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АКАДЕМИЯСЫ» РҚБ

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ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫ» РҚБ

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ИЗВЕСТИЯ

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LONG-TERM DYNAMICS OF TOXIC COMPOUNDS INFLOW OF THE ZHAIYK RIVER TO TERRITORY OF KAZAKHSTAN AND THEIR DOWNSTREAM TRANSFORMATION

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Abstract. The article presents the results of studies of the assessment of multi-year dynamics of the volume of transboundary inflow of toxic compounds to the territory of Kazakhstan along the Zhaiyk River: synthetic surfactants, petroleum products, phenols, boron and a number of heavy metals. On the basis of analysis of long-term material of the State monitoring of "Kazhydromet" RSE, the volume of transboundary inflow and peculiarities of transformation of toxic compounds runoff along the river flow are considered, also taking into account natural and anthropogenic factors influence. A study of the environmental contaminants present in the territory of Kazakhstan reveals the presence of priority pollutants, including phenols, petroleum products, iron, and hexavalent chromium. The significant level of river water contamination by these toxic compounds is attributable to two primary factors: transboundary runoff and the entry of industrial and other wastewater into the river system within the Republic's territory. The maximum

runoff of toxic compounds in the country is observed during the spring season. This phenomenon is attributed to the occurrence of spring floods, which serve to exacerbate denudation processes within the catchment area of the river. The elevated levels of hexavalent chromium in the water of the Zhaiyk river are associated with the presence of tailing ponds and other facilities of industrial enterprises, both in Kazakhstan and Russia.

The data with references to the works of leading scientists of the Russian Federation are given. This data includes information about determining influence of numerous objects of mining and metallurgical industry of the Russian Federation and also the technogenic metamorphization of chemical composition of water in the upper reaches of the Zhaiyk River. The article shows the role of transboundary flow of the Zhaiyk River as the main factor in the formation of the regime of toxic substances on the territory of Kazakhstan. The work quantifies the volume of transboundary inflow of these compounds and its seasonal dynamics.

Keywords: water quality, transboundary runoff (flow), toxic compounds, heavy metals.

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ЖАЙЫҚ ӨЗЕНІ АРҚЫЛЫ ҚАЗАҚСТАН АУМАҒЫНА КЕЛЕТІН УЛЫ ҚОСЫЛЫСТАР АҒЫНЫНЫҢ КӨПЖЫЛДЫҚ ДИНАМИКАСЫ ЖӘНЕ ОЛАРДЫҢ ӨЗЕН АҒЫСЫ БОЙЫНША ТРАНСФОРМАЦИЯСЫ

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Аннотация. Жұмыста Жайық өзені бойымен Қазақстан аумағына келетін улы қосылыстардың: СББЗ, мұнай өнімдері, фенолдар, бор және бірқатар ауыр металлдардың трансшекаралық ағыны көлемінің ұзақ мерзімді динамикасын бағалауға бағытталған зерттеулердің нәтижелері берілген. «Қазгидромет» РМК мемлекеттік мониторингінің көпжылдық мәліметтерін талдау негізінде табиғи және антропогендік факторлардың әсерін ескере отырып, трансшекаралық ағынның көлемі және өзен ағысы бойынша улы қосылыстар ағынының трансформациялану ерекшеліктері қаралды. Қазақстан аумағында негізгі ластаушы заттар анықталды, оларға фенолдар, мұнай өнімдері, темір және алты валентті хром жатқызылды. Өзен суының осы улы қосылыстармен ластануының жоғары деңгейі трансшекаралық ағынмен де, республика аумағындағы өзен жүйесіне түсетін өндірістік және басқа да сарқынды сулардың нәтижесімен байланысты. Ел аумағындағы улы қосылыстардың максималды ағыны көктемгі су тасқынына байланысты көктем кезінде тіркеледі, бұл өзеннің су жинау бөлігіндегі денудациялық процестерді күшейтеді. Жайық өзенінің суындағы алты валентті хромның жоғарғы мәндері Қазақстан аумағында да, Ресей аумағында да қалдық қоймалар мен өндірістік кәсіпорындардың басқа объектілерінің болуымен байланысты.

Ресей Федерациясының (РФ) жетекші ғалымдарының еңбектеріне сілтеме жасай отырып, Жайық өзенінің жоғарғы ағысы алабындағы өзен суының химиялық құрамын техногендік метаморфизациялаудағы РФ тау-кен және металлургия өнеркәсібінің көптеген нысандарының әсерін анықтайтын мәліметтер келтірілген. Қазақстан аумағында улы заттар режимін қалыптастырудың негізгі факторы ретінде Жайық өзенінің трансшекаралық ағынының рөлі көрсетілген. Осы қосылыстардың трансшекаралық ағынының көлеміне және оның маусымдық динамикасына сандық баға берілді.

Түйін сөздер: судың сапасы, трансшекаралық ағын, улы қосылыстар, ауыр металдар.

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МНОГОЛЕТНЯЯ ДИНАМИКА ПРИТОКА ТОКСИЧНЫХ СОЕДИНЕНИЙ ПО РЕКЕ ЖАЙЫК НА ТЕРРИТОРИЮ КАЗАХСТАНА И ИХ ТРАНСФОРМАЦИЯ ПО ТЕЧЕНИЮ РЕКИ

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Аннотация. В работе приводятся результаты исследований, посвященных оценке многолетней динамики объема трансграничного притока на территорию Казахстана токсичных соединений по р. Жайык: СПАВ, нефтепродукты, фенолы, бор и ряда тяжелых металлов. На основе анализа многолетнего материала Государственного мониторинга РГП «Казгидромет» рассмотрены объем трансграничного притока и особенности трансформации стока токсичных соединений по течению реки с учетом влияния природных и антропогенных факторов. Выявлены приоритетные загрязнители на территории Казахстана, к ним отнесены фенолы, нефтепродукты, железо и шестивалентный хром. Высокий уровень загрязнения речной воды этими токсичными соединениями обусловлены, как трансграничным стоком, так и результатом поступающих в речную систему производственных и других сточных вод на территории Республики. Максимальный сток токсичных соединений на территории страны регистрируется в весенний период, обусловленный весенними паводками, усиливающими денудационные процессы на водосборной части реки. Повышенное содержание шестивалентного хрома в воде р. Жайык связано с наличием хвостохранилищ и других объектов производственных предприятий, как на территории Казахстана, так и на территории России.

Приведены сведения, со ссылкой на труды ведущих ученых Российской Федерации (РФ), об определяющем влиянии многочисленных объектов горнодобывающей и металлургической промышленности РФ в техногенной метаморфизации химического состава речной воды в бассейне верхнего течения р. Жайык. Показана роль трансграничного стока р. Жайык как основного фактора формирования режима токсичных веществ на территории Казахстана. Дана количественная оценка объема трансграничного притока этих соединений и его сезонная динамика.

Ключевые слова: качество воды, трансграничный сток, токсичные соединения, тяжелые металлы.

Introduction. Water security in arid conditions of Kazakhstan is currently considered as an important component of national security. An important aspect of quantitative limitation of water resources in Kazakhstan is the fact, that all main rivers (Ertis, Ile, Syrdarya, Zhaiyk and others) are transboundary. Out of total surface water resources (91.3 km^3/year) 48.5 % (44.3 km^3/year) comes from

neighboring countries. Local runoff in about 47.0 km^3/year, that is formed on the territory of the republic (Dostay, et al., 2012).

Transboundary problems for Kazakhstan become acute both in the field of preservation of optimal volume of river water inflow to our water basins and other problems such as: inflow of various toxic compounds, interpenetration of alien hydrobionts, including fish, introduction of new types of fish diseases. This occurs due to the peculiarities of the geographical position of Kazakhstan, which occupies the downstream of all transboundary watercourses. Such problem also exists for the Zhaiyk River. It is aggravated by the fact, that further anthropogenic reduction of the river flow is expected in connection with the implementation of water management projects on the territory of the Russian Federation. The Zhaiyk River is the third longest river in Europe (total length is 2428 km, of which 1084 km are in Kazakhstan), with a basin area of about 380 thousand km^2. The upper reaches of the river are on the Russian Federation territory, and the lower reaches are in West Kazakhstan and Atyrau regions.

The Zhaiyk River is one of the main transboundary rivers of the Republic and plays a key role in providing water to the population and various economic sectors of Western Kazakhstan. The importance of water resources of the Zhaiyk River in the dynamics of the level regime and water-salt balance of the large transboundary inland Caspian Sea is extremely high. Water resources of the Zhaiyk River are widely used for various economic purposes. At the same time, the inflow of the river's low-salinity water into the Caspian Sea leads to significant desalination of the shallow water zone of the Kazakhstan sector of the sea. This circumstance creates favorable conditions for the reproduction of valuable commercial fish stocks, including sturgeon species.

In recent decades, the Zhaiyk River has experienced a downward change in water resources mainly due to anthropogenically induced flow reduction. This poses a serious threat to the sustainable development of the natural-economic system of Western Kazakhstan. According to long-term data, starting from 1971, there is a systematic step-by-step decrease in the annual runoff of the Zhaiyk River. The value of the annual river flow (12.0 km^3) decreased, compared to the average annual flow (Surface Water Resources of the USSR, 1970). In chronological order, these changes looked as follows: by 1995 – on average to 10.0 km^3 (16.7 %), and by 2016 – on average to 7.47 km^3 (37.8 %) (Medeu, et al., 2017).

In addition to the problems of transboundary inflow reduction, anthropogenic transformation of the qualitative composition of water resources of the Zhaiyk River remains one of the threats to hydro-ecological security. Technogenic pollution of surface water of the Zhaiyk River basin has progressive character, there is a deep disturbance of ecological balance of river ecosystems. The river receives a large number of pollutants of anthropogenic origin. Stable pollution of watercourses occurs, exceeding maximum permissible concentrations (MPC) by many parameters.

The primary factor contributing to the anthropogenic metamorphosis of the

chemical composition of river water over a period of 50-60 years are beyond in the basin of the upper reaches of the Zhaiyk River on the territory of the Russian Federation is the presence of numerous mining and metallurgical facilities (Sivokhip, et al., 2017; Pavleichik, et al., 2013). The authors have identified 20 primary sources of chemical contamination in surface water spanning the area from Magnitogorsk to Orsk. These sources provide data on the high water pollution of the Zhaiyk River and its tributaries by a number of toxic compound, the content of which reaches high and extremely high levels.

In light of the aforementioned considerations, with a focus on the imperative of safeguarding the normative quality of the river water resources, the primary objective of the research endeavors was delineated by the following questions: first, to conduct a quantitative assessment of the volume of transboundary inflow of toxic compounds along the river into the territory of Kazakhstan over a multi-year period; and second, to determine the nature of transformation of the flow of these substances along the river within the Republic's territory.

According to the analysis of long-term data provided by "Kazhydromet" RSE, synthetic surfactants, phenols, petroleum products, boron (borates), and heavy metals have been identified as priority pollutants in river water. These pollutants have been found to have an extremely negative impact on the aquatic environment and on humans. Consequently, their content in natural water is strictly regulated.

Synthetic surfactants have been found to adsorb at phase interfaces, thereby reducing surface tension. Phenols under natural conditions are formed as a result of metabolic processes of aquatic organisms, as well as during biochemical decomposition and transformation of organic substances in water and bottom sediments. Petroleum products are among the most hazardous pollutants of surface water. The presence of boron compounds in the human body has been demonstrated to exert deleterious effects. Boron oxide and orthoboric acid are potent toxic substances with polytropic and embryotoxic effects, causing chronic intoxication. Heavy metals are defined as toxic substances that have the capacity to accumulate in the body, thereby including a state of chronic intoxication. This condition, in turn, has the potential to disrupt numerous physiological functions.

Materials and research methods

The quantitative assessment of the runoff of toxic compounds along the Zhaiyk River and the nature of its temporal dynamics are based on the monitoring data of "Kazhydromet" RSE for the period 2000-2022. The data set, which included measurements of water flow and the presence of toxic compounds, was obtained at six gauging stations (hydroposts) situated along the river in Kazakhstan. These stations included Yanvartsevo village (border hydropost with the Russian Federation), Uralsk city, Kushum village, Taipak village, Atyrau city, and Malaya Damba village (the final hydropost at the river's mouth). The calculation of runoff of toxic substances was made in accordance with the generally accepted methodology (Alekin, 1963). The normative indicators of MPC for the studied toxic parameters

are determined in accordance with the standards of the 1st quality class of the Unified system of classification of water quality in water bodies, approved by the Decree of the Chairman of the Committee of Water Management of the Ministry of Water Resources and Irrigation of the Republic of Kazakhstan (20.03.2024 No 68-NK).

Results and discussion

Transboundary inflow of toxic compounds of complex composition

The range of concentrations of toxic compounds of complex composition in the transboundary runoff of the Zhaiyk River are given in Table 1, and their annual average values are presented in Table 2. For phenols, upon evaluating the annual average values, it was observed that there were exceedances of the standards of MPC of fishery (MPC_f). There weren't exceedances of MPC_f recorded for synthetic surfactants, petroleum products, and boron. It is imperative to acknowledge that boron compounds constitute the primary class of pollutants within the Elek River, that is significant left-bank tributary of the Zhaiyk River. The Surface Water Quality Yearbook (1989) contains data regarding boron pollution of the Yelek River in the area of Alga city, attributed to effluents from aged sludge ponds of the coolers at Aktobe Chemical Plant. In the water samples collected from this river, boron concentrations consistently exceeded MPC_f concentrations, with concentration values ranging from 15 to 42 MPC_f. A comprehensive analysis of the levels of contamination by boron compounds in the Yelek River was provided in the following studies (Burlibayev, et al., 2013; Amirgaliyev, 2013; Amirgaliyev, et al., 2022).

Table 1 – Concentration limits of toxic compounds of complex composition in transboundary runoff of the Zhaiyk River, 2000-2022, mg/dm^3

Toxic compounds	MPC, mg/dm^3	Fluctuation range	Average
Synthetic surfactants	0.1	0-0.093	0.046
Phenols	0.001	0-0.002	0.001
Petroleum products	0.05	0.003-0.047	0.025
Boron	0.5	0.00-0.19	0.08

Observations of boron content in the Zhaiyk River's transboundary flow near Yanvartsevo village were conducted in 2021-2022. The concentrations of boron in the water were registered at the level below MPC_f.

The concentrations of synthetic surfactants exhibited significant variability during the observation period, ranging from undetectable levels to 0.093 mg/dm^3, with an average value of 0.046 mg/dm^3. The range of petroleum products was recorded between 0.003 and 0.047 mg/dm^3, with an average value of 0.025 mg/dm^3. For the period from 2000 to 2022 phenols concentrations were from 0 to 0.002 mg/dm^3, with an average concentration of 0.001 mg/dm^3. The main annual concentrations of synthetic surfactants, phenols, and petroleum products are presented in Table 2.

Table 2 – Average annual concentrations of toxic compounds of complex composition in the water of the border section of the Zhaiyk River, 2000-2022, mg/dm^3

Years	Parameters		
	Synthetic surfactants	Phenols	Petroleum products
2000	n/a	n/a	n/a
2001	0.004	0.002	0.010
2002	n/a	n/a	n/a
2003	n/a	n/a	n/a
2004	n/a	0.001	0.034
2005	0	0.002	0.035
2006	0	0.001	0.047
2007	0	0.001	0.028
2008	0	0.001	0.022
2009	0.084	0.001	0.025
2010	0.093	0.001	0.033
2011	0.090	0.001	0.037
2012	0.092	0.001	0.034
2013	0.092	0.001	0.029
2014	0.089	0.001	0.019
2015	0.007	0.001	0.016
2016	0.001	0.001	0.025
2017	0.004	0	0.004
2018	0.026	0	0.012
2019	0.021	0	0.010
2020	0	0	0.003
2021	0	0.001	0.003
2022	0	0.001	0.005
ПДК	0.1	0.001	0.05
Note: n/a – no data available			

The Zhayik River is a transboundary water body, thus necessitating a quantitative assessment of the pollutants it carries to the territory of the Republic of Kazakhstan. Toxicant transport was calculated for the period 2009-2021, because more complete data about pollutant concentrations and water runoff were available for this time period.

The transfer mass of synthetic surfactants, as demonstrated in Table 3, exhibited significant variability, ranging from zero (2020-2021) to a maximum of 743.953 tons (2014). Phenols in river water were observed in low concentrations, resulting in lower transporting mass, ranging from 0.755 tons (2019) to 14.175 (2011). The range of variation in petroleum product exhibited significant annual fluctuations, ranging from a minimum of 12.347 tons (2021) to a maximum of a maximum of 273.427 tons (2016). The transboundary boron runoff was determined for 2021 only, because the observations for this element were resumed in 2021, and amounted to 352.975 tons.

Table 3 – Transboundary runoff of toxic compounds of complex composition in the Zhaiyk River, 2009-2021, tons

Year	Parameters		
	Synthetic surfactants	Phenols	Petroleum products
2009	304.963	4.553	87.826
2010	525.326	8.502	230.301
2011	613.285	14.175	269.401
2012	565.754	6.267	195.348
2013	711.367	7.299	257.073
2014	743.953	9.734	113.397
2015	112.990	9.272	44.062
2016	7.540	3.529	273.427
2017	45.803	6.784	44.103
2018	76.450	1.984	125.741
2019	161.229	0.755	34.771
2020	0	1.228	15.801
2021	0	6.394	12.347

The maximum values of toxic compounds runoff were observed during the spring flooding period (Figure 1), which may be a consequence of increased water runoff during this period and flushing of chemical pollutants from the watershed surface.

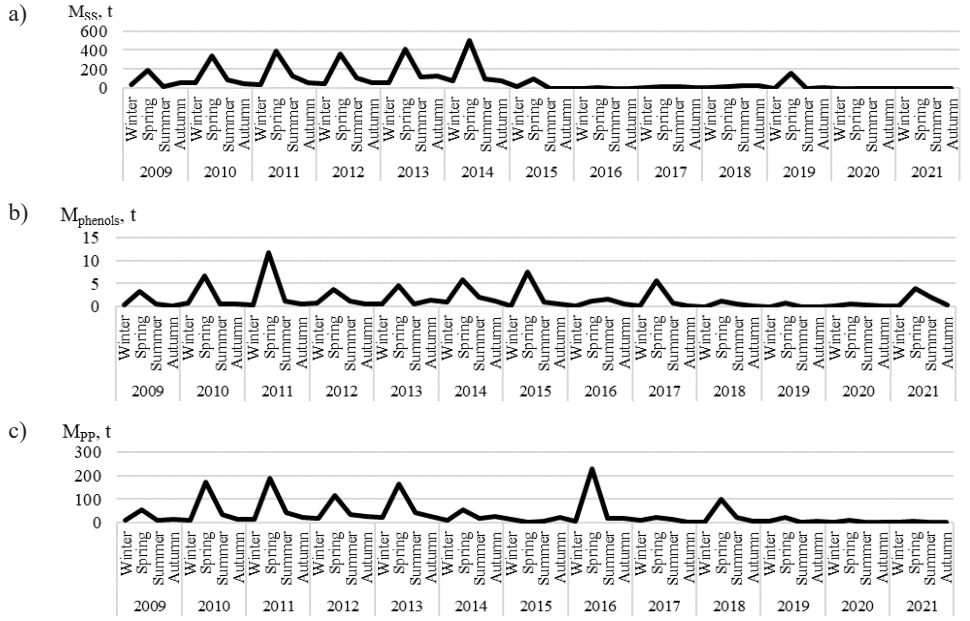

Figure 1 – Intra-annual fluctuations of toxic compounds transfer mass in the transboundary hydropost of the Zhaiyk River - Yanvartsevo village: a) synthetic surfactants; b) phenols; c) petroleum products

Heavy metals

A significant environmental concern is the evaluation of the quantity of heavy metals entering the country's territory through transboundary watercourses. A comprehensive data set pertaining to the heavy metal concern present within transboundary hydropost water was collected over the period of 2000-2022. However, for a considerable period, concentration data for the majority of the critical toxic elements were not accessible in the materials. More comprehensive array of data was obtained during the monitoring observations spanning the period from 2009 to 2022. These data have been deemed suitable for consideration of transboundary inflow of heavy metals and attendant changes in their concentrations along the river.

Tables 4 presents general information on the content of heavy metals in the transboundary river runoff and their annual average concentrations.

Table 4 – Concentration limits of heavy metals in transboundary runoff of the Zhaiyk River, 2009-2022, mg/dm^3

Heavy metals	MPC, mg/dm^3	Fluctuation range	Average
Iron total	100	57.500-316.667	151.637
Chrome (6+)	20	0-44.167	9.549
Chrome total	100	0-3.558	1.413
Manganese	10	0-6.125	3.904
Copper	1	0-0.317	0.191
Zinc	10	0-3.367	1.568
Cadmium	1	0-0.350	0.139
Lead	6	0-2.600	0.995
Nickel	8	0-1.917	0.585
Cobalt	5	0-1.925	0.710
Arsenic	2	0-0.492	0.113
Mercury	0.02	0	0

Exceedances of the MPC_f standard for annual average concentrations of total iron in river water were observed in nearly all years from 2009 to 2022, with the exception of 2015 and 2016. The maximum annual average concentration recorded at the level of 316.667 μg/dm^3 in 2009, and the minimum concentration was 57.500 μg/dm^3 in 2015.

The content of hexavalent chromium in the transboundary hydropost exhibited significant variability, ranging undetectable levels to the maximum of 44.167 μg/dm^3 (2011). Furthermore, from 2011 to 2013, exceedances of the normative level by annual average values up to 2.21 MPC_f were documented.

For the majority of the elements under consideration, including total chromium, manganese, copper, zinc, cadmium, lead, nickel, cobalt, and arsenic, no exceedances of their annual average concentrations in the transboundary river

runoff were observed. In certain years during the period from 2009 to 2022, data concerning these concentrations was not available. In the intra-annual regime, the maximum values of metals runoff are also observed in spring period (Figure 2). This phenomenon is attributed to flushing from adjacent areas to the riverbed due to an increase in river water flow and release of water on the floodplain during the flood period. As indicated by the works (Xie, et al., 2025; Xiaojie, et al., 2025; AI-Obaidy, 2024), analogous occurrences have been documented in other rivers throughout the continent.

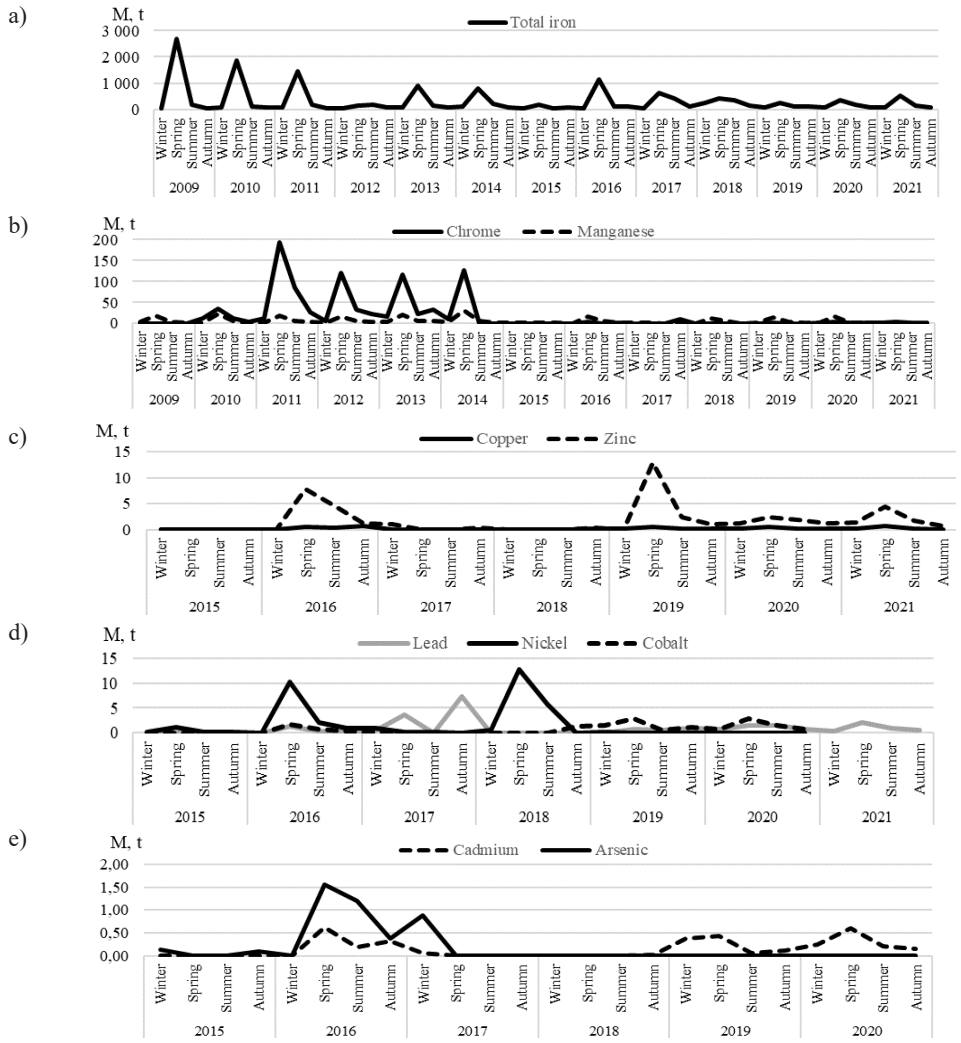

Figure 2 – Intra-annual fluctuations of heavy metals in the transboundary hydropost of the Zhaiyk River - Yanvartsevo village: a) total Iron; b) Chrome (6+), Manganese; c) Cooper, Zinc; d) Lead, Nickel, Cobalt; e) Cadmium, Arsenic

Transformation of toxic compounds occurs in the downstream section of the river

In order to conduct a comprehensive study of the nature of transformation along the Zhaiyk River, a set of substances was selected for analysis. These substances are characterized by elevated concentrations in the water samples and include: synthetic surfactants, phenols, petroleum products, and hexavalent chromium.

As illustrated in Figure 3, the average annual values of the synthetic surfactants in the water of the Zhayik River are depicted from the transboundary point (Yanvartsevo village) to the Malaya Damba village i.e., up to the confluence of the river with Caspian Sea. The figure illustrates the absence of exceedances of concentrations of synthetic surfactants (annual average) along the flow of the Zhaiyk River for the presented years. However, in certain years, namely 2014 near Uralsk ciry, Kushum and Taipak villages, 2012 near Atyrau city, and 2017 near Malaya Damba village, concentrations of synthetic surfactants were observed to come close to the normative value of 0.1 mg/dm^3.

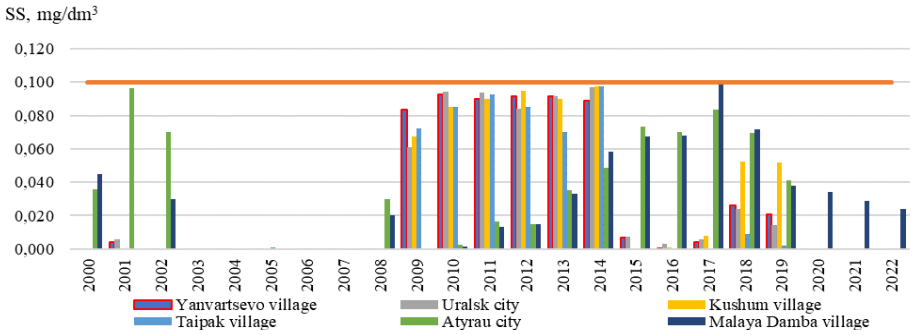

Figure 3 – Average annual values of synthetic surfactants in the water of the Zhaiyk River

As illustrated in Figure 4, phenols levels frequently exceed the normative level (0.001 mg/dm^3) in water of Yanvartsevo village (transboundary zone) and near Uralsk city. Further downstream, the maximum concentration of phenols was recorded near Kushum village (0.012 mg/dm^3) and Malaya Damba village (0.008 mg/dm^3) in 2010 and 2013, respectively.

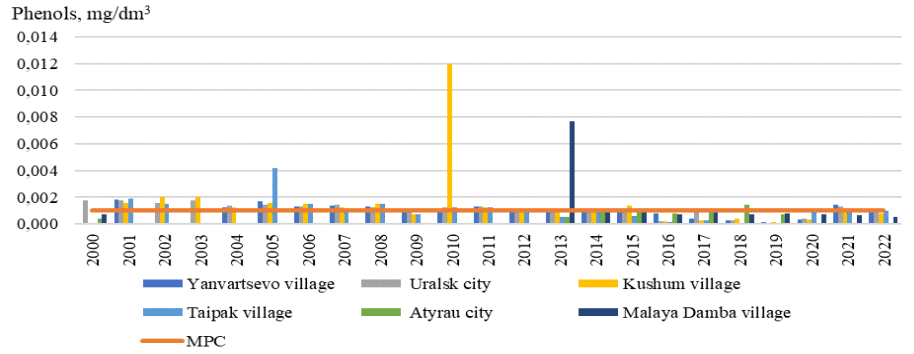

Figure 4 – Average annual values of phenols concentrations in water of the Zhaiyk River

As illustrated in Figure 5, there is a demonstrable multi-year fluctuation in the concentrations of petroleum products in water throughout the entire course of the Zhaiyk River. It is noteworthy that petroleum products exhibit a high degree of penetration into various environmental media (Vecchiato, et al., 2021), particularly soils and groundwater (Marić, 2020). For the years indicated in Figure 6, exceedances of the standards for this substance (0.05 mg/dm^3) were detected in a total of three cases: in Uralsk city in 2004 (0.071 mg/dm^3) and 2005 (0.058 mg/dm^3), as well as in Atyrau city in 2002 (0.070 mg/dm^3). These detections were made in areas with significant industrial activity. The examination of the data reveals a discernible downward trend in the annual average concentrations downstream of the river, commencing in 2018.

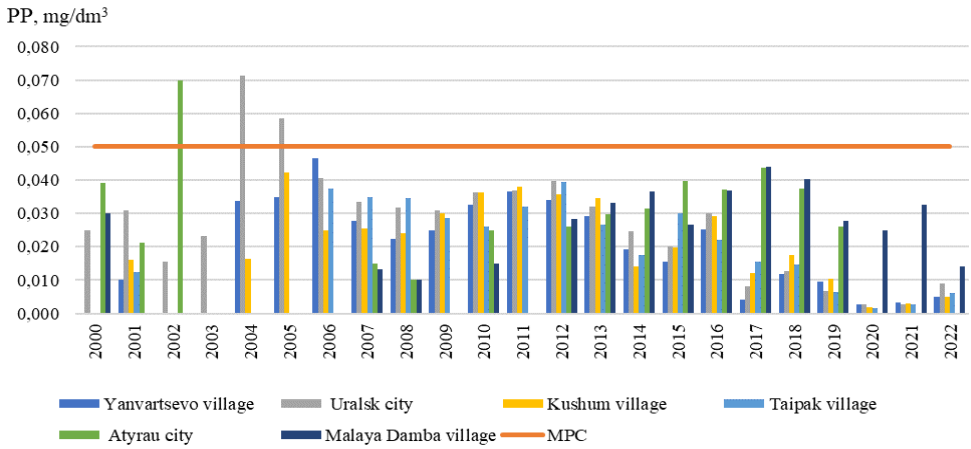

Figure 5 – Fluctuations of annual average concentrations of petroleum products in water of the Zhaiyk River

Among the heavy metals, the long-term dynamics of hexavalent chromium in river water is of particular interest (Figure 6). Increased pollution of water resources is associated with the presence of tailing ponds and other facilities of industrial enterprises both in Kazakhstan and Russia. Concentrations of this element exceeding the normative level (20 μg/dm^3) were recorded in the majority of river sections in 2008-2013. Its maximum concentrations were observed near Yanvartsevo village and Uralsk city in 2011, 2012, and 2013, with the concentrations of 44.2, 28.5, and 20.9 μg/dm^3 at the first point, and 30.0, 23.4, and 28.7 μg/dm^3 at the second one, respectively. Near Kushum village in 2011 and 2013 the maximum concentrations were 40.0 and 28.5 μg/dm^3; near Taipak village the maximum was observed in 2011 (50.0 μg/dm^3). Moreover, in the water of lower reaches of the river the content of this element significantly decreases, near Atyrau city only in 2008 the level of MPC_f was exceeded at the concentration of 68.8 μg/dm^3; and in Malaya Damba village exceeding concentrations were not observed.

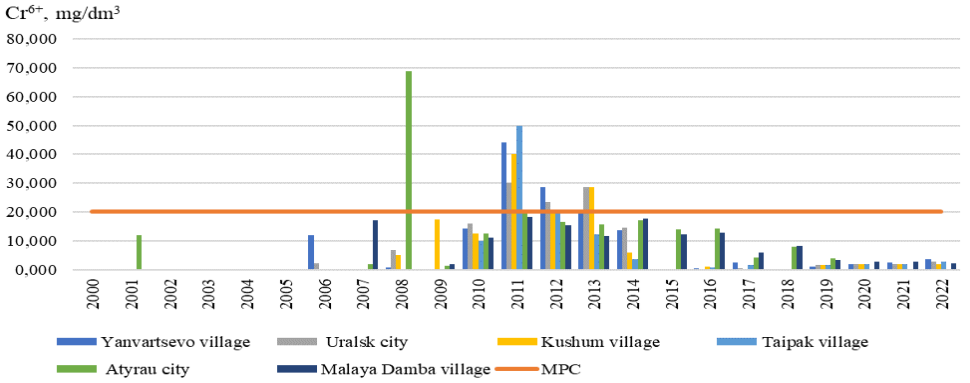

Figure 6 – Fluctuations of annual average concentrations of hexavalent chromium in water of the Zhaiyk River

Conclusion

The study of the toxic compounds present in the transboundary flow of the Zhaiyk River revealed that the concentrations of total iron, hexavalent chromium, and phenols exceeded the established normative levels. The presence of these toxicants above the established standards was frequently observed downstream of the river, in the majority of hydroposts, and in the vicinity of industrial cities.

The maximum inflow of all toxic compounds to the territory of the Republic of Kazakhstan is registered during spring floods, caused by the increase of water flow and intensification of denudation processes in the basin territory during snowmelt.

A comprehensive analysis of long-term materials from State monitoring indicates that phenols, petroleum products, and hexavalent chromium are the most critical pollutants affecting the river on the territory of Kazakhstan. The level of river water pollution by these toxic compounds is significantly higher in the transboundary zone of the river under the influence of transboundary runoff. However, the persistence of elevated concentrations of these compounds downstream may be attributed to the influx of industrial and other effluents into the river system within the Republic's territory.

The results of the study can be informed for the development of practical measures by the regional conservation authorities to protect the river from pollution. A thorough examination of the long-term monitoring observations reveals the irregularity of the performed observations for toxicants at several monitoring points (hydroposts). It is imperative to expend the scope of the study to encompass a more extensive array of analyzed toxic substances, including persistent organic pollutants. This expansion is particularly crucial in light of the significance of the significance of this transboundary river.

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D.B.; visualization, **D.B.**; writing—original draft, **N.A.** and **D.B.**; writing-review and editing, **D.B.** All authors have read and agreed to the published version of the manuscript.

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