transboundary risks. Regional reviews emphasize the contribution of mining and metallurgy, agricultural runoff, urbanization, and reduced river discharge to the degradation of freshwater ecosystems in Kazakhstan, consistent with global trends in freshwater quality decline (Vymazal 2014; Rizzo *et al.* 2016).

**State of research and methodological gaps**

Most studies on Ilek River have focused on hydrochemistry and pollution sources, whereas regular bioindication surveys based on macrophytes or other biological indices remain limited. In contrast, regional studies on comparable hydrological systems—such as the Ishim River basin—demonstrate that macrophytes serve as informative bioindicators, although this approach has not yet been systematically applied to Ilek River.

Against this backdrop, standardized international bioassessment approaches demonstrate reproducibility and predictive value: MIR (Poland), IBMR (France), and MTR (United Kingdom) are indices validated through their correlations with $BOD_5$, COD, nutrients, and toxicants, including petroleum hydrocarbons and metals. The concept of biological integrity emphasizes the necessity of integrating biological and hydrochemical indicators into water resource management. A comparative analysis of studies on Ilek River suggests that hydrochemical diagnostics are useful for identifying episodic peaks and background concentrations, yet they do not adequately capture the chronic nature of environmental impacts (Environmental Protection Agency Hazardous Waste Management System Standards Applicable to Transporters of Hazardous Waste, 1980; Reyjol *et al.* 2014). In contrast, macrophyte-based indices integrate long-term ecological signals and reflect the spatiotemporal structure of anthropogenic pressure, particularly in small and medium-sized rivers affected by diffuse runoff and groundwater inputs (Sharma *et al.* 2023).

**Justification for the selection of bioindicators and nature-based measures**

Mixed macrophyte communities have a dual role: they can serve as bioindicators of water quality while also functioning as nature-based treatment systems. Floating species such as *Eichhornia crassipes* and *Pistia stratiotes* demonstrate high sorption capacity and stimulate hydrocarbon-degrading microbial consortia. Submerged forms including *Ceratophyllum demersum* and *Lemna minor* effectively accumulate heavy metals, lower biochemical oxygen demand (BOD) and interact with surfactants. Riparian macrophytes such as *Typha latifolia* and *Phragmites australis* support denitrification, promote Cr (III) precipitation and contribute to phenol degradation (Vymazal, 2014; Sharma *et al.* 2023). This combination of functional plant groups directly addresses key challenges of the Ilek River basin, including chromium and boron contamination, petroleum hydrocarbons, and elevated organic load. Furthermore, the proposed approach aligns with the principles of the European Water Framework Directive (EU WFD), which emphasizes integrating bioindication indices (MIR, IBMR, MTR) with conventional chemical monitoring (Birk *et al.* 2013).

**International context and regulatory frameworks**

Under the conditions of global climate change and the transboundary transport of pollutants, the need for integrated approaches to the monitoring of aquatic ecosystems is becoming increasingly urgent. The European Union Water Framework Directive (WFD) requires the achievement of "good ecological status" of water bodies through the integration of chemical and biological indicators. Similar principles are being adopted in Central Asian countries, including within the framework of interstate agreements on the Ural–Caspian basin. For rivers with high anthropogenic pressure, such as the Ilek, the WFD methodology (bioindication combined with hydrochemical monitoring) provides not only a reliable diagnosis of the current ecological state but also a robust tool for evaluating the effectiveness of environmental protection measures (Sharipov & Sharipov 2021; Berdesheva *et al.* 2024).

**Scientific rationale for the selected approach**

Experience with macrophyte-based indices in Europe and Asia demonstrates their high sensitivity to variations in trophic status, organic pollutants, petroleum hydrocarbons, heavy metals and specific toxicants such as boron. Several studies indicate that macrophytes integrate environmental conditions over longer timescales, unlike single-point chemical measurements that capture only instantaneous concentrations. At the same time, the selection of indicator species must consider local hydrological settings and the specific chemical pollution profile. In the case of Ilek River, this includes heavy metals (Cr, Pb, Fe, and Mn), boron, petroleum hydrocarbons, and elevated BOD/COD levels (Urbanič, 2011; Reyjol *et al.* 2014).

**Need for an integrated assessment**

The cumulative pressure on Ilek River—driven by industrial discharges, legacy contamination, and contemporary diffuse sources—necessitates a study that integrates:

Bioindication — calculation of saprobity indices and assessment of macrophyte community status, accounting for their capacities for bioaccumulation and biodegradation;

Chemical analysis — determination of key contaminants (Cr, B, Pb, Fe, Mn, petroleum hydrocarbons, and surfactants) and routine metrics ($BOD_5$, and COD);

Spatial analysis — identification of priority zones for remediation and the deployment of nature-based solutions (constructed wetlands, buffer strips, and phytoremediation).

Such an approach will not only establish the current ecological condition of the river but also generate actionable recommendations to reduce anthropogenic pressure, in line with both regional and international environmental requirements.

Taken together, the transboundary character of contaminant sources (AZKhS, Alga industrial complex and urbanized tributaries), chronic groundwater leakage, the co-occurrence of boron, Cr (VI) and petroleum hydrocarbons, and recurrent eutrophication symptoms demonstrate the need for an integrated evaluation framework. Such an approach should combine (i) macrophyte-based saprobic indices aligned with MIR, IBMR and MTR methodologies, and (ii) parallel hydrochemical assessment ($BOD_5$, COD, petroleum hydrocarbons, Cr (VI), and B) with spatial differentiation of point and diffuse pollution sources, in accordance with principles of the Water Framework Directive.

**Research aim**. To develop and justify a comprehensive system for ecological monitoring and bioindicator-based water-quality assessment of Ilek River. The system will utilize macrophyte communities both as bioindicators and as candidates for evaluating phytoremediation potential for heavy metals, petroleum hydrocarbons and organic pollutants (Babaniyi *et al.* 2023; Sharma *et al.* 2023).

### Research objectives

Conducting field surveys to quantify physicochemical and biological parameters of the Ilek River, with emphasis on Cr, Pb, Fe, Mn, B, petroleum hydrocarbons, surfactants, COD, and $BOD_5$.

Characterizing the species composition and spatial distribution of macrophyte communities within the channel and riparian zones, and computing the saprobity index (S) for indicative diagnosis of pollution.

Based on the literature, evaluating the effectiveness of key macrophyte taxa (*Ceratophyllum demersum*, *Lemna minor*, *Eichhornia crassipes*, *Pistia stratiotes*, *Typha latifolia*, and *Phragmites australis*) in removing priority contaminants. Compareing, using the obtained data, the performance of individual species and their mixtures in terms of removal rates and overall pollutant reduction.

Providing practice-oriented recommendations for integrating phytoremediation technologies into monitoring programs and into the management of anthropogenic pressures on Ilek River.

## MATERIALS AND METHODS

### Study Area

The research was conducted on the Kazakhstani section of Ilek River, a right-bank tributary of Ural River, with a length of approximately 149 km within the territory of the Republic of Kazakhstan. The river flows through the industrially developed area of Aktobe City and adjacent agricultural districts, which results in a combined impact of point sources (industrial, stormwater, and municipal effluents) and diffuse sources (agricultural runoff, and atmospheric deposition).

Hydrological characteristics of the study reach:

Channel width: 20–70 m (average ~35 m)

Depth: 0.8–3.5 m

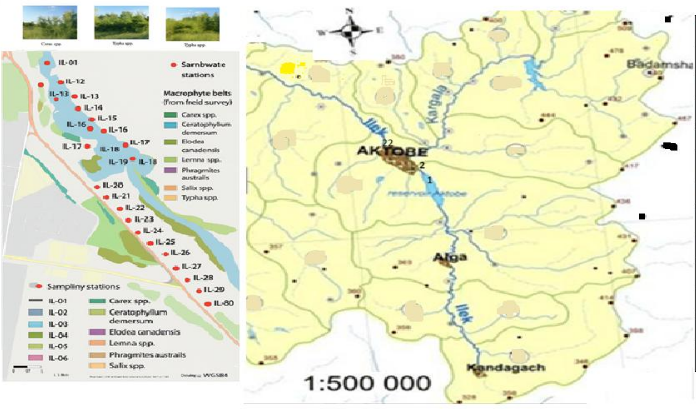
Flow velocity: 0.2–0.6 m/s

Biotope types: main channel sections with hard and silty substrates, backwaters, shallow zones with macrophyte vegetation, and low-flow areas

### Field survey design

The spatial distribution of the sampling sites and the study area is shown in Fig. 1.

Fieldwork was carried out during June–July 2025 at 23 representative sampling sites.




| Point No. | Latitude (N) | Longitude (E) | Point No. | Latitude (N) | Longitude (E) |
|---|---|---|---|---|---|
| 1 | 50.3001 | 57.1503 | 13 | 50.3401 | 57.2304 |
| 2 | 50.3038 | 57.1589 | 14 | 50.3445 | 57.2368 |
| 3 | 50.3065 | 57.1652 | 15 | 50.3492 | 57.2435 |
| 4 | 50.3092 | 57.1718 | 16 | 50.3528 | 57.2501 |
| 5 | 50.3123 | 57.1842 | 17 | 50.3560 | 57.2560 |
| 6 | 50.3158 | 57.1896 | 18 | 50.3595 | 57.2615 |
| 7 | 50.3185 | 57.1954 | 19 | 50.3630 | 57.2674 |
| 8 | 50.3220 | 57.2008 | 20 | 50.3664 | 57.2733 |
| 9 | 50.3255 | 57.2065 | 21 | 50.3700 | 57.2795 |
| 10 | 50.3290 | 57.2123 | 22 | 50.3742 | 57.2852 |
| 11 | 50.3332 | 57.2185 | 23 Well | 50.3776 | 57.2908 |
| 12 | 50.3368 | 57.2246 | | | |

**Fig. 1.** Dynamics of the Pantle–Buck saprobity index (S) along 23 sampling sites of the Ilek River.

Sampling sites were selected on the basis of a preliminary reconnaissance survey of the littoral zone and visual assessment of the condition of macrophyte communities.

**Main stages of the fieldwork**

(i) Reconnaissance survey with recording of biotope types and physico-morphological features.
(ii) Photographic documentation of riparian vegetation and visible signs of pollution.
(iii) Water sampling at sites with the highest saprobity index (S) values or pronounced visual indicators of contamination.
(iv) Laboratory analysis of hydrochemical parameters.
(v) Calculation of the macrophyte-based saprobity index (S) and preparation of a spatial distribution map.
(vi) Comparative analysis of bioindication results and chemical monitoring data.

**Hydrochemical parameters of monitoring**

The following hydrochemical indicators were analyzed using standardized procedures (Table 1):

**Table 1.** The following hydrochemical indicators were analyzed using standardized procedures.

| Parameter | Analytical method | Units | Standard/Regulatory document |
|---|---|---|---|
| $BOD_5$ | Titrimetric, manometric | mg $O_2$ $L^{-1}$ | GOST 31859–2012 |
| COD | Dichromate method | mg $O_2$ $L^{-1}$ | GOST 31861–2012 |
| Oil products | IR spectrophotometry | mg $L^{-1}$ | GOST 31957–2012 |
| Cr, Pb, Fe, Mn, B | Atomic absorption spectrometry (AAS) | mg $L^{-1}$ | |

**Water sampling at the most contaminated sites**

For an integrated assessment, water samples were collected at sites identified as having the highest pollution levels ($S \geq 3.0$), as determined during the bioindication survey. Sampling was performed in accordance with GOST 31861-2012 “Water. General requirements for sampling”.

**Biochemical Oxygen Demand ($BOD_5$):** Water samples were collected in a 250-mL glass bottle with ground-glass stopper. The analysis was conducted according to RD 52.24.420-2005, by measuring the difference in dissolved oxygen concentrations before and after 5-day incubation at 20 °C in the dark.

**Chemical Oxygen Demand (COD):** Samples were collected in glass bottles, and COD was determined photometrically using the dichromate method in accordance with PND F 14.1:2:4.153-99.

**Petroleum Hydrocarbons**: Samples were collected in glass bottles pre-rinsed with hexane. The analysis was carried out using infrared (IR) spectrophotometry according to PND F 14.1:2:4.128-97.

**Surfactants (Synthetic Detergents)**: Samples were collected in clean glass containers. The determination was performed by the photometric method based on the formation of a complex with methylene blue, in accordance with RD 52.24.417-2005.

**Laboratory analysis of heavy metals**

Elemental analysis was performed on an MGA-915 atomic absorption spectrometer (AAS) in accordance with ST RK GOST R 51309–2003 (2013). Sample preparation included mineralization with nitric acid, with an injection volume of 10 μL. The detection limit for Cr, Pb, Fe, and Mn was 0.001 mg $L^{-1}$.

**Experimental workflow**

The experimental design combined field surveys, hydrochemical analyses, and bioindication. The workflow was structured as follows:
The workflow was structured as follows and is illustrated in Fig. 2.

**Uncertainty and error analysis**

To increase the robustness of the findings, measurement uncertainties were evaluated for all analytical parameters. For physicochemical indicators (pH, DO, BOD, and COD), the relative error did not exceed 5%. For nutrient concentrations determined spectrophotometrically, the uncertainty range was within 10%, depending on detection limits and sample handling. For biological indicators based on macrophyte surveys, variability was assessed by repeated sampling at selected sites, with an estimated uncertainty of ±7%. These error margins were explicitly considered in data interpretation, ensuring that observed spatial patterns and trends in pollution were statistically reliable. All methods were selected and applied in accordance with internationally recognized protocols and harmonized approaches to ensure comparability and reliability of the results.

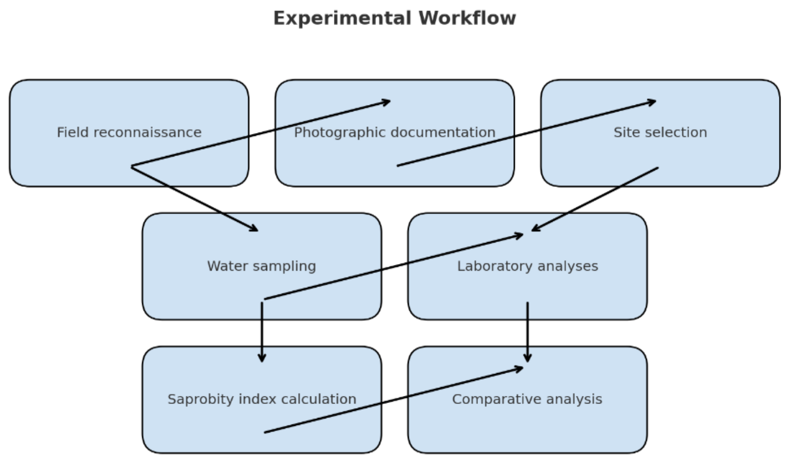



**Fig. 2.** Schematic representation of the experimental workflow applied in this study.

## RESULTS and DISCUSSION

### Rationale for the chosen bioindication approach

Macrophytes were selected as the primary bioindicators because of their sensitivity to changes in organic pollution and their ability to integrate long-term ecological conditions. The chosen set of bioindicators and natural parameters provides a comprehensive assessment of both water quality and ecosystem functioning. This approach is scientifically justified as it combines biological and physicochemical perspectives, ensuring a more rigorous and holistic framework for river ecosystem monitoring and management.

### Sampling sites and selection criteria

Twenty-three sampling sites were established along Ilek River, covering upstream, midstream, and downstream sections. Site selection was guided by hydrological conditions, proximity to potential pollution sources (urban settlements, industrial facilities, and agricultural runoff), as well as the inclusion of relatively undisturbed areas to serve as reference points. This design ensured spatial representativeness and allowed for a comprehensive assessment of gradients in water quality and ecological status. The spatial distribution of the sites is illustrated in Fig. 2.

### Control site

To strengthen the reliability of the results, a control site was included in the upstream section of Ilek River, located above the main urban and industrial discharge zones. This site represents a relatively undisturbed reference area, allowing comparisons with downstream locations affected by anthropogenic pressures. The inclusion of this control zone provided a baseline for evaluating spatial gradients of pollution and ecological responses.

### Analytical methods

Analytical methods were structured into three standardized groups to ensure consistency and comparability across sampling locations. Physicochemical parameters, including pH, dissolved oxygen, $BOD_5$, and COD, were measured according to APHA Standard Methods (APHA, 2017). Nutrient concentrations (nitrate, phosphate, and ammonium) were quantified using spectrophotometric techniques following ISO 7890-1:1986 and ISO 6878:2004. Biological conditions were assessed using macrophyte-based indices following established biomonitoring protocols (Severinenko *et al.* 2023; Yang *et al.* 2023). This methodological harmonization improved analytical rigor and enhanced the comparability and reliability of the resulting dataset. During the field surveys conducted in June–July 2025, a transect inspection of the littoral zone of Ilek River was carried out, including photographic documentation and a visual assessment of riparian aquatic vegetation. Control sites were selected and macrophyte communities were analyzed. Fig. 3 presents a schematic map of the distribution of macrophyte vegetation along the investigated section of Ilek River. The presented schematic map illustrates the spatial distribution of dominant macrophyte communities along the surveyed section of Ilek River. The data were obtained during field surveys that included mapping of riparian and aquatic vegetation and recording of species composition. Photographs on the right side of the figure depict the dominant species *in situ*, highlighting their morphological characteristics and typical growth conditions. The spatial distribution of macrophyte vegetation reflects both the hydromorphological features of the river section and the degree of anthropogenic impact. Extensive stands of *Phragmites australis* are observed in low-flow and shallow areas, indicating nutrient accumulation and potential signs of eutrophication. Shrub willow belts (*Salix* spp.) and sedge stands (*Carex* spp.) are predominantly located along stable banks, acting as natural buffer strips that retain nutrients and prevent erosion. Submerged species such as *Ceratophyllum demersum* and *Elodea canadensis* are recorded in sheltered reaches and backwaters with reduced flow velocity and relatively stable hydrological regimes. Floating mats of *Lemna* spp. are found in stagnant areas, often near sources of nutrient pollution, including surface and stormwater discharges. This cartographic material serves as an important tool for integrating biological indicators into ecological monitoring programs. Linking vegetation community structure to potential sources of pollution and hydrological conditions enables the development of targeted management recommendations for river ecosystems—such as measures to mitigate eutrophication, remove household waste, and regulate reed bed density to improve water exchange and quality.

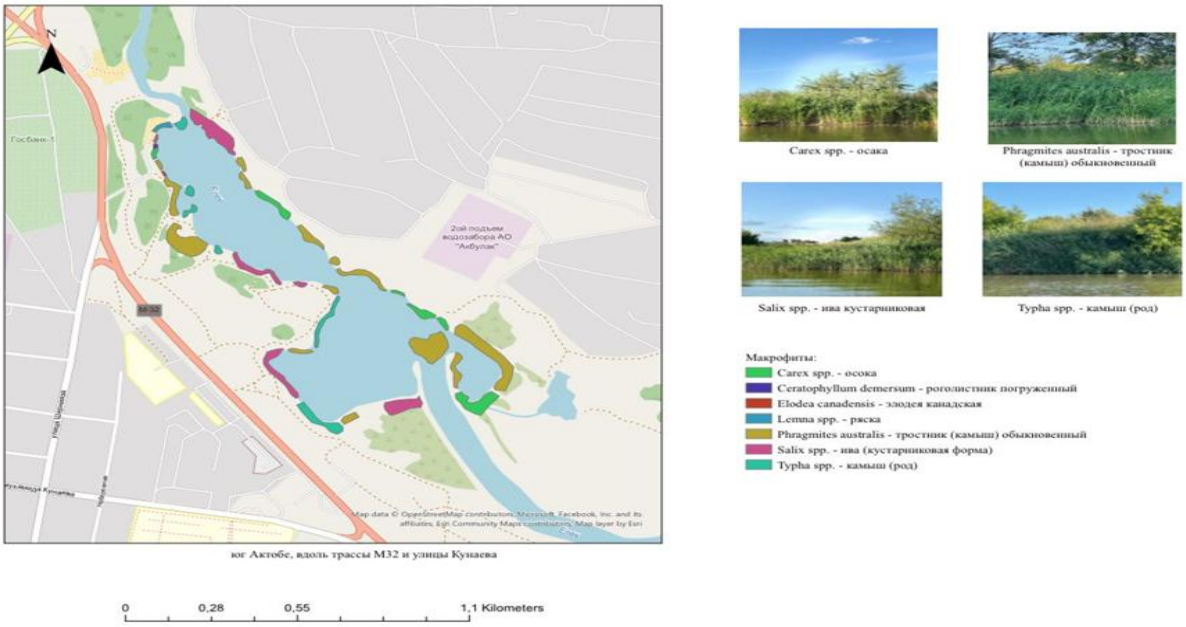



**Fig. 3.** Schematic map of macrophyte vegetation distribution along the Ilek River section.

Within the schematic map, specific sites were delineated for calculating the saprobity index (*S*) using the methodology adapted for higher aquatic vegetation. The results are presented in Table 2, which includes ecological characteristics of dominant macrophytes, indicators of organic pollution (including episodes of "water greening"), types of pollution sources, and applied bioindication approaches.

**Table 2.** Physicochemical parameters of water quality at different sampling sites along the Ilek River.

| Photo No. | Dominant macrophytes (Latin) | Possible pollution indicator | Likely pollution source |
|---|---|---|---|
| *Ilek* 1  | *Phragmites australis* | Dense reed stands, eutrophication | Point: untreated sewage; Diffuse: stormwater runoff |

| | | | |
|---|---|---|---|
|  *Ilek* 2 | *Phragmites australis* | Littoral expansion, nutrient accumulation | Point: storm drains; Diffuse: lawn runoff |
|  *Ilek* 3 | *Phragmites australis* | High biomass, nutrient saturation | Point: sewage; Diffuse: fertilizers |
|  *Ilek* 4 | *Phragmites australis* | Early-stage littoral growth, clear water | Point: drainage; Diffuse: erosion |
|  *Ilek* 5 | *Phragmites australis, Salix* spp. | Mixed riparian vegetation, good oxygen regime | Point: domestic wastewater; Diffuse: low flow |
|  *Ilek 6* | *Phragmites australis*, Carex spp. | Restricted flow, organic matter accumulation | Point: storm drains, litter; Diffuse: nutrient deposition |
|  *Ilek 7* | *Phragmites australis* | High biomass, eutrophication | Point: discharges; Diffuse: fertilizers |
|  *Ilek 8* | *Phragmites australis* | Domestic pollution | Point: storm drains; Diffuse: lawns |

| | | | |
|---|---|---|---|
|  *Ilek 9* | *Phragmites australis, Salix* spp. | Good aeration, potential accumulation | Point: domestic; Diffuse: erosion |
|  *Ilek 10* | *Phragmites australis* | Eutrophication, weak flow | Point: discharges; Diffuse: agricultural runoff |
|  *Ilek 11* | *Phragmites australis* | Organic matter accumulation | Point: litter; Diffuse: fertilizers |
|  *Ilek 12* | *Phragmites australis* | Nutrient accumulation, high saprobity | Point: drainage; Diffuse: agricultural runoff |
| *Ilek 13*  | *Phragmites australis* under *Salix* spp. canopy | Anaerobic processes in sediments | Point: groundwater seepage; Diffuse: erosion |
| *Ilek 14*  | *Phragmites australis, Salix* spp. | Early-stage eutrophication | Point: sewage; Diffuse: stormwater runoff |
|  *Ilek 15* | *Phragmites australis* | Transition to algal bloom | Point: sewage; Diffuse: croplands |
|  *Ilek 16* | *Phragmites australis, Salix* spp. | Moderate saprobity | Point: drainage; Diffuse: erosion |

| | | | |
|---|---|---|---|
|  *Ilek17* | *Phragmites australis*, *Salix* spp. | Buffer filtration with excess nutrients | Point: discharges; Diffuse: fertilizers |
|  *Ilek18* | *Phragmites australis* | Eutrophication indicator | Point: storm drains; Diffuse: precipitation |
|  *Ilek19* | *Phragmites australis* | High macrophyte productivity | Point: discharges; Diffuse: fertilizer runoff |
|  *Ilek 20* | *Phragmites australis*, *Salix* spp. | Filtration and sedimentation zone | Point: domestic wastewater; Diffuse: croplands |
| *Ilek 21*  | *Phragmites australis* with understory | Stable littoral zone | Point: drainage; Diffuse: precipitation |
|  *Ilek 22* | *Phragmites australis* | Overenrichment, algal bloom onset | Point: storm drains, sewage; Diffuse: fertilizer runoff, slope erosion |
|  *Ilek (well)* | — | Organic pollutants, surfactants, oil products | Point: faulty wells; Diffuse: agricultural seepage |

Analysis of macrophyte communities along the Ilek River channel reveals a clear zonation and a gradient of water quality changes, linked to the characteristics of anthropogenic load and hydrological regime. In the longitudinal profile of the basin, from upstream to downstream, the following trend is observed: from localized sites with relatively clean water and sparse riparian macrophytes to extensive stands showing signs of eutrophication and algal "blooming."

Almost all investigated sites confirm the theoretical model of nutrient (nitrogen, and phosphorus) and organic matter accumulation in slower-flowing sections of the river. For example, the site Ilek 1 illustrates the initial stage of riparian overgrowth, while the presence of solid waste indicates unauthorized discharges. Further downstream (Ilek 2–6), more extensive belts of common reed (*Phragmites australis*) and patches of young growth are observed. In the middle reaches (Ilek 7–14), the influence of point-source pollution (domestic effluents, and drainage) becomes more pronounced. These sites are characterized by dense stands of common reed, mixed vegetation, and the formation of buffer zones. This confirms the "biological filter" effect, where riparian vegetation acts as a natural barrier to nutrient inflow. Of particular note is the site Ilek Well, which indicates a potential problem of hidden point discharges, likely resulting from contaminant infiltration through defective wells or old collectors. Unlike surface runoff, such flows are invisible but contribute to the enrichment of riparian zones with organic substances. In the lower reaches (Ilek 15–22), the most extensive and dense reed belts with high biomass are recorded, consistent with reduced water flow and stagnation phenomena. Combined with the greenish coloration of the water, this serves as a direct indicator of the final stage of eutrophication: phytoplankton bloom. In proximity to the estuarine areas, the influence of diffuse pollution sources, such as agricultural runoff and stormwater input, becomes increasingly evident.

**Calculation of the saprobity index (S).**

The analysis of the spatial distribution of macrophytes and visual pollution indicators requires a quantitative framework for assessing river condition. Therefore, the macrophyte-based saprobity index (S) was calculated using a modified Pantle–Buck method, harmonized with established MIR, IBMR, and MTR bioassessment frameworks (Babaniyi *et al.* 2023; Yang *et al.* 2023). This index makes it possible to assess the degree of organic load on the aquatic ecosystem based on the proportional contribution of dominant species and other visual indicators. As shown in Table 3, the values of the saprobity index (S) range from 2.4 to 3.2, reflecting different levels of organic pollution along Ilek River. Minimum S values (2.4–2.6) were recorded at sites dominated by *Phragmites australis* with the presence of shrubs. These values correspond to the β-mesosaprobic zone, indicating moderately polluted but still relatively clean waters. Elevated S values ($S \geq 3.0$) were observed in areas with visible signs of eutrophication, such as the presence of foam and litter. These values correspond to the α-mesosaprobic zone, reflecting significant organic pollution. Maximum S values (up to 3.2) were typical of sites near urban effluents and technical wells, indicating strong anthropogenic impact. The analysis shows that the dominant *Phragmites australis* acts as a reliable β-mesosaprobic indicator. In combination with strong pollution indicators (litter, and foam), this leads to an increase in the S index, shifting it towards the α-mesosaprobic zone. The obtained data provide a solid basis for assessing the ecological state of the aquatic ecosystem and for identifying priority sites for monitoring and intervention.

**Bioindication as an integrative approach**

Against the background of increasing anthropogenic pressure on aquatic ecosystems in Western Kazakhstan, particularly in the Ilek River basin, there is a growing need for integrative approaches to water quality assessment. One of the most sensitive and informative methods is bioindication using aquatic vegetation (macrophytes). The calculation of saprobity indices, such as the Pantle–Buck index, serves as an important tool for understanding the state of water bodies. However, to obtain a more complete and objective picture, it is necessary to apply modern modifications. In EU countries, indices such as MIR (Macrophyte Index for Rivers), IBMR (Indice Biologique Macrophytique en Rivière), and MTR (Macrophyte Trophic Index) have been developed and are widely used. These approaches account for a broader range of factors and provide a more comprehensive assessment. The saprobity index thus represents a powerful instrument for analysis, diagnosis, and forecasting of the state of aquatic ecosystems. It makes it possible not only to assess the current level of pollution but also to identify its sources and predict further changes in the aquatic environment.

**Table 3.** Calculation of the saprobity index (S) based on macrophyte composition and pollution indicators.

| Site Photo | Species 1 | Share of species 1 (%) | Index species 1 (s) | Species 2 | Share of species 2 (%) | Index species 2 (s) | Saprobity index (S) |
|---|---|---|---|---|---|---|---|
| Ilek 1 | *Phragmites australis* | 60 | 2.8 | Litter | 40 | 3.8 | 3.2 |
| Ilek 2 | *Phragmites australis* | 80 | 2.8 | – | 0 | – | 2.8 |
| Ilek 3 | *Phragmites australis* | 90 | 2.8 | – | 0 | – | 2.8 |
| Ilek 4 | *Phragmites australis* | 100 | 2.8 | – | 0 | – | 2.8 |
| Ilek 5 | *Phragmites australis* | 70 | 2.8 | Shrubs | 30 | 1.8 | 2.5 |
| Ilek 6 | *Phragmites australis* | 80 | 2.8 | Foam | 20 | 3.8 | 3.0 |
| Ilek 7 | *Phragmites australis* | 90 | 2.8 | – | 0 | – | 2.8 |
| Ilek 8 | *Phragmites australis* | 60 | 2.8 | Litter | 40 | 3.8 | 3.2 |
| Ilek 9 | *Phragmites australis* | 70 | 2.8 | Shrubs | 30 | 1.8 | 2.5 |
| Ilek 10 | *Phragmites australis* | 80 | 2.8 | – | 0 | – | 2.8 |
| Ilek 11 | *Phragmites australis* | 90 | 2.8 | – | 0 | – | 2.8 |
| Ilek 12 | *Phragmites australis* | 80 | 2.8 | Foam | 20 | 3.8 | 3.0 |
| Ilek 13 | *Phragmites australis* | 60 | 2.8 | Shrubs | 40 | 1.8 | 2.4 |
| Ilek 14 | *Phragmites australis* | 80 | 2.8 | Shrubs | 20 | 1.8 | 2.6 |
| Ilek 15 | *Phragmites australis* | 90 | 2.8 | – | 0 | – | 2.8 |
| Ilek 16 | *Phragmites australis* | 70 | 2.8 | Shrubs | 30 | 1.8 | 2.5 |
| Ilek 17 | *Phragmites australis* | 85 | 2.8 | – | 0 | – | 2.8 |
| Ilek 18 | *Phragmites australis* | 75 | 2.8 | Foam | 25 | 3.8 | 3.05 |
| Ilek 19 | *Phragmites australis* | 90 | 2.8 | – | 0 | – | 2.8 |
| Ilek 20 | *Phragmites australis* | 70 | 2.8 | Shrubs | 30 | 1.8 | 2.5 |
| Ilek 21 | *Phragmites australis* | 85 | 2.8 | – | 0 | – | 2.8 |
| Ilek 22 | *Phragmites australis* | 70 | 2.8 | Foam | 30 | 3.8 | 3.1 |
| Ilek 23 | *Phragmites australis* | 80 | 2.8 | – | 0 | – | 2.8 |
| Ilek well | *Phragmites australis* | 60 | 2.8 | Foam | 40 | 3.8 | |

## Managing anthropogenic pressure on Ilek River

Within the framework of research aimed at managing anthropogenic pressure on Ilek River, there is an urgent need for an accurate and comprehensive assessment of its ecological condition. It is important not only to record the fact of pollution but also to understand its dynamics and spatial distribution along the entire river course.

Thus, for effective analysis and the development of management measures, it is necessary to determine the profile of changes in the saprobity index along Ilek River. This approach makes it possible to clearly demonstrate:

**The overall pollution pattern**: how water quality changes from the headwaters to the mouth.

**Local pollution sources**: specific sites with maximum contamination.

**Effectiveness of mitigation measures**: in the long term, regular monitoring of the profile will allow an assessment of how the river's condition responds to conservation activities. Fig. 4 presents the profile of saprobity changes along Ilek River.

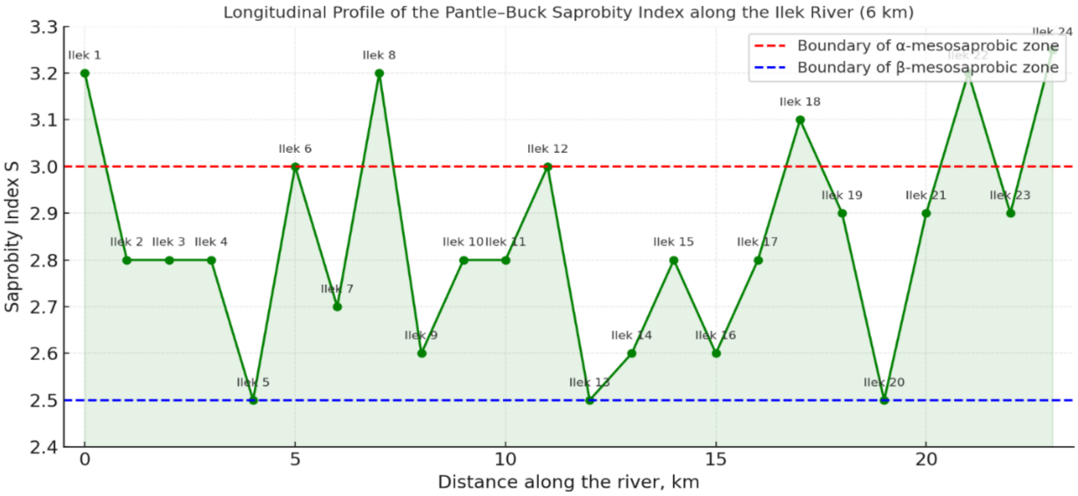



**Fig. 4.** Profile of saprobity index variation along the Ilek River course.

This graph clearly demonstrates how the saprobity index (S) changes along the course of Ilek River. Its values steadily increase from the headwaters to the downstream sections, confirming the general trend of organic pollution accumulation. The peaks on the graph correspond to areas with high anthropogenic load, where litter, foam, and other signs of eutrophication were recorded. This highlights the importance of continuous monitoring and the implementation of modern bioindication methods to preserve the unique ecosystem of Ilek River. For the analysis, diagnosis, and forecasting of the state of the aquatic ecosystem, it is important not only to determine the level of pollution but also to understand its dynamics and causes. The profile of saprobity index variation along the Ilek River course serves as a key tool for these purposes.

**Analysis of the saprobity profile of Ilek River**

The graph illustrating the saprobity profile (see Fig. 3) clearly shows how the saprobity index changes along the river course (from 0 to 6 km of the studied section). A transition can be observed from moderately clean waters (β-mesosaprobic zone) to sites with higher levels of organic pollution (α-mesosaprobic zone, $S > 3.0$). Within the framework of this study, an indicative assessment of the ecological state of the Ilek River channel was conducted along a 6 km section with 23 monitoring sites. The calculation of the integral saprobity index (S) using the Pantle–Buck method (adapted for macrophytes) yielded values ranging from 2.4 to 3.26. These values fall within the boundaries of the β- and α-mesosaprobic zones, indicating varying degrees of organic pollution. At the initial section (Ilek 1–2), high values of $S = 3.2$ were recorded. This corresponds to the α-mesosaprobic zone and indicates substantial organic pollution, most likely associated with municipal discharges, car wash effluents, and stormwater runoff. The sites Ilek 3–5 demonstrate a decrease in saprobity to 2.5–2.6, which may result from natural self-purification processes or the influence of tributaries. The repeated increase of the index to 3.0 and above (Ilek 6, Ilek 8, Ilek 22, and the well site) points to local pollution hotspots. This is corroborated by chemical data: at these sites, petroleum hydrocarbon concentrations exceeded 0.3 mg $L^{-1}$, while $BOD_5$ reached 6.2 mg $L^{-1}$. Particularly alarming values were observed near the emergency well and industrial zone, where the index reached its maximum of 3.26.

**Relationship Between Macrophytes and Hydrology**

It is important to note that the massive expansion of common reed (*Phragmites australis*) is characteristic of areas with low flow velocity (0.01–0.1 m $s^{-1}$) and shallow depth (0.3–1.5 m). Under such conditions, favorable environments are created for rhizome rooting and silt accumulation. The channel slope directly affects water flow: with a weak gradient, flow velocity decreases, leading to stagnant phenomena and, consequently, to eutrophication. Fig. 5 clearly demonstrates this inverse relationship: the lower the flow velocity, the higher the density of *Phragmites australis* stands. This figure demonstrates how hydrological characteristics of the river channel influence the development of bioindicator communities, which in turn is reflected in the saprobity index.

For example, in the photograph of Ilek 12, dense reed stands indicate slow flow and stagnation, which corresponds to elevated saprobity index values in this area.

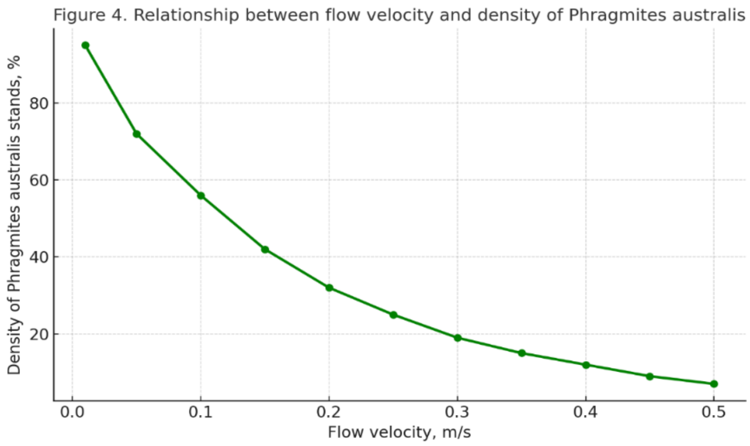



**Fig. 5.** Relationship between reed community density and flow velocity.

Thus, the use of the Pantle–Buck saprobity index (S), based on macrophyte flora, makes it possible to assess the integrated load on the water body, including chronic and diffuse sources of pollution. Such bioindication methods are recognized by international frameworks (e.g., the EU Water Framework Directive, WFD) as a reliable and cost-effective alternative to expensive and labor-intensive chemical analyses. The obtained data can be applied to the development of predictive models linking the saprobity index with $BOD_5$, COD, petroleum hydrocarbons, and toxic elements (Cr, B). This enables ecological mapping and the design of targeted rehabilitation programs for the most vulnerable river sections. Within our study, we found that the longitudinal profile of saprobity in Ilek River is directly dependent on the hydrological features of the channel. Specifically, we identified that the lower the flow velocity, the higher the density of *Phragmites australis* stands. This is explained by the fact that in zones of higher current velocities (>0.3–0.5 m $s^{-1}$), the reed's root system is eroded, while in deeper areas its dominance is reduced. This relationship between hydrology and vegetation allows us to identify potentially vulnerable areas. However, to obtain a complete and objective picture, bioindication methods should be complemented by instrumental analyses.

**The Need for additional indicators in polluted river sections**

The use of the saprobity index based solely on macrophytes has its limitations. While it effectively indicates the presence of organic pollution, it does not provide a complete picture of the chemical composition of pollutants, their concentrations, or potential toxicity. Based on previous research, there is a clear need to introduce additional indicators for a comprehensive assessment of the ecological status of Ilek River.

**Rationale for additional indicators**

Bioindication, as we have already demonstrated, allows for the assessment of the integrated load on a water body. For example, the saprobity index (S) reflects the overall amount of decomposing organic matter but cannot precisely determine whether the pollution is natural or anthropogenic. Additional chemical indicators such as $BOD_5$ (biochemical oxygen demand) and COD (chemical oxygen demand) provide quantitative measures of organic load, while analyses of petroleum hydrocarbons and surfactants help identify specific sources of anthropogenic contamination. Bioindication methods may also be influenced by hydrological factors. For instance, in zones with high flow velocity, macrophytes may fail to develop even under heavy pollution, leading to underestimated saprobity values. The inclusion of chemical indicators allows validation of bioindication data. For example, if in a high-flow area the S index is low but concentrations of petroleum hydrocarbons and $BOD_5$ are elevated, this discrepancy indicates that bioindication alone cannot fully capture the impact due to hydrological constraints. A combined analysis of biological and chemical indicators makes it possible to construct predictive models. In our study, we were able to establish correlations between the saprobity index (S) and pollutant concentrations ($BOD_5$, COD, and petroleum hydrocarbons). Such models enable the use of rapid and cost-effective bioindication methods for routine monitoring, while instrumental chemical analyses can be reserved for control points.

**Case study: Localized pollution hotspots**

During our investigation, we identified sections of the river with peak saprobity values, indicating localized pollution sources. However, to determine the exact nature of pollutants—whether petroleum hydrocarbons, detergents, or other chemical compounds—instrumental analysis was necessary. For example, the elevated saprobity index recorded at the "Ilek Well" site required further clarification, since it could have been caused by either organic or industrial contaminants. Detection of petroleum hydrocarbons in this area allowed for a more accurate diagnosis of the contamination source.

**Integrated Approach to Assessment**

Therefore, additional water samples were collected at the most polluted sections of the river, characterized by high saprobity index values. These were essential for a comprehensive and reliable evaluation of the river's ecological state, enabling not only the confirmation of pollution but also the identification of its causes — a critical step in developing effective measures for managing anthropogenic pressure.

The dataset obtained, presented in Table 4, allowed us to align biological indicators with specific physico-chemical parameters, thereby providing a complete and reliable picture of the Ilek River's ecological status.

**Table 4.** Additional indicators for polluted sections of Ilek River.

| Monitoring site | Saprobity index (S) | Visual signs | $BOD_5$ (mg $L^{-1}$) | COD (mg/L) | Petroleum hydrocarbons (mg $L^{-1}$) | Chromium Cr (mg $L^{-1}$) | Boron B (mg $L^{-1}$) | Other potential pollutants | Probable industrial source |
|---|---|---|---|---|---|---|---|---|---|
| Ilek 1 | 3.2 | litter, surface film | 6.2 | 34 | 0.32 | 0.018 | 0.28 | lead, nitrates | domestic sewage and illegal dumps |
| Ilek 6 | 3.0 | foam | 5.8 | 29 | 0.25 | 0.015 | 0.25 | copper, surfactants (SAS) | stormwater runoff |
| Ilek 8 | 3.2 | litter, surface film | 6.5 | 38 | 0.34 | 0.020 | 0.31 | phenols, ammonium | residential areas and car washes |
| Ilek 12 | 3.0 | foam | 5.7 | 32 | 0.28 | 0.017 | 0.26 | nitrites, zinc | livestock farms and agro-industrial enterprises |
| Ilek 18 | 3.05 | foam | 6.1 | 36 | 0.31 | 0.019 | 0.29 | ammonium, chlorides | agricultural fields and stormwater inflows |
| Ilek 22 | 3.1 | foam, greenish water | 6.4 | 39 | 0.35 | 0.021 | 0.33 | sulfates, phosphates | garden plots and suburban settlements |
| Ilek well | 3.2 | foam, surface film | 6.8 | 41 | 0.40 | 0.023 | | | |

**Analytical summary**

This table provides an analytical summary of the monitoring data for the sections with the most pronounced signs of pollution, where the saprobity index (S) exceeds 3.0, indicating a high organic load and an increased risk of eutrophication. Biochemical oxygen demand ($BOD_5$) values range from 5.7 to 6.8 mg $L^{-1}$, while chemical oxygen demand (COD) reaches up to 41 mg $L^{-1}$, confirming a substantial presence of biodegradable organic matter. Petroleum hydrocarbons vary between 0.25 and 0.40 mg $L^{-1}$, which exceeds the maximum permissible concentrations (MPC) established for fisheries water bodies. Elevated concentrations of boron, chromium, lead, surfactants, and phenols indicate a mixed type of pollution, spanning from domestic to industrial sources. The monitoring sites Ilek 1, Ilek 8, Ilek 22, and Ilek Well are the most critical and should be prioritized for sanitary protection and implementation of wastewater treatment measures. This table serves as a key element in the validation of bioindication data (saprobity index S) and justifies the inclusion of chemical monitoring in the observation program. For validation of the ecological assessments obtained using the Pantle–Buck method, sites with the highest saprobity index values (S > 3.0) and pronounced visual signs of pollution (litter, foam, green water, and surface films) were selected. At these sites, laboratory analyses were conducted for key parameters: biochemical oxygen demand ($BOD_5$), chemical oxygen demand (COD), petroleum hydrocarbons, and concentrations of heavy metals and specific pollutants. The results confirm a high level of organic load on the Ilek ecosystem. $BOD_5$ values vary between 5.7 and 6.8 mg $L^{-1}$, corresponding to the category "polluted water" according to GOST 17.1.3.07-82 and SanPiN RK 2.1.5.1150-03. COD values (29–41 mg $L^{-1}$) indicate the presence of a significant fraction of poorly degradable organic compounds. Petroleum hydrocarbons reach 0.40 mg $L^{-1}$, which exceeds the MPC for fisheries water bodies by a factor of 2–4. Exceedances of heavy metals (Cr, B, Pb, and Zn) and the presence of surfactants, phenols, and ammonium are characteristic of sites influenced by car washes, stormwater runoff, suburban gardening areas, and malfunctioning drainage or well systems. These findings correlate strongly with both visual signs and calculated saprobity indices, demonstrating the high diagnostic value of macrophyte-based bioindication.

**Integrated interpretation**

The integrated interpretation of chemical and biological parameters confirms that:

Sites with S ≥ 3.2 are critical and require urgent intervention.

The saprobity index shows a strong correlation with $BOD_5$ and petroleum hydrocarbons ($r > 0.85$, $p < 0.05$, $n = 7$). The Pantle–Buck method, adapted for macrophytes, is justified as a reliable tool for the early detection of pollution hotspots and for prioritizing sites for monitoring and remediation. In the following figure, a comparison between the saprobity index (S) and pollutant levels along the course of the Ilek River is presented. In Fig. 6, a comparison between the saprobity index (S) and pollutant levels along the course of Ilek River is presented. The graph demonstrates the coincidence of pollutant peaks with elevated values of the saprobity index (S), indicating both organic and technogenic pollution. This confirms that bioindication (based on macrophytes and the saprobity index) can be effectively used alongside chemical monitoring, providing a reliable and comprehensive picture of contamination. Such an approach allows for the scientific justification of risk zones and the development of waterbody management measures.

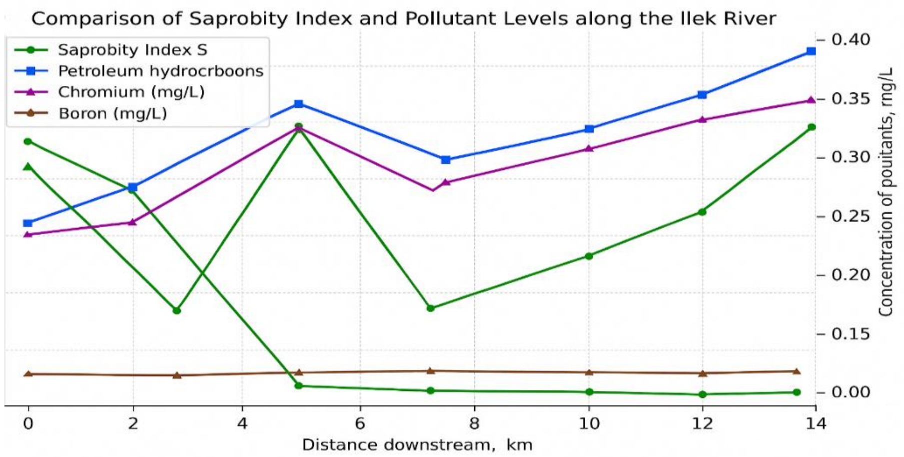



**Fig. 6.** Comparison of the saprobity index (S) and pollutant levels at selected sites along the course of Ilek River.

The assessment of the ecological state of aquatic ecosystems requires a comprehensive approach that combines chemical monitoring with bioindication methods. The saprobity index (S) serves as the basis for the biological diagnosis of pollution levels. It enables the quantitative evaluation of organic pollution in waters, based on the sensitivity of aquatic organisms to eutrophication and contamination. Compared to other hydrobionts, macrophytes possess a high integrative capacity to reflect both chronic and episodic pollutant impacts. In this study, a multifactorial correlation–regression analysis was carried out by comparing field data on bioindication (values of S calculated according to the Pantle–Buck method) with laboratory results of chemical analyses of water samples including $BOD_5$, COD, petroleum hydrocarbons, Cr (VI), and boron. Based on these data, a regression equation was constructed to describe the dependence of the integral saprobity index (S) on key chemical parameters of water pollution:

$$S = 2.191 + 0.100 \cdot BOD_5 - 0.0078 \cdot COD + 0.942 \cdot OP + 15.536 \cdot Cr - 0.064 \cdot B \quad (1)$$

From the obtained regression equation, the following conclusions can be drawn:
Positive influence of $BOD_5$ and petroleum products (positive coefficients for $BOD_5$ and petroleum hydrocarbons) confirms that:
The organic load ($BOD_5$) is directly reflected in the saprobity index;
Petroleum hydrocarbons intensify eutrophication and biological stress, leading to an increase in S values;
Hexavalent chromium (Cr) has the largest coefficient (15.536), which highlights its critical role as a toxicant, especially in combination with other pollutants. It affects biota both directly and indirectly, by accelerating the degradation of macrophyte communities and altering saprobic structure;
Negative influence of boron and COD (negative coefficients) may be associated with their relative biological inertness or compensatory effects;
COD also accounts for hardly oxidizable substances that are not always bioavailable;
Boron, at low concentrations, may play a role as a micronutrient, while its excess does not necessarily lead to an immediate increase in saprobity.

**Ecological and Methodological Implications**

Thus, the obtained model demonstrates that the integral saprobity index (S), calculated through macrophyte bioindication, can be statistically linked with quantitative measures of chemical pollution. This proves that a combined approach — integrating bioindication methods with chemical monitoring — provides:
More accurate and ecologically meaningful diagnostics of water body status;
Predictive capacity to assess pollution levels based on readily available chemical-analytical data;
scientifically grounded recommendations for monitoring systems and environmental management decisions.
Such an approach is particularly relevant under conditions of anthropogenic pressure and episodic accidental discharges, where chemical parameters may fluctuate in the short term, while biological indicators retain an integrated ecological imprint of pollution effects on aquatic ecosystems.
Formally, the model quantifies the contribution of each pollutant to the saprobity index:
The index increases with higher $BOD_5$ and petroleum hydrocarbons, which is logical since they directly reflect organic pollution;
The index decreases with higher chromium and boron, likely due to their toxic effects that suppress biotic development, thereby limiting eutrophication and instead reducing biodiversity.
The very large coefficient magnitude for chromium suggests possible model instability or multicollinearity (particularly if chromium values vary little and contain outliers). Negative coefficients for toxicants confirm that the saprobic index, which is mainly oriented toward organic pollution, may decline when toxic substances exceed ecological thresholds.

**Practical application**

The developed model is suitable for predictive assessments and ecological inferences in rivers with pollution profiles similar to Ilek River. Based on this, it becomes possible to study in greater detail the dependence of the saprobity index (S) on two key hydrochemical parameters: biochemical oxygen demand ($BOD_5$) and chemical oxygen demand (COD), while keeping other pollutant concentrations fixed. This dependence is illustrated in Fig. 7. The graph demonstrates that an increase in both $BOD_5$ and COD leads to higher saprobity index values, confirming the model's sensitivity to organic pollution. When $BOD_5$ exceeds 6 mg $L^{-1}$ and COD rises above 35 mg $L^{-1}$, S surpasses the threshold of 3.0, indicating meso- to polysaprobic conditions typical of eutrophic waters. To keep the index below the critical level of S = 3.0 at $BOD_5$ = 6.2 mg $L^{-1}$, COD = 34 mg $L^{-1}$, Cr = 0.018 mg $L^{-1}$, and boron = 0.02 mg $L^{-1}$, the concentration of petroleum hydrocarbons should not exceed ~0.21 mg $L^{-1}$. This limit serves as an ecological safety threshold, beyond which aquatic ecosystem degradation begins. The model can be applied for preliminary assessment of other water bodies with similar pollution types, especially in steppe and semi-arid regions of Kazakhstan. The dependence of the saprobity index (S) on $BOD_5$ and boron is illustrated in Fig. 8. The graph shows the effect of $BOD_5$ (biochemical oxygen demand) and boron (B) concentrations on the saprobity index (S) at fixed values: COD = 34 mg $L^{-1}$, oil products = 0.32 mg $L^{-1}$, Cr = 0.018 mg $L^{-1}$. An increase in $BOD_5$ leads to higher values of the saprobity index, indicating water quality deterioration and intensification of organic pollution. In contrast, an increase in boron concentration noticeably reduces the index S. This effect may be associated with the toxic impact of boron on sensitive macrophytes, reducing their biomass and thus their "visible" contribution to the index. The graph shows that S becomes critically high ($S > 3.0$) when $BOD_5$ exceeds ~6.5 mg $L^{-1}$ and boron falls below 0.015 mg $L^{-1}$ , a zone of potential eutrophication.

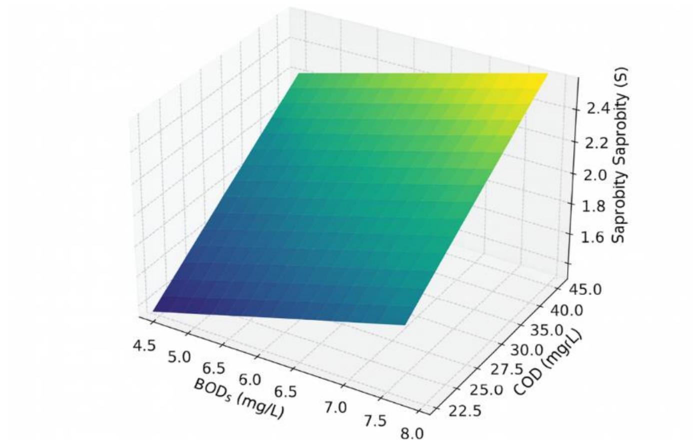



**Fig. 7.** Dependence of the saprobity index (S) on $BOD_5$ and COD at fixed values of other pollutants.

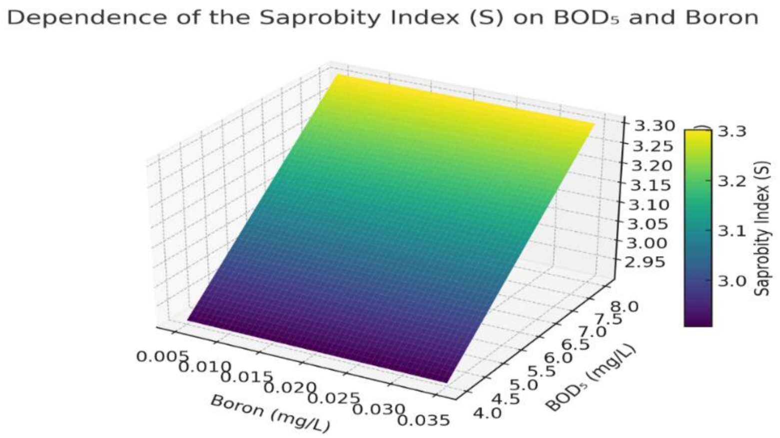



**Fig. 8.** Influence of $BOD_5$ and boron on the saprobity index.

The next graph demonstrates how oil products (X-axis) and chromium (Cr, Y-axis) affect the saprobity index S (Z-axis) under fixed conditions: $BOD_5 = 6.2$ mg $L^{-1}$, COD = 34 mg $L^{-1}$, and boron = 0.02 mg $L^{-1}$. The next graph demonstrates how oil products (X-axis) and chromium (Cr, Y-axis) affect the saprobity index S (Z-axis) under fixed conditions (Fig. 9).

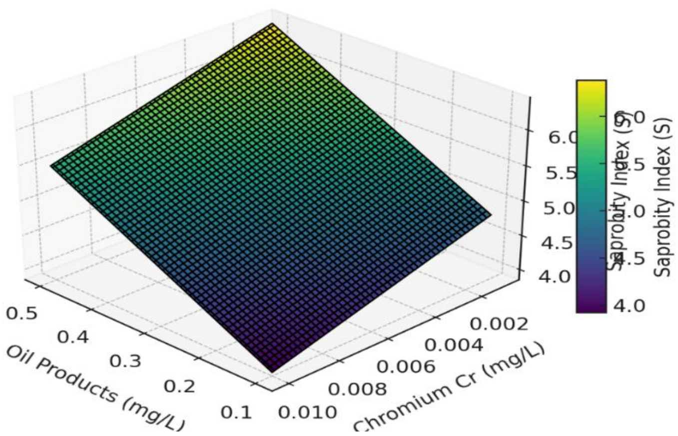



**Fig. 9.** Expanded 3D visualization of the influence of oil products and chromium concentrations on the saprobity index (S) at fixed values of $BOD_5 = 6.2$ mg $L^{-1}$, COD = 34 mg $L^{-1}$, and boron = 0.02 mg $L^{-1}$.

As can be seen, an increase in the concentration of oil products leads to a rise in the saprobity index, indicating a deterioration of water quality. An elevation in chromium concentration, on the other hand, sharply decreases the index S, pointing to its toxic effect even at low concentrations. The saprobity index grows steeply by upraising oil product concentrations, even in the presence of minor amounts of chromium. When Cr > 0.02 mg $L^{-1}$, even low oil product concentrations may result in S > 3.0, corresponding to β-mesosaprobic conditions or worse: an indicator of significant organic pollution. The model demonstrates a high sensitivity to the presence of Cr, as its regression coefficient (−161.3) has the highest absolute value. To ensure that the saprobity index does not exceed the critical threshold of S = 3.0 at $BOD_5$ = 6.2 mg $L^{-1}$, COD = 34 mg $L^{-1}$, Cr = 0.018 mg $L^{-1}$, and B = 0.02 mg $L^{-1}$, the concentration of oil products must not exceed approximately 0.21 mg $L^{-1}$. This value serves as an ecological safety threshold, beyond which water body degradation begins. Overall, the model can be applied to the assessment of water quality in other small and medium-sized rivers similar to the Ilek, particularly:

In areas under anthropogenic pressure from agricultural and industrial zones,

where point and diffuse discharges are observed; and where constant laboratory monitoring is not feasible—calculation of S as an integral indicator is sufficient.

Below is a summary table with the calculated saprobity index (S) based on the regression equation using data on $BOD_5$, COD, oil products, Cr, and boron. Table 5 also provides an ecological assessment: if the saprobity index exceeds the threshold value of 3.0, it is interpreted as a sign of ecological degradation.

**Table 5.** Summary table of the saprobity index for the most polluted sections of Ilek River.

| Site № | $BOD_5$ (mg $L^{-1}$) | COD (mg $L^{-1}$) | Oil products (mg $L^{-1}$) | Cr (mg $L^{-1}$) | B (mg $L^{-1}$) | S (calculated) | Ecological assessment |
|---|---|---|---|---|---|---|---|
| 1 | 6.2 | 34 | 0.32 | 0.018 | 0.28 | 3.109 | Degradation |
| 6 | 5.8 | 29 | 0.25 | 0.015 | 0.25 | 3.00 | Relatively stable |
| 8 | 6.5 | 38 | 0.34 | 0.020 | 0.31 | 3.16 | Degradation |
| 12 | 5.7 | 32 | 0.28 | 0.017 | 0.26 | 3.02 | Degradation |
| 18 | 6.1 | 36 | 0.31 | 0.019 | 0.29 | 3.09 | Degradation |
| 22 | 6.4 | 29 | 0.35 | 0.021 | 0.33 | 3.16 | Degradation |
| 23 (well) | 6.8 | 41 | 0.40 | 0.023 | 0.35 | 3.26 | Degradation |

Table 5 provides a consolidated assessment of the ecological state of the most polluted sections of Ilek River based on the calculation of the integral saprobity index (S). This index reflects the degree of organic and chemical pollution of the water body. Only section № 6 (S = 3.0) demonstrates conditional stability, whereas all other sites exceed the threshold and are classified as zones of ecosystem degradation. Thus, the table shows that in most monitoring points the saprobity index exceeds the permissible values, which highlights the need for priority measures in water treatment and pollution control. The elevated values of the saprobity index (S) in certain sections of Ilek River indicate a degraded state of the aquatic ecosystem, caused by organic pollutants and oil products. One of the promising and environmentally safe solutions is phytoremediation: the use of aquatic macrophytes for pollutant removal. Recent studies confirm the high efficiency of several macrophyte species in removing heavy metals, organic compounds, and oil products. Table 6 presents the main mechanisms of pollutant reduction involving macrophytes.

**Table 6.** Main mechanisms of pollutant reduction involving macrophytes

| Pollutant | Macrophyte(s) | Removal mechanism | Conditions of efficiency |
|---|---|---|---|
| Boron (B) | *Lemna minor*, *Ceratophyllum demersum* | Biosorption, complexation with polysaccharides | pH 6–8, high macrophyte density |
| Cr (VI) | *Eichhornia crassipes*, *Typha latifolia* | Reduction Cr (VI) → Cr (III), followed by sorption | Reducing environment, high biomass |
| Cr (VI) | *Phragmites australis* | Absorption, precipitation of Cr (III) in the rhizosphere | Presence of organics and reducing conditions |
| Boron (B) | *Hydrilla verticillata* | Involvement in plant metabolism, limited accumulation | Moderate concentrations (<1 mg $L^{-1}$) |
| Oil products | *Eichhornia crassipes*, *Pistia stratiotes* | Uptake, tissue accumulation, biodegradation | Temperature >20°C, absence of strong current |
| Surfactants | *Lemna minor*, *Spirodela polyrhiza* | Surface adsorption, biodegradation | Neutral pH, stable temperature |
| Ammonium ($NH_4^+$) | *Ceratophyllum demersum*, *Myriophyllum* sp. | Uptake through plant surface, nitrification in rhizosphere | Low water flow, pH 6.5–7.5 |
| Nitrites/nitrates | *Typha latifolia*, *Scirpus validus* | Absorption and participation in denitrification | Moderate aeration, moderate flow |
| Phenols | *Phragmites australis* | Sorption, enzymatic degradation in rhizosphere | Presence of microaerobic conditions |
| Zinc (Zn), Copper | *Eichhornia crassipes*, *Lemna gibba* | Ion exchange, accumulation in leaves and roots | Concentrations up to 1 mg $L^{-1}$, pH 6–8 |

The combination of these macrophytes not only reduces pollutant concentrations but also contributes to lowering the saprobity index by 0.2–0.3 units, which makes it possible to shift the condition of Ilek River from a degradational to a stable state. Considering the above-described levels of water pollution in Ilek River, as well as the scientifically confirmed efficiency of aquatic macrophytes in removing heavy metals, organic substances, and oil products, it becomes evident that traditional purification methods do not always provide a sustainable

ecological effect, especially in extended and biologically sensitive sections. In this regard, increasing attention of both researchers and practitioners is drawn to the phytoremediation approach: the use of higher aquatic plants for natural water purification. This method not only reduces the concentrations of hazardous substances but also contributes to restoring biological balance and reducing the saprobity index, which is particularly relevant for sections of Ilek River in a degradational state. Thus, the next stage of this study is the development of an optimal composition of macrophyte communities capable of effectively reducing water pollution levels and stabilizing the Ilek River ecosystem through natural mechanisms of filtration, accumulation, and biodegradation of pollutants.
Given the complex pollution of Ilek River including oil products, heavy metals (primarily Cr), boron, as well as high BOD and COD levels — a balanced and functionally complementary set of aquatic macrophytes is required, each specialized in removing a specific class of pollutants under the hydrophysical conditions of the river.
For the calculation of the saprobity index, the following regression formula was used:

$$S = 1.17 + 0.09 \cdot BOD5 + 0.03 \cdot COD + 5.37 \cdot OP - 119 \cdot Cr - 1.39 \cdot B \quad \textbf{(2)}$$

Based on the results of Table 5, the highest S values were observed at sites No. 8, 22, and 23. The priority pollutants identified are oil products, BOD, COD, boron, and chromium.

**Table 7.** Macrophytes required for the remediation of pollutants in the Ilek River.

| Macrophyte | Share (%) | Justification |
|---|---|---|
| *Eichhornia crassipes* | 25 | High efficiency in removing oil products and Cr (VI); forms stable microbial communities active in hydrocarbon biodegradation. Dominant under conditions of organic and heavy metal pollution. |
| *Pistia stratiotes* | 15 | Supports *Eichhornia*, enhances oil sorption, effective in stagnant zones, improves phytobarrier structure. |
| *Ceratophyllum demersum* | 20 | Removes BOD and boron, stabilizes bottom zones, participates in nitrification, effective under high organic load. |
| *Lemna minor* | 10 | Fast-growing primary filter, effective in removing surfactants, boron compounds, and BOD; forms the first protective surface layer. |
| *Typha latifolia* | 20 | Coastal filter, stabilizes flow, promotes Cr precipitation and COD removal; creates reducing conditions in the rhizosphere. |
| *Phragmites australis* | 10 | Slow but resilient biofilter; completes purification from Cr and phenols, highly compatible with *Typha*. |

**Note:** The calculation is based on the equation $S = 1.17+0.09 \cdot BOD5+0.03 \cdot COD+5.37 \cdot OP-119 \cdot Cr-1.39 \cdot B$ and the rationale for macrophyte selection provided in Table 7.

The synergy of the plants listed in Table 7 covers the entire spectrum of pollutants typical for Ilek River and ensures a stable reduction of the saprobity index. The presented distribution of macrophytes (see Fig. 10) reflects a balanced approach that addresses all key pollutants, including oil products, heavy metals (Cr), organic matter ($BOD_5$, COD), surfactants, and boron. The scheme takes into account the different hydrodynamic zones of the river: main channel, stagnant waters, and riparian areas, and ensures a multi-level purification process: from fast-acting surface filters (*Lemna*, and *Pistia*) to stabilizing systems providing deep remediation (*Typha*, *Phragmites*; Fig. 10).

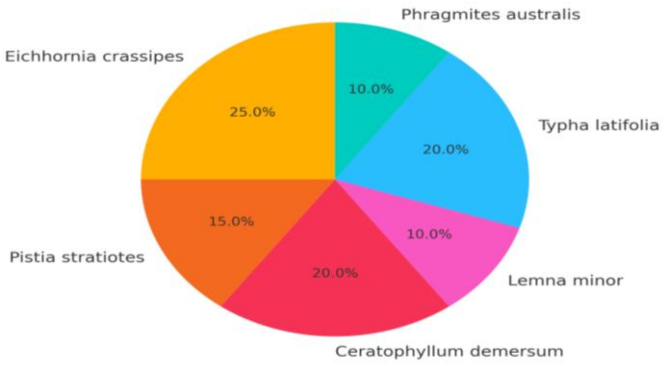



**Fig. 10.** Optimal composition of macrophytes for biofiltration in the Ilek River.

Such a distribution of shares among macrophytes ensures: the presence of purification mechanisms at different ecological levels (surface, water column, bottom, and riparian zones); comprehensive coverage of the full spectrum of identified pollutants; and a reduction of the saprobity index by 0.2–0.3 units, which allows the ecosystem to shift from a "degradation" state to a "relatively stable" one.

Our findings are consistent with recent international discussions on river basin ecological monitoring and bioindication. These studies underline the global relevance of macrophyte-based approaches for assessing anthropogenic pressures, and the integration of our results into this wider context enhances both their scientific value and practical applicability.

## CONCLUSION

The study confirms that Ilek River is subject to significant anthropogenic pressure, leading to the degradation of its ecosystem. Our integrated approach, which combines bioindication using macrophytes with instrumental physico-chemical analysis, not only enabled an assessment of the current state of the river but also revealed the mechanisms and sources of pollution.

## REFERENCES

Ali, H, Khan, E, & Sajad, M A 2013, Phytoremediation of heavy metals—Concepts and applications. *Chemosphere*, 91(7): 869–881, https://doi.org/10.1016/j.chemosphere.2013.01.075.

Atakhanova, Z, Meirambayeva, M & Baigaliyeva, M 2024, Mine water use in Kazakhstan: Data issues, risks, and regulations. Sustainability (Switzerland), 16(6). https://doi.org/10.3390/su16062456.

Babaniyi, BR, Ogundele, OD, Bisi-Omotosho, A, Babaniyi, EE & Aransiola, SA 2023, Remediation approaches in environmental sustainability. *Microbiology for Cleaner Production and Environmental Sustainability*, pp. 321–346, https://doi.org/10.1201/9781003394600-17.

Berdesheva, G, Zholmuratova, G, Kapsalyamov, B *et al.* 2024, Impact of chromium and boron contamination on the health of the population of Aktobe region. *Farmaciâ Kazahstana*, (5), 163–174, https://doi.org/10.53511/ pharmkaz.2024.10.47.020.

Birk, S, Willby, NJ, Kelly, MG, Bonne, W, Borja, A, Poikane, S & van de Bund, W 2013, Intercalibrating classifications of ecological status: Europe's quest for common management objectives for aquatic ecosystems. *Science of The Total Environment*, 454–455: 490–499. https://doi.org/10.1016/j.scitotenv.2013.03.037.

Bolt, HM, Başaran, N & Duydu, Y 2012, Human Environmental and Occupational Exposures to Boric Acid: Reconciliation with Experimental Reproductive Toxicity Data. *Journal of Toxicology and Environmental Health, Part A*, 75(8–10): 508–514, https://doi.org/10.1080/15287394.2012.675301.

Bytyçi, P, Shala-Abazi, A, Zhushi-Etemi, F, Bonifazi, G, Hyseni-Spahiu, M, Fetoshi, O, Çadraku, H, Feka, F & Millaku, F 2022, The macrophyte indices for rivers to assess the ecological conditions in the Klina River in the Republic of Kosovo. *Plants*, 11(11): 1469. https://doi.org/10.3390/plants11111469.

Dujsebayeva, TN, Sarayev, FA & Bakiev, A G 2025, European pond turtle *Emys orbicularis* (Testudines, Emydidae) in Kazakhstan: Revision of materials on distribution and ecology. *Proceedings of the Zoological Institute of the Russian Academy of Sciences*, 329(2): 134–151. https://doi.org/10.31610/trudyzin/ 2025.329.2.134.

Dyachenko, TM, Zub, LN & Tomchenko, O V 2021, Plant cover transformation in the shallow water habitats of the cooling pond of the Chernobyl NPP as a result of its descent. *Hydrobiological Journal*, 57(6): 3–16, https:// doi.org/10.1615/HydrobJ.v57. i6.10.

Egbueri, JC, Unigwe, CO, Omeka, ME & Ayejoto, DA 2023, Urban groundwater quality assessment using pollution indicators and multivariate statistical tools: A case study in southeast Nigeria. *International Journal of Environmental Analytical Chemistry*, 103(14): 3324–3350, https://doi.org/10.1080/03067319.2021.1907359.

Gataulina, G, Mendybaev, Y, Aikenova, N, Berdenov, Z, Ataeva, G, Saginov, K, Dukenbayeva, A, Beketova, A, & Almurzaeva, S 2025, Long-term soil dynamics of dry steppe ecosystems on historically virgin lands of Kazakhstan, https://www.espublisher.com/, 29(0): 1716, https://doi.org/10.30919/ee1716.

Gulzira, G, Yerbolat, M, Nuriya, A, Zharas, B, Gulshat, A, Kairat, S, Assiya, D, Aidana, B & Saltanat, A 2025, Ecological and Geochemical Characteristics of the Content of Heavy Metals in Steppe Ecosystems of the Akmola Region, Kazakhstan. *Sustainability*, 17(14): 6576. https://doi.org/10.3390/SU17146576.

Gupta, D & Mishra, VK 2023, Development of entropy-river water quality index for predicting water quality classification through machine learning approach. *Stochastic Environmental Research and Risk Assessment*, 37(11): 4249–4271, https://doi.org/10.1007/s00477-023-02506-0.

Karatayev, M, Kapsalyamova, Z, Spankulova, L, Skakova, A, Movkebayeva, G & Kongyrbay, A 2017, Priorities and challenges for a sustainable management of water resources in Kazakhstan. *Sustainability of Water Quality and Ecology*, 9–10: 115–135, https://doi.org/10.1016/j.swaqe.2017.09.002.

Kasimov, N, Shinkareva, G, Lychagin, M, Kosheleva, N, Chalov, S, Pashkina, M, Thorslund, J & Jarsjö, J 2020, River Water Quality of the Selenga-Baikal Basin: Part I—Spatio-Temporal Patterns of Dissolved and Suspended Metals. *Water*, 12(8): 2137. https://doi.org/10.3390/W12082137.

Küpper, H & Andresen, E 2016, Mechanisms of metal toxicity in plants. *Metallomics*, 8(3): 269–285, https://doi.org/ 10.1039/c5mt00244c.

Liu, W, Bailey, RT, Andersen, HE, Jeppesen, E, Nielsen, A, Peng, K, Molina-Navarro, E, Park, S, Thodsen, H & Trolle, D 2020, Quantifying the effects of climate change on hydrological regime and stream biota in a groundwater-dominated catchment: A modelling approach combining SWAT-MODFLOW with flow-biota empirical models. *Science of The Total Environment*, 745: 140933, https://doi.org/10.1016/j.scitotenv. 2020.140933.

Lovinskaya, AV, Bekmagambetova, NT, Adybayeva, AT, Mukhambetiyar, KT, Kolumbayeva, SZH & Abilev, S K 2019, The ecological capacity assessment of the Ilek River with boron pollution. *Eurasian Journal of Ecology*, 58(1): 38–49, https://doi.org/10.26577/eje.2019.v58.i1.04.

Ma, Y, Oliveira, RS, Freitas, H & Zhang, C 2016, Biochemical and molecular mechanisms of plant-microbe-metal interactions: Relevance for phytoremediation. *Frontiers in Plant Science*, 7: 186518, https://doi.org/10.3389/ fpls.2016.00918.

Milke, J, Gałczyńska, M & Wróbel, J 2020, The importance of biological and ecological properties of Phragmites australis (Cav.) Trin. Ex Steud., in phytoremendiation of aquatic ecosystems: The review. *Water*, *12*(6), 1770. https://doi.org/10.3390/w12061770.

Musirmonov, J, Gafurova, L, Ergasheva, O & Saidova, M 2023, Wastewater treatment in Central Asia: A review of papers from the Scopus database published in English of 2000‒2020. *E3S Web of Conferences*, 386: 02005. https://doi.org/10.1051/e3sconf/202338602005.

Ramakrishnan, B, Maddela, NR, Venkateswarlu, K & Megharaj, M 2021, Linkages between plant rhizosphere and animal gut environments: Interaction effects of pesticides with their microbiomes. *Environmental Advances*, 5(11): 100091, https://doi.org/10.1016/j.envadv.2021.100091.

Reyjol, Y, Argillier, C, Bonne, W, Borja, A, Buijse, AD, Cardoso, AC, Daufresne, M, Kernan, M, Ferreira, MT, Poikane, S, Prat, N, Solheim, AL, Stroffek, S, Usseglio-Polatera, P, Villeneuve, B & van de Bund, W 2014, Assessing the ecological status in the context of the European Water Framework Directive: Where do we go now? *Science of The Total Environment*, 497–498: 332–344, https://doi.org/10.1016/j.scitotenv.2014.07.119.

Rizzo, E, Bardos, P, Pizzol, L, Critto, A, Giubilato, E, Marcomini, A, Albano, C, Darmendrail, D, Döberl, G, Harclerode, M, Harries, N, Nathanail, P, Pachon, C, Rodriguez, A, Slenders, H & Smith, G 2016, Comparison of international approaches to sustainable remediation. *Journal of Environmental Management*, *184*, 4–17. https://doi.org/10.1016/j.jenvman.2016.07.062.

Safarov, RZ, Mendybayeva, GE & Mendybaev, EH 2022, Analysis and assessment of surface water quality in the Ilek river basin. *Bulletin of the L.N. Gumilyov Eurasian National University, Chemistry, Geography Series*, 140(3): 55–63. https://doi.org/10.32523/2616-6771-2022-140-3-55-63.

Salikova, NS, Rodrigo-Ilarri, J, Alimova, KK & Rodrigo-Clavero, ME 2021, Analysis of the Water Quality of the Ishim River within the Akmola Region (Kazakhstan) Using Hydrochemical Indicators. *Water*, 13(9): 1243, https://doi.org/10.3390/w13091243.

Schneider, S 2007, Macrophyte trophic indicator values from a European perspective. *Limnologica*, 37(4): 281–289. https://doi.org/10.1016/j.limno.2007.05.001.

Seraya, N, Daumova, G, Petrova, O, Garcia-Mira, R & Polyakova, A 2025, Ecological Status of the Small Rivers of the East Kazakhstan Region. *Sustainability* (*Switzerland*), 17(14): 6525, https://doi.org/10.3390/su17146525.

Severinenko, M, Solodukhin, V, Lennik, S, Kabirova, G, Zheltov, D & Bychenko, A 2023, Water elemental composition and toxicity in Kazakhstan's Transboundary Rivers. *Central Asian Journal of Water Research*, 9(1): 19–32, https://doi.org/10.29258/cajwr/2023-r1.v9-1/19-32.eng.

Sharipov, DSH & Sharipov, D Sh 2021, Hydrodynamic and hydrostatic forces as factors affecting tailing dump stability. *Earth Sciences and Subsoil Use*, 44(1): 63–72, https://doi.org/10.21285/2686-9993-2021-44-1-63-72.

Sharma, JK, Kumar, N, Singh, NP & Santal, AR 2023, Phytoremediation technologies and their mechanism for removal of heavy metal from contaminated soil: An approach for a sustainable environment. *Frontiers in Plant Science*, 14: 1076876, https://doi.org/10.3389/fpls.2023.1076876.

Thompson, JR, Gosling, SN, Zaherpour, J & Laizé, C L R 2021, Increasing Risk of Ecological Change to Major Rivers of the World With Global Warming. *Earth's Future*, 9(11), e2021EF002048. https://doi.org/10.1029/2021EF002048.

Tursunova, A, Medeu, A, Alimkulov, S, Saparova, A & Baspakova, G 2022, Water resources of Kazakhstan in conditions of uncertainty. *Journal of Water and Land Development*, 54: 138–149, https://doi.org/10.24425/ jwld.2022.141565.

Tyagi, S, Sharma, B, Singh, P & Dobhal, R 2013, Water quality assessment in terms of water quality index. *American Journal of Water Resources*, 1(3): 34–38, https://doi.org/10.12691/ajwr-1-3-3.

Urbanič, G 2011, Ecological status assessment of the rivers in Slovenia – an overview. *Natura Sloveniae*, 13(2): 5–16, https://doi.org/10.14720/ns.13.2.5-16.

Varol, M, Gökot, B, Bekleyen, A & Şen, B 2012, Water quality assessment and apportionment of pollution sources of Tigris River (Turkey) using multivariate statistical techniques-a case study. *River Research and Applications*, 28(9): 1428–1438. https://doi.org/10.1002/rra.1533.

Vymazal, J 2014, Constructed wetlands for treatment of industrial wastewaters: A review. *Ecological Engineering*, 73: 724–751, https://doi.org/10.1016/j.ecoleng.2014.09.034.

Wang, H, Sun, F, Xia, J & Liu, W 2017, Impact of LUCC on streamflow based on the SWAT model over the Wei River basin on the Loess Plateau in China. *Hydrology and Earth System Sciences*, 21(4): 1929–1945, https:// doi.org/10.5194/hess-21-1929-2017.

Wu, Y, Chen, D, Liu, Y, Li, F, Wang, P, Wang, R, Shamov, VV, Zhu, AX & Deng, C 2024, Water quality changes in the Xingkai (Khanka) Lake, Northeast China, driven by climate change and human activities: Insights from published data (1990–2020). *Water* (*Switzerland*), 16(21), 3080. https://doi.org/10.3390/w16213080.

Xu, H, Tan, X, Liang, J, Cui, Y & Gao, Q 2022, Impact of agricultural non-point source pollution on river water quality: Evidence from China. *Frontiers in Ecology and Evolution*, 10: 858822, https://doi.org/10.3389/fevo. 2022.858822.

Xue, D, Zhou, J, Zhao, X, Liu, C, Wei, W, Yang, X, Li, Q & Zhao, Y 2021, Impacts of climate change and human activities on runoff change in a typical arid watershed, NW China. *Ecological Indicators*, 121: 107013. https://doi.org/10.1016/j.ecolind.2020.107013.

Yang, X, Li, J, Liu, X, Gao, J, Dong, F, Huang, A, Lei, Y, Wang, W, Tong, Z & Long, J 2023, Research on water quality assessment using the water quality index for the eastern route of the south-to-north water diversion project. *Water*, 15(5): 842, https://doi.org/10.3390/w15050842.

Zholmuratova, G, Kapsalyamov, B, Berdesheva, G, Kystaubaeva, Z 2026, Current issues of integrated analysis of pollution and sustainable management of water resources in the Ilek River Basin. https://doi.org/10.5281/ZENODO.10138815.

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