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A review of water pollution arising from agriculture and mining activities in Central Asia: Facts, causes and effects☆

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ABSTRACT

Central Asia is one of many regions worldwide that face severe water shortages; nevertheless, water pollution in this region exacerbates the existing water stress and increases the risk of regional water conflicts. In this study, we perform an extensive literature review, and the data show that water pollution in Central Asia is closely linked to human activities. Within the Asian Gold Belt, water pollution is influenced mainly by mining, and the predominant pollutants are heavy metals and radionuclides. However, in the irrigated areas along the middle and lower reaches of inland rivers (e.g., the Amu Darya and Syr Darya), water pollution is strongly associated with agriculture. Hence, irrigated areas are characterized by high concentrations of ammonia, nitrogen, and phosphorus. In addition, the salinities of rivers and groundwater in the middle and lower reaches of inland rivers generally increase along the flow path due to high rates of evaporation. Soil salinization and frequent salt dust storms in the Aral Sea basin further increase the pollution of surface water bodies. Ultimately, the pollution of surface water and groundwater poses risks to human health and deteriorates the ecological environment. To prevent further water pollution, joint monitoring of the surface water and groundwater quantity and quality throughout Central Asia must be implemented immediately.

1. Introduction

The geopolitical region of Central Asia is characterized by a continental arid and semiarid climate with mean annual precipitation of 600–800 mm in the mountainous areas and 80–150 mm in the desert regions (Qadir et al., 2009). The specific climatic conditions of Central Asia determine the crucial role that water plays in urbanization, supporting life, and preserving unique natural objects (Karkra et al., 2017). With the impacts of global warming and the increased demands for food and energy due to rapid population growth throughout Central Asia, the water resources in this region are facing increasing pressure (Ruan et al., 2020). Therefore, the scarcity of water and the uneven spatial distribution of water resources greatly limit the socio-economic development of the Central Asian region (Guo et al., 2016).

In addition to the scarcity of water resources, water pollution and corresponding water-related health problems are growing problems throughout Central Asia (Bekturganov et al., 2016). Several studies have reported the excessive salinity of the water downstream of the Amu Darya (ADR) and Syr Darya (SDR) rivers and described the sources of pollutants discharged into surface water (Ososkova et al., 2000; Qadir et al., 2009; Tornqvist et al., 2011; Leng et al., 2021). Generally, two main driving forces govern the temporal variations in the ADR water salinity: the low drainage density with in the basin limits the salt loads caused by natural runoff processes, and the melting of snow and glaciers in the upper catchment area facilitates the dilution of dissolved salts during high-flow periods. During low-flow periods, salinity is strongly

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affected by the backflow of waters used for land washing and irrigation (Crosa et al., 2006a; Kulmatov et al., 2020). In particular, agricultural and industrial pollution affects the downstream areas of inland rivers such as the ADR and SDR, causing the Cu, Zn, and Cr concentrations to exceed the maximum allowable concentrations (MAC) in large tracts of water (Bekturganov et al., 2016). Overall, water pollution in Central Asia is worsening due to climate change and the ongoing expansion of irrigation, and as a consequence, groundwater is associated with much higher health risks than surface water (Tornqvist et al., 2011).

In the transboundary basin of the Chu and Talas Rivers of Kazakhstan (KZ) and Kyrgyzstan (KG), the dissolution and weathering of carbonate and silicate rocks are the main sources of ions in the river water. However, there are significant differences among the sources of major ions and potentially toxic elements (PTEs), such as Zn, Pb, Cu, Cr and As. PTEs may be affected by human activities (Ma et al., 2020). Hence, studying the accumulation of PTEs in lake sediments can reflect the changes in the surrounding watershed: the geoaccumulation indices of various PTEs (V, Cr, Zn, Co, Pb, Ni, Cu and Cd) indicate a moderately polluted state since 1970, whereas As has remained at unpolluted to moderately polluted levels (Liu et al., 2020a).

In the areas in which water runoff disperses, which include most of KZ, Turkmenistan (TM) and Uzbekistan (UZ), almost all local and foreign scholars have identified two main problems: rising levels of water salinity and desertification coincident with land salinization (Crosa et al., 2006a; Schettler et al., 2013; Zhang et al., 2020). Moreover, the storage of toxic and radioactive substances has become a potential environmental problem associated with water resources in surface runoff catchment areas, mainly in the territories of KG and Tajikistan (TJ), and in the foothills of KZ and UZ (Valentini et al., 2004).

In addition, the water environment of Central Asia has been greatly impacted by the use of mineral fertilizers and pesticides in agriculture and by the operations of mining, chemical production and other industries related to the utilization and storage of many harmful substances (Tornqvist et al., 2011; Leng et al., 2021). Accordingly, the dilapidation of industrial and urban sewage systems and treatment facilities is a considerable concern in regard to water quality (Bekturganov et al., 2016). Furthermore, the distribution of environmental pollution sources has changed; for example, in cities, domestic waste is retained in leaky landfills, the discharge of which has become a major factor in the pollution of fresh groundwater and river ecosystems (UNECE, 2019).

Given the above, water-related issues in Central Asia have recently received increasing attention from the international community (Liu et al., 2020d; Alifujiang et al., 2021; Bissenbayeva et al., 2021; Lobanova et al., 2021; Su et al., 2021). Nevertheless, despite the deteriorating water pollution problems and corresponding human activities plaguing Central Asia, with the amount and utilization of water resources being the primary focus of previous research, inadequate attention has been paid to the changes in the quality of the water environment. Furthermore, the few studies that have been published have focused mainly on a particular type of water pollution. Therefore, in this paper, based on the existing studies, we make full use of the data in Chinese, Russian and English research articles to comprehensively evaluate the types and spatial distributions of water pollution and the main factors influencing water pollution throughout Central Asia. Correspondingly, the objectives of this study are to 1) ascertain the main types of water pollution and their spatial distributions in Central Asia and 2) establish the relationship between the pollution in different types of water bodies and human activities.

2. Materials and methodology

2.1. Study area

The study area consists of the five countries of Central Asia, namely, KZ, KG, TJ, UZ, and TM, which are surrounded by China, Russia, Afghanistan, Iran, Pakistan and Azerbaijan (Fig. 1). The elevation in this region gradually decreases from southeast to northwest, reflecting a transition from high mountains to plains and deserts. The Tianshan Mountains act as a barrier that blocks air masses moving from the Siberian and Kazakh steppes to Central Asia, resulting in continuous gradients of temperature and precipitation across the region (Sorg et al., 2012).

The Central Asian orogenic belt, which stretches across the Siberian Plate, Eastern European Craton, Karakum Plate and Tarim-North China Plate, has experienced intense and frequent episodes of orogenesis in different periods (Şengör et al., 1993; Hu et al., 2014). The regional evolution of the crust has led to the formation of giant Au deposits, such as Muruntau in UZ and Kumtor in KG, as well as giant Au–Cu deposits such as Almalyk in UZ and dozens of ultra-large Au and Cu polymetallic deposits; collectively, these deposits compose the colossal Au–Cu polymetallic mineralization belt of the western Tianshan Mountains known as the Asian Gold Belt (Xue et al., 2015).

The meltwater originating from glaciers and snow in the Tianshan and Pamir-Alai Mountains is the source of many rivers and lakes in Central Asia, creating a network of runoff and groundwater (Liu et al., 2020c). Southern KZ, KG, TJ, UZ and TM are strongly dependent on the

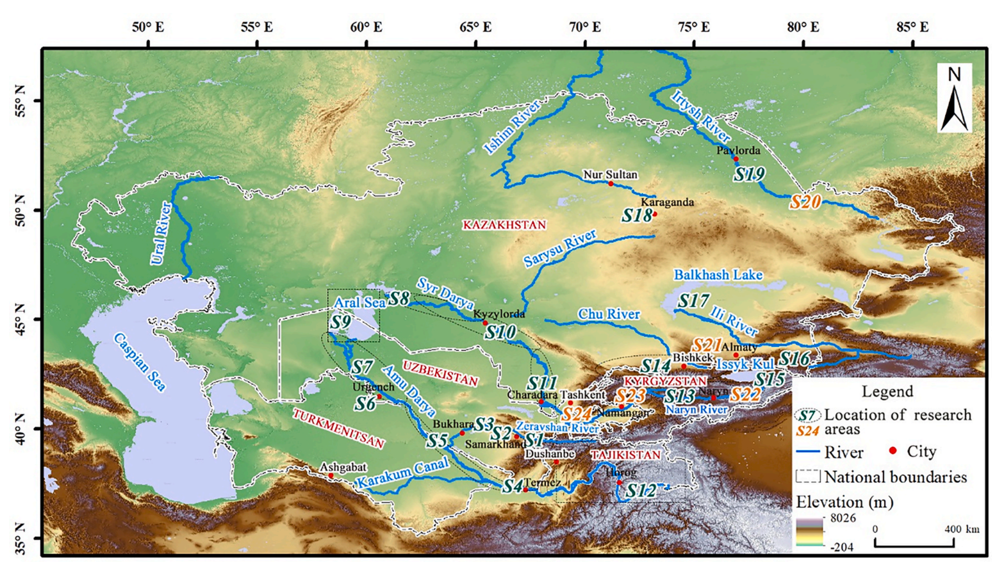

Fig. 1. Map of Central Asia (S1–S19 indicate water pollution from agriculture and mineral resources; S20–S24 represent radioactive water pollution).

surface waters of the Aral Sea basin. In contrast, the main sources of water in northern KZ are the three rivers at the headwaters of the Ob: Irtysh, Ishim and Tobol. The major toxic trace elements in the surface water bodies monitored in KZ are Cd and Pb, although less-toxic Cu, Zn and Mn have also been detected in some areas (Baubekova et al., 2021).

The ADR, SDR and their branches originate in the mountainous regions of KG and TJ, travel through KZ, UZ and TM, and eventually enter the Aral Sea or disappear into the deserts. In 2019, the total annual flow in the ADR and SDR basins was 109.1 km^3 or 93% of the average annual flow (UNRCCA, 2019). The mountains in KG and TJ located at the headwaters of these two rivers are characterized by favourable geological and metallogenic environments. Mining activities in KG take place mainly in the mountainous areas (UNECE, 2009). However, the mining and processing of various mineral deposits, including U, has accelerated the release of hazardous substances into the environment; the impact of mining activities on water has been particularly serve. For example, mining activities in TJ have introduced heavy metal pollutants into the upper reaches of the Zarafshan River (Groll et al., 2015). Water from the mountains of TJ is typically cold and clear because it originates from natural geological formations rich in lime and minerals. As a results, half of the surface water and groundwater used in this region is extremely hard and mineralized (UNECE, 2012b). Nevertheless, most of the river water in TJ is suitable for drinking and irrigation, while the waters from the Gunt River and SDR require measures to control their salinity to reduce the Na hazard (Wu et al., 2020).

Located between the two largest rivers in Central Asia, namely, the ADR and SDR, UZ provides favourable conditions for groundwater formation in mountains, intermontane depressions and foothills. Regionally, the groundwater quality is generally considered satisfactory. However, local issues with respect to salinity and the effects of agriculture, industry and/or anthropogenic activities have arisen (UNECE, 2020; Kulmatov et al., 2021; Hamidov et al., 2020). In addition, water resources are very limited owing to the geographical conditions and climate of TM. While, the flow of rivers in TM originates mainly beyond its boundaries, the ADR in TM is affected predominantly by agricultural irrigation and is moderately polluted (O'Hara and Hannan, 1999; Papa et al., 2004; UNECE, 2012a).

2.2. Data

The water pollution situation of Central Asia can be discerned from the literature. Table 1 summarizes the studies conducted on water pollution in these countries and their data sources. Note that although this reference list may not be exhaustive, we believe that it should represent a comprehensive synopsis of field research conducted in Central Asia.

2.3. Methods

Two pollution indices, namely, the water pollution index (WPI) and the heavy metal pollution index (HPI), were employed to determine the pollution status of water bodies in this study. WPI is a relative indicator of water pollution characterized by the cumulative availability of the largest concentrations of 6 measured parameters, including dissolved oxygen (DO) and biochemical oxygen demand (BOD). WPI values are defined as follows: ≤ 0.3 = class I (very clean); 0.3–1.0 = class II (clean); 1.0–2.5 = class III (moderately polluted); 2.5–4.0 = class IV (polluted); 4.0–6.0 = class V (dirty); 6.0–10.0 = class VI (very dirty); and >10.0 = class VII (extremely dirty) (UNECE, 2020).

HPI describes the combined effect of individual heavy metals on water quality (Sheykhi and Moore, 2012). In this index, the rating is obtained by comparing the relative significance of individual heavy metals and defined as inversely proportional to the recommended standard (S_i) for each heavy metal. HPI is calculated with the following equation:

$$HPI = \frac{\sum_{i=1}^{i=n}(Q_i \times W_i)}{\sum_{i=1}^{i=n} W_i}$$

where W_i is the unit weight of the ith heavy metal, Q_i is the sub-index for the ith heavy metal, and n is the number of heavy metals considered. The unit weight (W_i) is computed by:

$$W_i = K/S_i$$

where S_i is the standard permissible value of the ith heavy metal and K is the proportionality constant. The value of W_i ranges from 0 to 1. The sub-index (Q_i) is calculated by:

$$Q_i = \sum_{i=1}^{n} \frac{|M_i - I_i|}{S_i - I_i} \times 100$$

where M_i and I_i are the monitored value of the ith heavy metal and the ideal value, respectively, in μg/L. The concentration of each heavy metal is converted into an HPI value, where an HPI value higher than 100 indicates critical contamination with heavy metals.

The water quality and metals present in the waters downstream of the ADR and SDR were investigated further using a data analysis tool known as principal component analysis (PCA), which is employed to reduce a large number of measured variables to a small number of principal components (PCs) by decreasing the dimensionality of multivariate datasets (Karkra et al., 2017). The PCs, which are usually extracted from the directions with the largest and second largest differences in data, represent information about different "statistical dimensions" in the dataset (Helena et al., 2000; Tripathi and Singal, 2019). This method allows the variables in multivariate data to be summarized and visualized more easily. Analyses were performed with Origin 2019b software (https://www.originlab.com/2019b).

Using the traditional chemical division of water types, Piper diagrams (Piper, 1944) were drawn to compare the surface water and groundwater in typical regions of Central Asia. On this basis, the relationship between representative pollutants and water quality was studied.

3. Results and discussion

3.1. Water pollution from agriculture in the Aral Sea basin

3.1.1. Surface water pollution

The lower reaches of the ADR and SDR in the Aral Sea basin, which includes UZ, eastern TM, and southern KZ, face severe surface water and groundwater pollution and land salinization due to agricultural activities (Hamidov et al., 2016). In particular, agricultural irrigation and production processes are the main cause of water pollution in the middle and lower reaches of the ADR and affect the ionic compositions from the upstream to the downstream areas (Olsson et al., 2013). For example, a recent study (Zhang et al., 2020) showed that the concentrations of N, P and other nutrients are much higher in the lower reaches of the ADR than in the upper reaches.

Due to the increasing population density in the cities and surrounding areas therein, the lower reaches of the Zarafshan River in UZ are polluted mainly by sewage collectors and industrial wastewater from the Samarkand and Navoi regions, as well as by municipal wastewater (S1 and S2 in Fig. 1) (Olsson et al., 2012; Olsson et al., 2013; Normatov et al., 2015). Overall, the available surface water in the Navoi region (S3) is characterized by significant mineralization. This mineralization occurs because the southern part of this region currently exhibits intensive agricultural irrigation and above-average fertilizer use, which leads to significant soil and groundwater salinization (Kulmatov et al., 2018). The upstream region of the Zarafshan River is composed predominantly of calcium bicarbonate, while the downstream region has high levels of SO_4^{2-}, Cl^- and Mg (Olsson et al., 2013). Generally, the

Table 1
Summary of field measurements of water pollution in Central Asia.

No.	Country	Site	Site no.	Measurement period	Type of water source	pH	Salinity (g/L)	TDS (g/L)	Water type	Contaminants	References
1	TJ, UZ	Zarafshan River	S1	1998–2012	RW	6.95–8.40			Ca–SO_4	PO_4, NO_3	(Olsson et al., 2012; Normatov et al., 2015)
2	UZ	Zarafshan River	S2	1980–2009	RW	6.0-	0.29–1.26		Ca–Mg–CO_3–HCO_3; Ca–Mg–SO_4–Cl		(Olsson et al., 2012; Olsson et al., 2013)
3	UZ	Navoi Zarafshan River	S3	2000–2015	RW GW		0.29–1.98 <1.0–5.1				Kulmatov et al. (2018)
4	UZ, TM	ADR from Samanbay station to Termez station	S4	1996–2001	RW	7.0–8.7	0.35–2.76				Crosa et al. (2006a)
5	UZ	ADR from Bukhara to the Tuyamuyn Hydro Complex	S5	Apr 2003	RW	7.2–8.2	0.4–3.2			Fe, Mn, Ni, Cr, Pb	Crosa et al. (2006b)
6	UZ	Khorezm	S6	2006–2008	LW	7.7–7.8	3.1–13.7			NH_4^+	Shanafield et al. (2010)
7	UZ	Khorezm	S6	1990–2000	GW		0.49–15.01				Ibrakhimov et al. (2007)
8	UZ	Khorezm	S6	Nov 2002, Sep 2003, May 2004	GW		1.0–2.97			Zn, Cr, Cu, Fe, Pb	Froebrich et al. (2006)
9	UZ	Khorezm	S6	1991–2017	GW		1.4–1.8 and more				Hamidov et al. (2020)
10	UZ	ADR delta	S7	Jul–Oct 2007, May–Jul 2008	RW GW					Cu, As, F, Cd, NO_2^-, DDT Cr, Pb, Cu	Tornqvist et al. (2011)
11	UZ, KZ,	ADR SRD	S7 S8	Apr–Jul 2019	RW	7.21–8.96				N, P	Zhang et al. (2020)
12	UZ	Aral Sea	S9	Jun–Aug 2009	RW GW	6.8–8.7	0.684 10.1–95.0		NaCl (SO_4)	NO_3, U, Mo, Se,	Schettler et al. (2013)
13	KZ	SRD	S10	1940–2013	RW		0.9–2.0		Ca–SO_4 (Na + K)–SO_4	Cl	Bissenbayeva et al. (2020)
14	KZ	SRD	S11	Jun–Oct 2015	RW					DDT, lindane	Snow et al. (2020)
15	KZ	SRD	S8 S10 S11	Jun 2017	RW	8.2–9.3				Fe, Co, Ni	Yegemova et al. (2018)
16	TJ	Panj, Vakhsh, Gunt, Bartang, Syr Darya, and Zeravshan	S12	Oct 2011	RW	7.4–9.0		0.0596–1.408	Ca–HCO_3		Wu et al. (2020)
17	KG	SRD	S13	May, Aug 2017	RW	7.68–8.46		0.15–0.45	Ca–HCO_3	Cu, Pb, Zn, Cd	Ma et al. (2019)
18	KZ, KG	Transboundary basin of the Chu-Talas River	S14		RW	7.14–8.99		0.076–0.475	Ca–CO_3	Zn, Pb, Cu, Cr, As	Ma et al. (2020)
19	KZ, KG	Transboundary rivers and the Big Chu Channel	S14		RW					As, B, Ba, Li, Mo, Pb, Sb, Sr, U	(Solodukhin et al., 2016; Solodukhin et al., 2020)
20	KG	Issyk-Kul basin	S15	May–Aug 2017	RW	7.55–8.94		0.11–0.39	Ca–HCO_3	Cr	Liu et al. (2020b)
21	KZ	Ultra-fresh mountain lakes of Kolsay National Nature Park Kazakhstan	S16	Aug 2015	LW	8.2–8.6				Cu	Krupa et al. (2016)
22	KZ	Ili–Balkhash basin	S17	2009 2009	LW RW	8.38–9.05 8.44		1.45–5.76 0.50			Dzhetimov et al. (2013)
23	KZ	Nura River	S18		RW					Hg	(Heaven et al., 2000a; Heaven et al., 2000b; Guney et al., 2020)
24	KZ	Irtysh River Lake Balkyldak	S19	Jul–Aug 2001 Sep 2002 Aug 2004	RW LW	8.4–9.0				Hg	(Ullrich et al., 2007a; Ullrich et al., 2007b)
25	KZ	Kazakhstan	S8, S10, S11, S14, S16–19	1997–2007	GW	7.0–8.5		0.027–133.4		Cu, Zn, Pb, Cr	Krupa et al. (2019)
26	KZ	Sarzhal region of the Semipalatinsk Nuclear Test Site	S20	Jul 2001	GW	7.5–8.0		0.189–0.936		U	Leon Vintro et al. (2009)
27	KZ	Semipalatinsk Nuclear Test Site	S20		GW	7.0–8.1				U	Yamamoto et al. (2010)
28	KZ	Shagan River nearby the Semipalatinsk Nuclear Test Site	S20	2014	RW	7.1–8.6				U, Li	Gorlachev et al. (2020)
29	KZ, KG	Chu River Kurdai site	S21	Oct 2008 – Jul 2009	RW	8.05–8.44		0.25–0.59	Ca–HCO_3		(Uralbekov et al., 2011; Burkitbayev et al., 2012)

(*continued on next page*)

Table 1 (*continued*)

No.	Country	Site	Site no.	Measurement period	Type of water source	pH	Salinity (g/L)	TDS (g/L)	Water type	Contaminants	References
30	KZ	Kurdai site	S21	May–Jun 2006	LW RW GW	7.2–8.5				U, As, Mo, Ni U, As, Mo, Ni, Mn	(Salbu et al., 2013; Stromman et al., 2013)
31	KG	Kadji-Sai site	S22		LW, GW	7.56–8.7				As	(Uralbekov et al., 2011; Lind et al., 2013)
32	KG	Mailuu Site	S23	Aug 2013	GW RW	8.3–8.6			Na–SO_4	As, Se, Cr, V, U, F Fe, Mn, Al	Corcho Alvarado et al. (2014)
33	TJ	Taboshar site Digmai tailings	S24	2006–2008	LW GW	7.4–8.3				As, Mo, Mn, Fe	(Skipperud et al., 2013; Stromman et al., 2013)
34	TJ	Taboshar site	S24	2009–2014	RW					U	Zoriy et al. (2018)

Type of water source: RW-river water; LW-lake water; GW-groundwater. TDS-total dissolved solids.

ionic composition of the surface water in this river shows significant increases in the concentrations of almost all major ions from the upstream to the downstream reaches, especially those of SO_4^{2-} and Cl^- (Olsson et al., 2013).

Monitoring from Termez station to Samanbay station (S4 and S5, respectively, in Fig. 1) in the ADR shows that the water quality of the ADR shows characteristic temporal and spatial variations, and two main driving forces control the variation in salinity of the ADR (Crosa et al., 2006a): the melting of snow and glaciers in the upstream catchment facilitates the dilution of dissolved salts in the high-flow period, while during low-flow periods, the salinity of the ADR is strongly affected by the backflow of waters used for land washing and irrigation (Crosa et al., 2006a; Crosa et al., 2006b).

Agricultural irrigation negatively affects the water quality of not only rivers but also lakes. For example, the ammonium concentrations in four small lakes in the Khorezm region of UZ (S6 in Fig. 1) are highest during winter and early spring, while the concentrations are low during summer and autumn (Shanafield et al., 2010). During flood irrigation in early spring, there is a hydraulic connection between the ADR and these lakes; as a result of mixing between these waters, the ammonium concentration observed in the ADR is similar to those in the lakes. Nevertheless, although the ammonium concentration in the ADR is slightly lower than those in the lakes, the concentrations in these water bodies show similar temporal dynamics.

Flood irrigation also transports some chemical elements (e.g., As) from farmland soils into rivers. As, which generally originates from soils and rocks, is released into surface and groundwater during agricultural or mining activities. Hence, As concentrations in river water exhibit high spatial variability, likely dependent on the amount of As in the soil (Tornqvist et al., 2011). In addition, the use of Cu-containing fertilizers and pesticides in upstream farmland leads to peak Cu concentrations in the ADR after the ground thaws and snow melts (Tornqvist et al., 2011). Concentrations of Cu and phenols exceeding the MACs by up to three times have been recorded in some instances (Groll et al., 2015; UNECE, 2020). The Siab collector channel in Samarkand and the Salar channel downstream of Tashkent and Yangiyul are characterized by high average concentrations of NO_2^-, and Cu (Table 2). It is estimated that more than 5.3 billion m^3 of water is discharged from irrigation collector drainage into the ADR in TM; as a result, river water mineralization reaches its highest level of approximately 2.2 g/L at Darganata (UNECE, 2012a).

The observation areas marked S8, S10, and S11 in Fig. 1 are distributed along the SDR. Before 1940, the mineralization of river water in the SDR reached 0.4–0.6 g/L, and the water was characterized by calcium bicarbonate and a relatively high content of SO_4^{2-} ions (Bissenbayeva et al., 2020). Currently, the surface water mineralization is approximately 0.9–1.2 g/L in the upper reaches and 1.5–2.0 g/L in the lower reaches of the SDR. These numbers indicate that water mineralization has increased by two to three times compared with the pre-1940 levels. Currently, the ion composition of the river water is dominated by SO_4^{2-}, Na^+ and K^+, and high concentrations of Cl^- have been observed in the lower reaches of the SDR (Bissenbayeva et al., 2020).

Extensive use of pesticides has contaminated the soil and drinking water throughout Central Asia (Papa et al., 2004; Barron et al., 2017; Toichuev et al., 2018). Organohalogen pesticides (OCPs), such as dichlorodiphenyltrichloroethane (DDT) and lindane, also known as gamma-hexachlorocyclohexane (γ-HCH), may be used in the upstream region of the SDR (Ali et al., 2014). γ-HCH has been detected in river water samples from the SDR, with the highest concentrations occurring in June (Snow et al., 2020). Moreover, residues of γ-HCH detected in water samples range from 0.014 to 0.24 mg/L, which are some of the highest concentrations reported in rivers globally (Snow et al., 2020). Four water samples were taken by Toichuev et al. (2018) from an area where pesticides have been applied; HCH, DDT, and dichlorodiphenyldichloroethylene (DDE) were found in the outflow water samples, showing that OCPs partly wash out of the soil into the water.

3.1.2. Groundwater pollution

The locations marked S6, S7, and S9 in the ADR area exhibit salinization due to the high mineralization of shallow groundwater in the middle and lower reaches of the ADR. The Aral Sea basin is a dynamic hydrological system characterized by an arid climate that receives an inflow of river water with high seasonal and interannual variability (Crosa et al., 2006a). In particular, the spatial dynamics of the groundwater levels and salinity in the Khorezm region (S6) of UZ show that the groundwater in the western and southern parts of this region is particularly shallow and saline (Ibrakhimov et al., 2007). In the ADR delta (S7 and S9), there is a distinct contrast in salinity between the low-salinity river water (~1 g/L) and the high-salinity unconfined groundwater (10–95 g/L) (Schettler et al., 2013). The Aral Sea is currently shrinking, which affects groundwater discharge; this discharge manifest as changes in the groundwater levels and salinization. Thus, shallow groundwater with predominantly moderate salinity is likely to contribute to the increase in soil salinization.

Due to the effects of intensive irrigation, the groundwater in the middle and lower reaches of the Zarafshan River (S3) is no longer suitable for drinking (UNECE, 2020). The highest mineralization and SO_4^{2-} contents have been recorded in the lower reaches of the Zarafshan River, where the maximum concentrations of SO_4^{2-} reach 6.1–12.0 times the MAC (UNECE, 2020). However, both groundwater and soil salinity have improved slightly in recent years.

Rural well water in KZ has been shown to contain high levels of NO_3^- due to the excessive use of agricultural fertilizers, despite strict regulations requiring sanitary protection zones around water inflow zones (UNECE, 2019).

Table 2
Most polluted water bodies in UZ, 2014–2018 (UNECE, 2020).

	WPI					MAC exceedances in 2018		
	2014	2015	2016	2017	2018	NO_2^-	NH_4^+	Cu
Salar channel – Yangiyul	4.02	4.22	4.29	4.93	5.96	15.5	–	3.5
Salar channel – Tashkent	4.74	3.4	3.09	3.29	3.06	5.8	2.3	2.5
Siab collector channel – Samarkand	4.55	3.91	3.32	3.85	3.99	5.0	2.3	3.2
Zaravshan River – Navoiy	3.42	2.16	1.52	2.05	1.83	–	–	1.9
Collector GPK-S – Tashkent	1.37	2.68	1.23	1.2	2.29	–	–	–
Chirchik River – Chirchik	1.94	1.95	2.47	1.38	2.63	8.5	1.6	1.9
MAC (mg/L)						0.02	0.5	0.001

Source: Yearbooks of the Surface Water Quality in the Uzhydromet Network for 2017 and 2018.

In addition, HCH and DDT have been detected in the groundwater around pesticide-contaminated sites in KG (Toichuev et al., 2018). Unfortunately, pesticides have been used extensively for agriculture throughout Central Asia in the past (Barron et al., 2017). Hence, pesticide residues in surface soil may be one source of this pesticide contamination of groundwater.

3.1.3. Correlation matrix of water quality and metals

To compare and evaluate the water quality of the ADR and SDR, water samples were divided into two groups, and PCA was performed on the water quality parameters and eight elements (As, Cr, Fe, Li, Mn, Se, Sr, and Zn) (Fig. 2).

Nine sets of parameters, namely, pH, total dissolved solids (TDS), dissolved organic carbon (DOC), total dissolved carbon (TDC), total phosphorus (TP), SO_4^{2-}, Ca^{2+}, Mg^{2+}, and Na^++K^+, were projected onto independent axes known as PCs. The first PC (PC1) alone explained more than 50% of the variance; the first four PCs explained more than 95% of the total variability in the standardized ratings, and the individual eigenvalues were greater than or close to 1. Therefore, the first four PCs were reasonably retained.

The relationship between PC1 and PC2, which contribute the most to the total variance can be seen in Fig. 2a. PC1 plotted on the horizontal axis has positive coefficients for TDC, DOC, TDS, SO_4^{2-}, Ca^{2+}, Mg^{2+}, and Na^++K^+, whereas it has negative coefficients for pH and TP, which are high in the waters of the ADR. PC2 plotted on the vertical axis has positive coefficients for pH, TP, TDC, DOC, TDS and Na^++K^+, whereas it has negative coefficients for SO_4^{2-}, Ca^{2+}, and Mg^{2+}.

Table A1 shows the eigenvalues, individual variances and cumulative variance. Four PCs were extracted from the analysis of the primary contaminant data. The rotated factor loadings of these four PCs are listed in Table A2. The first four PCs account for 85.62% of the total variance, while the individual eigenvalues of the first three PCs are greater than 1.

PC1 alone explains 39.48% of the data variance and has positive coefficients for Mn, Se, Zn, Li and Sr and negative coefficients for Cr, Fe, and As. Fig. 2b shows that the SDR has higher Li and Sr contents than the ADR, whereas the ADR has high levels of Cr, Fe, and As.

The above analysis suggests that compared with the water of the SDR, the waters of the ADR are more affected by TP, while Cr, Fe, and As are representative elements of the pollution in the ADR. The TDS in the SDR are affected by ions (Na^++K^+, Ca^{2+}, Mg^{2+}, and SO_4^{2-}), and the contents of Li and Sr in the SDR are higher than those in the ADR.

3.2. Water pollution resulting from mining activities

The upper reaches of the ADR and SDR are located in the western Tianshan Mountains, which extend from UZ to TJ, KG and southern KZ. This region is the main zone of the Asian Gold Belt and demonstrates the obvious potential for Au–Cu–Zn–Pb mineral resources (Xue et al., 2015). A superior mineralization environment, on the one hand, indicates that the geological background values of certain elements may be high (Krupa et al., 2019); on the other hand, mining processes may lead to the release of heavy metals into the surface environment. Several ultra-large Au deposits have developed in the Asian Gold Belt, including orogenic Au mines and porphyry-skarn Au–Cu mines. Some metallic minerals composing Au ores are pyrite, chalcopyrite, galena, and native Au. During the mining and extraction of diverse raw materials, including various metal resources and rare earth elements, contaminants can enter the surface environment as the main water pollutants (Karthe et al., 2017). The regional or seasonal increases in the concentrations of some of the metals (Table 3) in water bodies are affected by the geological metallogenic environment and mining activities in the upper reaches of the Central Asian rivers.

In the territory of KZ, the high Cu concentrations are closely related to the locations of background water in the mineral zone and geochemical anomalies in the mountains of KZ (Krupa et al., 2016; Krupa et al., 2019). In the mountain streams of the Ili River basin, water resources are polluted by Cu and F^-, and high mineralization occurs in the lake systems of Balkhash-Alakol and the lakes of the Shchuchinsk-Borovoe resort area (UNECE, 2019).

The PTEs in the transboundary basin of the Chu- and Talas Rivers in KG (S14 in Fig. 1) adjacent to the southeastern part of KZ are Zn, Pb, Cu, As and Cr (Ma et al., 2020). In addition, heavy metals are exposed to various factors in different hydrological periods in the Issyk-Kul basin (S15 in Fig. 1) (Liu et al., 2020b), and the heavy metal Cr may have the same rock source as the base ions (Liu et al., 2020b; Ma et al., 2020).

The most important environmental impacts in the upper catchment of the Zarafshan River in TJ are associated with the extraction and processing of Au, Ag, and Cu (Olsson et al., 2012). The Zarafshan River flows from east to west through southern Sogd, where, according to incomplete statistics (DiggingsTM, 2021), 21 deposits of Sb, Bi, Cd, Cu, and Au have been found (Fig. 3). There are Au–Cu–Zn–Pb deposits on both sides of the Zarafshan River and its tributaries, such as the Au open-pit mine in Jilau and the Anzob Zn mine, which are surface mines, and the Taror Au mine, which is an underground mining operation. In the territory of UZ, W mines are located mainly near the Zarafshan River basin.

Associated metal pollution in the ADR waters upstream from the Tuyamuyn Hydro Complex involves Fe, Mn, Ni, Cr and Pb concentrations exceeding human consumption limits; the origin of these metals is considered anthropogenic (Crosa et al., 2006b). In addition, heavy metals Cr, Cu, Fe, Pb and Zn have been detected in 10 groundwater lenses in the lower ADR region (S6 in Fig. 1) (Froebrich et al., 2006). HPI calculations (Table 4) indicate that the surface water at the position marked by the large red circle in Fig. 3 is highly contaminated by heavy metals. Cu concentrations peak after the ground thaws and snow melts, indicating that Cu originates from the upstream area of the ADR. The main sources of Cu contamination are the tailings of Cu mines (Tornqvist et al., 2011).

Previous studies have shown that in the core area of the Asian Gold Belt, the background concentration of Cu in the unpolluted surface water is higher than the background concentrations in other regions (Xue et al., 2015; Krupa et al., 2016; Krupa et al., 2019). Moreover, the distribution of surface water polluted by Cu, Pb, and Zn is consistent with the Asian Gold Belt. Hence, the mining of mineral resources in the

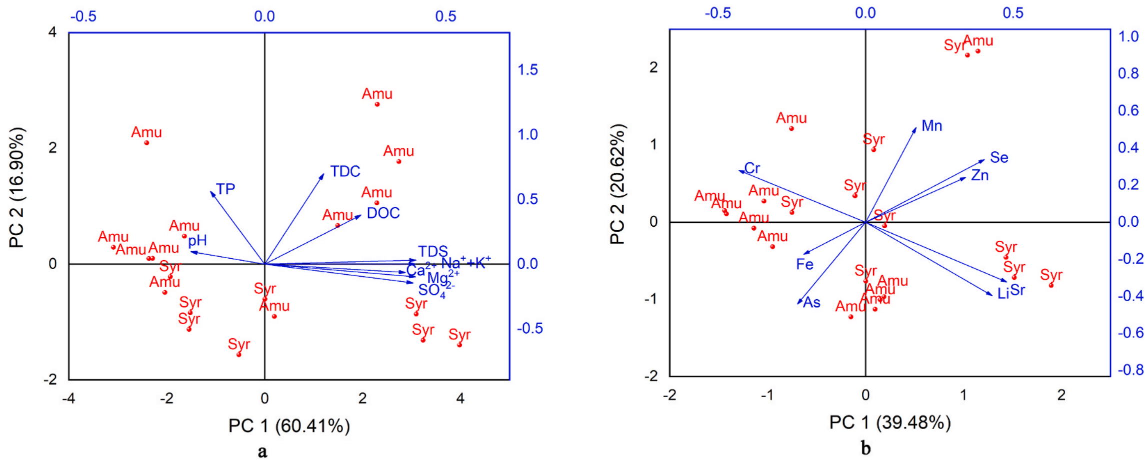

Fig. 2. PCA of the water quality (a) and metals (b) in water from the ADR and SDR. Data source (Zhang et al., 2020).

upstream region had certain impacts on heavy metal pollution in the waters of Central Asia.

3.3. Water radioactive pollution

At present, U mining in Central Asia is a potential source of U pollution for the water environment. As shown in Fig. 1 and Table 1, the locations marked S20–S24 have been identified as U ores. These locations are individually located mainly along the Irtysh River in northeastern KZ, in the transboundary basin of the Chu- and Talas Rivers and in the upper reaches of the SDR.

The Semipalatinsk Nuclear Test Site (SNTS) (S20 in Fig. 1) is situated in eastern KZ. After the first explosion of a nuclear device in August 1949, 468 nuclear tests were conducted at the SNTS (Leon Vintro et al., 2009). As a consequence, the U levels in wells and streams in the study area exceed the natural background levels (Leon Vintro et al., 2009). However, the high concentrations of ^{238}U found in some localities around the SNTS are not due to fallout from nearby nuclear explosions at the test site but rather to the intense weathering of rocks containing U (Yamamoto et al., 2010).

The groundwater around the SNTS was compared with the water from the largest waterway, the Shagan River (Fig. 4). The surface water of the Shagan River is composed mostly of Na–Mg–Cl–SO_4, while the Irtysh River is predominantly composed of Ca–Na–HCO_3. HCO_3^- is the main anion in groundwater samples, and individual well water samples contain SO_4^{2-}. The surface water and groundwater around the SNTS are mostly alkaline in terms of pH (7.0–8.6) (Yamamoto et al., 2010; Gorlachev et al., 2020). Such waters are typical for steppes, deserts and groundwater flowing through limestone. The values of total mineralization along the Shagan River range from 4 g/L to 9 g/L, which classifies the water as brackish (Gorlachev et al., 2020). The TDS in wells around the SNTS reach concentration in the range of 0.2–0.9 g/L (Yamamoto et al., 2010). Five elements have been revealed as having concentrations in excess of the MAC in KZ: U, Fe, Li, Mn and Sr (Gorlachev et al., 2020). At some sampling points along the Shagan River, the average U content is more than twice the MAC, and the water corresponds to a moderate level of pollution (Gorlachev et al., 2020). The concentration of ^{238}U in groundwater southwest of the SNTS is far lower than that to the southeast, and the ^{238}U contents found in wells around the SNTS are several to several tens of times higher than the reported global values (Yamamoto et al., 2010). These variations in ^{238}U contents may be associated with different geological and hydrological conditions in the investigated waters. The concentration of ^{238}U generally appears to increase with increasing mineralization (Yamamoto et al., 2010). The total concentrations of U in the surface waters near U sites in KZ and KG are higher than the provisional guideline value of 15 μg/L in drinking water recommended by the WHO, which reflects the impact of radioactive waste from U production on the aquatic environment (Uralbekov et al., 2011). In the majority of transboundary watercourses from KG to KZ, the chemical toxicity of water, calculated as the "limiting hazard index" from the sanitary guidelines of KZ, exceeds the normative values established in KZ for drinking water by a factor of 2–12 (Solodukhin et al., 2020). Furthermore, the U concentrations in water samples taken from transboundary rivers at their entry points into KZ from KG exceed the corresponding MAC established for drinking water by the WHO $MAC_{WHO} = 30\ \mu g\ kg^{-1}$ by a factor of 1.1–6.7 (Solodukhin et al., 2020).

The open-pit Kurday U mine (S21 in Fig. 1), which was operated during 1954–1965, is located in southern KZ and forms an artificial pit lake that is approximately 100 m long, 35 m wide and 150 m deep and is filled with water due to groundwater inflow and precipitation (Salbu et al., 2013). The pit lake area is surrounded by rivers. The Ni, Mo and U concentrations decrease downstream from the pit lake at the Kurday mine and significantly exceed the reference levels in the Shu River (Salbu et al., 2013). An increasing trend of the total U concentration is observed downstream along the Shu River between the cities of Tokmak and Shu along a stretch of the river that has been affected by U ore mining and processing activities in the past (Burkitbayev et al., 2012). The Kadji-Sai U legacy site (S22 in Fig. 1) in KG represents a source of potential environmental pollution by natural radionuclides and associated trace elements (Lind et al., 2013). The U concentrations in the water within the Kadji-Sai area range from 0.01 to 0.05 mg/L, except for the area downstream from the mining area, where the U concentration exceeds values 10 times higher (or 0.2 mg/L). Hence, the tailings of the former Kadji-Sai U mine may pose a risk of contaminating the Issyk-Kul

Table 3
Statistics of the concentrations of various heavy metals (μg/L) in water bodies. Data source (Crosa et al., 2006b).

	Cr	Mn	Fe	Ni	Cu	Zn	Cd	Pb
Minimum	1.35	9	130	2.1	3.1	15	0.02	0.12
Maximum	643	1720	55,400	105	75.7	189	0.37	51
Mean	322.18	864.5	27,765	53.55	39.4	102	0.2	25.56
Range	641.65	1711	55,270	102.9	72.6	174	0.35	50.88
Standard deviation	453.72	1209.86	39081.79	72.76	51.34	123.04	0.25	35.98

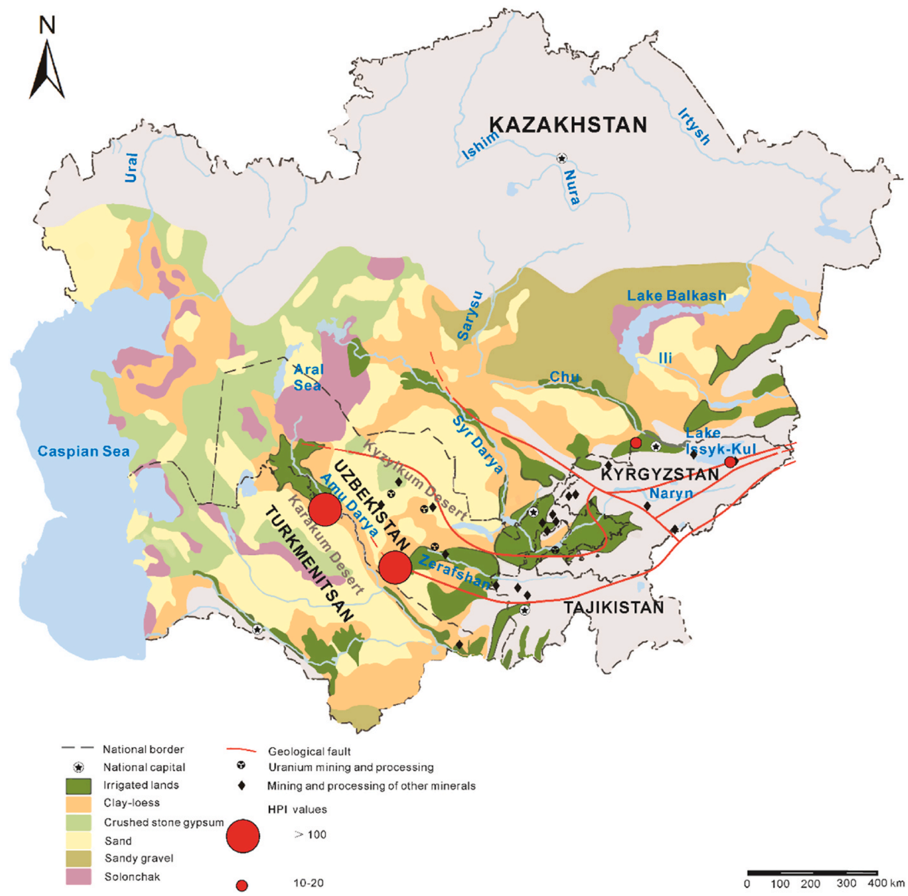

Fig. 3. Pollution issues in Central Asia (based on maps from www.cawater-info.net/infographic/index_e.htm; modified from Xue et al., 2015; data sources: Crosa et al., 2006b; Froebrich et al., 2006; Liu et al., 2020b; Ma et al., 2020).

Table 4
Calculated HPI values for various heavy metals in water bodies based on the World Health Organization (WHO) guidelines (WHO, 2017) for drinking water.

Heavy metal	Mean value (M_i)	Highest permissible value for drinking water (S_i)	Maximum desirable value (I_i)	Sub-index (Q_i)	Unit weight ($W_i = K/S_i$)	$W_i \times Q_i$
Cr	322.18	50	10	780.45	0.02	15.61
Mn	864.5	4000		21.61	2.5×10^{-4}	5.4×10^{-3}
Fe	27,765	1000	100	3073.89	1×10^{-3}	3.07
Ni	53.55	70	20	67.1	1.4×10^{-2}	0.96
Cu	39.4	2000	50	−0.54	5×10^{-4}	-2.7×10^{-4}
Zn	102	4000		2.55	2.5×10^{-4}	6.4×10^{-4}
Cd	0.2	3		6.67	0.33	2.22
Pb	25.56	10		255.6	0.1	25.56

$\Sigma W_i = 0.47$; $\Sigma W_i \times Q_i = 47.43$ and HPI = 101

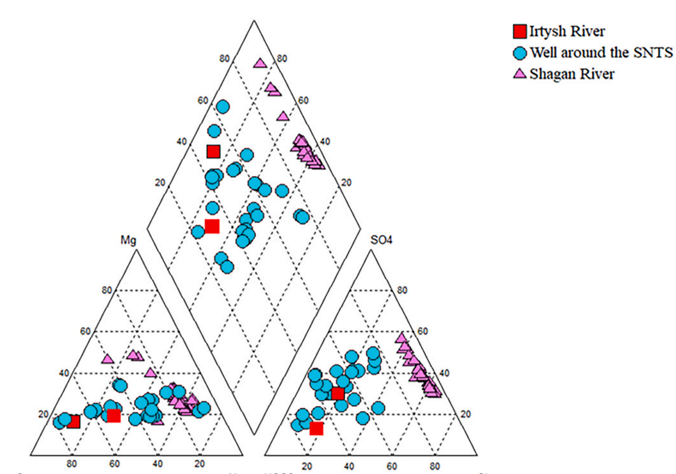

Fig. 4. Piper diagram for groundwater around the SNTS and surface water from the Shagan River, KZ. Data sources (Yamamoto et al., 2010; Gorlachev et al., 2020).

River (Gavshin et al., 2004; Gavshin et al., 2005).

At the former U mines and processing sites at Mailuu-Suu (S23 in Fig. 1) in KG, as expected, drainage from the mine tailings is highly contaminated with many chemicals (e.g., As) and radioactive contaminants (e.g., U). The concentration of U is more than 200 times the 30 mg/L WHO guideline for U in drinking water (Corcho Alvarado et al., 2014).

The Taboshar U mine site (S24 in Fig. 1) operated from 1949–1963 and is located along the upper reaches of the SDR close to the UZ–TJ border. Due to precipitation and the influx of groundwater, the open-pit mine used for extracting U has since filled with water, forming a pit lake. Taboshar's pit lake and the outflowing stream are characterized by high concentrations of As, Mo, Mn and Fe, all of which exceed the maximum concentrations recommended by the WHO for drinking water

(Skipperud et al., 2013). These U-containing substances affect lakes and downstream waters (Stromman et al., 2013). Seven out of nine drinking water samples analysed in the areas surrounding Taboshar exceeded the WHO guideline value of 30 μg/L for U concentration; some of the measured values were even 4 times higher than this guideline (Zoriy et al., 2018). Accordingly, the increased concentrations of U in the SDR in northwestern TJ may be due to the higher concentrations of U upstream in UZ and KG, although this correlation needs to be further confirmed (Zoriy et al., 2018).

4. Conclusions

Our study synthesizes the results of the existing research and demonstrates that Central Asia is currently facing challenges associated with considerable water pollution. The pollution of surface water and groundwater is closely related to human activities such as agricultural irrigation and mining. Spatially, water pollution with heavy metals and radionuclides as the typical pollutants is distributed predominantly throughout the Asian Gold Belt. In contrast, water pollution with nitrogen and phosphorus as the typical pollutants is distributed mainly in the irrigated areas of the middle- and lower reaches of the Amu Darya and Syr Darya rivers.

Agricultural and mining pollutants with high concentrations of NO_2^-, Cu, As, etc., in surface and groundwater systems result in cumulative health hazards in downstream surface waters (Tornqvist et al., 2011). In particular, the expansion of irrigation throughout Central Asia has resulted in a dramatic decline in the groundwater level, increased mineralization, the chemical pollution of surface water and groundwater, and soil salinization (Saiko and Zonn, 2000). Consequently, land desertification and water quality deterioration are accelerating in Central Asia.

Despite the scarcity and pollution of water resources in Central Asia, the region lacks a network for systematically monitoring water quantity and quality changes. Therefore, the management of surface water and groundwater in the transboundary basin requires the joint monitoring of water quantity and quality by countries both upstream and downstream (Karthe et al., 2015; Liu et al., 2020c). In particular, with the rapid population growth and socio-economic development in Central Asia, there is a need to develop a joint surface and groundwater monitoring network to provide a basis for the protection of scarce water resources.

Author contributions

Conceptualization, Y.L. and P.W.; methodology, P.W.; investigation, Y.L.; resources, Y.L. and P.W.; data curation, Y.L., P.W., and B.G; writing—original draft preparation, Y.L.; writing—review and editing, P.W., B.G., J.Y., L.W., D.L., and T.X.; visualization, Y.L.; supervision, P.W.; funding acquisition, J.Y.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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