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Tracking pollution and its sources in the catchment-lake system of major waterbodies in Kazakhstan

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Abstract

The objective of the present study was to identify the sources and routes of entry of heavy metals and nutrients into several large waterbodies in the arid zone of Kazakhstan, namely Lake Balkhash and Samarkan and Shardara reservoirs. A data visualization method was used for this purpose. Statistical mapping, based on referencing coordinates of the material selection points, was performed with the Statistics 12.0 program. Matching statistical maps with the waterbody contours was performed in Adobe Photoshop. Maps of the spatial distribution of heavy metals (cadmium, nickel, cobalt, lead, zinc and copper) and nutrients were constructed for all three study waterbodies. Data visualization clearly illustrated the relationship between the distribution of pollutants in the study waterbodies, as well as the sources of anthropogenic pollution. Based on the mapping exercise, it was established that Cu and Zn entered the waterbodies mainly in agricultural waste waters, while Cd, Ni, Co, Pb and partly Zn entered the waterbodies mainly in industrial and surface run-off. Nutrients enter the waterbodies mainly in river and municipal waters. The constructed maps demonstrate the role of the constant flow in the distribution of pollutants in the waters of Lake Balkhash. The results also indicate that statistical mapping is an effective tool for identifying the sources and routes of pollutant entry into waterbodies. The imposition of statistical maps on the contours of waterbodies of concern provides a mapping method allowing for more visually compelling data and information for a wide circle of users and managers.

KEYWORDS
catchment-lake system, heavy metals, Kazakhstan, nutrients, statistical mapping, Waterbodies

1 | INTRODUCTION

Observing anthropogenic impacts on aquatic ecosystems occurs not only in countries with an arid climate and water scarcity (Lapworth et al., 2017), but also in densely populated areas with industrial and agricultural development (Bhateria & Jain, 2016; Strzebońska, Krzemińska, & Adamiec, 2017). Assessing water quality and its suitability for various purposes is typically based on determining the concentrations of pollutants in a waterbody (Bhutiani, Kulkarni, Khanna, & Gautam, 2017; Mahato, Mahato, Karna, & Balmiki, 2018; Zhao, Ye, Yuan, Ding, & Wang, 2017), soils (Maleki, Amini, Nazmara, Zandi, & Mahvi, 2014) or in aquatic biota (Abalaka, 2015). This approach, however, has several limitations, attributable primarily to annual increases in the types of pollutants entering the environment. Because of the multidirectional interactions of pollutants with each other, it is extremely difficult to assess the magnitude of their negative impacts to natural ecosystems and human health (Tijani, Fatoba, Babajide, & Petrik, 2016). Since it is not feasible to control all pollutants entering waterbodies, one can only consider a limited set of the most significant pollutants within the process of environmental monitoring. Major attention is given to heavy metals (Ojekunle et al., 2016; Rajkowska & Protasowicki, 2013), which represent a particular hazard to the health of natural ecosystems and humans (Ahmed et al., 2016; Javed & Usmani, 2016; Kawser et al., 2016).

In contrast to chemical analysis methods, bioindicator methods allow for an integrated assessment of the quality of the aquatic environment (Aazami, Sari, Abdoli, Sohrabi, & Van den Brink, 2015; Dembowska, Mieszczankin, & Napiórkowski, 2018). The widespread use of bioindicators for assessing the ecological situation of waterbodies rests in the fact that the structure of biological communities is a function of the influence of the whole spectrum of natural and anthropogenic factors, with the bioindicators providing an integral response to this situation. The effectiveness of the bioindication method in environmental studies has been reported by a number of researchers (Ieromina, Musters, Bodegom, Peijnenburg, & Vijver, 2016; Ochocka & Pasztaleniec, 2016; Rocha, Andrade, & Lopes, 2015; Svensson, Bellamy, Van den Brink, Tedengren, & Gunnarsson, 2018).

In addition to using proper assessment methods, an important step in environmental research is presentation of the obtained results. Water quality assessment results are typically presented in the form of tables, graphs and diagrams (Ali, Hamed, & El-Azim, 2011; Dembowska et al., 2018; El-Kassas & Gharib, 2016; Klimaszyk, Rzymski, Piotrowicz, & Joniak, 2015; Ochocka & Pasztaleniec, 2016), making it sometimes difficult to readily interpret them. Accordingly, an informative method of presenting spatial data is development of statistical maps, which can be used for any data, including physical (Firoz, Laxmi, & Abdul, 2017), hydrochemical, toxicological (Krupa, Barinova, Tsoy, Lopareva, & Sadyrbaeva, 2017a), biological (Barinova, Krupa, & Kadyrova, 2017; Bresciani et al., 2018), evaluative and integrative (Barinova, Bilous, & Ivanova, 2016; Bilous, Barinova, Ivanova, & Huliaieva, 2016). Previous research has highlighted the effectiveness of this method for solving theoretical and applied ecology issues (Barinova & Krupa, 2017; Barinova et al., 2017; Krupa & Barinova, 2017; Krupa, Barinova, Amirgaliyev, Issenova, & Kozhabayeva, 2017b; Krupa, Barinova, Assylbekova, & Isbekov, 2018c; Krupa, Barinova, Isbekov, & Assylbekova, 2018a; Krupa, Barinova, Ponamareva, & Tsoy, 2018b; Krupa, Barinova, Tsoy, et al., 2017a). The present study demonstrates further possibilities of utilizing cartographic methods in the ecological study of aquatic ecosystems.

Lake Balkhash and the Samarkan and Shardara reservoirs represent one of the largest fishery waterbodies in Kazakhstan. Their pollution is attributable mainly to the salts of heavy metals, with priority contributors being cadmium (Cd), copper (Cu), zinc (Zn) and lead (Pb) (Central and Eastern Kazakhstan, 2015; Russell et al., 2018). Further, significant quantities of nickel (Ni) and cobalt (Co) enter Lake Balkhash (Kudekov, 2002).

The present study focuses on identifying the sources and routes of the entry of heavy metals (Cd, Cu, Zn, Pb, Ni, Co) and nutrients into several large water bodies in Kazakhstan's arid zone, utilizing statistical maps.

2 | MATERIALS AND METHODS

2.1 | Description of study sites

The spatial distribution of pollutants was investigated in three large waterbodies of Kazakhstan, including Balkhash Lake (46°32′27″N and 74°52′44″E), Shardara Reservoir (41°07′51″N and 068°10′59″E) and Samarkan Reservoir (50°05′57″N and 072°55′32″E).

Balkhash Lake is the largest endorheic lake in Kazakhstan, located in the arid climatic zone in the southeast part of the country. The average temperature in January is about −14°C, which warms up to 30°C and higher in July. The average annual precipitation is 129.8 mm (Uteshev, 1959). North and northeast winds dominate in the region, with an annual average wind speed reaches 4.5–5.1 m/s (Cherednichenko & Cherednichenko, 2017).

The narrow strait divides the lake into the Western Balkhash and Eastern Balkhash. Balkhash Lake is 614 km long at a water level of 342 m. Its width reaches 9 to 19 km in the eastern part and up to 74 km in the western part (Kudekov, 2002). The water surface area is ~16,400 km^2, with a lake catchment area of 41,300 km^2. The Ili River flows into the Western Balkhash, while the Lepsy, Aksu and Karatal rivers flow into the Eastern Balkhash. The total volume of river flow into Lake Balkhash varies from 21.62 to 28.85 km^3, depending on the weather and climate conditions. More than 90% of the river flow is from the Ili River. There is a constant flow in the lake beginning in the Western Balkhash from the mouth of the Ili River towards the opposite bank, then moving through the strait to the eastern part (pink arrows in Figure 1).

Lake Balkhash is characterized by a pronounced gradient of all hydrophysical and hydrochemical parametrs (Tarasov, 1961). The maximal depth in the western and eastern parts of the lake reaches 7–11 and 20–27 m, respectively. The water transparency increases from 0.1–0.2 m in the western part in the zone of influence of the Ili River, to 10–12 m in the eastern part of the lake. Depending on the prevailing climatic conditions, the total dissolved solids (TDS) concentration in the lake water ranges from 0.6 to 1.2 g/dm^3 in the western part, to 4.0–5.6 g/dm^3 in the eastern part of the water area (Kudekov, 2002). The pH values vary from 8.05 to 8.60. The dissolved oxygen content reaches 7.40–9.32 mg/dm^3 (Samakova, 2003), with the oxidation of the water being 4.2–12.4 mg O/dm^3. The constant winds and relatively shallow depths result in constant wind mixing of the lake water, and the temperature and salinity stratification are very poorly expressed (Tarasov, 1961).

Deposits of polymetallic ores (Mazurov, 2005) determine the naturally occurring elevated levels of heavy metals in the soils of the region (Tilekova, Oshakbayev, & Yerubayeva, 2015), and in the sediments (Sharipova, 2015) and water of Balkhash Lake (Kudekov, 2002).

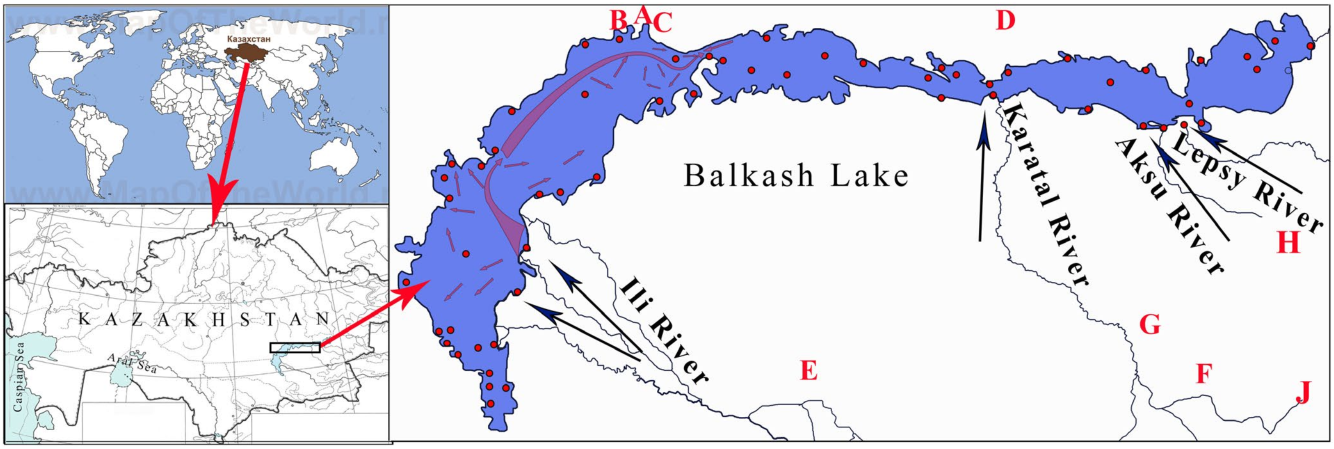

FIGURE 1 Map of study sites and potential pollution sources of Lake Balkhash. "Pollution Sources: A, Balkhash industrial complex and Konyrat field; B, tailing dump of Balkhash mining and smelting complex and central heating and power plant (TPP); C, "Balkhashfishprom" LLP and mining company "ABS-Balkhash"; D, Sayak field; E, Akdala array of rice cultivation; F, city of Taldykorgan; G, city of Ushtobe; H, irrigation fields; J, lead-zinc ore processing plant in city of Tekeli; blue arrows indicate direction of movement of water masses; pink arrows indicate the scheme of constant flow in Lake Balkhash"

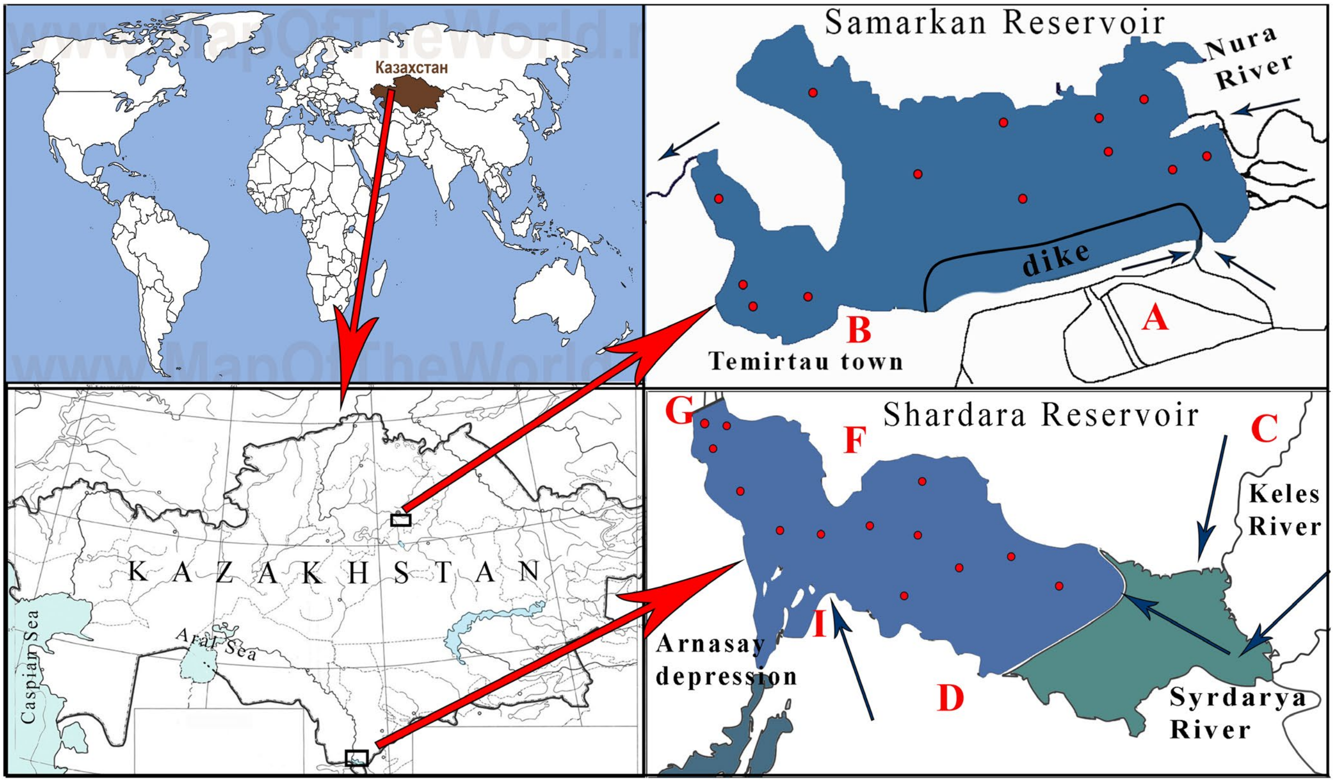

FIGURE 2 Map of study sites and potential pollution sources for Samarkan and Shardara reservoirs. "A, Industrial complex "ArcelorMittal Temirtau"; B, discharge of municipal waste waters of city of Temirtau; C, D, F, irrigation fields; E, agricultural wastewater discharges into Arnasay Bay; G, irrigation water withdrawal along Kyzylkum Canal; blue arrows indicate direction of movement of water masses"

Industrial complexes are located directly on the lake shore area (Figure 1A–C), and along the banks of the Karatal River (Figure 1G, F, J). The Konyrat copper deposit is located 15 km north of Balkhash city. The Sayak polymetallic deposit is 210 km east of Balkhash city and 30 km north of Balkhash Lake. The Akdala array of rice cultivation is located in the lower reaches of the Ili River (Figure 1E). The total area of irrigated land is ~30,000 ha, with the water volume withdrawn from the Ili River in 1990 to 2012 ranging from 629.8 to 990.2 million m^3, and the volume of return water being 112.36–320.12 million m^3 (Kurmashev & Sarsenbaev, 2013). Irrigation fields also exist along the Aksu and Lepsy Rivers (Figure 1H).

The Samarkan Reservoir (Figure 2) is situated in Central Kazakhstan in an extreme continental climate (Climate of Kazakhstan, 1959). The lowest average monthly air temperature in January reaches −30 to −31°C, with a maximum average July temperature of 24–28°C (Baltabaeva & Bogolyubova, 2012). The average monthly wind speed is 4–6 m/s, with the maximum wind speed reaching 15–28 m/s. The annual average quantity of precipitation does not exceed 250–300 mm.

Samarkan Reservoir is located on the Nura River, which originates at an altitude of 1,186 m above sea level and flows into Teniz Lake. The river is 978 km long, with a width varying from 5 to 10 m in the upper reaches to 30–40 m in the lower reaches (Akpambetova, 2005). The maximum depth in the summer is five metres, with an average of 1.0–1.5 m. The territory of the river basin is characterized by areas of pronounced insufficient moisture. The main annual runoff water volume (up to 90%) occurs in a short spring flood period.

Samarkan Reservoir was constructed in 1939 to supply water to the industrial Karaganda region. It has an area of ~51.5 km^2. The maximum depth is up to 9–11 m in the western part of the reservoir, while its eastern part is shallow, with depths of no more than 1.0–1.5 m (Malinovskaya & Ten, 1983). The maximum water temperature (up to 24–25°C) occurs in July. The water transparency reaches 0.2–0.8 m (Krupa, 2012). Depending on the year and season, the TDS varies from 0.8 to 1.2 g/dm^3. Industrial waste water discharged into the reservoir has a higher salinity of up to 1.2–1.4 g/dm^3 (Slivinsky, Krupa, & Akberdina, 2009). The oxygen content in the water reaches 8.4–11.6 mg/dm^3. The reservoir is not stratified because of its shallow depth and wind mixing of the water (Malinovskaya & Ten, 1983).

The city of Temirtau, with a population of about 180,000 people is located on the southern bank of the reservoir. Municipal sewage is discharged into the lower southern third of the reservoir (Figure 2B). The 'ArcelorMittal Temirtau', an industrial complex for the production of steel, is located on the eastern outskirts of the city. Industrial waste water flows into the southern part of the reservoir (Figure 2A), being fenced off with a dike to protect the main water area.

Shardara Reservoir (Figure 2) is located in south Kazakhstan in a continental climatic region (Uteshev, 1959). The winters are moderately warm, with thaws up to +10°C and cold spells up to −15°C, sometimes reaching −30°C. The summer is typically long and hot. The maximum temperatures reach 45–49°C. The average annual precipitation is 100–200 mm, reaching up to 1,600 mm in the mountains. The average wind speed reaches 2–4 m/s, with a maximal up to 30 m/s, with strong winds blowing for 55 days annually.

Shardara Reservoir was constructed in 1965 in the middle course of the Syrdarya River, which originates in the mountains of the Central Tien Shan. The river is fed mainly by snow and glacial melt and rainfall. It has a length of 2,212 km. The average long-term water flow is 724 m^3/s. The Keles River, which originates in the Karzhantau mountain range, also flows into the upper part of the reservoir. The river has a length of 241 km, with an average long-term water flow rate of about 6.5 m^3/s.

Shardara Reservoir is used for electricity generation, fishing and agricultural irrigation. Because of the annual water withdrawal for irrigation purposes, the reservoir water area varies from 150 km^2 in autumn, to 750 km^2 in spring. The upper part of the water area was drained during the present study (Figure 2, double line). The maximal depth recorded near the western dam of the reservoir varies from 9 to 20 m, depending on seasonal water level changes. The eastern part of the water area near the mouth of a river is shallow, with depths not exceeding 1.0–1.5 m. The water transparency is 0.2–6.0 m. The water temperature in May and July reaches 20–25°C, and up to 29–30°C in August (Malinovskaya & Ten, 1983). The oxygen content is 7.6–11.2 mg/dm^3, with a water oxidation of 2.5–5.2 mg O/dm^3. The TDS of the water reaches 0.9–3.2 mg/dm^3.

Irrigation fields are located along the southern and partly along the northern shore of the reservoir (Figure 2D–G). The drainage waters are discharged into its middle southern part into the narrow Gulf of Arnasai. The Keles River floodplain (Figure 2C) is also used for growing crops.

2.2 | Sample collection methodology

Study of Lake Balkhash was carried out in the summer of 2004, the Shardara Reservoir in the summer of 2016, and the Samarkan Reservoir in the summer of 2001 and 2008. A total of 84 surface water samples were collected to determine the heavy metal contents, including 58 water samples in Lake Balkhash, 13 samples in the Samarkan Reservoir and 13 water samples in the Sharada Reservoir. The same numbers of surface water samples were collected taken to determine the nutrient content (ammonia, nitrate, nitrite, phosphate). The heavy metal water samples were collected in plastic bottles with a volume of a half-litre and fixed in situ by adding nitric acid. The nutrient water samples were collected in glass bottles with a volume of a half-litre and fixed with 1 ml of chloroform. All collected samples were transported to the lab in an icebox. The geographical coordinates of the sampling sites were determined with a Garmin eTrex GPS-navigator.

2.3 | Methods for analysing nutrient and heavy metal contents

Standard methods of chemical analysis for nutrients were used for the collected water samples, which were analysed in three to four replications (Semenova, 1977). The error of estimate for major ions in the water was 0.5 to 5.0%, depending on the analyte.

The concentrations of cadmium (Cd), copper (Cu), zinc (Zn) and lead (Pb) were determined for all three waterbodies. Cobalt (Co) and nickel (Ni) were also determined for Lake Balkhash water samples. Heavy metal concentrations were carried out in the analytical laboratory 'KAZEKOANALIZ' (accreditation certificate No. KZ.I.02.1017), consistent with the Interstate standard ISO 17294-2-2006, M-02-1109-08 (2013). Heavy metals were measured by mass spectrometry analysis with inductively coupled plasma, using Agilent 7500 A manufactured by Agilent Technologies, USA (National Standard

RK ISO). This device detects various chemical elements in complex matrices, including those in the sea and greywater, and also in biological samples in micro-trace quantities. Concentrated nitric acid (based on 1 cm^3 of nitric acid per 200 cm^3 of water) was added to the analysed water samples before the analysis. The samples were heated in a current of inert gas (argon) according to a program comprising drying, ashing, atomization, and annealing of the furnace (abundance sensitivity of Agilent 7500 A: Low Mass <5 × 10^{-7}, High Mass <1 × 10^{-7}. The minimal detection limit for Cd is 0.001 mg/dm^3, for Co is 0.0004, for Cu is 0.0006, for Ni is 0.0025, for Pb is −0.005 and for Zn is 0.001 mg/dm^3.

2.4 | Statistical analysis

Maps of the distribution of the analysed variables across the waterbodies were constructed by referencing the coordinates of sampling sites, using the program Statistica 12.0, including 3D Graphs 'Surface Plot'. The contours of the waterbodies were then drawn, based on Google maps in the Adobe Photoshop program. Statistical maps were combined in the same program with contour maps of the waterbodies, based on the combination of sampling points on a contour map and a statistical map. All the statistical maps had legends, indicating the location of the gradients of the measured concentrations of heavy metals and nutrients, with the highest values of the analysed variables marked in red and the lowest values marked in dark green.

3 | RESULTS

3.1 | Brief hydrophysical and hydrochemical characteristics of the waterbodies

Shardara Reservoir water was characterized by the highest temperatures, maximum average water transparency and minimum total dissolved solids (TDS) values during the study (Table 1). The hydrophysical and hydrochemical variables in the shallow Samarkan reservoir were close to each other in both 2001 and 2008. The water transparency was minimal, compared to other waterbodies. The TDS concentration was on average slightly higher than in Shardara Reservoir, but lower than in Lake Balkhash. Further, all the variables varied significantly in Lake Balkhash. Water temperature, depth, water transparency, TDS, pH and water oxidizability increased in a west to east direction, and the average oxygen concentration was slightly decreased.

3.2 | Heavy metals and nutrients

The heavy metal concentrations in the water varied significantly among the waterbodies (Table 2). The highest average concentrations of Zn and Cu were observed in Shardara Reservoir, and Cd in Samarkan Reservoir. The average Pb concentration was at the same level in Shardara Reservoir and Lake Balkhash. Phosphate and ammonia were present at the highest concentrations in Samarkan Reservoir, while the maximum nitrate concentration was observed in Shardara Reservoir.

The average Zn, Cu, nitrate and nitrite concentrations in the western part of Lake Balkhash were higher than in the eastern part (Table 2). Compared to the western part, the eastern part of Lake Balkhash was characterized by higher average Pb, Co and phosphate concentrations.

3.3 | Spatial data mapping

3.3.1 | Lake Balkhash

The heavy metal distribution across Lake Balkhash was uneven (Figure 3). The highest Cd, Ni, Co and Pb concentrations were observed in the eastern part of the lake, while Zn and Cu concentrations were higher in the western part of the lake. The highest Zn, Cu, Ni and Co concentrations were only observed in certain areas of the lake, while elevated Cd and Pb concentrations were observed across larger areas of the lake.

High concentrations of nitrite, nitrate, ammonia and phosphate were observed in certain locations (Figure 4). Increased nutrient contents, except for ammonium, were observed at the estuaries of the rivers, or in more extensive areas under the influence of river flows. The highest concentrations of ammonium were observed near the northern shore and in the area of the strait connecting the western and eastern parts of the lake.

Correlation analyses indicated strong positive statistically significant relationships between the spatial distribution of Cd and Pb, Cd and Co, PO_4 and Pb, Cd and Co over the lake (Table 3). The relationships between the contents of Cd and Ni, Co and Ni in water were moderate in strength. Weak relationships were revealed between the spatial distribution of nitrites, nitrates and copper, as well as between nitrites and zinc.

3.3.2 | Samarkan Reservoir

The obtained data indicate the Cu and Pb concentrations decreased in the direction from the shallow eastern part of Samarkan Reservoir towards the western deeper part (Figure 5). Increased Zn concentrations were observed in the southeastern part of the reservoir, including the zone adjacent to the protective dike. Cd was most abundant in the southwestern part of the reservoir, including the area immediately next to the dike.

The nutrient concentrations changed significantly across the water area (Figure 6). The maximal nitrite and ammonium concentrations were observed in the Nura River estuary, and partly in the area adjacent to the dike. High phosphate concentrations were observed nearly across the entire water body, except for a small area along

TABLE 1 Hydrophysical and hydrochemical variables of study waterbodies (mean value with standard error)

Variable	Lake Balkhash 2004 Whole lake	West	East	Samarkan Reservoir 2001	2008	Shardara Reservoir 2016
Temperature (°C)	24.14 ± 0.14	23.49 ± 0.16	24.77 ± 0.14	23.40 ± 0.10	23.80 ± 0.61	27.54 ± 0.46
Depth (m)	5.58 ± 0.49	4.34 ± 0.28	6.86 ± 0.81	2.03 ± 0.80	3.83 ± 0.49	7.85 ± 1.15
Water transparency (m)	1.13 ± 0.15	0.53 ± 0.02	1.74 ± 0.25	0.28 ± 0.05	0.31 ± 0.49	1.47 ± 0.24
Total dissolved solids (TDS; mg/ dm^3)	2.29 ± 0.24	1.08 ± 0.08	3.44 ± 0.29	1.20 ± 0.05	1.34 ± 0.23	1.05 ± 0.02
pH	8.63 ± 0.04	8.52 ± 0.02	8.74 ± 0.09	8.30 ± 0.03	8.25 ± 0.05	8.55 ± 0.01
Dissolved oxygen (mg/ dm^3)	7.40 ± 0.31	7.76 ± 0.35	7.39 ± 0.38	–	–	–
Oxidizability (mg O/dm^3)	7.25 ± 0.41	5.07 ± 0.40	9.13 ± 0.45	–	–	–

TABLE 2 Heavy metal and nutrient concentrations in study waterbodies (mean value with standard error)

Variable	Balkhash Lake Whole lake	West	East	Samarkan Reservoir	Shardara Reservoir
Concentration (mg/dm^3)					
Zn	0.028 ± 0.009	0.039 ± 0.018	0.017 ± 0.002	0.004 ± 0.001	0.121 ± 0.040
Cu	0.018 ± 0.003	0.022 ± 0.005	0.013 ± 0.002	0.004 ± 0.001	0.040 ± 0.006
Cd	0.004 ± 0.0002	0.003 ± 0.001	0.004 ± 0.001	0.006 ± 0.001	0.003 ± 0.001
Pb	0.034 ± 0.003	0.021 ± 0.002	0.047 ± 0.004	0.001 ± 0.0001	0.034 ± 0.014
Ni	0.039 ± 0.001	0.037 ± 0.002	0.042 ± 0.002	–	–
Co	0.013 ± 0.001	0.010 ± 0.005	0.017 ± 0.001	–	–
NH_4	0.102 ± 0.017	0.103 ± 0.013	0.102 ± 0.033	0.685 ± 0.041	0.115 ± 0.020
NO_3	0.945 ± 0.244	1.379 ± 0.412	0.492 ± 0.226	0.006 ± 0.003	5.450 ± 0.130
NO_2	0.042 ± 0.011	0.060 ± 0.013	0.024 ± 0.016	0.020 ± 0.007	0.092 ± 0.025
PO_4	0.017 ± 0.004	0.011 ± 0.003	0.023 ± 0.007	0.180 ± 0.023	0.026 ± 0.004

Note: Zn, zinc; Cu, copper; Cd, cadmium; Pb, lead, Ni, nickel; Co, cobalt; NH_4, ammonium; NO_3, nitrate; NO_2, nitrite; PO_4, phosphate.

the northern coast of the reservoir, with maximum values observed along the whole length of its southern coast. The highest nitrate concentration was observed in the southwestern and central parts of the reservoir.

Correlation analysis revealed a close positive statistically significant relationship between the spatial distribution of copper and lead ($R = 0.939$, $p < .05$), as well as nitrite and ammonium ($R = 0.985$, $p < .05$).

3.3.3 | Samarkan Reservoir

The maximum Zn concentrations, based on mapping, were observed in the northeastern part of the reservoir, whereas the maximum Cu concentration was observed in the area from Arnasai Bay to the dam (Figure 7). The highest Cd and Pb concentrations were observed in the central part of the reservoir and near the dam.

The nutrient distribution in Shardara Reservoir is illustrated in Figure 8. The eastern part of the reservoir was characterized by the highest nitrite concentration and partially phosphate. Elevated nitrate concentrations were observed over a wide area from about the middle of the reservoir to the western zone near the dam. The maximal ammonium concentration was observed in a relatively small zone occupying the middle part of the reservoir between the southern and northern shores.

Correlation analysis revealed a close positive statistically significant relationship between the spatial distribution of nitrite and zinc ($R = 0.939$, $p < .05$), as well as lead and ammonium ($R = 0.985$, $p < .05$).

4 | DISCUSSION

Complex analysis methods, such as multidimensional statistical methods, are typically used to assess the contribution of anthropogenic sources to the overall pollution levels of natural ecosystems (Esakkimuthu, Vinod Kumar, & Ponram, 2015; Zamani, Yaftian, & Parizanganeh, 2012), in combination with GIS technologies (Ahmed et al., 2016) and modelling (Zhang & Xin, 2017). The results of the present study, however, suggest a simpler means

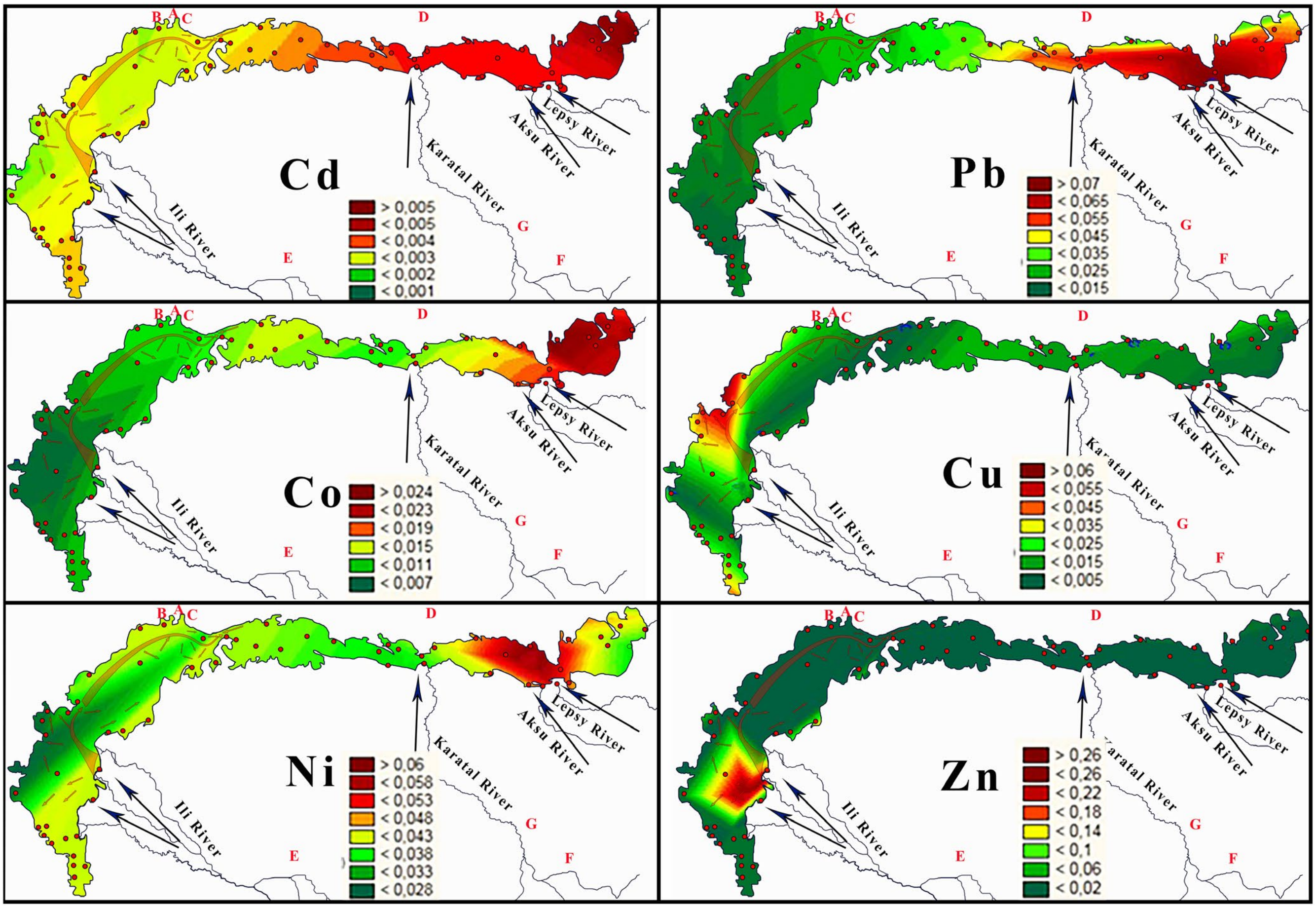

FIGURE 3 Heavy metal distribution in Lake Balkhash

of solving a main ecology; namely, identification of the potential sources of pollution, and how the pollutants enter the aquatic ecosystems.

Statistical maps were used in earlier environmental studies (Barinova & Krupa, 2017; Barinova et al., 2017; Krupa & Barinova, 2017; Krupa, Barinova, Amirgaliyev, et al., 2017b; Krupa, Barinova, Assylbekova, et al., 2018c; Krupa, Barinova, Isbekov, et al., 2018a; Krupa, Barinova, Ponamareva, et al., 2018b; Krupa, Barinova, Tsoy, et al., 2017a). Within the framework of the present study, however, overlaying of statistical maps on the contours of waterbodies for the first time made data visualization easier for analysis purposes, compared to previous methods.

The data mapping employed in the present study allowed for identification of some general trends of pollutant movement and flows into the examined waterbodies, allowing also for a reasonable assumption about the main sources of the observed pollutants. As illustrated in the maps (Figure 3), the heavy metals can be conditionally divided into three groups, based on the nature of their spatial distribution, as discussed in the following sections.

The first group included copper and zinc. The maximum Zn concentration observed in the present study was in the southeastern bay of West Lake Balkhash, into which the Ili River flows. In contrast, the Cu concentration was greatest near the opposite shore of the lake. These distribution features suggest that Zn and Cu entered West LakeBalkhash mainly via discharges into the Ili River, or drainage discharges from rice fields located in its lower course (Figure 1E). Copper and zinc are components of complex fertilizers, and their increased concentrations in the river flow zone of influence also indirectly suggest the input of a whole complex of other pollutants as well (Sadykova, 2002). Elevated copper concentrations in Lake Balkhash are also associated with natural causes, being observed in the background parts of the Ili river (Slivinsky, Krupa, Lopatin, Mamilov, & Prikhodko, 2010). The existing constant current carries these metals further along the water area, as clearly seen on the maps (Figure 3). Water masses move from the mouth of the Ili River to the northwestern coast, and further to the east, of the lake (Figure 1, pink arrows). The map indicates the Sayak copper deposit on the northern coast of East Lake Balkhash (Figure 1D) made a significantly smaller contribution to the lake pollution, compared to agricultural run-off.

The second group of metals included Co and Ni, with their maximum concentrations being observed in East Lake Balkhash in the Lepsy and Aksu rivers zone of influence. The Cd and Pb distribution (third group) was different from the distribution of other metals, since the zone of their maximum concentrations was more extensive, including almost the entire East Lake Balkhash water area. Based on

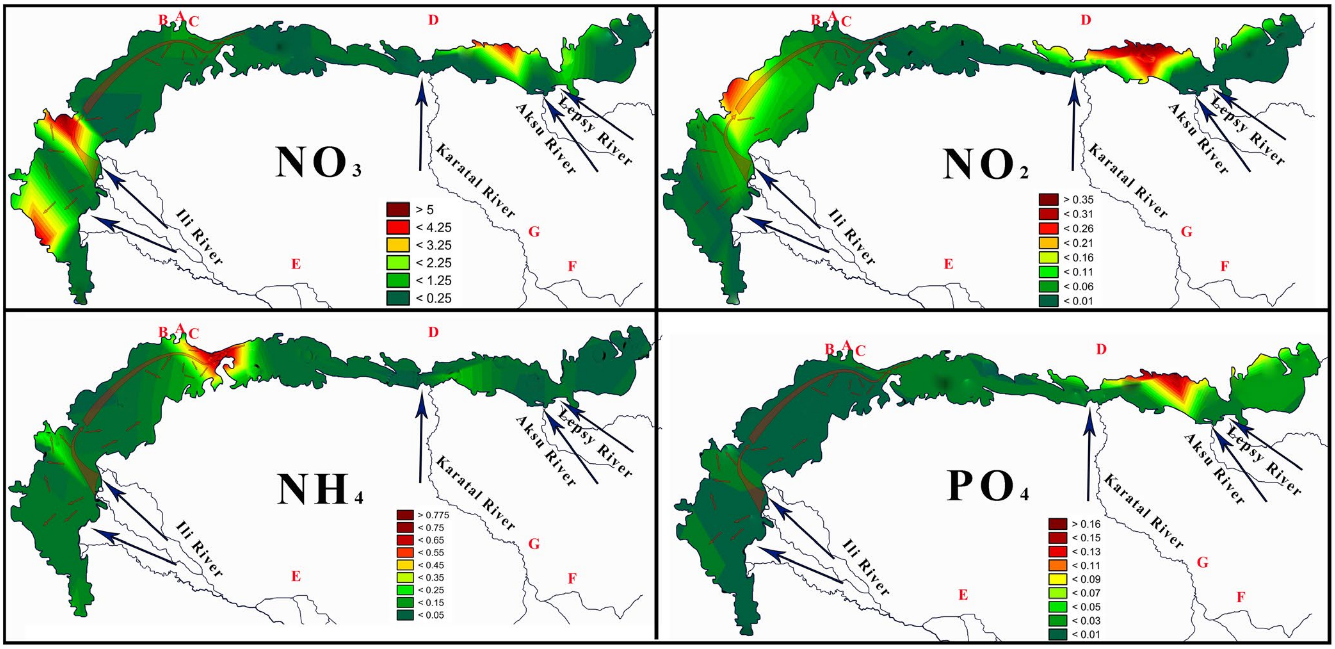

FIGURE 4 Nutrient distribution in Lake Balkhash

TABLE 3 Spearman correlation coefficients for heavy metal and nutrient concentrations in Lake Balkhash (p < .05)

Paired variables	Spearman rank correlation coefficient	Paired variables	Spearman rank correlation coefficient
Cd–Pb	0.843	PO_4–Pb	0.715
Cd–Ni	0.554	PO_4–Co	0.779
Cd–Co	0.783	NO_2–Cu	0.527
Co–Ni	0.528	NO_3–Cu	0.457
PO_4–Cd	0.714	NO_2–Zn	0.420

Note: Cd, cadmium; Pb, lead; Ni, nickel; Co, cobalt; PO_4, phosphate.

the maps (Figure 3), the increased pollution of East Lake Balkhash by Cd, Ni, Co and Pb is attributable to several factors. The source of toxic pollution in this part of the lake may be industrial enterprises of cities located in the middle and upper reaches of the Karatal River (Figure 1F, G, J). The town of Tekeli, for example, has a lead and zinc plant, and a tailing dump area of 69 hectares (Samakova, 2003). After a preliminary biological treatment, the industrial waste water is discharged into the Karatal River (Mitrofanova & Kalita, 2014). It appears the treatment of industrial waste water was not effectively carried out during the study period, with the pollutants flow into Lake Balkhash with the waste waters and accumulating there. Toxic pollutants can be attributable to the Aksu and Lepsy river flows because of the drainage waters entering them (Figure 1H). A potential source of toxic pollution to the lake may be the Sayak field (Figure 1D), although it is located in the lake offshore. Contaminants also can be carried into Lake Balkhash through the atmosphere. As the mapping exercise reveals, however, based on an assessment of the impacts of the Ryazan Thermal Power Plant on the environment (Barinova, 2017), the pollutant influx into the lake via the atmosphere is significantly less than the contribution from river and surface run-off into the lake.

Elevated nutrient concentrations also have been observed in selected areas of Lake Balkhash. The highest nitrate, nitrite and phosphate concentrations were confined to the river estuaries and larger areas influenced by river flows (Figure 4). It is evident the input of fresh organic pollution is mainly attributable to wastewater discharges from the Balkhashrybprom Enterprise (Figure 1C), which carries out fish processing, as exemplified by a local increase in ammonium concentrations near the northern coast of West Lake Balkhash (Figure 4).

Positive statistically significant relationships between some metals, as well as between metals and phosphate (Table 3) indicated the combined entry of toxic and organic pollution into Lake Balkhash.

The mapping results (Figures 5, 6) indicate the three main Samarkan Reservoir pollution sources include Nura River inflows (Cu, Pb, Zn, nitrite, partially phosphate, and ammonium), municipal waste waters of the city of Temirtau (nitrate, partly phosphate) and industrial effluents (Cd, partly Zn) positioned at the southern coast (Figure 2). Although this part of the reservoir is fenced with a dike, industrial effluents contaminated with Cd and Zn are seeping into the main part of the reservoir water area. The Nura River is one of the most polluted rivers in Kazakhstan (Akpambetova, 2005), with

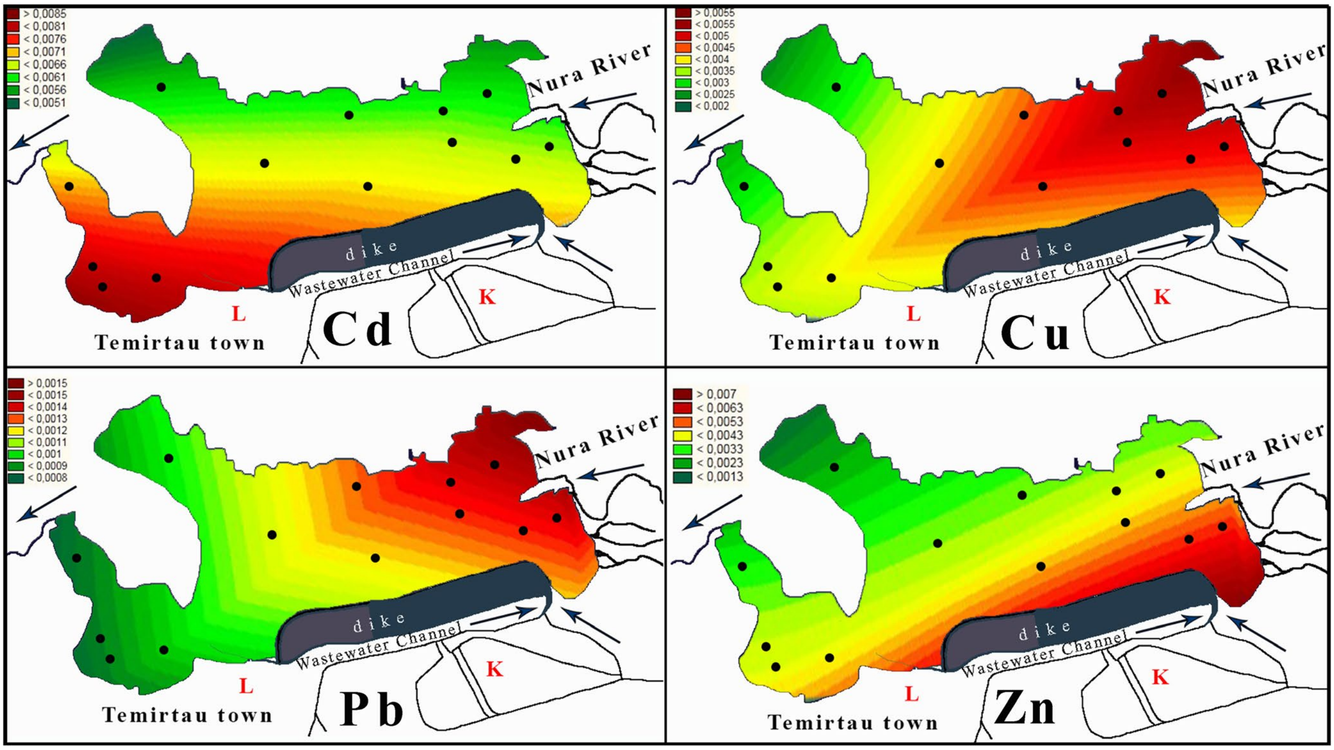

FIGURE 5 Heavy metals distribution in Samarkan Reservoir

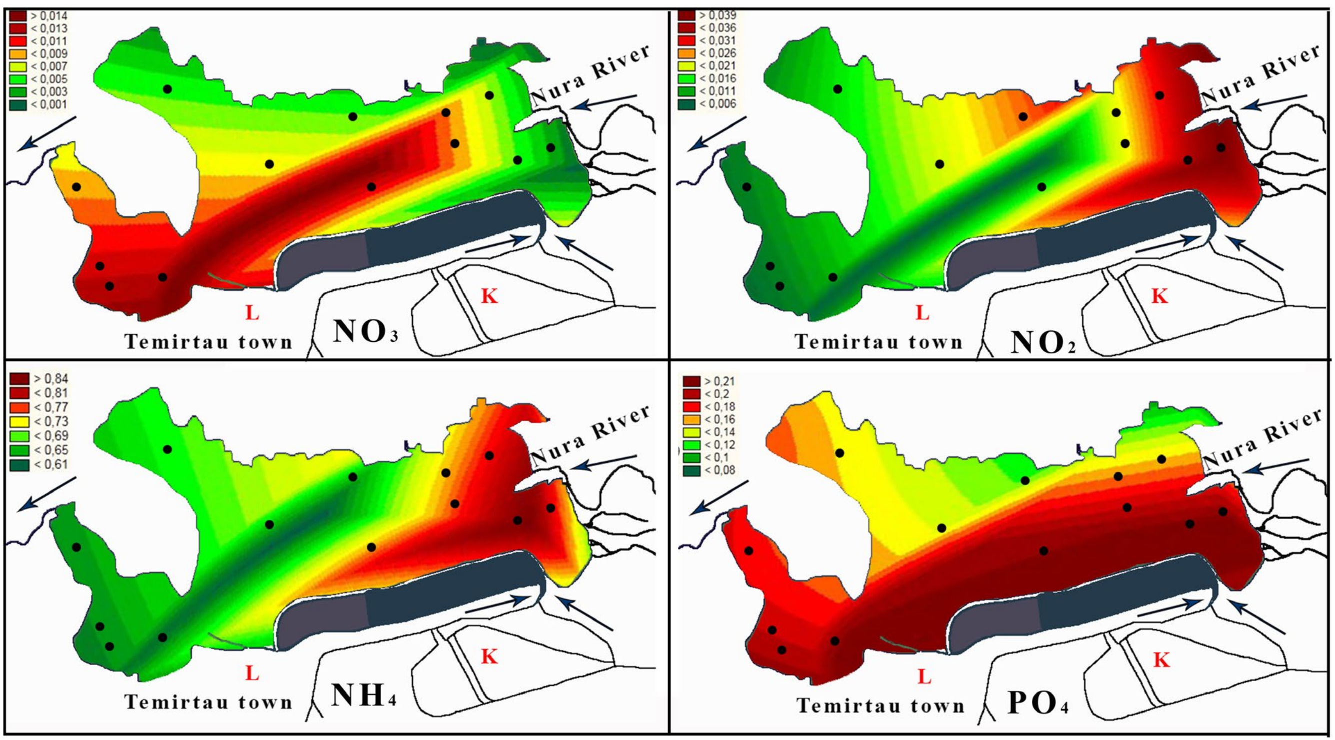

FIGURE 6 Nutrient distribution in Samarkan Reservoir

available data indicating elevated concentrations of heavy metals, oil products, organic and nitrogen-containing substances, phosphates, synthetic surfactants, cyanides, fluorine being observed in various parts of the river ecosystem (Alexandrova & Novikova, 1996) and in industrial wastewater canals (Matmuratov et al., 2005).

The spatial distribution of pollutants in Shardara Reservoir (Figures 7, 8) leads to the conclusion that Zn, nitrite and phosphate enter the reservoir mainly in river run-off, whereas Cu, nitrate and ammonium enter with drainage waste water. This is exemplified by the identified zones with maximum values of analysed

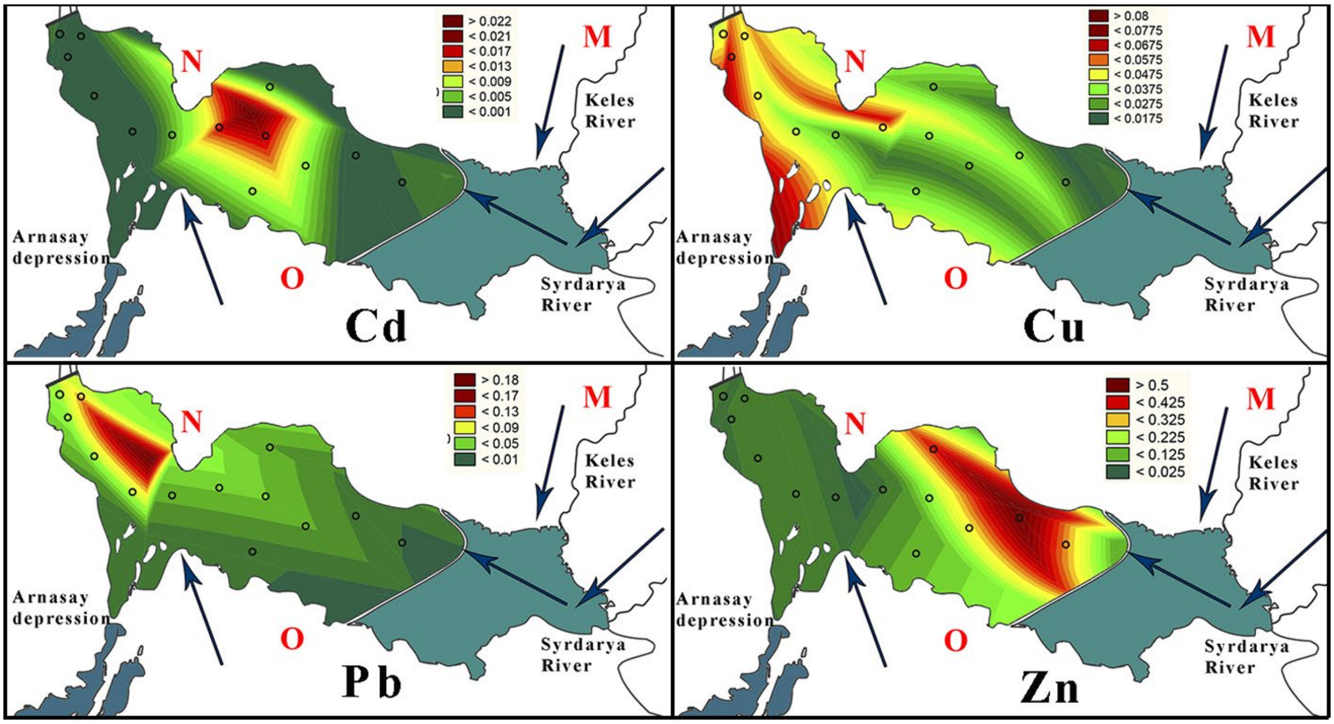

FIGURE 7 Heavy metals distribution in Shardara Reservoir

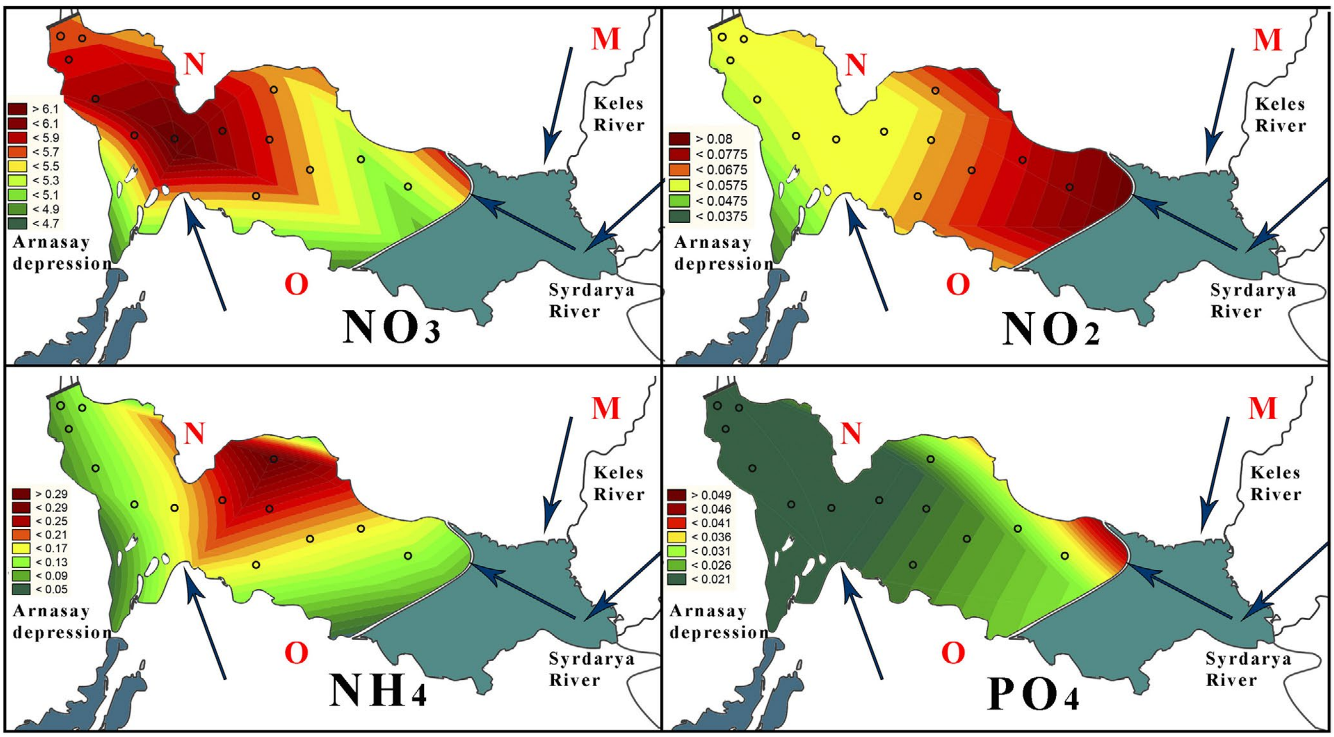

FIGURE 8 Nutrient distribution in Shardara Reservoir

variables, with Zn, nitrite, and phosphate being most abundant in the eastern upper part of the reservoir in the zone of influence of the Syrdarya and Keles rivers, while Cu, nitrate and ammonium are most abundant in the western lower part of the reservoir in the water area from Arnasai Bay to the opposite northeastern coast. As noted above, drainage water is discharged directly into Arnasai Bay (Figure 2E). Nitrate and ammonium also can flow into Shardara Reservoir in run-off from livestock farms, with livestock grazing occurring mainly along the northern shore of the reservoir (Figure 2F). The predominant flow of Zn with the Syrdarya waters is attributable to the transboundary position of the river (Abbink, Moller, & O'Hara, 2010; Guo, Zhou, Xia, & Huang, 2016) which absorbs agricultural run-off from the territory of neighbouring states. Irrigation fields are also located in the Keles River floodplain (Figure 2C), contributing to the overall pollution of the reservoir.

Based on these mapping results, the main pollution sources of the study waterbodies are agricultural fields, industrial enterprises located directly on the shore of the water bodies and on the territory of their catchment basins, and municipal waste waters. It is noted that the water pollution from Cu and Zn is attributable mainly to agricultural run-off, which contains many complex fertilizers components (Wang et al., 2014). Industrial effluents are the source of Cd, Ni, Co and Pb to the study lakes. Thus, the results of the present study highlight existing problems related to water uses in the arid regions of Central Asia, a condition also noted by other researchers (Barrett, Feola, Khusnitdinova, & Krylova, 2017; Russell et al., 2018).

In conclusion, the results of the present study indicate data mapping is a fast, convenient and descriptive means of assessing the ecological state of waterbodies. The value of this method for environmental monitoring was earlier reported for waterbodies in various other natural zones, including the Jordan River (Israel), Sassyk Reservoir (Ukraine), and Ryazan State District Power Plant (Russian Federation) (Barinova, 2017; Bilous et al., 2016). Thus, it is easier to interpret cartographic data, rather than analysing tables and histograms. Indeed, data visualization provides a good means of presenting complex data and information to the public, officials and politicians, the latter being especially important for making management decisions to reduce anthropogenic pressures on aquatic ecosystems (Haddaway, Bernes, Jonsson, & Hedlund, 2016), as well as regulating water uses, including the transboundary implications.

5 | CONCLUSION

Analysis of the spatial distribution of heavy metals and biogenic elements make it possible to identify the potential sources and routes of pollutants entering the three examined Kazakhstan waterbodies. The data mapping results identified the main sources of toxic pollution of the study waterbodies are agricultural fields and industrial enterprises located directly on the banks of the waterbodies, and in the territory of their catchment basins. River and surface run-off deliver pollutants to waterbodies, with the mapping results of the present study highlighting the role of intrabasin flows in the spread of pollutants in the waters of Lake Balkhash. It is noted that the pollution from Cu and Zn is attributable mainly to agricultural wastewater discharges, with the quantity of these heavy metal pollutants in these drainage discharges being greater than in industrial effluents of enterprises engaged in direct mining and processing of polymetallic ores. On the other hand, industrial enterprise activities contribute to pollution of the study waterbodies from Cd, Ni, Co and Pb. Livestock farms and municipal waste waters are sources of nitrogen and phosphorus compounds to the waterbodies. The present study results also demonstrate the usefulness of data mapping as a tool for assessing the ecological state of waterbodies. To this end, the imposition of statistical maps on the contours of waterbodies makes the mapping method more convenient for a wide range of officials and ecologists to perceive environmental information. These results also indicate data visualization can be widely used in environmental monitoring focused on conservation and rational use of water resources.

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