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Assessment of quantity and quality indicators of water resources in the Zarafshan river basin (within the territory of Uzbekistan)

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Abstract. In the context of climate change and growing antrophogenic activities, the depletion and pollution of water resources is a global concern, posing significant threats worldwide. This study evaluates the volume and quality of water resources, the heavy metal concentrations, the total mineralization and the quantity of collector-drainage waters, and the primary factors contributing to the pollution of the Zarafshan River in Uzbekistan, based on in situ data from 2013 to 2023. The perennial results show that the average annual indicator of the volume of collector-drainage water has increased from 2,787 million m^3 to 3,418 million m^3, the amount of salts grow up 2,914 thousand tons from the annual average of 4,808,000 tons. The heavy metal concentrations (Cu, Zn, Cr (VI)) were analyzed from the upper part to the lower part of the Zarafshan River. Cu has increased from 1.3 times to 1.35 times, Zn has increased from 1.2 times to 4.7 times, Cr (VI) hasincreased from 1.1 times to 8 times over the years from 2013 to 2023. Long-term research show the mineralization of the water of the Zarafshan River has increased from the upper part of to the lower part within the territory of Uzbekistan from 3.9 to 6.5 times in the observed years. The minimum average annual salinity value of collector-drainage water in the Zarafshan River basin is 0.79 g/L in the Samarkand region, while the highest value is 2.9 g/L in the Navoi region.

1 Introduction

Water pollution is a serious global issue, resulting in significant challenges worldwide [1]. As a critical issue for agriculture, it leads to degradation of water and land resources, particularly in arid areas [2]. In the context of climate change and growing human activities, water pollution is a global concern, with severe far-reaching consequences [3]. Central Asia (CA), due to its semiarid to arid climate, is a region facing severe environmental and agricultural challenges, including water pollution and water shortages [4-5].

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These issues are particularly pronounced in irrigated fields within the Aral Sea Basin (ASB), being the major obstacle for the sustainable agricultural development [6]. Recent changes in climate, including rising air temperatures, decreasing precipitation, increasing evaporation rates, and accelerating glacier melting in high-altitude regions, have exacerbated water resource scarcity not only on a global scale but also within the Aral Sea Basin, creating substantial regional challenges [7-8]. Due to water management, dysfunctional drainage system and inadequate irrigation practices in the ASB, 55.0–60.0 million tons of collector-drainage waters are generated annually, including 2.9–4.8 million tons of salts from the irrigated lands within the Zarafshan River basin, leading to the pollution of inland water bodies [9]. Therefore, constant monitoring of the river water quality in CA is essential for the sustainable agriculture.

The Zarafshan river basin is part of the ASB, covering an approximate area of 143,000 km^2 and it is divided into two parts, the upper narrow mountain river valley in Tajikistan and the lower-wide basin plains river valley in Uzbekistan [10]. Currently, the Zarafshan River serves as the primary source of water for meeting the demands of various economic sectors in Uzbekistan's Zarafshan Valley, which encompasses the Samarkand, Navoi, and Bukhara regions [11]. However, due to climate change, the water not only in the Amu Darya and Syr Darya rivers, but also in the Zarafshan river is becoming scarce and heavily polluted by human activities, particularly mining and agricultural practices [12]. High concentrations of calcium bicarbonate, calcium (Ca), magnesium (Mg), sodium sulfate (Na_2SO_4), and sodium chloride (NaCl) in the river water are formed as a result of agricultural fertilization within the basin are. They have been becoming increasingly prevalent in these waters [13]. In addition to this phenomenon, Khusanov et al. (2025) concluded that the pollution of the Zarafshan River with plastic particles is also increasing in the Samarkand and Navoi regions [14].

Considering the importance of the Zarafshan River basin for irrigation, industrial, and potable purposes, numerous studies have been conducted by local researchers in Uzbekistan. For example, Nazaraliyev et al. (2024) investigated the impact of regional climatic factors on the Zarafshan River flow [11]. Urunova and Xudayberdiyeva (2022) analyzed the impact of anthropogenic factors on the formation of water resources of the Zarafshan River [15]. Polatov and Tursunov (2023) examined the rational use of water resources in the river basin [16]. Shoergashova et al. (2024) assessed the temporal and spatial variations of water quality parameters, incorporating previously unexamined sampling points [17]. From international perspectives, Olsson et al. (2010, 2012, 2013) studied environmental impacts and water quality patterns [10, 18]. Opp & Groll (2014) have focused on status quo and perspectives of the Zarafshan River [19]. Liu Yu et al. focused on the general water pollution issues across all river basins in Central Asia, with particular emphasis on the Zarafshan River Basin, which is one of the most polluted due to agricultural and mining activities there [12]. Researchers from Central Asia and Germany have realized joint analyses of both selected quantitative and qualitative water parameters along the transboundary Zarafshan River from upstream Tajikistan to downstream Uzbekistan.

All these previous studies have shown that the main problems of both water quantity and water quality are especially essential in the lower Uzbekian part of the Zarafshan River basin. However, the studies focused on the volume and quality changes in the water resources of the Zarafshan River within Uzbekistan remain limited. Therefore, this study aims to (1) examine the dynamics of heavy metals in the river water over space and time, (2) identify the mineralization and quantity of collector-drainage waters formed in the region, (3) evaluate the main factors contributing to the pollution of the river water, and (4) make recommendations for the protection of the water volume and the water quality.

2 Materials and methods

2.1 Study area

The study area includes the middle and lower parts of the Zarafshan River within Uzbekistan, covering an area of 131,000 km², or 90% of the total basin (Figure 1). The Zarafshan River originates at 2,750 meters above sea level in the Tajik Alai-Mountains as an outflow of the Zarafshan glacier, located between the Turkestan and the Zarafshan mountain ranges in northern Tajikistan [18]. It flows for the first 300 km through Tajikistan and ends after a total length of 870 km in the Bukhara region of Uzbekistan. Until 1957 the Zarafshan River was a tributary of the Amu Darya, and the third largest river in Central Asia. Due to enormous amounts of water withdrawal mostly for irrigation purposes the Zarafshan River did not reach the Amu Darya River since that time.

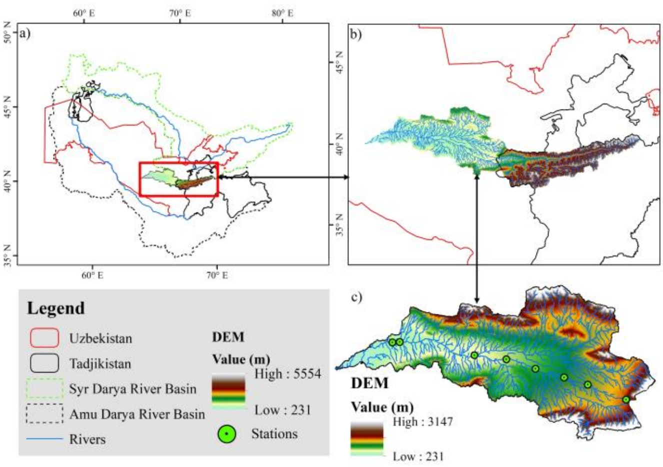

Fig. 1. (a) Zarafshan River basin, (b) River networks and (c) Uzbek part of the basin with the stations.

Located between the Amu Darya and Syr Darya basins, the Zarafshan River is one of the key water resources not only in Tadjikistan, but also in Uzbekistan. Although its water volume is significantly smaller than that of the aforementioned major rivers, its economic importance is substantial. The majority of the river's flow formation originates from the neighboring Republic of Tajikistan. The average multi-year water discharge from the catchment areas in the mountainous and middle parts of the Zarafshan River basin is 171 m³/s, with an annual flow volume of 5,395.0 × 10^6 m³. Each year, 95.3% of the replenished water resources in the basin come from the mountainous region, while 4.7% are contributed by the small rivers and streams in the middle part of the basin [20].

2.2 Climate

The Zarafshan River basin consists of two distinct areas based on its relief; the mountainous regions that generate the main part of the river flow and the plain areas where the water is distributed. As the effects of climate change become more apparent, the amount and duration of precipitation in the Zarafshan River basin are becoming increasingly variable. The basin's elongated shape, with significant variations in elevation, along with the diverse relief and landscape forms, leads to various climatic conditions within the region. Due to its location far from seas and oceans, the Zarafshan River basin has a continental climate, characterized by many hot and sunny days per year. A portion of the basin is covered by the Kyzylkum Desert, and it also includes large plains semi-deserts plains [20]. Figure 2 shows monthly variations of air temperature in the Uzbek part of the Zarafshan basin. In the middle reaches of the river, the average annual temperature ranges from +14.8°C to +15.3°C, with winter temperatures varying between +3°C and +3.5°C, and summer temperatures ranging from +26.8°C to +27.3°C.

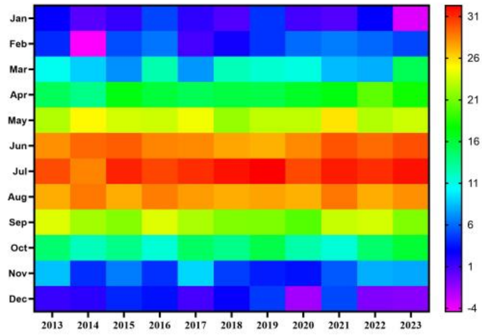

Fig. 2. Average multi-year air temperatures of the Zarafshan River basin (in °C).

In the lower reaches of the river, the average annual temperature is slightly higher, ranging from +16.3°C to +16.8°C, with winter temperatures between +2.7°C and +3.2°C, and summer temperatures rising between +30.0°C and +30.5°C. According to multi-year data from 20 hydrometeorological stations under the management of Uzhydromet, located across the Zarafshan River basin, the average annual temperature during the period from 2013 to 2023 ranged from +15.2°C to +15.8°C. The average maximum temperature was between +29.0°C and +29.5°C, while the average minimum temperature ranged from +2.2°C to +2.7°C.

The annual precipitation in the basin can vary in both the Tajik and Uzbek parts, as the location determines the local climate. Figure 3 illustrates the temporal and spatial variations in annual precipitation across the basin. The annual precipitation of the Uzbek part of the Zarafshan River basin ranges from 75 mm to 460 mm.

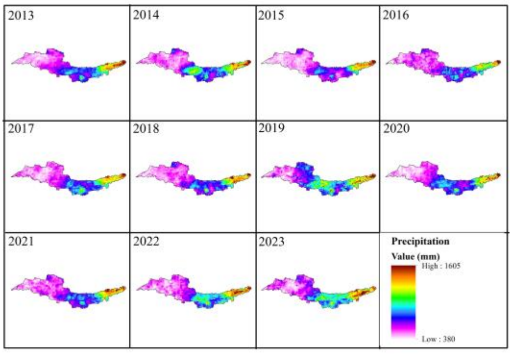

Fig. 3. Average multi-year precipitation in the Zarafshan River basin.

The annual average precipitation in the river basin is approximately 320 mm, while in the lower reaches of the Zarafshan River, the amount of precipitation does not exceed 100 mm. From the total annual precipitation, approximately 40-45% occurs in spring, 40-45% during winter, and 10-15% in autumn, normally zero precipitation during summer time.

2.3 Data acquisition

In this study, we utilized the surface water annual data provided by the Center for Hydrometeorological Service of the Republic of Uzbekistan (Uzhydromet). The Hydrometeorological Service conducts monthly assessments of the Zarafshan River's water quality using established laboratory techniques, including flame atomic absorption spectrometry, ion chromatography, as well as conventional titrimetric and electrochemical methods. The study relied on data from eight gauging stations operated by Uzhydromet in the research area, including: (S1) Ravatkhodja Dam; (S2) Samarkand city, 1.5 km upstream of the Akdarya water division; (S3) 0.5 km downstream from the mouth of the Siab collector; (S4) 3.7 km downstream from the mouth of the Taligulyan collector; (S5) 0.8 km downstream of Kattakurgan city; (S6) Karadarya, near the settlement of Khatirchi (Yangirabad), close to the confluence of the Karadarya and Akdarya rivers; (S7) Navoi city, 1 km upstream of the wastewater discharge point at the Navoiazot factory; (S8) Navoi city, 0.8 km downstream from the wastewater discharge point at the Navoiazot chemical factory as shown in Figure 1 [17]. The data regarding collector-drainage networks was obtained by the Ministry of Water Resources. The primary data was processed with in-depth statistical methods.

3 Results and Discussion

3.1 Mineralization levels of Zarafshan River water

The mineralization level of river water is a critical indicator for assessing its suitability for various purposes. During the studied years (2013-2023), the average mineralization levels of the Zarafshan River water increased significantly, ranging from 0.27-0.32 g/L at the Rovot-Khoja dam state boundary to 1.15-1.8 g/L at the point where wastewater from Navoiazot factory is discharged (Figure 4). The results revealed that the average mineralization level of the Zarafshan River water increased sharply by 2.7 to 3.7 times from the point where the Karadarya tributary joins (Hydropost 6) to the location where wastewater from Navoiazot factory is discharged (Hydropost 7). Additionally, when comparing the mineralization levels of river water measured at Hydropost 1 with those at Hydropost 8, it was determined that the mineralization had increased by 3.9 to 6.5 times.

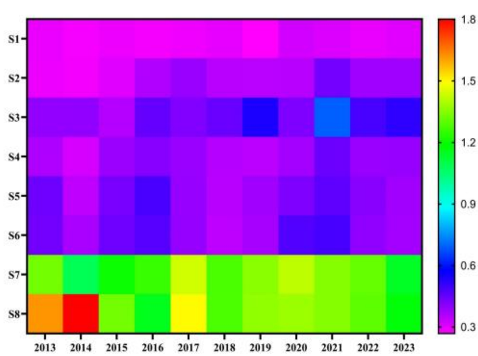

Fig. 4. Average mineralization (g/L) of the Zarafshan River water.

The inflow of collector-drainage waters is formed after the irrigation of agricultural fields, as well as wastewater from industrial enterprises, into the Zarafshan River. It has caused an increase in mineralization of river water along the hydro-post cross-sections.

3.2 Impact of climate change on the mineralization level of river water

The relationship between the mineralization level of Zarafshan River water and atmospheric precipitation levels was analyzed. The correlation coefficient values (Pearson correlation) indicated a weak relationship at Hydropost 6 with $R^2 = 0.13$. Negative significant correlation was observed between precipitation levels and climate change at the remaining hydroposts.

During colder times (winter), a strong correlation ($0.5 < R^2 < 0.7$) was observed at Hydroposts 5 and 6, while a moderate correlation ($0.3 < R^2 < 0.5$) was identified at Hydroposts 3, 4, and 7. A weak correlation ($R^2 = 0.29$) was noted at Hydropost 2. Negative correlation was observed at Hydroposts 1 and 8. During warmer summer conditions, a moderate correlation ($0.3 < R^2 < 0.5$) was seen at Hydroposts 2 and 4, while a weak correlation ($R^2 = 0.17$) was recorded at Hydropost 6. Negative correlations were detected at the other hydroposts (Table 1).

Table 1. Relationship of river water mineralization with air temperature and precipitation.

N/o	The value of correlation coefficients.		
	Air temperature, °C (summer).	**Air temperature, °C (winter).**	**Precipitation, mm.**
1	-0.022	-0.218	-0.639
2	0.414	0.286	-0.536
3	0.401	0.328	-0.658
4	0.485	0.507	-0.361
5	0.061	0.690	0.086
6	0.170	0.526	0.126
7	-0.145	0.347	0.079
8	-0.500	-0.544	-0.010

The seasonal differences in the correlation coefficients of water flow volume and mineralization levels are attributed to the reduced discharge of drainage and collector waters into the river during the winter.

3.3 Dynamics of Cu^{2+}, Zn^{2+}, and Cr^{6+} concentrations in Zarafshan River water

The dynamics of changes in the average concentrations of heavy metal ions in the Zarafshan River water from 2013 to 2023 were studied across hydroposts over the years (Figures 5-8). The average concentrations of Cu^{2+}, Zn^{2+}, and Cr^{6+} varied as follows depending on the location of the hydroposts: The concentration of copper ions increased by 1.1 to 2.0 times from Hydropost 1 to Hydropost 6, but decreased by 1.1 to 3.2 times at Hydroposts 7 and 8.

Overall, the concentration of copper ions increased by 1.3 to 1.35 times from Hydropost 1 to Hydropost 8 in 2017 and 2018. However, in other years, the copper ion concentration tended to decrease as the river flows from the middle section to the lower section. This trend can be attributed to the river’s flow dynamics and the phenomenon of "settling" (Figure 5).

As a concequence of the wastewater discharge from Navoiazot factory near the Rovot-Khoja dam state, the concentration of zinc ions increased from 1.2–4.3 μg/L to 1.1–14.6 μg/L, and the concentration of Cr^{6+} increased from 0.1–0.6 μg/L to 0.1–2.5 μg/L (Figures 6 and 7).

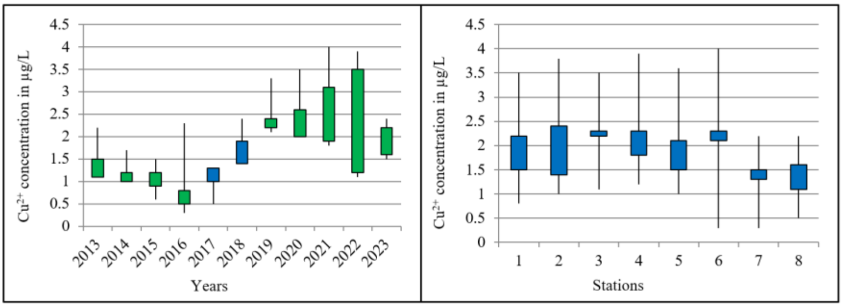

Fig. 5. Dynamics of average Cu^{2+} concentrations in the Zarafshan River water over the years and across hydroposts.

As the river flows from upstream to downstream (from Hydropost 1 to Hydropost 8), the annual average concentration of zinc ions increased by 1.2 to 4.7 times (Figure 6).

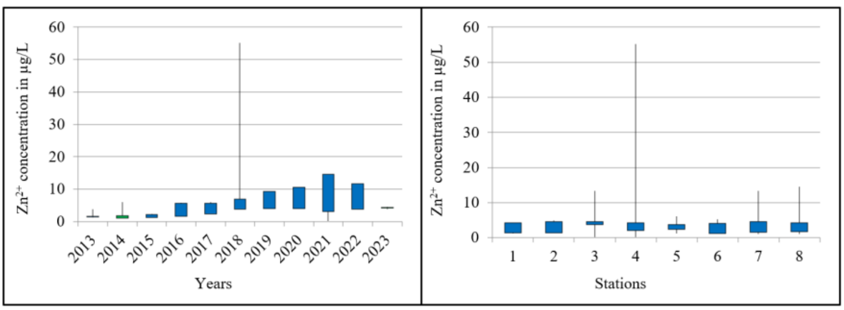

Fig. 6. Dynamics of average Zn^{2+} concentrations in the Zarafshan River water by years and across hydroposts.

As the river flows from the upper section to the lower section of the basin (from Hydropost 1 to Hydropost 8), the concentration of chromium (VI) increased by an average of 1.1 to 8 times over the years (Figure 7). Compared to 2013, the concentration of chromium (VI) at the hydroposts decreased by 1.25 to 4 times in 2023.

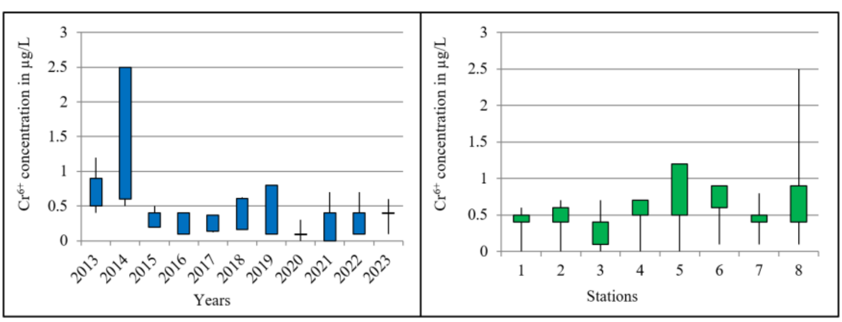

Fig. 7. Dynamics of average Cr^{6+} concentrations in Zarafshan River water by years and across hydroposts.

Additionally, it was found that the concentration of Fe ions in Zarafshan River water is 3-4 times lower than the permitted threshold (Figure 8).

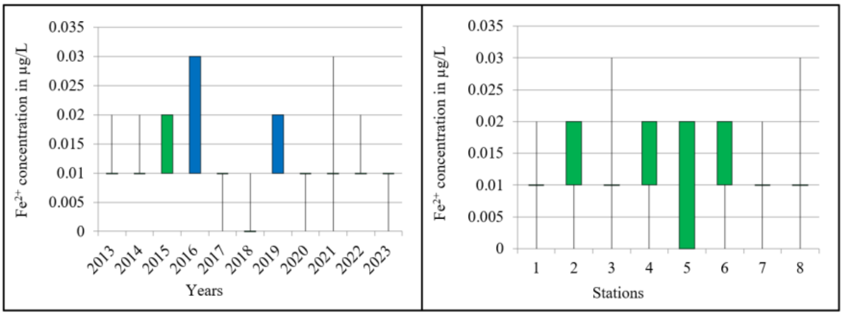

Fig. 8. Dynamics of average Fe^{2+} concentrations in the Zarafshan River water by years and across hydroposts.

Copper and iron concentrations decreased towards the lower parts of the river probably because of the lower humic amounts of the sediment flow in the downward river section. Among the zinc concentrations there are only a few differences between the hydroposts. Chromium concentrations are fluctuating between the hydroposts.

In both the middle and lower sections of the Zarafshan River (at the hydropost at the Rovot-Khoja dam state boundary), the concentrations of heavy metals (Cu, Zn, Cr (VI)), and Fe) decreased. This pattern can be observed for zinc, copper, chromium (VI), and iron. One of the main reasons for the increase in the concentration of heavy metals in the river water is related to input of discharge of collector-drainage water after irrigation of agricultural fields and the wastewater discharge from industrial enterprises into the river.

3.4 3.4. Collector-drainage water in the Zarafshan River basin

The majority of the collector-drainage water formed in the river basin ends up in the Zarafshan River. When evaluating the volume, mineralization, and salt content of the collector-drainage water in the Zarafshan River basin, the following findings were observed. The average annual volume of collector-drainage water in the river basin ranges from 4463 million m³ to 5539 million m³, with the annual average salt content varying from 8078 thousand tons to 11755 thousand tons (Table 2).

Table 2. Volume and mineralization of collector-drainage water in the Zarafshan River basin, and the total salt content.

Regions	Description	Unit	Years				
			2018	2019	2020	2021	2022
Samarkand	Volume	million.m³	2080.98	2080.98	2329.81	2097.35	1956.21
	Mineralization	g/L	0.85	0.85	0.798	0.790	0.80
	Total salt content	thousand ton	1758.51	1758.51	1859.06	1657.86	1573.92
Navoi	Volume	million.m³	860.52	1187.37	1088.66	966.1	830.41
	Mineralization	g/L	2.914	2.569	2.419	1.313	1.613
	Total salt content	thousand ton	2507.87	3050	2633.83	1268.68	1339.78

Mineralization ranging from 0.79-3.5 g/L. The largest volume of collector-drainage water is formed in the Samarkand region, averaging 2.1 km³ annually. In the upper and middle parts of the river basin, most of the collector-drainage water flows into the riverbed, while in the lower stream, it flows into desert and lowland areas. The annual average mineralization of the collector-drainage water in the river basin was lowest in the Samarkand region at 0.79 g/L and highest in the Navoi region at 2.91 g/L. The highest mineralization level of the collector-drainage water in the Navoi region, compared to that of the Samarkand region, can be explained by two main reasons. First, the higher salinity of the soil in the Navoi region, and second, as the water of the Zarafshan River moves from the upper to the lower stream, its mineralization increases. This, in turn, leads to an increase in the mineralization of irrigation water used in agriculture and the mineralization of the collector-drainage water formed in the irrigated areas of these regions. The relatively lower mineralization level of the collector-drainage water in Samarkand region can be explained by the fact that the majority of the irrigated areas in the region are watered with river water that here has a lower mineralization level.

The impact of climate change (precipitation and temperature) on the mineralization of the collector-drainage water was studied. The values of the correlation coefficients, which express the strength of this relationship (Pearson correlation), were analyzed (Table 3).

Table 3. Mineralization of collector-drainage water in the Zarafshan River basin and its correlation with air temperature and precipitation.

N/o	Regions	Correlation coefficient		
		Air temperature, ˚C (summer)	Air temperature, ˚C (winter)	Precipitation, mm.
1	Samarkand	-0.171	0.089	0.431
2	Navoi	-0.821	-0.299	0.485

An average correlation between precipitation and mineralization of the collector-drainage water was observed in Samarkand and Navoi regions. However, negative correlation was observed between summer and winter air temperatures and the mineralization in either Samarkand or Navoi regions.

4 Conclusion

Pollution of water resources has long been a major concern, particularly in Central Asia. In this study, we assessed the current status, quantity, and quality of water resources in the Uzbek part of the Zarafshan River basin using long-term data from relevant organizations. The findings indicate that the mineralization of river water has increased over the observed years due to the discharge of collector-drainage from irrigated lands and wastewater from industries. The mineralization of collector-drainage water in the Samarkand region is lower than in the Navoi region. This higher mineralization in the Navoi region is attributed to the higher soil salinity and the higher mineralization of irrigation water. Similarly, heavy metal concentrations have increased along the river, exceeding threshold values. To halt the pollution of Zarafshan River water, it is crucial to control the excessive use of mineral fertilizers in agriculture, ensure that mineral fertilizers are supplied to crops using drip irrigation technologies, ensure adequate purification of wastewater from industrial enterprises, and implement regular monitoring. Due to periods with lower discharge and lower river volume, even in consequence of climate change, when small and medium glaciers in the upper Tajik part of the Zarafshan River basin got totally melted, special attention must be taken to the dynamics of water quality values.

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