OnLine Journal of Biological Sciences

Research Article

Floodplain Plant Diversity and Anthropogenic Impacts in the Irtysh River Valley, Northeastern Kazakhstan

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Article history
Received: 31-03-2025
Revised: 30-05-2025
Accepted: 18-07-2025

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Abstract: This study investigates the composition, diversity, and ecological adaptation strategies of plant communities in the Irtysh River floodplain (Northeastern Kazakhstan) under natural and anthropogenic pressures. Field-based geobotanical surveys were conducted from May to August 2024 across 40 representative plots. Standard phytocoenotic description methods were employed, along with phenological and ecological assessments. A total of 549 vascular plant species from 74 families were identified. Ten rare and protected species were recorded in the region. Major anthropogenic threats included hydrological regulation, grazing, seasonal burning, and biological invasions. Notably, *Acer negundo, Echinocystis lobata, and Cyclachaena xantifolia* were dominant among invasive species. Variability in flood patterns (36% inundation in 2023 vs. full coverage in 2024) significantly affected plant productivity and composition. The floodplain demonstrates high biodiversity but is increasingly vulnerable. Maintaining flood regimes, controlling invasive species, and managing grazing practices are essential for ecological resilience. This study provides a foundation for regional conservation planning and sustainable land use policy.

Keywords: Adaptation Strategies, Anthropogenic Impact, Floodplain, Irtysh River

Introduction

The Irtysh River (Ertis, Yertis) is the longest transboundary watercourse in Central Asia, flowing through Kazakhstan, China, and Russia. In Kazakhstan, the Irtysh River flows through Pavlodar, East Kazakhstan, and Abay regions, performing an important hydrological and economic function in these regions. Special attention in the last decade has been paid to the study of floodplain vegetation, as these ecosystems have unique characteristics that influence water regime, biological productivity, and biodiversity conservation (Xu *et al*., 2024). The flora of the Irtysh floodplain exhibits remarkable adaptations to fluctuating water levels and heterogeneous soil conditions, making it a significant subject for ecological research, especially under climate variability (Bolatova *et al*., 2023) and anthropogenic disturbance (Akhmetov *et al*., 2025).

The composition and structure of anthropogenic vegetation are determined by the characteristics of the original coenoses, the type and intensity of anthropogenic impact, as well as the presence of viable diasporas of ruderal and adventive plant species (Popova, 2019). Vegetation cover in different natural zones responds variably to the same environmental changes and exhibits differing levels of resistance (Cao & Natuhara, 2020; Wang *et al*., 2022; Yu *et al*., 2023).

The response of vegetation to anthropogenic pressures depends largely on the nature of these pressures. For Pavlodar Priirtyshye several anthropogenic factors are identified, of which the strongest impact on vegetation is hydrotechnical, pyrogenic, grazing, haying, and recreational types of impact.

One of the most significant impact factors is the construction of a cascade of reservoirs, (Bukhtarma, Shulbinsk, Ust-Kamenogorsk) which leads to changes in the natural hydrological regime and as a consequence a reduction in biodiversity, erosion of banks, loss of soil fertility and destruction of ecosystems.

The Irtysh River is subjected to pollution by wastewater from functioning industrial enterprises in large industrial cities such as Pavlodar, Ust-Kamenogorsk, and Omsk. (Kolpakova *et al*., 2024; Kondratyev *et al.,* 2024). Elevated concentrations of heavy metals such as iron, copper, and manganese, along with sporadic peaks of zinc and chromium, have been detected in various sections of the river (Arynova *et al*., 2024; Krupa *et al.*, 2024; Zhalmagambetova *et al*., 2024).

Pasture impacts (grazing, overgrazing) are potentially reversible. Grazing has a stronger negative impact on grassland biogeocoenoses than haying (Bashinskiy *et al*., 2024; Mayora *et al*., 2021). Cattle easily destroy the turf of wet soils, turning the upper layer into a mud-like mass, deforming the surface up to the formation of cattle ruts. Soil compaction leads to a decline in water retention capacity, infiltration rate, and pore space, accompanied by a reduction in populations of aerobic microorganisms such as *Azotobacter*. Conversely, it favors the proliferation of anaerobic bacteria, including denitrifying species, and may facilitate the emergence of zoonotic parasites such as *trematodes*. On dry and moderately wet soils, grazing results in even drier soils. In areas where soil water rich in easily soluble salts is close to the soil, soil salinization occurs. All this causes xerophytisation and halophytisation of vegetation. In wet and damp meadows, grazing can lead to waterlogging.

In the vast majority of cases, ecosystems in the Irtysh basin are affected by many factors simultaneously, but the cumulative effect of these impacts is not uniform and depends on the initial state and potential stability of vegetation in specific areas.

Under conditions of increasing anthropogenic impact, analyses of the composition and structure of plant communities help to establish the resilience of ecosystems to changes caused by economic activity. Special attention is paid to adventive species, which are a consequence of anthropogenic impact on the flora.

The study of floristic diversity of the Irtysh River is limited in several publications, including species composition of the Black Irtysh (Argynbayeva *et al.,* 2024), conservation of genetic diversity (Li *et al*., 2024), determination of resource characteristics of plants and factors affecting their distribution (Xu *et al*., 2024).

The Irtysh River floodplain faces ecological and anthropogenic challenges similar to those in other major river systems, such as the Danube. As shown by Funk *et al.,* (2019), preserving floodplain multifunctionality is threatened by regulation, land-use change, and invasive species - issues also relevant to the Irtysh.

The purpose of this study is to examine the flora of the Irtysh River floodplain, focusing on the identification of dominant plant communities and their adaptive strategies. The research outlines key species typical of the Irtysh ecosystem and assesses their role in sustaining ecological stability under the influence of climate variability and anthropogenic factors. The central research question is: How do hydrological changes and anthropogenic pressures (e.g., grazing, burning, pollution, invasive species) affect the composition, structure, and functional stability of floodplain vegetation in the Irtysh River valley?

The working hypothesis is that regulated hydrology and increasing human activity are causing significant shifts in floristic composition, promoting aridisation, halophytisation, and invasion by non-native species, which together reduce ecosystem resilience and biodiversity.

Scientific Novelty: Unlike previous studies that addressed individual floristic or resource aspects, this study integrates floristic inventory with ecological profiling, anthropogenic impact assessment, and analysis of hydrological fluctuations. It provides one of the first comprehensive, ecosystem-based evaluations of current floristic diversity and vegetation degradation processes in the Irtysh River floodplain, supported by detailed field observations and spatial profiling.

Materials and Methods

Field investigations were carried out in the floodplain ecosystems of the Irtysh River valley within the Pavlodar Region during the period from May to August 2024. The research route, shown in Fig. 1, extended for a total of 1,097 kilometers, covering both banks of the Irtysh River – from the border with the Russian Federation to the administrative boundary of Abai Region.

Fig. 1. Schematic map of the research route (the study area is indicated in bold).

A total of 40 geobotanical sample plots (100 m² each) were established in key ecological genetic sectors of the floodplain, representing a variety of landscape conditions (riverbanks, terraces, oxbow lakes, meadows, wetlands, etc.). Site selection was based on preliminary landscape mapping and aimed at capturing the spatial variability of vegetation types. When describing communities, we took into account floristic composition, abundance, plant height, longevity, species life state, plant phenophase, total projective cover, species distribution pattern, community aspect, as well as ecological (terrain, soil type, groundwater depth, salinity, moisture pattern, etc.) and anthropogenic factors affecting vegetation. Dominant and indicator species were recorded in each plot.

The ecosystem approach was applied in vegetation studies (Ogar, 1999). Established geobotanical approaches formed the foundation for conducting the field research, including detailed descriptions of plant communities and landscape-ecological profiling. The survey emphasized the analysis of vegetation spatial patterns about key landscape features such as topography and soil types. Additionally, the research involved evaluating the condition of plant communities, documenting the presence of rare and endemic species, and assessing overall biodiversity within the study area (Ydyrys *et al.,* 2024).

Plant species were identified using specialized botanical literature (Flora of Kazakhstan, 1956; Flora of Siberia, 1966). Latin nomenclature was verified according to Vascular Plants of the USSR (Cherepanov, 1981).

In assessing phenological phases, both vegetative and generative states for each species were considered. The analysis of the flora was based on both the field-collected specimens and existing literature concerning the vegetation and plant diversity of the study region.

In addition to traditional geobotanical survey methods, semi-quantitative and descriptive statistical approaches were applied. A five point scale (0–4) was used to assess the degree of anthropogenic disturbance in each plot, based on observed indicators such as degradation of species composition, dominance by ruderal or invasive species, reduction of vegetative cover, and morphological deterioration of plants. Species were also grouped by ecological (e.g., mesophytes, xerophytes) and economic (e.g., forage, medicinal, technical) categories, and their frequency of occurrence across plots was recorded. Floristic composition was compared along environmental gradients (e.g., north–south, elevation, salinity), enabling spatial pattern analysis of vegetation transformation under hydrological and anthropogenic pressures. While no formal multivariate statistics were applied, these structured comparative techniques provided a sound basis for ecological interpretation and classification.

Results

The flora was analysed on the basis of herbarium collections and on the materials of published works on the Irtysh valley in Pavlodar region. A total of 549 vascular plant species from 74 families were recorded. The most species-rich families included *Asteraceae* (87 species), *Poaceae* (58), *Fabaceae* (34), and *Brassicaceae* (30). The dominant life forms were herbaceous perennials (89%), mainly mesophytes (53.6%), followed by xerophytes (28.8%), as shown in Fig. 2.

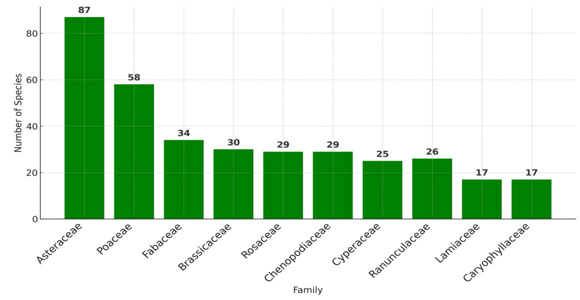

Fig. 2. Distribution of plant families based on the number of species recorded during the field survey

The economic spectrum of the flora is presented in Fig. 3.

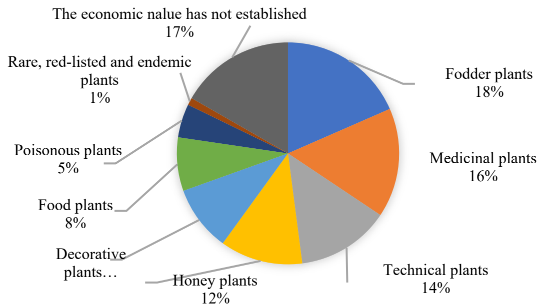

Fig. 3. Economic spectrum of the flora of the Irtysh River valley

Plant species demonstrated various adaptation strategies to ecological stressors, as shown in Table 1:

- *Alopecurus pratensis* and *Glyceria aquatica* exhibited high flood tolerance via aerenchymatic roots and flexible culms.
- *Artemisia austriaca* dominated degraded dry sites due to xeromorphic traits and deep taproots.
- *Cyclachaena xantifolia* showed opportunistic spread in disturbed areas, with rapid seed set and allelopathic effects on native flora.

According to literature data (Beysembayeva *et al*., 2016; Government of the Republic of Kazakhstan, 2006; Red Data Book of Kazakhstan, 2014) and conducted research, 10 rare and protected plant species grow in the surveyed area: *Centaurea sibirica, Cypripedium guttatum, Delphinium elatum, Equisetum sylvaticum, Euphorbia microcarpa, Hemerocallis lilio-asphodelus, Rosa pavlovii, Saussurea robusta, Serratula kirghisorum* and *Tulipa biebersteiniana*. *Pavlov's rosehip* is included in the Red Data Book of Kazakhstan. It should be noted that none of these protected species grew on the model sites described in the 2024 field season.

Table 1: Distribution of plant species in the Irtysh River valley across the Pavlodar Region

No	Family	Number of species	Area of distribution			
			Southern districts of the region	Northern districts of the region	Ubiquitous	Singly
1	*Aceraceae*	1			+	
2	*Alismataceae*	6	+		+	
3	*Alliaceae*	4	+		+	
4	*Amaranthaceae*	1			+	
5	*Apiaceae*	11		+	+	
6	*Araceae*	1			+	
7	*Asclepiadaceae*	1	+			
8	*Asparagaceae*	3	+		+	
9	*Asteraceae*	87	+		+	
10	*Betulaceae*	1		+		
11	*Boraginaceae*	8	+	+	+	
12	*Brassicaceae*	30	+	+	+	
13	*Butomaceae*	1			+	
14	*Campanulaceae*	2	+			
15	*Cannabaceae*	2			+	
16	*Caprifoliaceae*	1			+	
17	*Caryophyllaceae*	17	+		+	
18	*Chenopodiaceae*	29	+		+	
19	*Convolvulaceae*	2			+	
20	*Crassulaceae*	2	+		+	
21	*Cucurbitaceae*	1			+	
22	*Cuscutaceae*	2	+		+	
23	*Cyperaceae*	25	+		+	
24	*Dipsacaceae*	2	+		+	
25	*Elaeagnaceae*	2			+	
26	*Ephedraceae*	1			+	
27	*Equisetaceae*	7			+	
28	*Euphorbiaceae*	4			+	
29	*Fabaceae*	34	+		+	
30	*Frankeniaceae*	1				+
31	*Gentianaceae*	1			+	
32	*Geraniaceae*	3	+		+	
33	*Haloragaceae*	1			+	
34	*Hippuridaceae*	1	+			
35	*Hydrocaryaceae*	1			+	
36	*Hydrocharitaceae*	3			+	
37	*Iridaceae*	6	+	+	+	
38	*Juncaceae*	5	+		+	
39	*Juncaginaceae*	2			+	
40	*Lamiaceae*	17	+		+	
41	*Lemnaceae*	2			+	
42	*Lentibulariaceae*	1			+	
43	*Liliaceae*	5	+		+	
44	*Limoniaceae*	3			+	
45	*Lythraceae*	2			+	
46	*Malvaceae*	2			+	
47	*Menyanthaceae*	1			+	
48	*Nitrariaceae*	2	+		+	
49	*Nymphaeaceae*	4			+	
50	*Onagraceae*	2		+		
51	*Ophioglossaceae*	1		+		
52	*Orchidaceae*	1		+		
53	*Pinaceae*	1				+
54	*Plantaginaceae*	8	+		+	
55	*Poaceae*	58	+	+	+	
56	*Polygonaceae*	11	+	+	+	
57	*Potamogetonaceae*	4			+	
58	*Primulaceae*	4			+	
59	*Ranunculaceae*	26	+		+	
60	*Rhamnaceae*	2			+	
61	*Rosaceae*	29	+	+	+	
62	*Rubiaceae*	5	+		+	
63	*Salicaceae*	14		+	+	
64	*Salviniaceae*	1			+	
65	*Santalaceae*	1	+			
66	*Grossulariaceae*	1			+	
67	*Scrophulariaceae*	16	+	+	+	
68	*Sparganiaceae*	3	+	+		
69	*Solanaceae*	4			+	
70	*Typhaceae*	3			+	
71	*Ulmaceae*	1			+	
72	*Urticaceae*	1			+	
73	*Valerianaceae*	1		+		
74	*Zygophyllaceae*	1	+			

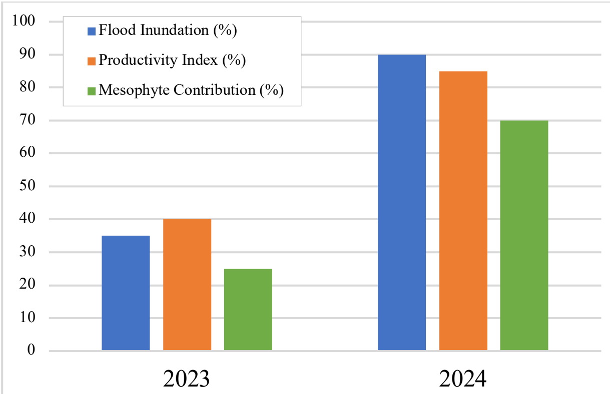

Fig. 4: Dynamics of flood inundation, productivity index, and mesophyte contribution in 2023 and 2024

When assessing anthropogenic impacts on floodplain ecosystems, the impact of hydrotechnical impacts in the form of a regulated hydrological regime of the river should be taken into account. All parts of the flood plain are subject to hydrological impact, which was most evident in 2023, when flood inundation amounted to only 36% of the floodplain area. The lack of flood inundation, together with abnormal heat and drought in May and June, resulted in significant aridisation and halophytisation of floodplain ecosystems and a significant reduction in the yield of flood plain grasslands (Fig. 4).

The year 2024 was characterised by favourable conditions of floodplain inundation, which significantly increased the productivity of meadow vegetation and the cenotic role of mesophytes and hygrophytes.

Among the main threatening factors for botanical biodiversity of the Irtysh floodplain the following eight threats can be specified:

1) Alterations in the hydrological regime of the Irtysh River, including decreased frequency and volume of flooding. This represents a primary driver of aridisation and halophytisation processes within floodplain ecosystems. Insufficient intensity of floods poses a special threat to boreal relict hydrophytes - *Nymphoides peltata (S.G. Gmelin) O. Kuntze, Nuphar lutea (L.) Smith*, *Nymphaea candida* J. et C.Presl, *Nymphaea tetragona* Georgi, and *Trapa* spp. which may disappear from the flora of the territory due to increased shallowing and overgrowing of floodplain water bodies in the absence of natural flushing of their beds
2) Use of floodplains for grazing. In addition to the direct impact on the herbage by eating it, there is an intensive mechanical impact on floodplain soils, which leads to disruption of soil integrity, formation of cattle ruts, waterlogging, salinization and water erosion
3) Implementation of spring fires of last year's dry grass. Spring fires have a serious impact on floodplain ephemerals and ephemeroids, as well as on tree and shrub vegetation
4) Non-compliance with the water protection zone regime with grazing and watering of cattle on the river bank. The consequence of cattle on the Irtysh bank is destruction of soil and vegetation cover both by direct impact of animals and indirect erosive impact of the river flow
5) Creation of hydraulic structures in the form of dams. Attempts to create estuarine irrigation in Lebyazhinsky and Maysky districts of Pavlodar province led in combination with overgrazing to complete degradation of soil and vegetation cover with loss of self-recovery and productivity. Dams are an artificial barrier on the way of spring floods, depriving cut-off segments of water supply and floodplain alluvium deposits - the basis of fertility and soil formation of floodplain soils
6) Species such as *Pulsatilla patens, Tulipa biebersteiniana, Ornithogalum fischerianum, Hemerocallis lilio-asphodelus* and *Cypripedium guttatum - Spotted Slipper* are threatened by the illegal collection of Red-listed ornamental plants
7) The ploughing of steppe landscapes on the upper floodplain terraces, as well as their use for grazing of agricultural animals is the main threat to the populations of *Stipa pennata*, which are currently being actively replaced by populations of fescue *(Festuca valesiaca)* and *Artemisia australis*.
8) Anthropogenic invasion of alien flora, or biological contamination

Adventive flora as a young and dynamic element in natural communities seems to be the most interesting for analysis. Adventive flora of Pavlodar region, according to the proposed classification, looks as follows (Table 2, Fig. 5).

These findings parallel ecological transformations reported in other Central Asian and temperate floodplains. For example, in the Ob River basin, regulated flood regimes have led to reduced biodiversity and increased dominance of disturbance-adapted species (Beysembayeva *et al.,* 2016). Similarly, in the Amur River floodplain, studies have documented vegetation shifts linked to floodplain fragmentation and overuse. Comparative evidence from the Yellow River basin in China also reveals hydrological overregulation as a key driver of habitat degradation, with comparable transitions in vegetation structure (Xu *et al.,* 2024). These analogues underscore the broader relevance of our findings to transboundary water management and conservation planning.

Table 2: Adventive flora of Pavlodar region

Plant Species	Method of Introduction	Degree of Naturalisation
Acorus calamus L.	xenoergasiophyte	agriophyte
Elodea canadensis Michx.	xenophyte	agriophyte
Acer negundo L.	ergasiophyte	agriophyte
Amaranthus albus L.	xenophyte	epecophyte
Amaranthus retroflexus L.	xenophyte	epecophyte
Cichorium intybus L.	ergasiophyte	epecophyte
Cyclachaena xantifolia (Nutt) Fresen.	xenophyte	epecophyte
Erigeron acris L.	xenophyte	epecophyte
Erigeron canadensis L.	xenophyte	epecophyte
Erigeron lonchophyllus Hook.	xenophyte	epecophyte
Erigeron podolicus Bess.	xenophyte	epecophyte
Cannabis sativa L.	ergasiophyte	agriophyte
Humulus lupulus L.	ergasiophyte	agriophyte
Echinocystis lobata (Michx.) Torr. et Gray	ergasiophyte	agriophyte
Elaeagnus angustifolia L.	ergasiophyte	colonophyte
Elaeagnus argentea Pursh.	ergasiophyte	colonophyte
Hippophae rhamnoides L.	ergasiophyte	colonophyte
Medicago sativa L.	ergasiophyte	colonophyte
Salvia officinalis L.	ergasiophyte	colonophyte
Populus balsamifera L.	ergasiophyte	agriophyte
Verbascum lychnites L.	xenophyte	epecophyte
Datura stramonium L.	xenophyte	epecophyte
Hyoscyamus niger L.	xenophyte	epecophyte
Solanum depilatum Kitag.	xenophyte	colonophyte
Solanum dulcamara L.	xenophyte	agriophyte
Solanum kitagawae Schonbeck	xenophyte	colonophyte
Solanum nigrum L.	ergasiophyte	epecophyte
Ulmus pinnato-ramosa Dieck	ergasiophyte	colonophyte

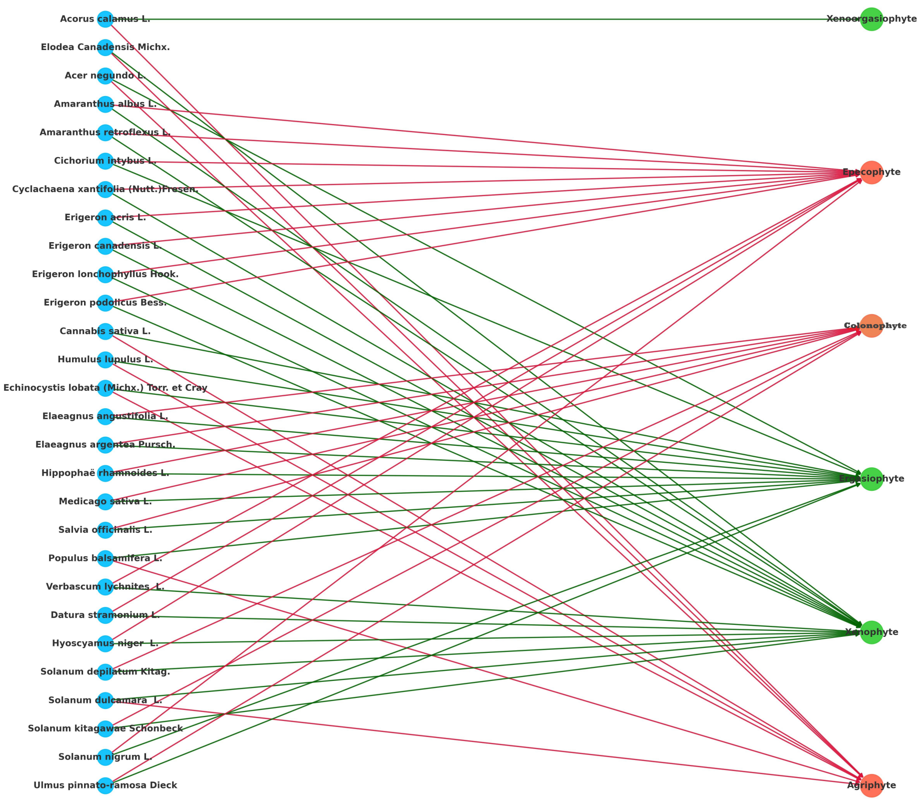

Fig. 5. Adventive flora of Pavlodar region depending on the method of introduction and degree of naturalization

The inclusion of young elements of the flora and those naturalised in natural plant communities in the adventive fraction does not raise doubts, especially for species whose range lies far from the study area. To date, there is no unified classification of adventive species. Adventive species of the Pavlodar region can be conveniently classified according to Schroeder's classification (Schroeder, 1968), based on the method of introduction and degree of naturalisation of the species:

- By the method of introduction: xenophytes - unintentionally introduced species; xenoergaziophytes
- Plants cultivated in other regions, accidentally introduced into the study area in the course of economic activity; ergasiophytes - species introduced into culture in the given territory and then spread to non-cultural habitats (both anthropogenic and natural)
- By degree of naturalisation: ephemerophytes - plants occurring in introduced sites for 1-2 years, but not reproducing, and then disappearing; colonophytes - plants renewed, but their distribution is limited mainly to introduced sites; epecophytes - introduced plants spreading through one or several types of anthropogenic habitats; agriophytes - plants introduced into natural coenoses

Among representatives of the adventive flora, the most aggressive behavior has been observed in *Acer negundo L., Echinocystis lobata (Michx.) Torr. et Gray*, and *Cyclachaena xantifolia (Nutt.) Fresen*., which invade natural communities and displace native species.

Discussion

To sustain the natural structure and functional dynamics of floodplain ecosystems–particularly their productive vegetation–it is crucial to preserve the natural hydrological regime of the Irtysh River. Historically, this regime resulted in the annual inundation of approximately 89–97% of the floodplain area. During high-water years, extensive and prolonged flooding facilitated the flushing of river channels, oxbow lakes, and wetland systems, while also contributing to the desalinization and drainage of saturated zones. Therefore, reducing winter discharges from upstream reservoirs is recommended to support the survival and development of young woody and shrubby vegetation in newly established floodplain habitats.

Additionally, livestock grazing in floodplain areas should be prohibited, and these meadows should be used exclusively for haymaking. Mowing should be conducted at staggered intervals to promote the natural regeneration of meadow grasses and enhance seed dispersal efficiency.

It is necessary to monitor the invasion of adventive flora species and track the population dynamics of the most aggressive representatives. It is advisable to mow the detected *Cyclachaena xantifolia* thickets before seed formation, from June to mid-July.

Measures should be implemented to prevent overexploitation and restore disturbed communities. These actions should be differentiated based on the degree of ecosystem degradation.

In areas with minor disturbances, maintaining a rational pasture-haymaking rotation and preventing overuse will be sufficient to restore the structure and productivity of phytocoenoses through their inherent capacity for self-regulation.

In moderately disturbed areas, temporary cessation of exploitation is required to restore the natural structure and dynamics of phytocoenoses, prevent water and wind erosion, and allow recovery succession to reach completion before resuming use.

Severely degraded areas, in addition to being withdrawn from use, require additional reclamation measures to restore soil and vegetation cover. These measures include the seeding of valuable plant species, fertilizer application, and erosion control efforts.

For highly and catastrophically degraded areas, comprehensive reclamation should be undertaken, including the importation of fertile soil, sowing of regionally appropriate grass mixtures suited to the landscape conditions, and irrigation.

The key stakeholders involved in implementing the proposed conservation measures for the Irtysh River floodplain ecosystems include environmental protection agencies, water management authorities, local governments, research institutions, and agricultural enterprises.

Limitations and Future Research

This study is limited by its temporal scope (single field season), the absence of fine-scale soil and water chemistry analysis, and the lack of long-term monitoring data. Additionally, while 40 sample plots were used, the spatial coverage may still not fully capture the entire heterogeneity of the Irtysh floodplain vegetation. Seasonal variations in plant phenology and hydrological dynamics may also influence the generalizability of the findings.

Future research should include:

- Multi-seasonal and multi-year monitoring of key vegetation parameters
- Remote sensing analysis to quantify flood extent and biomass changes
- Development of phytobioindicators for early detection of ecological stress
- Modeling the impact of altered hydrological regimes on plant community trajectories

Such approaches will strengthen the predictive and management value of regional geobotanical assessment and enhance the evidence base for adaptive conservation policies.

Conclusion

The study confirms the high floristic diversity of the Irtysh River floodplain and emphasizes its ecological vulnerability under anthropogenic pressure. The results emphasize the necessity of implementing focused conservation measures, such as regulating grazing practices, preserving natural flooding patterns, and managing the spread of invasive species. These measures, supported by local stakeholders and environmental authorities, are essential for preserving the stability and functionality of floodplain ecosystems. Further research with extended temporal and spatial coverage is recommended to strengthen the scientific basis for sustainable management.

Acknowledgment

The authors are grateful to V. A. Kamkin, Candidate of Biological Sciences, Associate Professor at Toraighyrov University, for his consulting assistance.

Funding Information

This research was conducted as part of the IRN Project BR 21881921 titled "Assessment of the aquatic ecosystem of the Yertis River basin under conditions of industrial development and global processes," and was financially supported by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan.

Author's Contributions

Shynar Zhanybekovna Arynova: Conceptualization, Supervision, Literature review, Writing – original draft.

Kanat Kombarovich Akhmetov: Investigation (fieldwork), Writing – review & editing.

Galymbek Sovetovich Azhayev: Visualization, Writing – review & editing (final draft).

Irina Yurievna Chidunchi: Methodology, Project administration, Investigation (experiments).

Ainagul Balgauovna Kaliyeva: Formal analysis, Data curation, Validation.

Ethical Approval

This study did not involve human participants or animals. Field investigations were conducted in compliance with national and regional regulations, and no endangered or protected plant species were harmed during the research.

Author Statement

This manuscript presents original and previously unpublished work. The corresponding author confirms that all co-authors have reviewed and approved the final version, and that no ethical concerns are associated with its content.

Conflicts of Interest

The authors report no conflicts of interest related to this publication.

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