applied sciences

MDPI

Article

Assessment of Anthropogenic Load on the Ile River Ecosystem Considering Regional Peculiarities

Ainur Mussakulkyzy [1,*], Christian Opp [2,*], Nariman Amirgaliev [1], Azamat Madibekov [1,3], Laura Ismukhanova [1,3] and Askhat Zhadi [1,4]

[1] Laboratory of "Hydrochemistry and Environmental Toxicology", JSC Institute of Geography and Water Security, Almaty 050010, Kazakhstan; namirgaliev.n.a@ingeo.kz (N.A.); madibekov@ingeo.kz (A.M.); ismukhanova@ingeo.kz (L.I.); zhadi@ingeo.kz (A.Z.)
[2] Faculty of Geography, Philipps-Universität Marburg, D-35032 Marburg, Germany
[3] Department of Meteorology and Hydrology, Al-Farabi Kazakh National University, Almaty 050010, Kazakhstan
[4] Department Water Resources and Reclamation, Water, Land and Forest Resources Faculty, Kazakh National Agrarian Research University, Almaty 050010, Kazakhstan
* Correspondence: musakulkyzy@ingeo.kz (A.M.); opp@geo.uni-marburg.de (C.O.)

Abstract

The Ile River is the main water artery of the Lake Balkhash basin and the main fresh water resource supplying the south-eastern part of Kazakhstan. Increasing human economic activity makes it necessary to assess the anthropogenic load of the river on various ecosystems, including possible harmful effects. The assessment of anthropogenic load on the Ile River ecosystem was realized by the anthropogenic load fraction indicator and by the values of the chemical substance inflow modulus. For this purpose, the Ile River was divided into 3 sections: section I—from the border post HP Dobyn to 164 km above Kapshagai hydroelectric power plant (HPP); section II—between the points 164 km above and 37 km below Kapshagai HPP; and section III —from 37 km below HPP to Ushzharma village. The anthropogenic load strongly depends on the share of anthropogenic impact contributed by pollutants. Characteristic pollution components are copper, and in some cases zinc, ammonium, and nitrite nitrogen. The assessment of anthropogenic load also considers organic and biogenic substances in the chemical composition of river water. The variability in the volume of dissolved chemical inflows in different sections of the river made it possible to assess the transformation of anthropogenic load along the length of the Ile River.

Keywords: Ile River; share of anthropogenic impact; chemical inflow modulus; modal interval; flow volume; pollutant concentration

check for updates

Academic Editor: Nathan J. Moore

Received: 16 July 2025
Revised: 7 August 2025
Accepted: 11 August 2025
Published: 14 August 2025

Citation: Mussakulkyzy, A.; Opp, C.; Amirgaliev, N.; Madibekov, A.; Ismukhanova, L.; Zhadi, A. Assessment of Anthropogenic Load on the Ile River Ecosystem Considering Regional Peculiarities. *Appl. Sci.* **2025**, *15*, 8979. https://doi.org/10.3390/app15168979

Correction Statement: This article has been republished with a minor change. The change does not affect the scientific content of the article and further details are available within the backmatter of the website version of this article.

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Water resources, especially surface water, are fundamental to human civilization and support important activities [1]. Globally, water quality degradation is a widespread problem affecting river systems and water bodies in all territories. Used contaminated water has serious consequences not only for ecosystems and environmental sustainability but also for food security and human health [2–4]. Water quality problems, mostly caused by industrial discharges, agricultural runoff, and urban development, could be characterized by pollutants that degrade water quality [5–9].

Increasing global population, urbanization, and industrialization are putting significant pressure on the world's water systems. For example, rivers such as the Nile in Africa,

the Ganges in South Asia, and the Yangtze in China face severe pollution, impacting not only the environment but also downstream ecosystems [10,11]. Seasonal variability also affects quality, with monsoon rains, dry periods, and extreme events affecting the distribution and concentration of pollutants, further complicating sustainable water management [12–14]. In Bangladesh, surface water is facing increasing challenges from human activities and natural processes due to extensive river systems, putting additional pressure on water resources and threatening sustainable water management practices [15,16].

Kazakhstan belongs to the least water-secure countries in Central Asia. This situation is aggravated by the fact that the distribution of water sources in Kazakhstan is uneven in space and time in most rivers, including the transboundary Ile River. The water resources of the Ile River are widely used for irrigation, drinking and domestic water supply, electricity generation, and other purposes. The development of the economy in the Ile River basin has been accompanied by a deficit of water resources, both in terms of quantity and quality [17,18]. With such increasing rates of human economic activities, there is a need to assess the anthropogenic load on various ecosystems, including environmental objects, taking into account both the totality of harmful impact factors and the natural peculiarities of regional features. Such anthropogenic loads will be considered acceptable when the deviation of the system from the normal natural state does not lead to the violation of natural stable biogeochemical relations within ecosystems and does not deteriorate the quality of the environment.

The Ile River is characterized by a high level of water quality pollution along the entire length of the water course. Typical polluting ingredients for the river are nitrite nitrogen and copper. The high pollution level of the Ile River is characterized by the increased content of copper ions in the water, reaching concentrations 10 times above the maximum permissible concentration (MPC) [17,18] during the study period. Along the length of the Ile River, the highest pollution level was detected at Dobyn Hydrological Station, where the source of pollution was identified as wastewater entering the river from the territory of China [17–20].

Recently, the anthropogenic impact has increased, influencing the flow of dissolved substances, its quantitative and qualitative indicators, and its distribution in the water body in space and in time. At the same time, the type and intensity of economic activities have become dominant factors determining both the water volume and the qualitative chemical composition of river water. According to Amirgaliyev 2024 [21], there are different classifications of rivers, where either one or a number of indicators or formative factors are taken as a basis, which are dominant in determining hydrological and hydrochemical regimes.

Maintaining a healthy aquatic environment requires sustainable water quality management, which suffers from unplanned industrialization and development [22]. The assessment of biological, physical, and chemical characteristics of water is essential for resource classification and tracking changes caused by anthropogenic activities or natural processes [23,24]. Considering these global water quality issues and the limitations of traditional assessment methods, there is an urgent need for improved analytical approaches that can capture the complex interactions between multiple water quality parameters under different hydrological conditions. Despite the crucial role of the Ile River in regional water use, no studies until now have integrated the regional peculiarities of water quality assessment. To fill this gap in assessing anthropogenic load on river ecosystems, the objective of this study is to identify the boundaries between areas of normal functioning and altered functioning under the influence of different impact factors and their peculiarities. This makes it possible to assess different ecosystem states, from natural to anthropogenically transformed, in which significant changes in the state of the ecosystem have occurred.

2. Materials and Methods

2.1. Study Area

The Ile River is the main waterway of the Balkhash Lake basin. It originates from the Muzart glaciers in Central Tanirtau (Kazakhstan) by the source of the Tekes River. The stock-forming part of the basin is located in China, where the hydrographic network is quite developed (from 0.6 to 3 km/km^2) [17]. The river network density decreases in the middle and lower parts of the catchment (up to 0.01 km/km^2) [25]. There are vast areas completely devoid of surface runoff; only the left bank zone is active there. About 30% of the water resources of the Ile River are formed on the territory of Kazakhstan [18,21]. In addition to the rivers Charyn and Chilik, in the left-bank part of the catchment in the middle reaches of the Ile River, there are a number of mountain rivers: Turgen, Issyk, Talgar, Kaskelen, with tributaries Kishi and Ulken Almaty (Small and Large Almaty) Kurty, forming the rivers' runoff on the northern slope of the Trans-Ili Alatau. In the right bank part, the largest tributaries of the Ile River are the Khorgos, Usek, and Borokhudzir Rivers, flowing from the southern slopes of the Dzungarian Alatau. Most of the tributaries, including the Turgen, Talgar, and Borokhudzir, do not reach the Ile River due to high flow losses in the foothills for infiltration and irrigation. The Ile River basin includes many small rivers, flowing from the slopes of the Ketmen Range and the Chu-Ili Mountains in the left-bank part and the low-lying spurs of the Zhongar Alatau in the right-bank part, as well as a whole system of low-water intermittent watercourses, forming a rather dense network at the foothills of the mountains, where they originate. Most of these small rivers dry up in summer, and none of the watercourses reaches the Ile River. After leaving the Kapchagay Gorge, the Ile River carries its waters across the deserted Balkhash plain to Lake Balkhash, where it breaks into numerous branches and ends in an extensive delta [17,18]. The Lake Balkhash basin is also called the "Land of the Seven Rivers". This term typically refers to the main rivers that shape the hydrological regime of the region and provide water resources for the basin. In most sources, the "Seven Rivers" are identified as follows: (1) Ili, (2) Charyn, (3) Chilik, (4) Turgen, (5) Talgar, (6) Kaskelen, and (7) Karasu.

2.2. Differentiation of the Ile River in River Sections

Assessing the variability of the state of river ecosystems makes it possible to identify the fluctuation of indicator intervals and deviations, which leads to the transition to another ecosystem state. Ecosystems functioning in different states experience different levels of anthropogenic load. The anthropogenic load on different sections of the Ile River is mainly caused by the inflow of chemical substances with river runoff from upstream sections. To assess the anthropogenic load on different sections of the Ile River, the following hydro-posts (HPs) were selected: (1) Dobyn hydro-post (HP 1), (2) "164 km" upstream of Kapshagai hydroelectric power plant (HP 2), (3) "37 km" downstream of Kapshagai (HP 3), and (4) Ushzharma locality (HP 4). These river HPs were selected because there are stationary measuring points of the runoff regime observations, unevenness of anthropogenic impact, and different physio-geographic conditions of river ecosystem functioning (Figure 1).

The assessment of anthropogenic load along the length of the river is based on the analysis of long-term hydrological and hydrochemical data of the state monitoring of the RSE 'Kazgidromet' at the hydro points from 2003 to 2022. The characteristics of the observation points are given in Table 1.

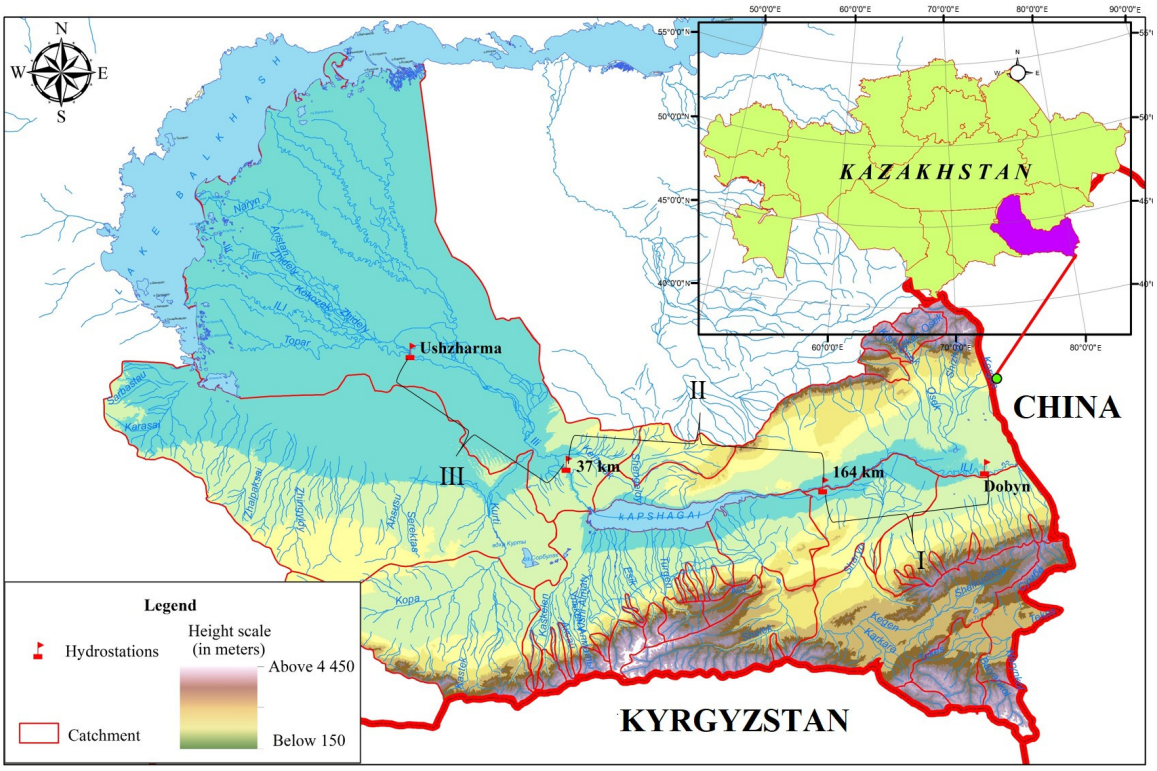


Figure 1. Scheme of Ile River sections: Section I—between Dobyn HP 1 and "164 km" above the Kapshagai Hydro Power Plant (HPP); Section II—HP 2 "164 km" above and "37 km" below the Kapshagai HPP; Section III—"37 km" below the Kapshagai HPP until Ushzharma village HP 4.

Table 1. Characteristics of observation points along the length of the Ile River [17,18].

Hydro Point (HP)	Distance from the Mouth, km	Watershed Area, Thou. km^2
Dobyn HP 1	723	64.388
"164 km" HP 2 upstream of Kapshagai HPP	607	85.400
"37 km" HP 3 downstream of Kapshagai HPP	434	111.000
Ushzharma village HP 4	264	129.000

2.3. Assessment Approach Studying the Anthropogenic Load of the River

The anthropogenic load of the Ile River was assessed by the share of the anthropogenic impact indicator and by the values of the chemical substance inflow modulus [26]. The share of anthropogenic impact has an ecological meaning, assessing the participation of anthropogenic components in the formation of the composition of the aquatic environment [27]. It is a coefficient of water complexity calculating an Integrated Water Pollution Index (IWPI) [28]. The anthropogenic load, determined by the share of the anthropogenic impact, is mainly caused and influenced by pollutants. The assessment of anthropogenic load with the values of the chemical inflow modulus considers the chemical composition of water. Due to the variable volume of dissolved chemical substance inflow at different river sections, it is possible to assess the transformation of the anthropogenic load along the river course crossing different river sections. Conventionally, the anthropogenic load can be 'low', 'moderate', 'critical', "high", or 'very high' [27].

For the selected river sections (I–III), the share of anthropogenic impact is calculated according to [29], and the volumes and modulus of chemical inflows and the assessment of anthropogenic load at specific river sections are determined. This approach allows the identification of variable patterns (trends) of anthropogenic load along the course of

the river and the ranking of its aquatic ecosystems by the degree of anthropogenic load experienced.

To assess the anthropogenic load on the river ecosystem, the following characteristics were used:

(a) the modal interval of indicator values for the assessment of the state and anthropogenic load [27];
(b) the exceedance multiplicity of maximum permissible concentrations (MPCs) [30] of pollutants;
(c) the range of maximum values of the modulus of dissolved chemical substance inflow [26].

2.3.1. Assessment of Anthropogenic Load Based on the Share of Human Impact

The assessment of anthropogenic load on the basis of anthropogenic load fraction values was carried out in the following sequence:

(a) Long-term studies have shown the validity of the anthropogenic impact share indicator used for the assessment of the anthropogenic load. Its values were determined by the results of LULUCF calculations, using the mandatory list of the most regularly determined normative indicators [26].

The share of anthropogenic impact (D, in percent) evaluates the participation of the anthropogenic component in the formation of the component composition of the abiotic part of the ecosystem. This indicator is calculated in accordance with [26,29] using Formula (1):

$$D = \frac{N_1}{N} 100, \quad (1)$$

where N_1 is the number of ingredients exceeding the MPC;

N is the total number of regulated ingredients used in the calculation of the IWPI.

We obtained a sample of the values of the indicator of anthropogenic impact for each river section. The samples obtained should be large enough (at least 6 years) and preferably statistically homogeneous.

(b) The modal interval of the values of the anthropogenic impact share is selected, and the anthropogenic load is assessed according to the criteria given in Table 2.

Table 2. Classifier for assessing the anthropogenic load on river ecosystems by the share of anthropogenic impact [26].

Anthropogenic Load	Modal Interval of the Anthropogenic Influence, %
Small	Less than 30
Moderate	From 30 to 45 inclusive.
Critical	From 45 to 55 inclusive.
High	From 55 to 70 inclusive.
Very high	Over 70

2.3.2. Identification of the Modal Interval of Indicator Values

The modal range of indicators used in assessing the state of river ecosystems and anthropogenic load is selected as follows:

(a) Ranking of the variable series of indicator values.
(b) Calculation of the sample size (number of indicator values) n and calculation of the arithmetic mean. Before calculating the arithmetic mean of the series of indicator

values, indicators with abnormal high or low values must be removed, which may be due only to gross errors in obtaining information according to [31].

(c) Grouping of the values of the range is done on the basis of using the standard deviation (σ) as the optimum width of the interval. The calculation of the step of grouping the values is carried out according to Formula (2):

$$\sigma = \pm\sqrt{\frac{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2}{n-1}} \quad (2)$$

where X_i is the i-th value of the sample indicator,

$\overline{X}$ is the arithmetic mean value of the sample indicator,

and n is the number of indicator values in the sample.

To assess the anthropogenic load in a particular observation point based on the modulus of chemical substances, inflow, a modal interval of the indicator values is selected. From the obtained variation series of values of chemical substances in the inflow modulus of ammonium and nitrite nitrogen, copper, and zinc, we allocate their modal intervals. For this purpose, firstly, we rank the variation series of inflow modulus values, then we calculate the sample volume n and the arithmetic mean $\overline{X}$. Before calculating the arithmetic mean, anomalously high or low values should be removed from the series of values, the occurrence of which can only be associated with gross errors in obtaining information, according to [31]. Next, group the values of the variation series, which is carried out on the basis of the use of standard deviation, σ, calculated by Formula (2), and determine the boundaries of intervals according to Formulas (3)–(5).

(d) Determination of the interval limits (minimum and maximum) of the variation series. The range is given with an accuracy of one point higher than the value of the indicator (i.e., if the value of the indicator is set to 0.1, the range is given with an accuracy of 0.01). The minimum boundary of the first interval of Int^1_{min} is the smallest value of the sample Xmin, according to Formula (3):

$$Int^1_{min} = X_{min}. \quad (3)$$

To obtain the maximum boundary of the first interval of Int^1_{max}, its minimum boundary is added a standard deviation using Formula (4):

$$Int^1_{max} = X_{min} + \sigma \quad (4)$$

The minimum limit of the second interval Int^2_{min} differs from the maximum first interval by the m_{int} value calculated according to Formula (5):

$$Int^2_{min} = X_{min} + \sigma + m_{int}. \quad (5)$$

The boundaries of the intervals are defined until the maximum boundary of the next interval exceeds the maximum value of the indicator in the sample.

2.3.3. Assessment of Anthropogenic Load Based on the Inflow Modulus of Chemical Substances

The quantity of substance transported during the calculation period (G) in thousand tons was determined according to the method [32] of Formula (6):

$$G = \sum_{i=1}^{m} W_1 * \overline{C_1} \quad (6)$$

where m is the number of intervals of the calculation period;

W_1 is the volume of water runoff for the *i*-th interval of the calculation period, km^3;

$\overline{C_1}$ is mean concentration of the substance over the *i*-th interval of the calculation period, mg/dm^3.

The changing content of ammonium and nitride nitrogen and copper and zinc in the aquatic environment has a negative effect, which can cause the disruption of structural-functional characteristics of aquatic communities and the deterioration of the ecosystem as a whole.

The calculation of the chemical flow modulus, M, t/km^2, of a specific river section for each year is done according to Formula (7):

$$M = \frac{G}{F} \quad (7)$$

where F is the catchment area in thousand km^2.

2.3.4. Determination of Statistical Homogeneity of Indicator Value Series

The determination of the statistical homogeneity of the indicator value series, as a proportion of anthropogenic exposure (D) and/or chemical inflow modulus (M) for the estimation of anthropogenic load, is performed by analyzing the resulting population of the coefficient of variation (C_v), which is calculated using Formula (8):

$$C_v = \frac{\sigma \bullet 100\%}{\overline{X}} \quad (8)$$

where $\overline{X}$ is the average arithmetic sample of values for anthropogenic effects.

The evaluation of homogeneity of the C_V value samples was carried out using the following gradations [33]:

- <17%—absolutely uniform;
- 17% to 35%—fairly uniform;
- 35% to 40%—not homogeneous enough;
- 40% to 60%—heterogeneous;
- >60%—completely heterogeneous.

The algorithm for analyzing the sample values of the anthropogenic exposure and/or chemical flow modulus with varying degrees of homogeneity is shown in Figure 2.

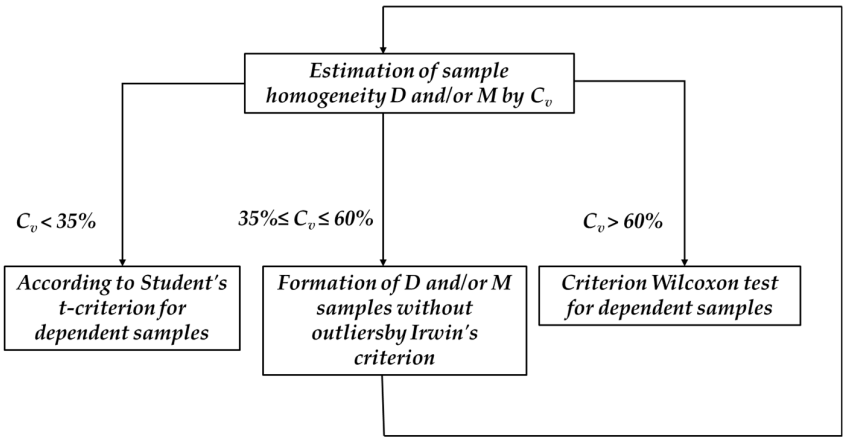


Figure 2. Sample analysis scheme with varying degrees of homogeneity [24].

For further analysis using Student's t-criterion for pair-dependent samples, absolutely and fairly homogeneous samples are required. For samples that are not homogeneous or heterogeneous, it is recommended to analyze the sample for gaps (strongly differing values)

and to evaluate the C_V-sampling of D and/or M values after exclusion of gaps. Completely heterogeneous samples are analyzed using the Wilcoxon criterion for dependent samples.

The calculation of Student's t_{fact} criterion value is done using Formula (9):

$$t_{fact} = \left| \frac{\overline{d}}{S_{\overline{d}}} \right| \quad (9)$$

where $\overline{d}$ is the arithmetic mean of the differences between the corresponding indicators (for the same year) in the comparable items;

$S_{\overline{d}}$ is a standard error of the indicator differences.

The arithmetic mean of the differences between the corresponding indicators is calculated using Formula (10):

$$\overline{d} = \frac{1}{\acute{n}} \sum_{i=1}^{\acute{n}} d_i = \frac{1}{\acute{n}} \sum_{i=1}^{\acute{n}} (x_i - y_1) \quad (10)$$

where ń is the number of pairs of values of the indicator;

x_i, y_i are the values of indicator D at points A and B.

The standard error of indicator differences is calculated using Formula (11):

$$S_{\overline{d}} = \frac{S_d}{\sqrt{\acute{n}}} \quad (11)$$

where S_d is the standard deviation of the sampling of the variables.

The standard deviation of a sample of variables is calculated according to Formula (12):

$$S_d = \sqrt{\frac{\sum \left(d - \overline{d} \right)}{\acute{n}}} \quad (12)$$

where (n′−1) is the number of degrees of freedom, k, to determine t_{theor} (see Table 3).

The values of Student's t-criterion, t_{theor}, at $p < 0.05$ for samples of 20 years or less are shown in Table 3. The recommended level of significance is not lower than $0.1 < p < 0.05$. For larger samples, t_{theor} with different levels of significance are given in the reference tables [34,35]. If $t_{fact} < t_{theor}$, then the null hypothesis is accepted; otherwise, an alternative one is accepted.

The definition of statistical criteria for comparing samples on the presence or absence of statistically significant differences according to the Wilcoxon criterion is calculated using Formula (13):

$$W_{fact} = \sum_{i=1}^{\acute{n}} R_z \quad (13)$$

where n′ is the number of pairs of indicator values;

Rz is a sign rank of indicator changes.

The obtained value W_{fact} for the accepted significance level p and the number of paired observations n′, which is taken without zero differences, is compared with the criterion W_{theor}, given in Table 4. If $W_{fact} \leq W_{theor}$, hypothesis H_1 is accepted. Otherwise H_0 is accepted. The recommended level of significance is at least $p < 0.05$. The null hypothesis (H_0) assumes that the differences observed in the indicators are due to random variation, whereas the alternative hypothesis (H_1) suggests a systematic pattern.

Table 3. Theoretical values of the t_{theor} criterion for different levels of significance p and number of degrees of freedom k [26,35].

k	r Less							
	0.2	**0.1**	**0.05**	**0.02**	**0.01**	**0.005**	**0.002**	**0.001**
3	1.6377	2.3534	3.182	4.540	5.840	7.458	10.214	12.924
4	1.5332	2.1318	2.776	3.746	4.604	5.597	7.173	8.610
5	1.4759	2.0150	2.570	3.649	4.0321	4.773	5.893	6.863
6	1.4390	1.9430	2.4460	3.1420	3.7070	4.316	5.2070	5.958
7	1.4149	1.8946	2.3646	2.998	3.4995	4.2293	4.785	5.4079
8	1.3968	1.8596	2.3060	2.8965	3.3554	3.8320	4.5008	5.0413
9	1.3830	1.8331	2.2622	2.8214	3.2498	3.6897	4.2968	4.7800
10	1.3720	1.8125	2.2281	2.7638	3.1693	3.5814	4.1437	4.5869
11	1.3630	1.7950	2.2010	2.7180	3.1050	3.4960	4.0240	4.4370
12	1.3562	1.7823	2.1788	2.6810	3.0845	3.4284	3.9290	4.1780
13	1.3502	1.7709	2.1604	2.6503	3.1123	3.3725	3.8520	4.2200
14	1.3450	1.7613	2.1448	2.6245	2.9760	3.3257	3.7870	4.1400
15	1.3406	1.7530	2.1314	2.6025	2.9467	3.2860	3.7320	4.0720
16	1.3360	1.7450	2.1190	2.5830	2.9200	3.2520	3.6860	4.0150
17	1.3334	1.7396	2.1098	2.5668	2.8982	3.2224	3.6458	3.9650
18	1.3304	1.7341	2.1009	2.5514	2.8784	3.1966	3.6105	3.9216
19	1.3277	1.7291	2.0930	2.5395	2.8609	3.1737	3.5794	3.8834
20	1.3253	1.7247	2.0860	2.5280	2.8453	3.1534	3.5518	3.8495

Table 4. Theoretical values of the Wilcoxon W_{theor} criterion (two-sided criterion) at $p < 0.05$ [24].

Number of Observation Pairs (n)	W_{theor}	Number of Observation Pairs (n)	W_{theor}
6	1	16	31
7	3	17	36
8	5	18	41
9	7	19	47
10	9	20	53
11	12	21	60
12	15	22	67
13	18	23	74
14	22	24	82
15	26	25	90

2.4. Consideration of Selected Values Indicating Anthropogenic River Load

The integrated water pollution index (IWPI) was calculated based on available data regarding actual concentrations of hydrochemical and toxic indicators in the database. Variants of using such methods were developed under the guidance of M.J. Burlibayev [28,36–38].

In accordance with the recommended methods for the integrated water pollution index (IWPI) determination and considering the data availability for the study period 2003–2022, it was possible to select pollutant constituents whose concentration exceeds the established maximum permissible concentrations (MPCs) for their own constituents. The list of ingredients that are included in the calculation of the IWPI is divided into the following conventional groups: major ions, nutrients, heavy metals, toxic compounds, organic substances, and organochlorine pesticides. From these groups of hydrochemical and toxicological indicators, the state monitoring database has long-term information on three groups: major ions, nutrients, and heavy metals.

According to the requirements of the existing methods to calculate the IWPI of the Ile River, the ion-salt composition of natural waters should not be included, because their content depends on soil-climatic, hydrogeological, and other natural and genetic features of the territory, as well as the hydrological regime of water bodies. Ammonium and nitrite nitrogen as biogenic substances were included in the present investigation for the calculation of IWPIs, as well as copper and zinc as heavy metals, the concentration of which exceeds their own maximum permissible concentrations for fishery standards, MPC_f.

3. Results

3.1. Assessment of Anthropogenic Load Along the Length of the Ile River on the Basis of Anthropogenic Impact Share Values

On the basis of materials for the study period 2003–2022, the results of the water pollutant index calculation—WPI (ratio of concentration to maximum permissible concentrations, MPC_f [30]), of pollutants—are given in Table 5.

Table 5. Water pollution index (WPI) of the Ile River for 2003–2022, MPC_f [30].

Hydro Point	NH_4		NO_2		Cu		Zn	
	Limits	Average	Limits	Average	Limits	Average	Limits	Average
Dobyn HP 1	0.02–1.9	0.7	0.8–8.4	2.9	1.2–20.0	6.1	0.1–2.4	0.5
"164 km" HP 2 upstream of Kapshagai HPP	0.03–1.5	0.6	0.5–3.8	1.6	0.9–10.8	4.5	0.1–1.2	0.4
"37 km" HP 3 downstream of Kapshagai HPP	0.01–1.5	0.3	0.3–1.4	0.8	1.1–8.7	3.7	0.1–1.7	0.3
Ushzharma HP 4	0.01–1.3	0.4	0.3–1.3	0.7	1.0–10.5	3.7	0.1–2.1	0.4

The analysis of data on the chemical composition of water in the Ile River has shown that the average annual values of WPI of the pollutants considered downstream from the border station (HP 1) to the terminating station (HP 4) tends to decrease, which shows a significant negative impact on the water resources of the river and the transboundary effect of the pollution.

For the Ile River water, the polluting nutrients are ammonium nitrogen and nitrite nitrogen, although their average annual concentrations are within the norm. Exceeding MPC_f average concentration of nitrite nitrogen is recorded at the border station HP 1 (2.9 MPC_f) and "164 km" HP 2 upstream of the Kapshagai HPP (1.6 MPC_f). Downstream of the reservoir, exceeding nitrite concentration is noted only in the maximum values of MPC_f: 1.3–1.4. The exceedance of MPC_f of ammonium nitrogen is recorded only at maximum values ranging from 1.3 to 1.9.

Copper is a typical polluting ingredient for the Ile River. Its average annual concentration varies from 3.7 to 6.1 $\mu g/dm^3$. The maximum copper content of 20 $\mu g/dm^3$ is recorded at HP 1 Dobyn in 2003 due to wastewater inflow from China. In Kazakhstan, the copper content in river water remains high, with maximum WPIs ranging from 8.7 to 10.8 MPC_f. Average annual zinc WPIs remain below their own MPC_f, with only maximum WPIs in the range of 1.2–2.4 MPC_f.

Based on the data calculated above, Table 6 presents the weighted average IWPI values for river water downstream from 2003 to 2022. The average annual maximum downstream IWPI values gradually decreased from 7.8 (Dobyn HP) to 5.4 (Ushzharma HP 4). And the minimum values also decreased from 1.6 to 1.0. This trend in the average annual values of the IWPI is maintained if, in the border zone, water quality is characterized by a high level

of pollution. In this case, in the direction of Ushzharma station, water quality improves to a moderate level of pollution.

Table 6. Integrated water pollution indices (IWPIs) of the Ile River at four hydro points.

Year	Dobyn HP (1)	164 km Upstream of Kapshagai HPP (2)	37 km Downstream of Kapshagai HPP (3)	Ushzharma Locality (4)
2003	7.8	2.5	2.9	3.2
2004	4.4	2.9	2.5	2.4
2005	3.6	3.9	2.5	4.0
2006	5.6	3.4	4.4	4.3
2007	7.1	4.6	3.9	3.6
2008	6.5	5.0	4.5	4.8
2009	7.4	3.8	3.1	2.9
2010	5.7	5.9	5.8	5.4
2011	3.9	4.2	2.8	4.2
2012	4.8	3.2	2.9	3.2
2013	3.1	2.6	2.8	1.8
2014	3.3	5.5	4.0	1.7
2015	1.7	2.1	2.7	2.2
2016	1.7	1.4	1.3	1.6
2017	2.1	1.7	1.4	1.3
2018	1.9	1.5	1.5	1.4
2019	1.8	1.4	1.3	1.2
2020	1.6	1.2	1.4	1.1
2021	1.6	2.1	1.1	1.0
2022	1.8	1.8	2.4	1.9
Maximum value	7.8	5.9	5.8	5.4
Minimum value	1.6	1.2	1.1	1.0
Average value	3.9	3.0	2.8	2.7

Thus, based on the results of the IWPI calculation, the values of the share of anthropogenic impact for each year in the selected observation points (HPs) are calculated in accordance with Formula (1). The calculated values of the indicator are shown in Figure 3.

Based on the results of the IWPI calculations, the share of anthropogenic impact was determined for each year at the selected monitoring points. The calculation was performed in accordance with Formula (1), taking into account both the total number of parameters included in the WPI assessment and the number of components whose concentrations exceeded the established MAC.

The resulting values reflect the contribution of anthropogenic (technogenic) factors to overall water quality and serve as an indicator of the ecological pressure on aquatic ecosystems.

The calculated values are presented in Figure 3, providing a visual representation of the spatio-temporal dynamics of anthropogenic influence along various sections of the Ile River.

The obtained samples of anthropogenic impact share values for each river section are calculated for a sufficiently long period (20 years). For each sample, the homogeneity analysis of the calculated values of the proportion of anthropogenic impact is carried out by the coefficient of variation (Formula (8)), the value of which is used to calculate the degree of homogeneity. The results of the homogeneity analysis of samples of anthropogenic impact share values at different sites along the length of the Ile River are presented in Table 7.

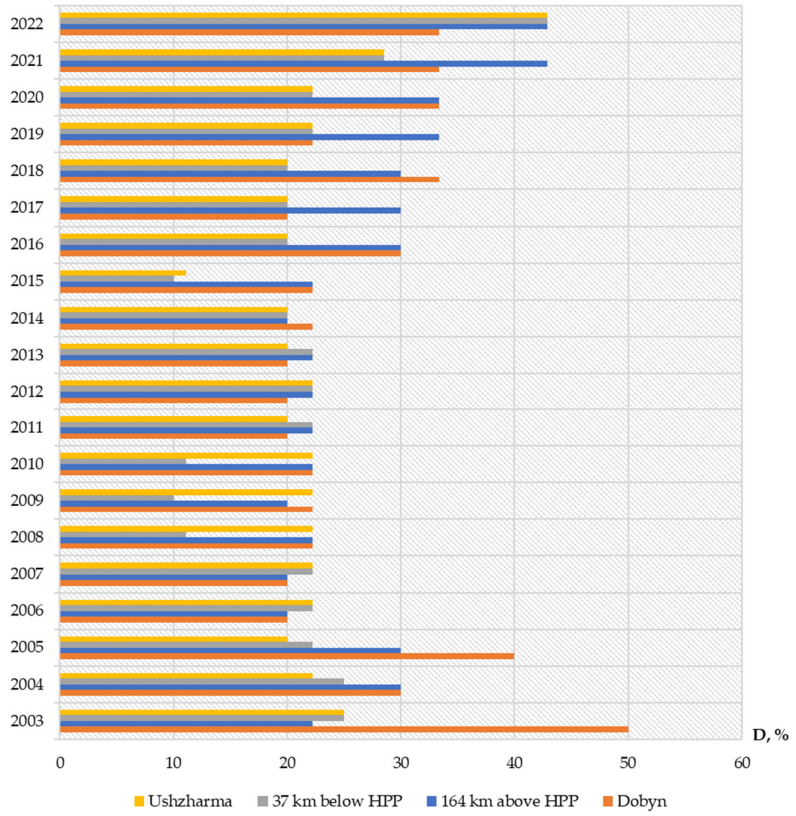


Figure 3. Proportion (D, %) of anthropogenic impact along the course of the Ile River at four hydro points between 2003 and 2022.

Table 7. Characterization of sample values for the share of anthropogenic impact at different hydro points of the Ile River.

Hydro Point	Arithmetic Mean Value. $\overline{X}$	Standard Deviation. σ	Coefficient of Variation. C_V	Degree of Sample Homogeneity
		%		
Dobyn HP 1	27	8.29	30.9	fairly homogeneous
"164 km" HP 2 upstream of Kapshagai HPP	27	7.20	26.8	fairly homogeneous
"37 km" HP 3 downstream of Kapshagai HPP	21	7.33	34.8	fairly homogeneous
Ushzharma HP 4	22	5.76	25.8	fairly homogeneous

To assess the anthropogenic load at a particular observation point by the share of anthropogenic impact, a modal interval of indicator values is allocated, compared with the criteria given in Table 2, and a conclusion is made about the load. Then, the modal interval of values of indicators used in assessing the state of the river ecosystem and anthropogenic load of the Ile River is calculated using Formulas (2)–(5). Along the length of the Ile River, anthropogenic load varies from small to critical in the border zone (HP 1) and from small to moderate on the territory of the Republic of Kazakhstan (Table 8).

The assessment of statistically significant differences between the values of the indicator samples calculated for the considered sections of the Ile River (Figure 1) is given in Table 9. Since the obtained samples of anthropogenic impact values are quite homogeneous (Table 7), Student's *t*-test is used for their comparison. According to Formulas (9)–(12), it is necessary to calculate the t-fact for the comparison of the values of the share of anthropogenic impact on the Ile River.

Table 8. Anthropogenic load according to the indicator of the proportion of anthropogenic impact at different observation points of the Ile River.

Hydro Point	Modal Interval for the Proportion of Anthropogenic Impact, %	Particularity, %	Anthropogenic Load
Dobyn HP 1	From 20 to 50	60	Minor with transition to critical
"164 km" HP 2 upstream of Kapshagai HPP	From 10 to 43	70	Minor with transition to critical
"37 km" HP 3 downstream of Kapshagai HPP	From 10 to 43	95	Minor with transition to critical
Ushzharma HP 4	From 11 to 43	95	Minor with transition to critical

Table 9. Calculation for the actual value of Student's t-criterion.

Parameters	I Section	II Section	III Section
S_d	8.31	8.43	4.7
$S_{\overline{d}}$	1.86	1.89	1.05
$\overline{d}$	1312	1350	420
$\overline{\mathrm{d}}$	−0.06	5.83	−1.31
t_{theor} at $p < 0.05$	2.09	2.09	2.09
t_{fact}	0.03	3.09	1.24

Section I from HP 1 Dobyn to "164 km" HP 2 above HPP. Section II from "164 km" HP 2 above HPP to "37 km" HP 3 below HPP. Section III from "37 km" HP 3 below HPP to Ushzharma HP 4.

The results of calculations of Student's criterion value t_{fact} for section I is 0.03, for section II it is 3.09, and for section III it is 1.24. The theoretical value of the criterion, t_{teor}, at a significance level of $p < 0.05$ and number of degrees k = 19: $t_{teor} = 2.09$ is shown in Table 3.

Therefore, 0.03 < 2.09 (section I) and 1.24 < 2.09 (section III), i.e., $t_{fact} < t_{teor}$; thus, it is accepted the null hypothesis of statistically significant differences between the general parameters of the compared samples of the values of the proportion of anthropogenic impact. Sections III and I of the Ile River located between HP 1 Dobyn and "164 km" HP 2 above Kapshagai HPP and "37 km" HP 3 below Kapshagai HPP to the top of the delta experience systematic anthropogenic load on the share of anthropogenic impact.

The actual value of the criteria, t_{fact}, in section II is higher than t_{theor} (3.09 > 2.09). Therefore, the alternative hypothesis about the presence of systematic statistically significant differences between the general parameters of the compared samples of values of the share of anthropogenic impact is accepted. The section located between "164 km" HP 2 above and "37 km" HP 3 below Kapshagai HPP experiences an uneven anthropogenic load on the share of anthropogenic impact. Taking into account the fact that the arithmetic mean value in the "37 km" HP 3 below the reservoir exceeds the same value in the "164 km" HP 2 above the HPP, it can be concluded that at this site the anthropogenic load increases along the length of the watercourse.

3.2. Assessment of Anthropogenic Load by the Indicator of the Modulus of Inflow of Chemical Substances Along the Length of the Ile River

To identify the anthropogenic component of pollution for the contaminants studied, dependencies on water flow were calculated (Figure 4). The results showed a strong relationship between copper runoff and water flow at monitoring point HP 2 (164 km upstream of the HPP) and HP 4 (Ushzharma village). The validity and reliability of this relationship are supported by correlation coefficients (R) of 0.66 and 0.70, respectively.

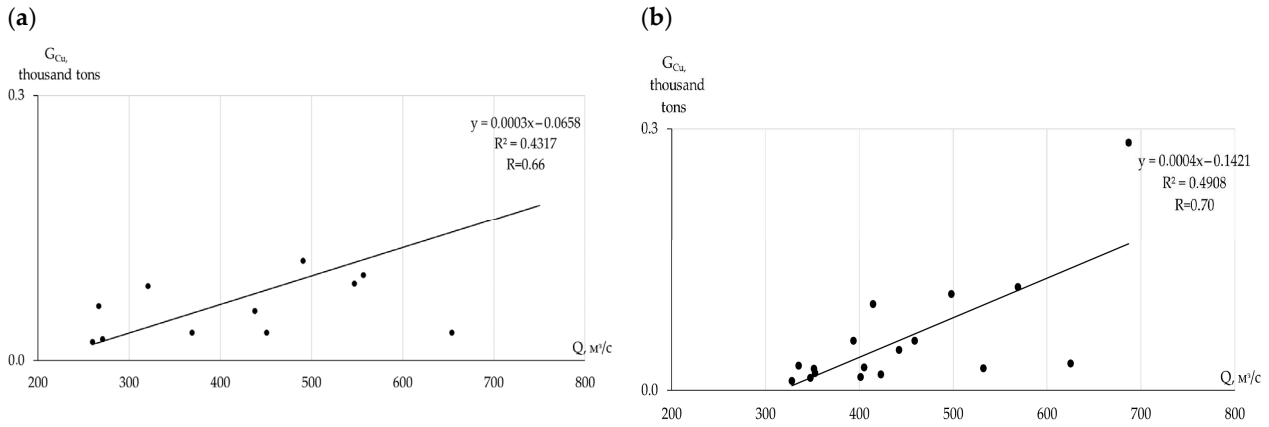


Figure 4. Correlation between copper runoff and water discharge in the Ili River at "164 km" HP 2 upstream of the HPP and at Ushzharma HP 4. (**a**) 164 km upstream of Kapshagai HPP. (**b**) Ushzharma locality.

The inconsistency of the annual runoff of copper and other pollutants, and in other sections of the river water, is a natural phenomenon, indicating its general presence in the catchment area of the river coming from sources of anthropogenic pollution by these compounds. Consequently, the increase in the concentration of toxicants occurs mainly due to the introduced pollutants. The role of denudation processes in the basin obviously has a subordinate position [19].

Annual runoff volumes of the considered chemical substances are given in Table 10.

Table 10. Ammonium nitrogen, nitrite nitrogen, copper, and zinc runoff contents along the Ile River at four observation points for 2003–2022 (in thousand tons).

Hydro Point	NH_4		NO_2		Cu		Zn	
	Limits	Average	Limits	Average	Limits	Average	Limits	Average
Dobyn HP 1	0.14–13.64	3.76	0.21–3.02	0.78	0.01–0.20	0.07	0.02–0.28	0.06
"164 km" HP 2 above HPP	0.28–10.48	2.88	0.16–0.67	0.39	0.02–0.31	0.08	0.01–0.2	0.05
"37 km" HP 3 below HPP	0.03–6.52	1.75	0.09–0.55	0.22	0.01–0.11	0.05	0.01–0.30	0.06
Ushzharma HP 4	0.03–6.12	1.96	0.08–0.42	0.2	0.01–0.28	0.06	0.01–0.11	0.04

Table 10 shows that the flow of ammonium and nitrite nitrogen in river water varies over a rather wide range. The maximum inflow of ammonium nitrogen (13.64 thousand tones) and nitrite nitrogen (3.02 thousand tones) is recorded in the transboundary flow (HP 1 Dobyn). The average annual flow of ammonium nitrogen and nitrite nitrogen downstream in Kazakhstan decreases from 3.76 to 1.75 thousand tons and from 0.78 to 0.2 thousand tons, respectively.

The average annual discharge of copper and zinc fluctuates within the range of 0.05–0.08 and 0.04–0.06 thousand tons. The maximum levels of copper (0.31 thousand tons) and zinc (0.30 thousand tons) were recorded in the area of gauging stations "164 km" HP 2 upstream and "37 km" HP 3 downstream of the HPP. The dynamics of the volume of annual values of chemical runoff are shown in Figure 5.

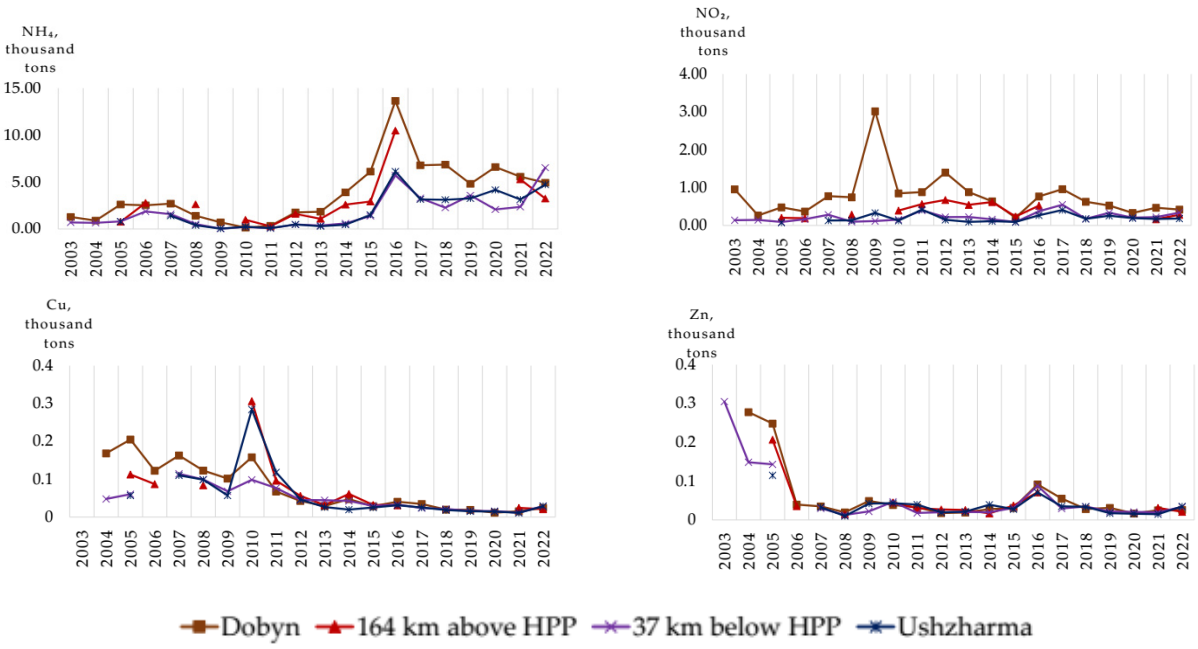


Figure 5. Dynamics of annual runoff of ammonium nitrogen, nitrite nitrogen, copper, and zinc in the Ile River at four observation points (hydro points).

Analyzing the long-term data, it can be noted that the volume of inflow into the river in recent years has shown a downward trend, which is reflected in Figure 6. This positive dynamic is typical for all studied elements. However, the average long-term volume of ammonium nitrogen input into the river after 2016 was higher compared to 2003.

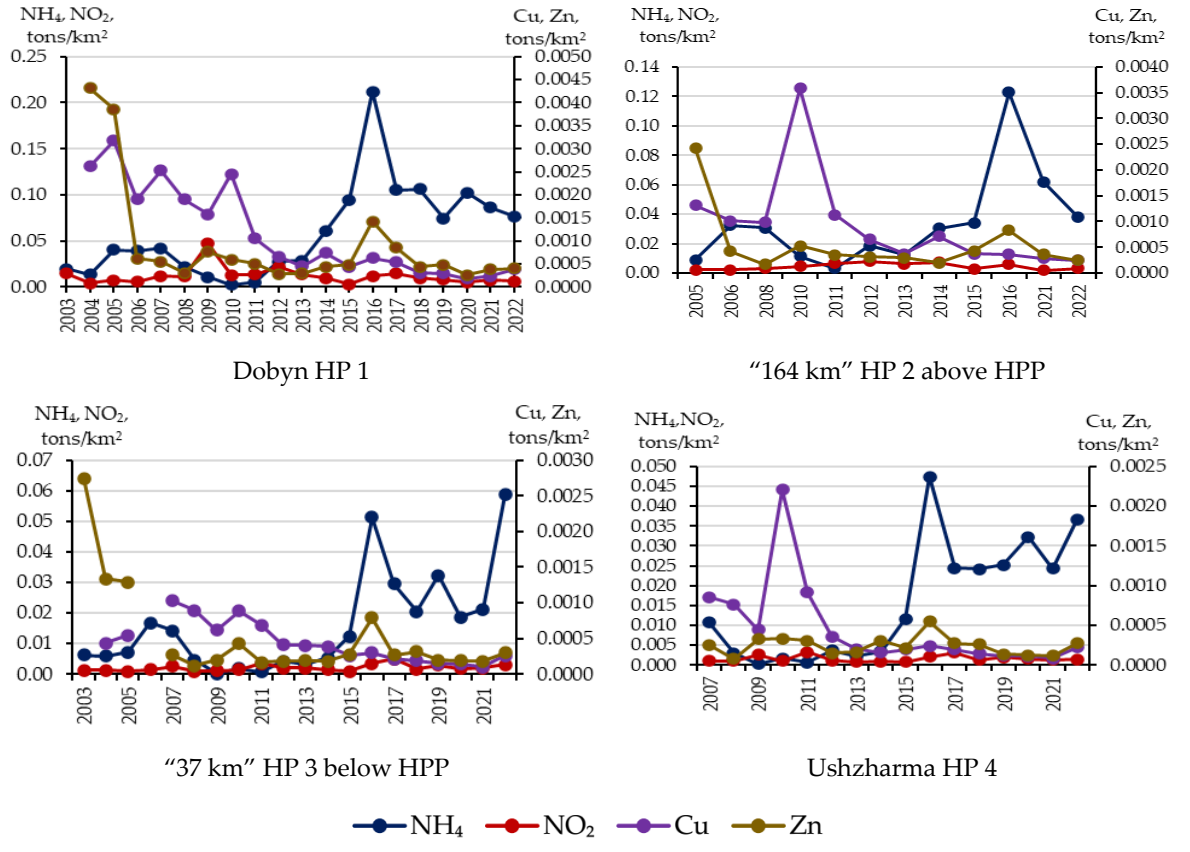


Figure 6. Modulus of dissolved chemical substance inflow in the Ile River at four observation points (hydro points).

On the basis of the obtained amount of transported substance for the calculation period, a calculation of the value of the modulus of the inflow of chemical substances to a particular section of the river is carried out using Formula (7).

The distribution of values of indicators by the defined intervals is presented graphically in the form of a frequency histogram, where the values of interval boundaries are plotted along the abscissa axis, and rectangles, the height of which is proportional to the frequencies, stand on their bases (Figures 7–10).

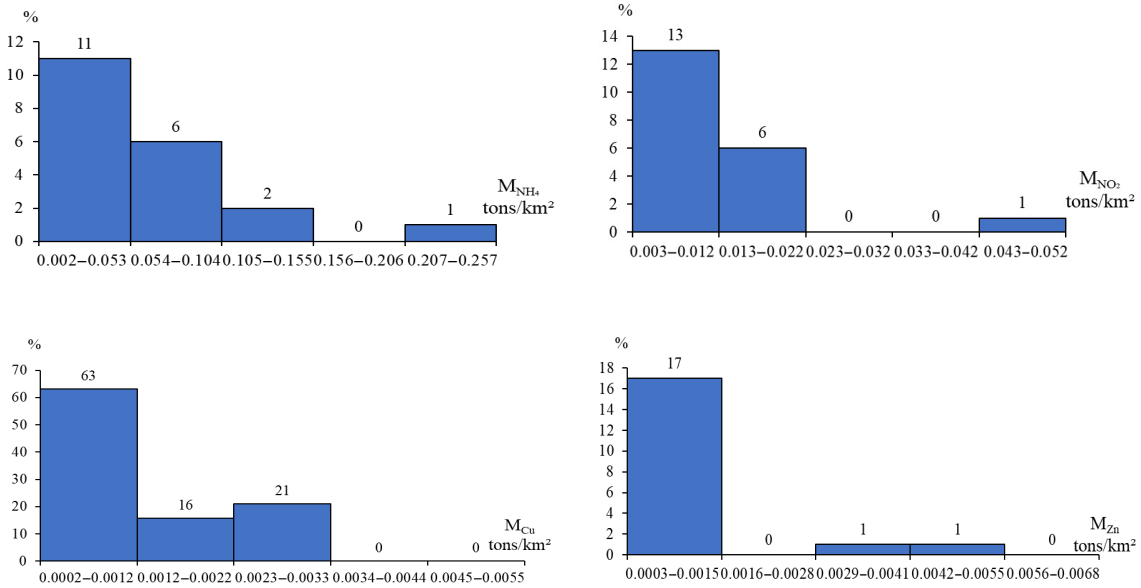


Figure 7. Frequency of pollutant inflow modulus of pollutants in the water of the Ile River at Hydro Point Dobyn (HP 1).

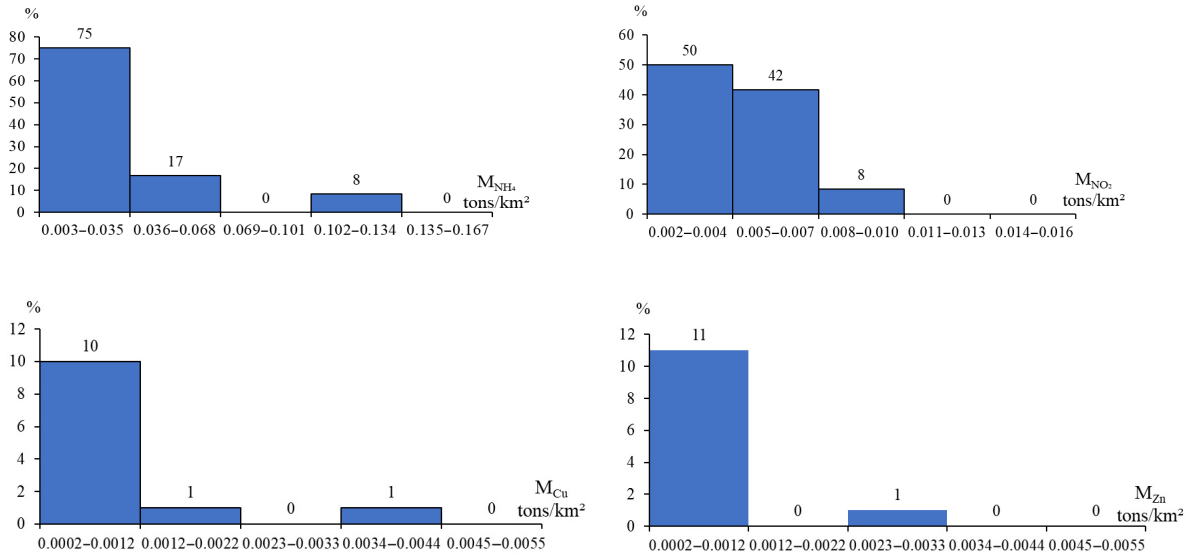


Figure 8. Frequency of pollutant inflow modulus of pollutants in the Ile River water at Hydro Point "164 km" (HP 2) upstream of Kapshagai HPP.

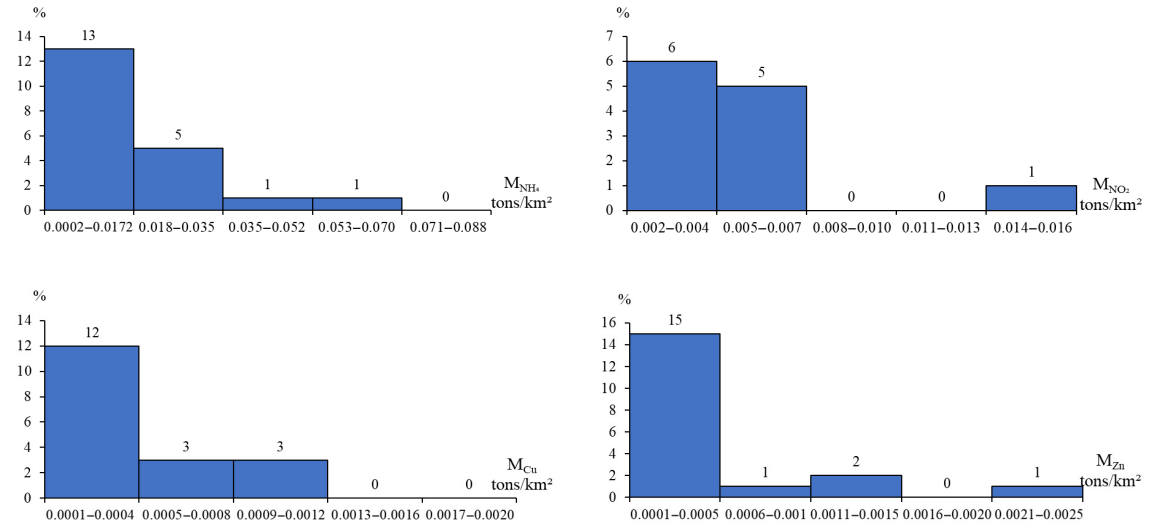


Figure 9. Frequency of pollutant inflow modulus of pollutants in Ile River water at Hydro Point "37 km" (HP 3) downstream of Kapshagai HPP.

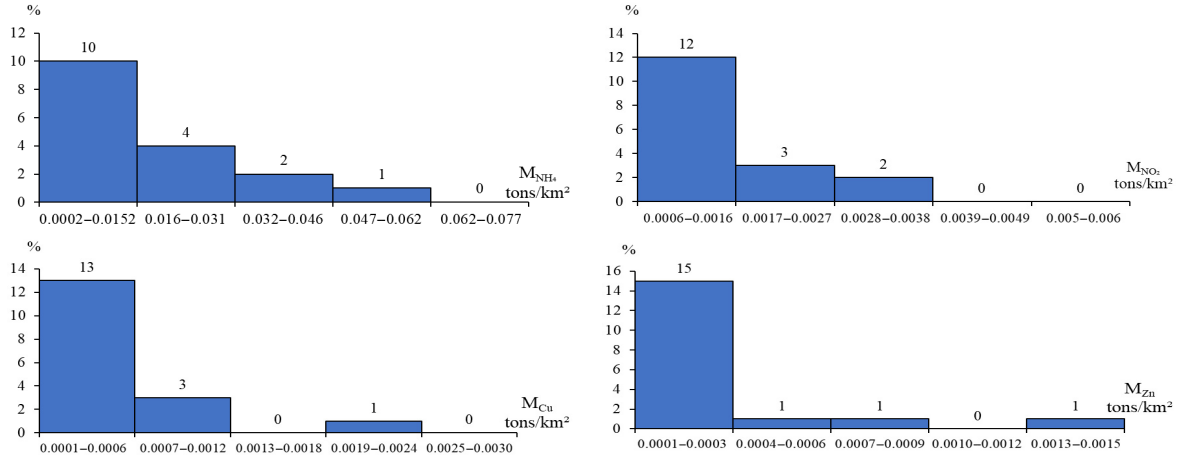


Figure 10. Frequency of the inflow modulus of pollutants in the water of the Ile River at Hydro Point Ushzharma (HP 4).

For each indicator, the minimum and maximum values are identified from all values exceeding the upper boundary of the modal interval. The interval of these values (maximum values of the inflow modulus) is compared with the assessment criteria given in Table 2, and the anthropogenic load at a particular point in the river is determined. The anthropogenic load by chemical inflow modulus at different sections of the Ile River is given in Table 11.

Along the length of the Ile River, anthropogenic load of ammonium and nitrite nitrogen inflow is assessed as low with transition to moderate, while copper inflow varies from low to critical, and zinc inflow is assessed as low, only below Kapshagai HPP with transition to critical.

The analysis of the samples' homogeneity of calculated values of modulus of chemical substances inflow is carried out for each sample using the coefficient of variation. Based on this value, conclusions regarding the degree of sample homogeneity are made according to Formula 8 and Figure 2. The results of the analysis are presented in Table 12.

Table 11. Anthropogenic load in terms of the chemical inflow modulus at different observation points of the Ile River.

Hydro Point	Anthropogenic Load			
	Ammonium Nitrogen	Nitrite Nitrogen	Copper	Zinc
Dobyn HP	Small with transition to moderate	Small with transition to moderate	Small with transition to critical	Small
"164 km" HP 2 upstream of Kapshagai HPP	Small	Small with transition to moderate	Small	Small
"37 km" (HP 3) downstream of Kapshagai HPP	Small with transition to moderate	Small with transition to moderate	Small with transition to critical	Small with transition to critical
Ushzharma HP 4	Small with transition to moderate	Small with transition to moderate	Small with transition to moderate	Small

According to the data in Table 12, samples of inflow modulus values are used to assess statistically significant differences in indicators of anthropogenic impact on watercourse sections between the studied points. Since the samples are non-uniform and taken over the same time intervals, the Wilcoxon signed-rank test for paired dependent observations is used for comparison [39]. The null hypothesis (H_0) assumes that the differences between the observed indicators are random, while the alternative hypothesis (H_1) assumes that the differences are systematic.

The calculation using the Wilcoxon criterion is carried out as follows:

(a) For each year, the value of the change in the indicator (d_i) between point A (x_i) and point B (y_i) is determined. Pairs of observations, which correspond to zero change, should be excluded from the analysis, accordingly reducing the sample size by one unit;

(b) the calculated changes are ordered in ascending order of their absolute value (without taking into account the sign) and numbered; thus, the smallest difference gets the first rank, R. Differences of the same value are assigned the same rank calculated as the average of the places they occupy in the ordered series;

(c) the obtained ranks are assigned a sign in accordance with the direction of change and get a sign rank (R_z) negative for decreasing and positive for increasing;

(d) calculate the sum of sign ranks W fact separately for positive ranks and separately for negative ranks according to Formula (13). A 'typical shift' is the sum of the ranks predominant by sign, and an atypical shift is the sum of the ranks rare by sign;

(e) the smaller of the two sums of differences ('atypical shift') without taking into account its sign is used as the actually established value W_{fact}. The obtained W_{fact} value for the accepted significance level p and the number of paired observations n', which is taken without zero differences, are compared with the W_{theor} criterion given in Table 4. If $W_{fact} \leq W_{theor}$, hypothesis H_1 is accepted, otherwise H_o is accepted. The recommended significance level is at least $p < 0.05$.

A comparison of sample values of dissolved chemical inflow modulus at the Ile River sites is given in Table 13.

Table 12. Characteristics of sample values of dissolved chemical substance inflow modulus along the length of the Ile River at four observation points.

Observation Point	Arithmetic Mean M. tonnes/km^2 Per Year	Standard Deviation of Sampling M. tonnes/km^2 Per Year	Coefficient of Variation. %	Degree of Sampling Homogeneity
Ammonium nitrogen				
Dobyn HP 1	0.058	0.051	86.5	Completely heterogeneous
"164 km" HP 2 upstream of Kapshagai HPP	0.034	0.032	95.7	Completely heterogeneous
"37 km" HP 3 downstream of Kapshagai HPP	0.016	0.017	102	Completely heterogeneous
Ushzharma HP 4	0.02	0.15	96.9	Completely heterogeneous
Nitrite nitrogen				
Dobyn HP 1	0.012	0.009	77.3	Completely heterogeneous
"164 km" HP 2 upstream of Kapshagai HPP	0.005	0.002	47.5	Heterogeneous
"37 km" HP 3 downstream of Kapshagai HPP	0.002	0.001	53.6	Heterogeneous
Ushzharma HP 4	0.002	0.001	54.1	Heterogeneous
Copper				
(1) Dobyn HP	0.0012	0.001	83.8	Completely heterogeneous
(2) 164 km upstream of Kapshagai HPP	0.001	0.001	99.4	Completely heterogeneous
(3) 37 km downstream of Kapshagai HPP	0.0004	0.0003	64.2	Completely heterogeneous
(4) Ushzharma locality	0.0005	0.0005	116	Completely heterogeneous
Zinc				
(1) Dobyn HP	0.0009	0.0012	127	Completely heterogeneous
(2) 164 km upstream of Kapshagai HPP	0.001	0.001	112	Completely heterogeneous
(3) 37 km downstream of Kapshagai HPP	0.0004	0.0004	97.4	Completely heterogeneous
(4) Ushzharma locality	0.0003	0.0002	69.4	Completely heterogeneous

Table 13. Comparison of sample values of chemical inflow modulus along the length of the Ile River.

River Section	HPs 1	HPs 2	W_{fact}	ń	W_{theor}	Significance Level	Accepted Hypothesis
Ammonium nitrogen							
I Section	Dobyn HP 1	164 km above HPP	9	12	15	$p < 0.05$	Point 1 H_1—differences are statistically significant
II Section	HP 2 above HPP	37 km below HPP	6	11	12	$p < 0.05$	H_1—differences are statistically significant
III Section	HP 3 below HPP	Ushzharma locality	39	17	36	$p < 0.05$	H_0—differences statistically not significant
Nitrite nitrogen							
I Section	Dobyn HP 1	HP 2 above HPP	0	12	15	$p < 0.05$	H_1—differences are statistically significant
II Section	HP 2 above HPP	HP 3 below HPP	1	12	15	$p < 0.05$	H_1—differences are statistically significant
III Section	HP 3 below HPP	Ushzharma HP 4	19	17	36	$p < 0.05$	H_1—differences are statistically significant
Copper							
I Section	Dobyn HP 1	HP 2 above HPP	19	12	15	$p < 0.05$	H_0—differences statistically not significant
II Section	HP 2 above HPP	HP 3 below HPP	3	11	12	$p < 0.05$	H_1—differences are statistically significant
III Section	HP 3 below HPP	Ushzharma HP 4	32	17	36	$p < 0.05$	H_1—differences are statistically significant
Zinc							
I Section	Dobyn HP	164 km above HPP	4	12	15	$p < 0.05$	H_1—differences are statistically significant
II Section	164 km above HPP	37 km below HPP	4	11	12	$p < 0.05$	H_1—differences are statistically significant
III Section	37 km below HPP	Ushzharma locality	43	17	36	$p < 0.05$	H_0—differences statistically not significant

According to the data given in Table 13, in river sections I and II of the Ile River the river ecosystem experiences an uneven anthropogenic load on ammonium nitrogen, as the condition $W_{fact} < W_{theor}$ is fulfilled; therefore, the alternative hypothesis about the presence of statistically significant differences in the sample values of ammonium nitrogen inflow modulus between the compared points is accepted. In river section III, the value of $W_{fact} < W_{theor}$; thus, the null hypothesis about the absence of statistically significant differences in samples of ammonium nitrogen inflow modulus, is accepted. The river ecosystem between the "37 km" HP 3 downstream of Kapshagai HPP and Ushzharma HP 4 is experiencing uniformity regarding ammonium nitrogen.

In samples of nitrite nitrogen inflow modulus between the compared points along the whole river flow, there are statistically significant differences. The alternative hypothesis is accepted, since the condition $W_{fact} < W_{theor}$ is fulfilled. Thus, the river ecosystem experiences uneven anthropogenic load on nitrite nitrogen.

In samples of copper inflow modulus between Dobyn HP 1 border Hydro Post and "164 km" HP 2 upstream of HPP, according to $p < 0.05$ at n = 12, the value of $W_{theor} = 15$; thus, 19 > 15, i.e., $W_{fact} > W_{theor}$; thus, the null hypothesis of statistically significant differences between the compared points is accepted. The river ecosystem in section I experiences a uniform anthropogenic load on copper. Sections II and III experience an uneven anthropogenic load using this indicator. If we take into account that the median

sample value of the copper inflow modulus at Dobyn HP 1 (0.0012 tones/km^2/year) exceeds the same value at "164 km" HP 2 upstream of the HPP (0.0009 tones/km^2/year), the transboundary inflow accounts for a large share of anthropogenic load.

In terms of zinc, sections I and II of the Ile River experience uneven anthropogenic loads, while section III experiences uniform anthropogenic load. Taking into account that the median sample value of zinc inflow modulus at Dobyn HP 1 (0.0008 tones/km^2 per year) exceeds the same value at "164 km" HP 2 upstream of the HPP (0.0005 tones/km^2 per year) and "37 km" HP 3 downstream of the HPP (0.0003 tones/km^2 per year), it can be concluded that at this site, the anthropogenic load decreases along the length of the watercourse.

4. Discussion

The hydrochemical regime of the Ile River has been thoroughly studied in numerous research works [17,18,40–44]. However, theoretical frameworks developed by researchers in the field of water quality assessment ultimately rest on assumptions about how water quality affects human health—whether through drinking water, food, or other pathways. A key criterion in such assessments is the degree to which maximum allowable concentrations (MAC) are exceeded or the overall level of contamination in the water body.

The introduction of chemically altered water into the river significantly affects ongoing physicochemical processes. While changes due to mechanical flow alterations may occur based on naturally present chemical elements, discharged water can contain substances that are not normally found in the river under natural conditions. Consequently, both quantitative factors (e.g., flow regulation, water withdrawal) and qualitative factors (e.g., pollutant composition) interact and may either amplify or mitigate their overall impact. This dual influence motivated an effort to assess the anthropogenic burden on the river ecosystem while considering regional characteristics.

Gradations of anthropogenic pressure are determined based on the degree of ecosystem disturbance and the identification of cause–effect relationships between stressors and biological responses. Classifiers for assessing anthropogenic impact on river ecosystems have been developed through the systematization of long-term monitoring data in Kazakhstan, capturing the diverse regional patterns of ecosystem formation and functioning. Understanding variability in river ecosystem states helps define threshold levels of indicators beyond which the system may shift to an altered state.

In this study of the Ile River, special attention was paid to the effects of anthropogenic factors and regional peculiarities on the river's hydrochemical regime [21]. This assessment not only helps capture the current state of the ecosystem but also tracks long-term trends in water quality over the past two decades. Distinct regional and transboundary features were identified that shape the peculiarities of technogenic influences.

A notable feature of the Ile River's hydrochemical structure is the complex interaction between local anthropogenic influences (e.g., wastewater discharges, water intake) and transboundary flows, the bioaccumulation of pollutants, and their redistribution in the estuarine zone [19,45,46]. Under natural hydrological conditions, the chemical composition of river water reflects the chemical composition of the river's catchment. However, full flow regulation disrupts this natural pattern. In the lower reaches, some micro and macroelements are absent or occur only in trace amounts [47,48]. Hydraulic infrastructure mechanically alters water flow, thereby triggering changes in physicochemical processes and the composition of dissolved substances [25]. In the estuarine zone, slower water flow enhances transformation and accumulation processes, which vary seasonally in intensity [49,50].

This study employs the Water Pollution Index (WPI) as the primary indicator of anthropogenic transformation in the aquatic environment—a metric widely used in ecological research led by M. Zh. Burlibayev [28,36–38]. By incorporating a Pollutant Index (PI) and analyzing MAC exceedances, this approach enables not only the detection of contamination but also the evaluation of its toxicological significance.

The anthropogenic load, determined by the share of anthropogenic impacts, is mainly caused by pollutants. In the average annual perspective, there is a mixed dynamics of water quality along the river. Despite the fact that the improvement in water quality is not always confirmed along the entire length of the Ile River, a moderate level of pollution can be observed within the territory of Kazakhstan. Characteristic polluting components are copper, in some cases zinc, ammonium, and nitrite nitrogen. Particular attention should be paid to the high content of copper in water, which in some cases exceeds MPC up to 20-fold. Results from the period 2003–2022 reveal that anthropogenic pressure on the Ile River exhibits clear spatial and temporal differentiation, shaped by both transboundary pollution sources and regional hydrological, topographical, and water use patterns. Although average pollution levels have declined along the river—evidenced by a decrease in the weighted average WPI from 7.8 to 5.4—a high level of technogenic impact persists in the border zone detected at Hydro Point 1. Elevated WPI values and a high proportion of anthropogenic influence were observed at the transboundary station (HP 1) near Dobyn, confirming the dominant role of external pollution sources, as also noted in [38]. Further downstream, the share of anthropogenic impact decreases, reflecting the operation of natural self-purification mechanisms.

Ammonium and nitrite nitrogen (among biogenic compounds), as well as heavy metals—primarily copper—were identified as the key pollutants in the Ile River. Maximum nitrite nitrogen concentrations (up to 2.9 MAC) were recorded in the transboundary zone (HP 1), aligning with earlier studies [21,38] that emphasize the significance of border inflows as major pollution sources in the arid regions of Central Asia.

Similar findings were reported in [51], where sustained MAC exceedances for copper and nitrogen were documented in other transboundary basins. This study [52] highlights that transboundary flow contributes up to 60% of total water pollution in Kazakhstan, consistent with the observed contribution in the Ile River.

In section I of the Ile River, from the border Hydro Point to the Kapshagai reservoir, the inflow modulus of ammonium nitrogen, nitrite nitrogen, and zinc experiences uneven anthropogenic load. In terms of copper inflow, this site experiences a uniform anthropogenic load. If we take into account the high copper pollution index of the Ile River in the border zone, we can conclude about the systematic inflow of its transboundary runoff. If we also take into account that the median of the sample values of the inflow modulus of all considered pollutants at the point of HP 1 near Dobyn exceeds the similar value in HP 2, 164 km upstream of the HPP, then we can conclude that at this site the anthropogenic load decreases along the length of the river.

In section II of the Ile River, from “164 km” HP 2 above and up to “37 km” HP 3 below Kapshagai HPP, the inflow modulus of all considered pollutants experiences a uniform anthropogenic load. The median sample value of the inflow modulus of these pollutants at HP 2, above the reservoir, is lower than the similar value at HP 3, 37 km below the HPP, which means the increase in anthropogenic load at this site along the length of the river.

In section III, the Ile River, from HP 3, 37 km downstream of the HPP to the top of the delta, HP 4, near Ushzharma locality experiences an uneven anthropogenic load regarding the inflow modulus of ammonium nitrogen and zinc. In terms of nitrite nitrogen and copper inflow, this river section experiences a uniform anthropogenic load. That means that the median of the sample values of the inflow modulus of the considered chemical

elements shows that the anthropogenic load at this section decreases along the length of the watercourse.

The use of WPI and the proportion of anthropogenic impact made it possible to quantify the technogenic load. The statistical homogeneity of data in river sections I and III points to stable pollution pressure, while section II (spanning 164 km upstream to 37 km downstream of the Kapshagai HPP) exhibited notable variability. This variability is attributed to reservoir hydrology, intensive water use and seasonal discharge changes.

A comparative analysis using Student's *t*-test revealed statistically significant differences between the upper and lower sections of the river. For the first time in this region, anthropogenic load was also evaluated based on the specific inflow of chemical substances, providing a quantitative measure of pollutant mass per unit watershed area. This method follows the recommendations in [31,32], and sample heterogeneity was assessed using the Wilcoxon test [39].

The analysis clarified that copper and zinc loads are most pronounced in the river's upper reaches and downstream of the Kapshagay HPP, indicating localized pollution sources [47,48,53]. Copper inflows showed a strong correlation with water discharge (R = 0.66–0.70), indicating a mixed (natural and anthropogenic) origin. This relationship, also observed in [54], serves as an indicator of point-source discharges.

Particular attention has been paid to the variability of pollutant inflow, especially for ammonium nitrogen and copper. Such variability may stem from uneven discharge patterns, seasonal dynamics and hydrological fluctuations, as noted in [19,21]. The strong correlation between discharge and copper concentration at the "164 km" HP 2, upstream of the Kapshagai HPP, points to a consistent pollution source with heightened activity during peak water withdrawal periods.

The overall reduction in pollution downstream is explained by natural self-purification, dilution, and biochemical decomposition processes. However, despite the positive trend in average pollution reduction, critical pollution hotspots remain—especially in the upper and middle reaches—underscoring the need for stronger transboundary environmental monitoring and improved water protection strategies, particularly near dams and hydropower facilities.

In conclusion, this study confirms a high level of anthropogenic transformation in the Ile River ecosystem and highlights the importance of considering regional factors—industrial activity, transboundary influences, and reservoir operations—in water quality management. These findings align with contemporary integrated water resource management frameworks that emphasize spatially detailed source identification and adaptive load management, accounting for seasonal and interannual variability.

5. Conclusions

The anthropogenic load was assessed according to the anthropogenic impact share indicator and chemical inflow modulus values. The share of anthropogenic impact has an ecological meaning, assessing the participation of anthropogenic components in the formation of the component composition of the aquatic environment. It was calculated as the coefficient of water complexity in the calculation of the complex water pollution index (IWPI).

The greatest degree of pollution of the river is noted in the section of the border station, Hydro Point 1, near Dobyn. Based on the results of the IWPI calculation, the share of anthropogenic impact was calculated for each year in the selected observation points. It is revealed that the Ile River sections from the border to the Kapshagai reservoir and after the reservoir to the top of the delta (river sections I and III) experience systematic anthropogenic load in terms of the share of anthropogenic impacts. Since the arithmetic

mean value of the share of anthropogenic impact at downstream sites in Kazakhstan is less than a similar value at the border site, it can be concluded that the anthropogenic load at these sites is mainly due to transboundary inflow.

River section II, where the Kapshagai reservoir itself is located, experiences uneven anthropogenic load by the share of anthropogenic impact. Taking into account that the arithmetic mean value at the "37 km" HP 3 downstream of the reservoir exceeds the similar value as at the "164 km" HP 2 upstream of the HPP, it can be concluded that at this site, the anthropogenic load increases along the length of the watercourse. Related to the inflow of polluted runoffs, there are a number of tributaries into the reservoir from the left side and from the right side of the Shengeldy irrigation massif.

The assessment of anthropogenic load according to the values of the chemical inflow modulus takes into account the contribution of organic and biogenic substances to the chemical composition of water. The variability in the volume of dissolved chemical inflows to different parts of the river makes it possible to assess the transformation of anthropogenic load along the length of the Ile River.

The anthropogenic load along the length of the Ile River by the inflow of ammonium and nitrite nitrogen is assessed as low with a transition to moderate, while the inflow of copper varies from small to critical, and the inflow of zinc is assessed as low, only below Kapshagai HPP with a transition to critical. This allowed us to reveal regularities (trends) of anthropogenic load variability along the river length and to rank the aquatic ecosystem by the degree of anthropogenic load experienced.

Thus, the aquatic ecosystem of the Ile River continues to experience a systematic anthropogenic load of transboundary inflow from the territory of China and technogenic load of industrial and municipal facilities and large settlements, as well as agriculture in Kazakhstan. That is why special attention must be paid to transboundary inflow monitoring. Interstate agreements about maximum permissible concentrations in the transboundary Ile River flow must be established. At the same time, industrial and agricultural discharches within Kazakhstan must be monitored continuously. The main task should be to prevent polluted wastewater inflow into the Ile River. Prevention is always better than rehabilitation!

On the basis of the obtained scientific results, it is possible and necessary to establish approaches for the assessment of anthropogenic load by indicators of the share of anthropogenic impact and/or inflow of chemical substances on river ecosystems taking into account their regional peculiarities, necessary for improvement of regime and operational monitoring, typification of water fund objects, forecasting of surface water quality and solution of other practical tasks.

Author Contributions: Conceptualization, N.A.; methodology, A.M. (Ainur Mussakulkyzy), A.M. (Azamat Madibekov); software, A.M. (Azamat Madibekov); validation, A.Z.; formal analysis, L.I.; investigation, A.M. (Ainur Mussakulkyzy) and L.I.; resources, A.Z.; data curation, A.Z.; writing-original draft preparation, A.M. (Ainur Mussakulkyzy) and A.M. (Azamat Madibekov); writing—review and editing, A.M. (Ainur Mussakulkyzy) and C.O.; visualization, A.Z. and L.I.; supervision, A.M. (Ainur Mussakulkyzy) and A.M. (Azamat Madibekov); project administration, N.A. and A.M. (Azamat Madibekov); funding acquisition, N.A. and A.M. (Azamat Madibekov). All authors have read and agreed to the published version of the manuscript.

Funding: The work was carried out within the framework of grant funding provided by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan, Grant No. AP19679150: <<Regularities of anthropogenic transformation of water quality in transboundary ba-sins, using the Ile River basin as an example>>.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. WMO. State of Global Water Resources 2023. Report WMO-No. 1362. 2024. Available online: https://library.wmo.int/viewer/69033/download?file=WMO-1362-2023_en.pdf&type=pdf&navigator=1 (accessed on 21 May 2025).
2. Kumar, D.; Kumar, R.; Sharma, M.; Awasthi, A.; Kumar, M. Global water quality indices: Development, implications, and limitations. *Total Environ. Adv.* **2024**, *9*, 200095. [CrossRef]
3. Hoque, M.M.; Islam, A.; Sarkar, B.; Saha, U.D. Assessing the surface and bottom river water quality for irrigation: A study of Damodar River. *India Int. J. Energy Water Resour.* **2022**, *8*, 545–562. [CrossRef]
4. Proshad, R.; Zhang, D.; Idris, A.M.; Islam, M.S.; Kormoker, T.; Sarker, M.N.I.; Islam, M. Comprehensive evaluation of chemical properties and toxic metals in the surface water of Louhajang River. Bangladesh. *Environ. Sci. Pollut. Res.* **2021**, *28*, 49191–49205. [CrossRef]
5. Bhowmick, G.D.; Anyango, G.W.; Bhattacharya, N.S. A critical review of irrigation water quality index and water quality management practices in micro-irrigation for efficient policy making. *Desalination Water Treat.* **2024**, *318*, 100304. [CrossRef]
6. Gitau, M.W.; Chen, J.; Ma, Z. Water quality indices as tools for decision making and management. *Water Resour. Manag.* **2016**, *30*, 2591–2610. [CrossRef]
7. Qaidi, S.M.; Tayeh, B.A.; Zeyad, A.M.; de Azevedo, A.R.; Ahmed, H.U.; Emad, W. Recycling of mine tailings for the geopolymers production: A systematic review. *Case Stud. Construct. Mater* **2022**, *16*, e00933. [CrossRef]
8. Qaidi, S.M.; Dinkha, Y.Z.; Haido, J.H.; Ali, M.H.; Tayeh, B.A. Engineering properties of sustainable green concrete incorporating eco-friendly aggregate of crumb rubber: A review. *J. Clean. Prod.* **2021**, *324*, 129251. [CrossRef]
9. Abbasi, T.; Abbasi, S.A. *Water Quality Indices*; Elsevier: Amsterdam, The Netherlands, 2012.
10. Chetelat, B.; Liu, C.Q.; Zhao, Z.Q.; Wang, B.L.; Wang, Q.L. Geochemistry of the dissolved load of the Changjiang Basin rivers: Anthropogenic impacts and chemical weathering. *Geochim. Cosmochim. Acta* **2008**, *72*, 4254–4277. [CrossRef]
11. Elsayed, S.; Hussein, H.; Moghanm, F.S.; Khedher, K.M.; Eid, E.M.; Gad, M. Application of irrigation water quality indices and multivariate statistical techniques for surface water quality assessments in the Northern Nile Delta, Egypt. *Water* **2020**, *12*, 3300. [CrossRef]
12. Chapman, D.; Kimstach, V. Selection of water quality variables. In *Water Quality Assessments: A Guide to the Use of Biota Sediments and Water in Environment Monitoring*, 2nd ed.; Chapman, D., Ed.; E & FN Spon: London, UK, 1996; pp. 59–126.
13. Ayers, R.S.; Westcot, D.W. *Water Quality for Agriculture*; Food and Agriculture Organization of the United Nations: Rome, Italy, 1985; p. 174.
14. Bhatt, S.; Mishra, A.P.; Chandra, N.; Sahu, H.; Chaurasia, S.K.; Pande, C.B.; Hunt, J. Characterizing seasonal, environmental and human-induced factors influencing the dynamics of Rispana River's water quality: Implications for sustainable river management. *Results Eng.* **2024**, *22*, 102007. [CrossRef]
15. Sarker, B.; Keya, K.N.; Mahir, F.I.; Nahiun, K.M.; Shahida, S.; Khan, R.A. Surface and ground water pollution: Causes and effects of urbanization and industrialization in South Asia. *Sci. Rev.* **2021**, *7*, 32–41. [CrossRef]
16. Islam, M.T.; Khatun, M.R.; Jahan, N.; Islam, M.R.; Partho, D.K.; Kibria, M.G.; Adham, A.K.M. Regional irrigation water quality index for the Old Brahmaputra River, Bangladesh: A multivariate and GIS-based spatiotemporal assessment. *Results Eng.* **2024**, *24*, 103667. [CrossRef]
17. Kudekov, T.K. (Ed.) *Modern Ecological State of the Lake Balkhash Basin*; Kaganat Publishing House: Almaty, Kazakhstan, 2002; 388p.
18. Samakova, A.B. (Ed.) *Problems of Hydroecological Sustainability in the Balkhash Lake Basin*; Kaganat Publishing House: Almaty, Kazakhstan, 2003; 584p.
19. Madibekov, A.S.; Ismukhanova, L.T.; Zhadi, A.O.; Mussakulkyzy, A.; Bolatov, K.M. Ranking the Territory of the Almaty Agglomeration According to the Degree of Pollution. *News Natl. Acad. Sci. Repub. Kazakhstan Ser. Geol. Tech. Sci.* **2023**, *3*, 130–148. [CrossRef]
20. Mussakulkyzy, A.; Opp, C.; Amirgaliev, N.; Madibekov, A.; Ismukhanova, L.; Zhadi, A. Transmission of Heavy Metals in River Water and Self-Purification Capacity of Ile River. *Appl. Sci.* **2025**, *15*, 6548. [CrossRef]
21. Amirgaliyev, N.A.; Madibekov, A.S.; Normatov, I.S. About the Criteria of Estimation of Surface Water Quality of Kazakhstan on the Basis of Accounting of Its Natural Features. *News Natl. Acad. Sci. Repub. Kazakhstan Ser. Geol. Tech. Sci.* **2019**, *4*, 188–198. [CrossRef]
22. Chawishborwornworng, C.; Luanwuthi, S.; Umpuch, C.; Puchongkawarin, C. Bootstrap approach for quantifying the uncertainty in modeling of the water quality index using principal component analysis and artificial intelligence. *J. Saudi Soc. Agric. Sci.* **2023**, *23*, 17–33. [CrossRef]
23. Mahanty, B.; Lhamo, P.; Sahoo, N.K. Inconsistency of PCA-based water quality index—Does it reflect the quality? *Sci. Total Environ.* **2023**, *866*, 161353. [CrossRef]

24. Shaaban, N.A.; Stevens, D.K. Transforming Complex Water Quality Monitoring Data into Water Quality Indices. *Water Resour. Manag.* **2025**, *39*, 3883–3899. [CrossRef]
25. Babkin, A.V.; Babkin, V.I.; Madibekov, A.S.; Mussakulkyzy, A.; Cherednichenko, A.V. Regularities of Monthly Variations of the Ili River Runoff and Its Forecasting. *Izv. Ross. Akad. Nauk. Seriya Geogr.* **2020**, *84*, 384–394. [CrossRef]
26. *R 52.24.819*; Assessment of Anthropogenic Load on River Ecosystems Taking into Account Their Regional Peculiarities. 2014. Available online: https://meganorm.ru/Data2/1/4293755/4293755832.pdf (accessed on 1 April 2025).
27. *R 52.24.776*; Assessment of Anthropogenic Load and Risk of Impact on River Estuaries Taking into Account Their Regional Peculiarities. 2012. Available online: https://meganorm.ru/Data2/1/4293753/4293753318.pdf (accessed on 1 April 2025).
28. Burlibayev, M.J. (Ed.) *Methodological Recommendations on the Integrated Assessment of Surface Water Quality by Hydrochemical Indicators*; Printing House "IP Volkova E.V.": Astana, Kazakhstan, 2012; 80p.
29. *R 52.24.661*; Risk Assessment of Anthropogenic Impact of Priority Pollutants on Land Surface Waters. 2004. Available online: https://files.stroyinf.ru/Index2/1/4293834/4293834036.htm (accessed on 1 April 2025).
30. Unified System of Water Quality Classification in Water Bodies, Approved by the Order of the Chairman of the Committee of Water Management of the Ministry of Water Resources and Irrigation of the Republic of Kazakhstan from 20 March 2024; № 70. Available online: https://adilet.zan.kz/rus/docs/V1600014513 (accessed on 1 April 2025).
31. *RD 52.24.622*; Methodological Guidelines. Calculation of Background Concentrations of Chemical Substances in Watercourses. 2001. Available online: https://meganorm.ru/Data2/1/4293748/4293748891.pdf (accessed on 1 April 2025).
32. *RD 52.24.508*; Methodical Guidelines. Organisation and Functioning of the Subsystem for Monitoring the State of Transboundary Surface Waters of Land. 1996. Available online: https://meganorm.ru/Data2/1/4293755/4293755227.htm (accessed on 1 April 2025).
33. Yudina, A.V. Statistics: Textbook. Electronic Textbook. Available online: https://www.vvsu.ru/files/BDFC149B-BDCD-4E2B-A6CE-A5830C516FD5.pdf (accessed on 1 April 2025).
34. Lakin, G.F. *Biometrics: Textbook for Biology Specialities of Universities*, 4th ed.; revised and supplemented; Vysshaya Shkola: Moscow, Russia, 1990; 352p.
35. Dörffel. *Statistics in Analytical Chemistry*; Adler, Y.P., Ed.; Mir Publishers: Moscow, Russia, 1994; 268p.
36. Burlibayev, M.J.; Pavlichenko, L.M.; Shesterneva, O.G. To the Concept of Complex Assessment of Surface Water Quality. In *Hydrometeorology and Ecology*; Scientific and Technical Journal of RSE "Kazhydromet": Almaty, Kazakhstan, 1998; pp. 86–112.
37. Burlibayev, M.J. *Theoretical Bases of Stability of Ecosystem of Transzonal Rivers of Kazakhstan*; Kaganat: Almaty, Kazakhstan, 2007; 515p.
38. Burlibayev, M.J.; Baimanov, J.N.; Tazhmagambetov, E.A. *Complex Assessment of Surface Water Quality by Hydrochemical Indicators*; Ғylym: Almaty, Kazakhstan, 2007; 95p.
39. Glantz, S. *Medico-Biological Statistics*; Praktika: Moscow, Russia, 1998; 459p.
40. Romanova, S.M.; Tursunov, E.A.; Dostay, Z.D.; Kazangapova, N.B. Hydrochemistry of the Ili River and its tributaries. *Bull. KazNU. Chem. Ser.* **2011**, *64*, 183–187. [CrossRef]
41. Burlibaev, M.Z.; Tursunov, E.A.; Tureniyazova, Z.K. Assessment of Surface Water Quality Based on Hydrochemical Indicators: A Case Study of the Ili River. Hydrometeorology and Ecology № 1. 2009, pp. 94–101. Available online: https://cyberleninka.ru/article/n/otsenka-kachestva-poverhnostnyh-vod-po-gidrohimicheskim-pokazatelyam-na-primere-reki-ile/viewer (accessed on 1 April 2025).
42. Mustafayev, Z.S.; Ryskulbekova, L.M. Geoecological Assessment of Surface Water of a River Basin with Mathematical Analysis (on the Example of the Ili River). *Hydrometeorol. Ecol.* **2021**, *4*, 6–19. [CrossRef]
43. Smolyar, V.A.; Smolyar, V.A.; Mustafayev, S.T. *Hydrogeology of the Lake Balkhash Basin*; Gylym: Almaty, Kazakhstan, 2007; 348p.
44. Tureniyazova, Z.K. Anthropogenic changes in the ionic runoff of the Ili River. In *Some Aspects of Hydroecological Problems in Kazakhstan*; Kaganat Publishing: Almaty, Kazakhstan, 2011; pp. 206–210.
45. Madibekov, A.; Ismukhanova, L.; Mussakulkyzy, A.; Kulbekova, R.; Zhadi, A. Results of AAS-Measurements of Atmospheric Deposition of Copper and Lead in the Snow Cover of Almaty Agglomeration. *Pure Appl. Chem.* **2022**, *94*, 275–280. [CrossRef]
46. Amirgaliyev, N.; Madibekov, A.; Mussakulkyzy, A.; Ismukhanova, L.; Zhadi, A. Spatial Distribution of Heavy Metals in Snow Cover for Almaty Agglomeration. *Int. Multidiscip. Sci. GeoConf. SGEM* **2019**, *19*, 679–685. [CrossRef]
47. Madibekov, A.S.; Karimov, A.M.; Ismukhanova, L.T.; Zhadi, A.O.; Yegorov, A.B. Copper Pollution of the Snow Cover in Almaty. *News Natl. Acad. Sci. Repub. Kazakhstan Ser. Geol. Tech. Sci.* **2023**, *1*, 141–153. [CrossRef]
48. Madibekov, A.; Ismukhanova, L.; Opp, C.; Saidaliyeva, Z.; Zhadi, A.; Sultanbekova, B.; Kurmanova, M. Spatial Distribution of Cu, Zn, Pb, Cd, Co, Ni in the Soils of Ili River Delta and State Natural Reserve "Ili-Balkhash". *Appl. Sci.* **2023**, *13*, 5996. [CrossRef]
49. Bryzgalo, V.A.; Ivanov, V.V. Dissolved substances runoff at the closing stations of the rivers of the Russian Arctic seas basins. Multiyear and seasonal variability. *Ecol. Chem.* **2000**, *9*, 76–89.
50. Nikanorov, A.M.; Galo, V.A.B.; Kosmenko, L.S.; Reshetnyak, O.S. The role of chemical river runoff in anthropogenic transformation of the state of aquatic environment of the Yenisei estuary. *Water Resour.* **2010**, *37*, 434–444. [CrossRef]

51. Isabekov, B.K.; Akhmetov, D.S.; Nursseitov, A.M. Hydrochemical state of Kazakhstan's transboundary rivers: Problems and prospects. *Water Resour. Kazakhstan* **2017**, *43*, 45–53.
52. Safarov, Z.T.; Kuanishbayev, A.N.; Abdullayev, S.M. Ecological monitoring of the Syr Darya River basin: Impact of anthropogenic load on water quality. *Ecol. Nat. Manag.* **2019**, *4*, 12–20.
53. Nursseitov, A.M.; Zhumagaliev, M.S.; Akhmetova, G.R. Hydrochemical analysis of water pollution in the Balkhash-Alakol system. *Water Resour.* **2015**, *42*, 30–38.
54. Goncharenko, V.V. Relationship between hydrological regime and heavy metal concentrations in river waters. *Water Resour. Ecol.* **2018**, *2*, 60–67.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.