sustainability

Review

Environmental Impact of Wastewater on Surface and Groundwater in Central Asia

Marzhan S. Kalmakhanova [1,*], Assel A. Kurtebayeva [1], Zhanna T. Tleuova [2], Bagdat Satybaldiev [3], Seitzhan A. Orynbayev [1], Arindam Malakar [4], Helder T. Gomes [5] and Daniel D. Snow [6]

[1] Department of Chemistry and Chemical Technology, M. Kh. Dulaty Taraz University, Taraz 080012, Kazakhstan; asselkurtebaeva001@gmail.com (A.A.K.); orynbayev2050@gmail.com (S.A.O.)
[2] Ahmedsafin Institute Hydrogeology and Geoecology, Satbayev University, Almaty 050000, Kazakhstan; tleuovazhanna.1990@gmail.com
[3] Chemistry and Chemical Technology, Kazakh National University, Almaty 050000, Kazakhstan; bagdat.satybaldiev@gmail.com
[4] Nebraska Water Center, Robert B. Daugherty Water for Food Global Institute, School of Natural Resources, University of Nebraska, Lincoln, NE 68588-0982, USA
[5] CIMO, LA SusTEC, Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253 Bragança, Portugal; htgomes@ipb.pt
[6] Nebraska Water Center, Robert B. Daugherty Water for Food Global Institute 2021 Transformation Drive, University of Nebraska, Lincoln, NE 68588-0844, USA; dsnow1@unl.edu
* Correspondence: marjanseitovna@mail.ru

Abstract: This review aims to increase attention on present water quality issues on Central Asia, finding gaps in the literature on ways to address treatment needs, and help ensure future use of Central Asia surface waters and groundwater for all beneficial uses. Central Asia is a landlocked region known for its harsh climatic conditions and scarce water resources, despite being home to some of the world's largest internal drainage basins. The available literature suggests that increasing salinity has rendered water unsuitable for irrigation and consumption; hazardous trace elements are found throughout Central Asia, most often associated with mining and industrial sources; and that legacy pesticides influence water quality, particularly in agriculturally influenced basins. This study also focuses on the effects of municipal and industrial wastewater discharge. Additionally, the impact of inadequately treated wastewater on water resources is analyzed through a review of available data and reports regarding surface and groundwater quantity and quality. Given the challenges of water scarcity and accessibility, the reuse of treated wastewater is becoming increasingly important, offering a valuable alternative that necessitates careful oversight to ensure public health, environmental sustainability, and water security. However, due to insufficient financial and technical resources, along with underdeveloped regulatory frameworks, many urban areas lack adequate wastewater treatment facilities, significantly constraining their safe and sustainable reuse. Proper management of wastewater effluent is critical, as it directly influences the quality of both surface and groundwater, which serve as key sources for drinking water and irrigation. Due to their persistent and biologically active nature even at trace levels, we discuss contaminants of emerging concern such as antibiotics, pharmaceuticals, and modern agrochemicals. This review thus highlights gaps in the literature reporting on impacts of wastewater inputs to water quality in Central Asia. It is recommended that future research and efforts should focus on exploring sustainable solutions for water quality management and pollution control to assure environmental sustainability and public health.

check for updates

Academic Editor: José Alberto Herrera-Melián

Received: 27 March 2025
Revised: 22 May 2025
Accepted: 29 May 2025
Published: 11 June 2025

Citation: Kalmakhanova, M.S.; Kurtebayeva, A.A.; Tleuova, Z.T.; Satybaldiev, B.; Orynbayev, S.A.; Malakar, A.; Gomes, H.T.; Snow, D.D. Environmental Impact of Wastewater on Surface and Groundwater in Central Asia. *Sustainability* **2025**, *17*, 5370. https://doi.org/10.3390/su17125370

Keywords: water quality; contaminants of emerging concern; organic contaminants; pesticides

1. Introduction

The water resources of Central Asia's transboundary rivers are an invaluable and shared natural legacy, essential to each republic in the region. Until a certain time, this resource was perceived as an inexhaustible and eternal component of the environment that has no economic value. Intensive technogenic human intervention in an extensive use of natural resources has significantly increased the volume of irretrievable water consumption and pollution of water resources [1]. Rational discharge and use of municipal and industrial wastewater are among the most serious problems in ecology and human health. Currently, tens of thousands of substances contaminate natural and industrial wastewater, yet effective removal methods have been established for only a limited number of compounds [2,3]. Cleaning polluted water in industrial zones remains a critical challenge for chemists and environmental scientists, with ensuring safe, high-quality water being particularly vital in water-scarce regions like Central Asia. The state of surface and groundwater quality of many parts of the former Soviet Union was extensively evaluated in a book published in 1998 [4]. The intent was to provide a synopsis and baseline of water quality issues from natural and anthropomorphic contaminant sources nearly 10 years after the dissolution of the USSR, acknowledging that rapid economic development had come at a cost to the environment. The influence of anthropogenic activity is discussed at length by Chernogaeva et al. [5], where it is acknowledged that the areas most impacted by anthropogenic influence have less than 2 percent of the total water resources of the former Soviet Union territories. Point sources of pollution in 1989 were estimated at approximately 160×10^9 m^3, with over 40 million tons of pollutants discharged annually and 20–25% of wastewater discharge that did not meet minimum standards for water quality [5]. Groundwater pollution was primarily associated with oil production, mining, metallurgical plants, fertilizer storage areas, municipal landfills, and untreated sewage. It was estimated that in 1990, over 10 km^3 of untreated municipal and industrial wastewater was discharged into surface water. It was also noted that existing treatment systems were grossly inefficient, resulting in poor quality effluent that severely impacted surface water use [5].

This paper provides an overview of the published literature reporting on groundwater and surface water quality throughout Central Asia since a comprehensive water quality assessment was published [4], with a focus on regular inputs from municipal and industrial wastewater sources. Table 1 shows a summary of some of the existing studies and their limitations. The literature evaluated here is based on the search criteria consisting of the following keywords: "water quality, water pollution, Central Asia, Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan, Turkmenistan", spanning a range of publications from the last 20 years. Sources included the Web of Science citation index and Scopus. The search was refined to organize and limit the contaminants to hazardous trace elements (e.g., As, B, Cd, Co, Cd, Cu, Cr, Fe, Pb, Li, Mn, Ni, Se, Ag, U, and Zn), most relevantly associated with wastewater sources, requiring treatment. Other contaminants that do not have human health or ecological concerns (Cl, SO_4, HCO_3, etc.) were not included in this review, and moreover this manuscript does not report all studies of water chemistry and quality published in the last 20 years.

Wastewater sources are typically the most concentrated sources of pollutants and are most easily controlled through treatment. A companion review article [6] on wastewater treatment technologies in Central Asia includes what is presently known about contaminants of emerging concern (CECs), e.g., pharmaceuticals and their metabolites, in effluents of urban wastewater facilities in the remote Central Asian region. Newer wastewater studies have reported contaminants in many aquatic systems of Kazakhstan, including heavy metals and organic compounds [7–10]. In addition, the presence of CECs—which are persistent in rivers, such as pesticide residues in Syr Darya—and the likelihood of occurrence of pharmaceuticals in effluents of urban wastewater treatment facilities are of critical concern. These emerging pollutants are not easily removed by conventional biological processes used in wastewater treatment facilities [11]. CECs can enter the human body through multiple exposure pathways, including oral ingestion, inhalation, and dermal absorption. One of the primary routes is through drinking water, particularly for perfluorinated and polyfluoroalkyl substances (PFCs), which are not fully removed during water treatment processes. The ingestion of contaminated food, especially aquatic products like fish and shellfish, is also a significant pathway, as these organisms bioaccumulate CECs such as persistent organic pollutants and flame retardants. Inhalation of dust and airborne particles contributes to exposure, particularly in the case of micro/nanoplastics and compounds like PFOA. Moreover, contact with contaminated consumer goods, personal care products, and soil also facilitates transfer. Occupational exposure to CECs, especially among workers in industries handling fluorinated compounds, results in significantly higher body burdens compared to the general population [12]. The toxic values of selected CECs are presented in Table S1.

Agricultural pollution, typically resulting from non-point sources, is also reviewed, as wastewater and municipal biosolids may be applied to cropland, thus presenting a potentially hazardous mix of pollutants [13,14]. Public health concern is serious and aggravated due to the lack of studies on identifying and quantifying CECs in Kazakhstan. The overall intention of this review is to increase attention on present water quality issues, find gaps in the literature on ways to address treatment needs, and help ensure future use of Central Asia surface waters and groundwater for all beneficial uses.

Table 1. Summary of some of the existing studies and their limitations.

Focus	Method	Key Findings	Limitations	Reference
Removal of organic compounds in oilfield water	AOPs	High efficiency for certain compounds	High cost, energy intensive	[2]
Safe water reuse	Comparative overview	Treatment alternatives summarized	Lacks experimental validation	[6]
CEC occurrence and fate	Literature review	CECs are widespread in WWTPs	Data gaps in low-income countries	[11]
Antibiotics in surface water/soil	Monitoring	Non-point pollution significant	Limited to regional context	[14]
Health risks of wastewater irrigation	Meta-analysis	Risk varies by income level	Limited focus on removal techniques	[13]
Wastewater methods in Almaty	Case study	Infrastructure outdated	No CEC-specific data	[10]
Groundwater contamination	Field study	Link between hydrogeology and pollutants	No solution proposed	[8]
Irrigation water quality	Hydrochemical survey	Water quality varies seasonally	Focus not on treatment	[7]
Petrochemical waste	Chemical characterization	Identifies raw materials potential	Outdated; lacks modern context	[5]

2. Scarcity of Water Resources in Central Asia

In terms of water scarcity, Central Asia is particularly vulnerable due to its arid and semi-arid climate, combined with rapidly growing populations and increasing demands for water from agriculture, industry, and households. The region also faces challenges in managing water resources due to inadequate infrastructure and limited access to modern technology. Central Asia comprises several hydrological basins [15,16], with the largest being the Aral Sea basin, covering an area of 1,778,000 km^2 [17] (Figure 1). Additionally, multiple transboundary basins exist, including the Ural, Irtysh, Tobol, Yesil, and Nura in Kazakhstan, as well as the Sary-Jaz and Issyk-Kul basins in Kyrgyzstan. The Ili River and Chu-Talas basins extend across both Kazakhstan and Kyrgyzstan. In Turkmenistan, there are three transboundary basins, two of which—the Murgab and Harirud (Tejen)—are part of the larger Amu Darya basin, while the third, the Atrek River basin, is comparatively smaller.

Figure 1. Surface water resources of Central Asia [18].

Kazakhstan is among the countries with the most limited freshwater resources globally. Water scarcity is a pressing issue, affecting not only drinking water availability but also the agricultural and industrial sectors [19]. The distribution of surface water across the country is highly uneven, with considerable variations in both annual and long-term availability. Kazakhstan's surface water system includes approximately 85,000 rivers, with nearly 90% exceeding 100 km in length, and around 48,000 lakes, 21 of which have a surface area greater than 100 km^2. Additionally, there are approximately 4000 reservoirs and ponds [20].

Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan, all situated in Central Asia, struggle with severe water scarcity and pollution in both surface and groundwater, which likely exacerbates water-related health issues [16]. The availability and quality of water resources in these nations are crucial for their economic growth, social well-being, and ecological sustainability. Central Asia's predominantly arid and semi-arid climate, coupled with increasing water demand, has intensified shortages across the region. Water supply in these countries heavily depends on mountain snowmelt and river flows, which can fluctuate significantly from year to year [21–23]. Additionally, excessive water consumption for irrigation, domestic needs, and industrial use has led to the depletion of groundwater reserves in many areas [24,25].

2.1. Groundwater Vulnerability

Yapiyev et al. reviewed aquifers of Central Asia, depicting distribution and estimated recharge of southern Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan, and the surrounding countries [21] (Figure 2). Major groundwater basins tend to occur along rivers where the shallow alluvial aquifers are prone to contamination from the surface. Domestic wells and public water supplies in shallow alluvial aquifers are most vulnerable to municipal or industrial contamination in urban areas. For example, the public water supply for Bishkek is contaminated with high nitrate and chloride, likely from urban wastewater [26].

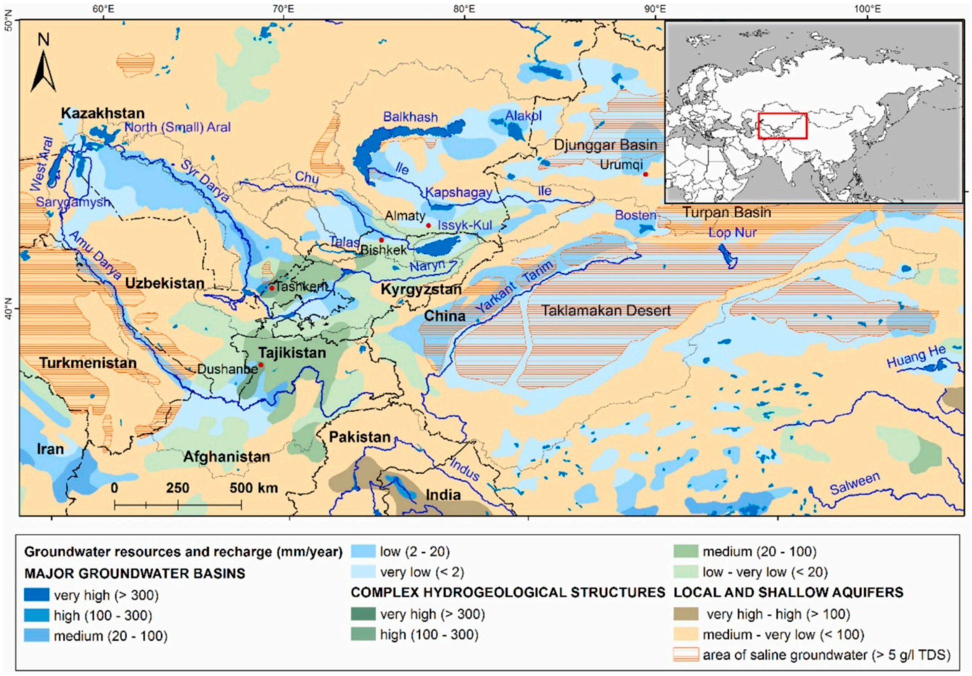

Figure 2. Distribution of groundwater resources and estimated recharge of southern Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan, and the surrounding countries [21].

Groundwater in other urban areas in Central Asia reported to likely be polluted from wastewater sources include Almaty and Shymkent in Kazakhstan [8,27] and Tashkent in Uzbekistan [28]. A diagnostic report of 2001 [17] attempted to update data on the evaluation of groundwater in 1997 (Table 2). Unregulated water abstractions and unauthorized construction negatively impacted fresh groundwater in the Aral Sea basin states. The existing monitoring system in the region is insufficient for accurately evaluating aquifer pollution, groundwater depletion, and waterlogging in inhabited areas. The usable groundwater stock is primarily allocated for drinking and household purposes. Groundwater abstraction through vertical drainage systems is common in Kazakhstan, Tajikistan, and Uzbekistan [17]. This table shows a comparative analysis of 2000 data with 2018 data regarding the evaluation of regional stock, approved usable stock, actual abstraction, and use for drinking water supply of all Central Asian countries: Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan. The table gives an idea of the change, for better or worse, in these data (Table 2).

Given the potential risks of groundwater quality degradation and its strategic importance for all countries, fundamental information and analytical assessments of groundwater are not readily accessible [17]. However, several countries have begun actively inventorying their groundwater resources and usage in recent years. For instance, Kazakhstan has significant groundwater resources, though they are unevenly distributed across the country. Of the total forecasted and explored groundwater resources, only 16.04 km^3 are deemed accessible [29]. A 2015 assessment of Kazakhstan's aquifers identified 2905 aquifers and groundwater abstraction sites [17]. Results from southern Kazakhstan indicate a regional stock of 8410 $\times$ 10^3 km^3 per year, a fourfold increase, though only 1052 $\times$ 10^3 km^3 per year of this is considered usable.

Table 2. Groundwater stock and its use by Central Asia countries (km^3/year) in 2018, compared with 2000 [17].

Country	Evaluation of Regional Stock		Approved Usable Stock		Actual Abstraction		Use for Drinking Water Supply	
	2000	2018	2000	2018	2000	2018	2000	2018
Kazakhstan	1846 $\times$ 10^3	8410 $\times$ 10^3	1270 $\times$ 10^3	1052 $\times$ 10^3	963 $\times$ 10^3	859 $\times$ 10^3	200 $\times$ 10^3	367.6 $\times$ 10^3
Kyrgyzstan	1595 $\times$ 10^3	14,212 $\times$ 10^3	632 $\times$ 10^3	622 $\times$ 10^3	548 $\times$ 10^3	545 $\times$ 10^3	304 $\times$ 10^3	340 $\times$ 10^3
Tajikistan	18,700 $\times$ 10^3	na	6020 $\times$ 10^3	2965 $\times$ 10^3	2294 $\times$ 10^3	2300 $\times$ 10^3	485 $\times$ 10^3	461 $\times$ 10^3 **
Turkmenistan	3360 $\times$ 10^3	69,000 $\times$ 10^3	1220 $\times$ 10^3	1270 $\times$ 10^3	457 $\times$ 10^3	1200 $\times$ 10^3	210 $\times$ 10^3	558 $\times$ 10^3
Uzbekistan	18,455 $\times$ 10^3	na	7796 $\times$ 10^3	6336 $\times$ 10^3	7749 $\times$ 10^3	5577 $\times$ 10^3	3369 $\times$ 10^3	1825 $\times$ 10^3
Total	**43,956 $\times$ 10^3**	**91,622 $\times$ 10^3 ***	**16,938 $\times$ 10^3**	**12,245 $\times$ 10^3**	**12,011 $\times$ 10^3**	**10,481 $\times$ 10^3**	**4568 $\times$ 10^3**	**3552 $\times$ 10^3**

* Data from the year 2000 was used to estimate average values for countries where 2018 data were unavailable. ** The figures vary: according to "TajikGlavGeology", 39.3% (903.3 $\times$ 10^3 km^3) is allocated for drinking water needs. Source: The data of Central Asia experts involved in the work on the diagnostic report [17].

In Kyrgyzstan, an updated assessment has identified 44 aquifers, 20 of which are designated for drinking and industrial use [17]. The total usable groundwater slightly decreased from the previous assessment, with total abstraction reaching 545 $\times$ 10^3 km^3. In Tajikistan, the forecasted groundwater resources amount to 18,688 $\times$ 10^3 km^3 annually, with a developed usable stock of fresh groundwater in valley areas totaling 2774 $\times$ 10^3 km^3 per year [17]. There are over 4600 operational water wells in the country, and the overall situation with groundwater has remained stable, with abstraction slightly reduced to 793 $\times$ 10^3 km^3 per year.

These recent assessments suggest that the situation with groundwater in both Kyrgyzstan and Tajikistan has remained relatively stable, with a slight decrease in abstraction in Tajikistan. However, it is important to continue monitoring and managing these resources to ensure their sustainability and availability for future uses. Currently, Turkmenistan's total groundwater reserves are estimated at 69,000 $\times$ 10^3 km^3, with 1270 $\times$ 10^3 km^3 considered usable [17]. However, much of this groundwater is brackish and unsuitable for drinking or domestic purposes. In Uzbekistan, there are 97 identified aquifers, 19 of which are designated as protected natural areas for fresh groundwater formation [20]. Groundwater distribution across the country is uneven, but total reserves have slightly increased by 27.5 $\times$ 10^3 km^3 per year, including both fresh and brackish water. This represents a 9 $\times$ 10^3 km^3 rise compared to 1999 estimates. The officially approved usable groundwater stock amounts to 6336.4 $\times$ 10^3 km^3, with an annual abstraction of 5577.3 $\times$ 10^3 km^3.

Between February and March 2017, an inventory of over 10,000 water wells was conducted, revealing ongoing negative impacts on groundwater resources. The findings showed that more than 60% of wells were subject to uncontrolled groundwater extraction, contributing to further pollution and depletion. Additionally, 59% of groundwater was being drawn from unapproved reserves, posing a serious risk of irreversible losses, potentially leading to the depletion of over half of Uzbekistan's fresh groundwater in the coming decades. Groundwater resources in the Aral Sea basin have decreased, with deterioration of aquifer quality in some places and a decrease in annual abstractions by 25–30% in Uzbekistan. The water deficit is compensated through increased use of surface sources, raising the further risk of water quality deterioration [30,31].

A comprehensive approach to water management is needed to address these challenges, including measures to improve efficiency and promote more sustainable practices, as well as provide public education about groundwater importance and challenges [32]. The depletion of groundwater availability and decreased quality is pushing the need to assess other alternatives of water for irrigation purposes, such as the use of treated wastewater.

2.2. Surface Water

A recent assessment reveals a decline in available surface water resources in the Amu Darya and Syr Darya basins, with runoff reductions of 0.51 km^3 and 0.9 km^3, respectively, compared to 2001 data [17]. However, river runoff has generally fluctuated within expected patterns, with a slight overall decline over the past 12 years. In the Amu Darya basin, higher runoff was recorded in 11 of the last 30 years, including eight occurrences in the first decade and two in the second. Conversely, there were instances of lower-than-expected flow (below 80% probability) in 1 year of the first decade, 5 years of the second, and 4 years of the third.

Table 3 presents surface water runoff changes in other basins [17]. While Kazakh experts have conducted a detailed assessment of Kazakhstan's hydrological basins, similar analyses for other basins remain unavailable due to a lack of surface runoff data. Even in basins where dedicated commissions exist, these key indicators have not been subjected to thorough examination.

Table 3. Characteristics of hydrological basins in Kazakhstan and Kyrgyzstan (outside Aral-Syrdarya basin), km^3/year [17].

	Average Long-Term Runoff		**Transfers to Other Basins**	**Inside Countries**	**Available Runoff**	**Decrease in External Inflow**	**Catchment Area, Thousand km^2**
	Total	**External Inflow**					
Kazakhstan's water resources, excluding Aral-Syrdarya basin:							
Balkhash-Ili	27.8	11.4	7		3.3	−5	68.4 (131)
Irtysh	33.5	9.8	7.9		5.6	−3.5	210 (1592)
Yesil	2.6				1.1		113 (156)
Nura-Sarysu	1.3			0.9	0.9		
Tobol-Turgai	2				0.6		130 (395)
Chu-Talas	4.2	3.1			2.8		78 (115)
Ural-Caspi	11.2	7.9			4.6	−3.6	73 (231)
Total	**82.6**	**32.2**	**14.9**	**0.9**	**18.6**	**−12.1**	
Kyrgyzstan's water resources:							
Chu-Talas	6.74	-	3.1		3.6		37.3 (115.2)
Ili	0.36	-			0.36		
Sary-Jaz	6.15	-	3	1.6	1.55		28.5
Issyk-Kul	4.65				4.65		22
Total	**17.9**		**3.1**		**10.16**		

Water inflow in Central Asia outside the Aral Sea basin has declined, with a reduction of 16.2 km^3 in Kazakhstan and 12.1 km^3 in transboundary rivers such as the Black Irtysh, Ili, and Ural [17]. China has increased water withdrawals by 8.5 km^3 from the upper reaches of the Ili and Black Irtysh rivers, while the Russian Federation has extracted an additional 3.6 km^3 from the Ural River [17]. The rising trend of China's water consumption from the Ili River poses a potential risk to the water balance of Lake Balkhash.

A proposal has been put forward to redirect a portion of the Irtysh River's runoff to the Syr Darya basin to help sustain water resources. Meanwhile, water quality across Central Asia—both surface and groundwater—continues to be impacted by agricultural runoff, industrial discharges, and municipal wastewater [16].

In Kazakhstan, surface water quality is significantly impacted by pollution from industries such as chemical production, oil extraction, manufacturing, and metallurgy. Of the 44 water sources analyzed, only nine rivers, two lakes, and two reservoirs were classified as unimpaired, while six rivers and one reservoir were identified as contaminated [33]. The remaining sources fall within legally permissible contamination levels. Additional pollution originates from urban infrastructure, agricultural activities, waste containers, and storage facilities.

Salinity levels in Kazakhstan's lakes vary from 0.12 g/L in the east to 2.7 g/L in the central region, with more than 4000 lakes classified as saline. Excessive water use for irrigation in the Ili River basin has led to the depletion of smaller lakes, with approximately 8000 lakes lost due to overexploitation.

In contrast, Kyrgyzstan's rivers generally maintain good water quality, as they are primarily fed by glacial melt with low salt concentrations and minimal pollution. Groundwater serves as the primary drinking water source for 90% of the population [33] and largely meets drinking water quality standards. However, a significant environmental concern in the region is the unresolved issue of nuclear tailing dumps, which continue to pose a serious threat [33].

In Tajikistan, most water sources are considered safe for drinking, except for certain lakes and groundwater reserves. Salinity levels generally range between 0.05 and 0.40 g/L [33].

In Turkmenistan, surface water quality in rivers and drainage systems is poor due to elevated concentrations of salts and pesticides [33]. This contamination stems from both local sources and upstream countries. Over the past few decades, the discharge of drainage and industrial wastewater into the Amu Darya has significantly degraded water quality, contributing to rising annual salinity levels. While groundwater quality remains largely unaffected for now, continuous monitoring is essential to ensure its safety.

Furthermore, intense human activity and the release of highly saline drainage water from neighboring Uzbekistan into the Amu Darya are exacerbating regional water quality concerns [34].

Water pollution in Uzbekistan is a significant issue, with the primary sources being sewage discharge and industrial wastewater [16]. The high concentrations of salts and pollutants in rivers and drainage networks not only degrade water quality but also negatively impact the surrounding environment. Salinity levels in irrigation water have risen, especially in the lower reaches of rivers, while the presence of organic pollutants, including phenols and nitrates, remains a growing concern.

Groundwater contamination along the Amu Darya River has also worsened, with heavy metals such as lead and cadmium exceeding maximum allowable concentrations [35]. Addressing these challenges requires urgent action to mitigate pollution sources and enhance the overall quality of water resources in the region. Accurate simulation of heavy metal transport in riverine systems is essential for understanding their behavior, fate, and potential environmental impacts. Several studies have incorporated hydrodynamic and water quality models to simulate these processes. For example, Poshtegal and Mirbagheri (2023) [36] developed a one-dimensional qualitative model that simulates the phase transfer of dissolved heavy metals by accounting for environmental parameters such as temperature, dissolved oxygen, pH, and electrical conductivity. Their approach integrates the HEC-RAS hydrodynamic model and the QUAL2KW water quality model, providing a comprehensive framework for modeling heavy metal transport in rivers. This type of integrative modeling is particularly valuable in regions with variable hydrochemical conditions and limited observational data.

To address these challenges, it is crucial for the governments of Central Asian countries to take action to improve water quality and manage water resources more effectively. This includes investing in modern water treatment facilities, implementing better agricultural practices to reduce pollution, and promoting water conservation measures. International organizations and donor countries can also play a role in supporting these efforts through technical assistance, funding, and the transfer of technology and expertise. Collaborative approaches between countries in the region can also help to address cross-border water issues, such as the sharing of transboundary water resources. In conclusion, the quality and scarcity of water resources in Central Asia is a growing concern, affecting both public health and economic development. Addressing these challenges will require a coordinated effort from the government, international organizations, and the private sector to improve water management practices and ensure a sustainable supply of clean water for future generations.

3. Pollutants Detected

Industry- and Mining-Related. Central Asia, a region comprising Kazakhstan, Kyrgyzstan, Uzbekistan, Turkmenistan, and Tajikistan, is facing challenges with the quality of its water resources. Water quality in the region is affected by factors such as industrial and agricultural pollution, as well as the use of outdated infrastructure and insufficient treatment facilities. This has resulted in concerning levels of contaminants in the water supply, posing a significant threat to public health. After independence, Kazakhstan recognized the need for a new state system for ensuring regional environmental safety and environmental and natural resource management, with a territorially ratified system of executive bodies now regulating environmental protection [37]. Studies supporting these programs cited several rivers, including the Irtysh, Nura, Syr Darya, Ili, as well as Lake Balkhash as the most contaminated and problematic in Central Asia [38,39].

Table S2 compiles published data on water contamination across Central Asia, highlighting several critical issues summarized for inorganic contaminants in Table 4. In these complied works, in general, water sampling was carried out assuming that the selected locations represent the range of hydrogeological and anthropogenic conditions across the region, and during specific season, to reduce variability caused by temporal changes. We assumed that the accessible sites provide reliable data comparable to less accessible areas with similar characteristics. In these compiled works, in general, accuracy was ensured by running quality control samples and blanks alongside water samples, and sensitivity was confirmed through the selection of validated analytical techniques with low detection limits suitable for trace contaminants typical in Central Asian waters.

Ranges for hazardous inorganic contaminants are compared to regulatory limits for wastewater reuse and USEPA guidelines for drinking water [40]. Surface water quality standards are highly dissimilar across countries and it is impossible to compare ranges to all standards [39]. While untreated surface water is not generally used for a drinking water source, the concentrations listed here can provide useful benchmarks for differences across time. Moreover, organic contaminants are less frequently monitored worldwide, with even fewer benchmarks available for comparison [41].

In Kazakhstan, a recent study found that hazardous trace elements such as arsenic (As), copper (Cu), chromium (Cr), iron (Fe), manganese (Mn), and nickel (Ni) exceeded the country’s maximum pollutant concentrations for fishery water bodies at three sites in the Syr Darya basin [42]. Water quality index and Cd values classified these surface waters as highly polluted, suggesting a significant risk to fisheries, particularly in the Shardara Reservoir and other areas within the Syr Darya basin [42].

Similarly, research on Kazakhstan's sector of the Caspian Sea confirmed that heavy metals are the primary contaminants [43]. These pollutants can accumulate in fish tissue, posing ecological and human health risks. Additionally, monitoring of the Ishim River in the Akmola Region (Northern Kazakhstan) revealed that, despite stricter wastewater discharge regulations for the Ishim River basin, several key water quality indicators still fail to meet regulatory standards for surface water bodies [44].

An assessment of radioactive and chemical contamination in water resources near former uranium mines and processing sites in Mailuu-Suu, Kyrgyzstan, revealed mixed results [45]. While radionuclide and hazardous metal concentrations in the drinking water distribution system were generally low, levels of iron (Fe), aluminum (Al), and manganese (Mn) were excessively high, rendering the water unsuitable for drinking. As anticipated, drainage water from mine tailings exhibited severe contamination, containing high levels of arsenic (As) and radioactive pollutants such as uranium.

Another study on Kyrgyzstan's rivers indicated that fluoride and arsenic concentrations, as well as the number of samples exceeding the maximum permissible limits for drinking water, have been rising annually [46]. Fluoride contamination was most pronounced in basins and valleys, while arsenic levels exceeded safe limits in the Ak-Suu reach of the Chu River Valley.

Further research on the upper reaches of the Syr Darya River within the Aral Sea basin found that dissolved hazardous trace element concentrations remained well below permissible thresholds [47]. Additionally, Rzymski et al. [48] examined pollution from trace elements and rare earth metals in the lower Syr Darya River and Small Aral Sea, contributing to the growing body of evidence on water quality concerns in the region. Drinking water supplies sampled from settlements near uranium mining sites in Kazakhstan and Kyrgyzstan exhibited relatively low uranium concentrations compared to surface waters from the same locations [49]. In contrast, surface waters showed significantly higher levels of total uranium, indicating the impact of radioactive waste from past uranium mining activities.

A study conducted by Ivanova et al. [50] on the radiological effects of surface water and sediment near uranium mining sites reported concerning uranium contamination levels. However, other assessments of surface waters from the Shu River in Kazakhstan [51] and the Kharaa River basin in Mongolia [52] found that element concentrations remained within permissible limits.

Agricultural Pollutants. In Uzbekistan, a major cotton producer, the heavy use of pesticides and fertilizers has contaminated water sources, affecting not only the health of local communities but also the productivity of agriculture [16]. In Uzbekistan, salinization of the Amu Darya waters was found to be mainly due to the presence of sulfates and chloride diminishing its value for irrigation, fisheries, and human consumption [23].

The agricultural sector is one of the main contributors to non-point source water pollution in these countries, using large quantities of fertilizers and pesticides that can contaminate surface and groundwater sources [53]. Furthermore, untreated wastewater from cities and industries is often discharged into rivers and lakes, thereby degrading water quality. In addition, mining activities, oil and gas extraction, and transportation can also contribute to water pollution. The dramatic shrinkage of the Aral Sea has severely impacted the local environment, particularly in Uzbekistan's Amu Darya basin, where water quality has deteriorated to hazardous levels. The reduction in water volume, declining water quality, and increased pollutant emissions have significantly affected public health. These changes have led to rising infant mortality rates, slower growth in children, and higher morbidity levels among residents in the region [35,53].

Table 4. Comparison of dissolved hazardous trace element concentrations to earlier report [54] and US and global wastewater guidelines [40].

Pollutant	1973–93 [1] (µg/L)	2000–2024 Table S2 (µg/L)	Regulatory Limits for Wastewater [2] (µg/L)	EPA Drinking Water Guidelines [2] (µg/L)
Arsenic	No data	1.4–1600	100	10
Cadmium	0.04–0.9 (5.8) *	0.05–6.1	10	5
Cobalt	0.05–0.15	0.11–13	50	--
Copper	0.48–1.3 (443) *	1.25–316	200	1300
Chromium	No data	1.3–80	100	100
Iron	No data	354–20,600	5000	300
Lead	0.13–2.1(74) *	0.23–31	5000	15
Lithium	No data	-	2500	--
Manganese	4.2–30	6.7–2800	200	500
Mercury	0.09–10 (65.1) *	0.02–0.19		
Nickel	No data	0.61–78	200	--
Selenium	No data	3.4–35	20	50
Strontium	90–530	-	NA	--
Uranium	No data	22.1–8300	NA	30
Zinc	0.21–14 (646) *	1.0–82.87	2000	5000

[1] Tables 8.1 and 8.3 in [54]; recommended concentration limits from FAO Irrigation and Drainage 'Water Quality for Agriculture'. [2] Table 1 in [40] * values in brackets indicate the maximum detected concentration.

The rapid expansion of irrigated agriculture has led to significant changes in both surface and groundwater quality. These changes are primarily driven by the increased use of chemicals in farming, the discharge of collector–drainage waters into river systems, and the reuse of wastewater. This process contributes to the accumulation of pollutants and the deterioration of water quality in the region [53]. In Kyrgyzstan, the legacy of uranium and other mining operations is a serious problem [9]. In Tajikistan, on the other hand, water quality and supply are generally satisfactory [55], likely due to lower agricultural and industrial water uses. In Turkmenistan, river water and drainage networks are frequently contaminated with high levels of pesticides, originating from both domestic sources and upstream international basins [56]. To tackle the pressing issues of water scarcity and pollution in these countries, it is crucial to implement a sustainable water management strategy that balances the social, economic, and environmental dimensions of water use. This approach should include policies and strategies that encourage efficient water use, promote the reuse of wastewater, support alternative water sources such as rainwater harvesting, and enhance water resource monitoring and management. Investments in infrastructure and institutional capacity are also needed to address the water challenges, particularly in rural areas.

Municipal Wastewater. Driven by population growth and the need for increased agricultural production, water resources are coming under intense pressure across Central Asia, pushing the need to use treated wastewater for irrigation. However, wastewater treatment has not progressed substantially since the assessment of 1998 [5]. Over the past two decades, several studies have been conducted on a wide range of pollutants, but new pollutants are caused primarily by micro-pollutants, endocrine disruptors (EDs), pesticides, pharmaceutical preparations, as well as synthetic dyes of industrial production and dangerous pollutants containing dyes [57,58], and these are not currently removed from treated wastewaters.

There are currently no standardized guidelines for the safe levels of most emerging pollutants, yet even at low concentrations, these substances can pose significant risks to both human health and aquatic ecosystems. To combat the above-mentioned environmental threats, huge efforts have been made to improve the efficiency of recovery procedures or to develop new methods for detecting, quantifying, and improving the effectiveness of samples [59]. The varied mixtures and types of compounds that can cause harm to plants and the health of people who live in the vicinity where sewage and urban sewers are located were also investigated. Karthe et al. [60] and others [61–63] showed that improper management of municipal wastewater in growing urban areas is another serious factor leading to an increase in the level of pollution of rivers and groundwater with organic substances, nutrients, and pathogens.

Knowing that such problems exist in every country, and especially in cities and regions where effective technologies are not provided, the authors of this review conducted scientific work related to the determination of the composition of effluents at wastewater treatment plants in Kazakhstan, more specifically in the city of Taraz, Zhambyl region. Taraz is in the south of the country, near the border with Kyrgyzstan, on the Talas River. The population of the city is around 426,000 people, and Taraz is currently the only regional center in Kazakhstan where there is no sewage treatment plant for wastewater filtration [6]. According to the State Enterprise, the city sewerage system of the regional center has been operating since 1962. Over the years, the areas of filtration fields have expanded, and the number of maps and the capacity of settling tanks have increased. Due to the lack of sewage treatment facilities, sewage now flows directly to the settling tanks covering 14 hectares, and then they are discharged to the filtration fields, comprising a total area of about 200 hectares [64]. In addition to discharge into urban filtration fields, there are settling tanks of chemical plants and sewage-reinforced concrete collectors. The existing wastewater filtration fields, according to experts, are outdated, and plans are in place to retire this treatment system. The filtration area no longer accommodates the amount of waste that comes in every day, and the existing dams are in a dilapidated state. As a result, residents of the settlements of Zhambyl district near the filtration fields suffer from the stench, as well as from the penetration of sewage effluents into local groundwater. The drains from the filled sedimentation tanks merge into the channels of the adjacent villages of Kostobe (Asa) and Zhambyl, polluting the environment with harmful emissions and odor. According to experts, in the future, water from the canals may seep into the Asa River and Lake Bilikol, which could lead to an environmental disaster [64]. This situation is not unique, as there are other more visible examples of improper treatment and disposal of municipal wastewater in Central Asia [6,10] as well as throughout the world [11].

4. Gaps in Water Quality Assessment and Monitoring

Measuring water quality is an ongoing process governed by changes in monitoring technology and standards used to evaluate suitability for a particular use. Moreover, present surface water quality standards show considerable variation and are highly dependent upon regional priorities for water use and infrastructure [41]. Implemented changes in water monitoring technology depend on costs, ease of use, and acceptance of policy for requiring new measurements. New low-cost sensors, remote sensing [65], and other technologies are automating many of the routine measurements used in monitoring, thus making way for adoption of more complex and higher cost methods [66]. In addition, optical and electrochemical sensors can be used to target areas where additional sampling may be conducted. As global demand for freshwater increases, climate change and land-use changes, groundwater is becoming an increasingly important and vulnerable resource. The depletion of groundwater because of human activities poses a serious threat to the supply of drinking water and irrigated agriculture. On the other hand, the quality of groundwaters is affected by human activities at the surface, with the runoff/leaching of chemicals used in agriculture, as well as the discharge of effluents of wastewater treatment plants being examples of processes where transference of contaminants from the surface to groundwaters can occur.

Contaminants of emerging concern (CECs) are of particular importance for monitoring due to their persistent nature when subjected to conventional biological processes used in wastewater treatment facilities, accumulating in water reservoirs, and ultimately in groundwaters. CECs include pharmaceuticals, personal care products, pesticides, and other chemicals. As CECs are not currently regulated in the effluents of wastewater treatment plants [67], these have a great impact on the environment and on human health, particularly antibiotics and antibiotic resistance genes (ARG), even at trace levels. This is a gap, not only in Central Asia but throughout the world [68]. More research is needed to understand the occurrence and potential environmental and human health effects.

Central Asia is a vast and diverse region with an abundant supply of water resources that are essential for sustaining human life and supporting economic growth. However, like much of the rest of the world, the quality of these water resources is under threat due to the release of CECs. For example, a recent conference article reported the occurrence of aspirin in wastewater from Kazakhstan's capital city [69]. CECs can enter surface waters and groundwaters in Central Asia through a variety of sources, including agricultural runoff, wastewater discharge, and industrial activities. Agricultural activities, such as irrigation and the use of pesticides and fertilizers, can lead to the contamination of surface and groundwater with agricultural chemicals [47]. Wastewater discharge from municipal and industrial sources can also contribute to the presence of CECs in water systems. Additionally, the use of pharmaceuticals and personal care products by humans and animals can result in the release of these compounds into waterways through excretion.

Even legacy contaminants identified over two decades ago [4] continue to persist and affect water quality. For instance, a study on the Syr Darya River, which flows through Kazakhstan, Kyrgyzstan, and Uzbekistan, examined seasonal variations in the concentrations of both modern and legacy pesticides. Among the legacy chlorinated pesticides found in grab samples from the river, lindane (γ-HCH) was detected most frequently, with the highest concentrations recorded in June [70]. More detailed results of the study are summarized in Table S3. Another study in Kyrgyzstan identified pollution hotspots in the Chu River basin, the lower sections of the Kara-Darya and Naryn tributaries in the Osh and Djalal-Abad oblasts, as well as the Tyup rivers flowing into Lake Issyk-Kul. High concentrations of pesticides, including the banned insecticide DDT, were detected in these areas [71]. In a separate study by Amirgaliyev et al., monitoring the long-term trends of persistent organic pollutants in the Aral Sea–Syr Darya basin, metabolites of DDT, Heptachlor, and Aldrin HCCH (α, β, γ–Isomers) were found [72]. Similarly, Jin et al. [73] detected organochlorine pesticides in the surface water of the Amu Darya River basin in Uzbekistan. However, the regulation and management of CECs in Central Asia is currently limited. Most water systems in the region are not monitored for these contaminants, and there are no specific regulations in place to control their release into the environment. However, there have been some efforts to address the issue. For instance, some Central Asian countries, including Kazakhstan, have adopted the European Union's Water Framework Directive as a foundation for their water resource management strategies. This directive provides a comprehensive approach to protecting and managing water resources, aiming for sustainable water quality and availability [74].

CECs are an emerging concern in Central Asia, presenting a significant research gap due to their potential risks to human health and the environment. These pollutants, which include pharmaceuticals, personal care products, and industrial chemicals, are not typically monitored but could have harmful effects on ecosystems and public well-being. Although studies have detected these contaminants in water systems throughout the region, there is currently limited regulation and management of CECs in Central Asia. Further research is crucial to fully understand the scope of the CECs problem and to develop effective strategies for mitigating their impacts on water resources in the region. This research should focus on identifying the sources, concentrations, and long-term effects of CECs, as well as exploring sustainable solutions for water quality management and pollution control. Figure 3 presents a summary of the identified gaps in water quality assessment and monitoring in Central Asia.

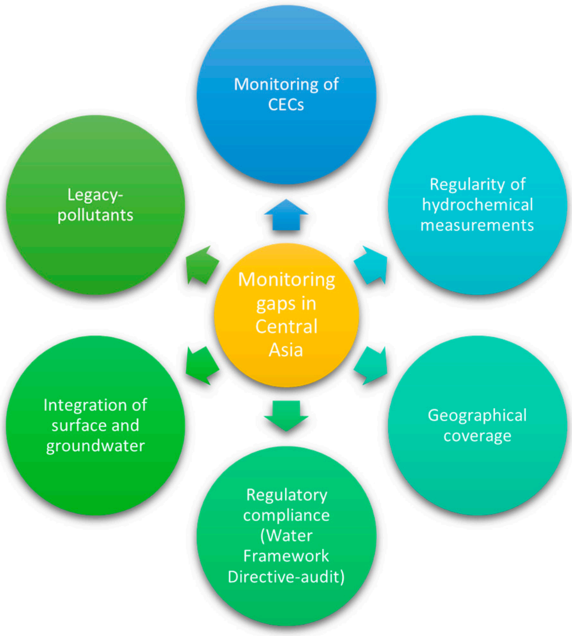

Figure 3. Identification of gaps in water quality assessment and monitoring in Central Asia.

5. Conclusions

Central Asia is facing critical challenges with the quality of its water resources, affected by factors such as industrial and agricultural pollution, as well as the use of outdated infrastructure and insufficient treatment facilities, leading municipal wastewater to be large contributor sources to pollution. The runoff/leaching of chemicals used in agriculture, as well as the discharge of effluents of wastewater treatment plants are examples of processes of contamination of surface waters, further transferred to groundwaters with high impact to the quality and availability of water resources, posing a serious threat to the supply of drinking water and irrigated agriculture. With a growing population and improving standard of living, freshwater resources are even more important than ever in Central Asia. Since these water quality issues were highlighted more than 20 years ago, pollution of these resources appears to be a chronic problem in all countries of Central Asia. Reported declines in water quality are particularly problematic in continuing to supply safe water for drinking, irrigation, and habitat. The available literature suggests that increasing salinity has rendered water unsuitable for irrigation and consumption in most of the water-scarce arid and semi-arid regions. Hazardous trace elements such as arsenic, chromium, nickel, and fluoride continue to be found throughout Central Asia, but are most often associated with mining and industrial sources. Elevated levels of uranium are also associated with ore deposits and mining activities. Legacy pesticides continue to influence water quality, particularly in agriculturally influenced basins. Underdeveloped wastewater treatment technology has impacted and continues to affect surface and groundwater quality throughout this region. Emerging contaminants from wastewater, a function of improved standards of living and our ability to measure them, are a significant but largely unknown group of pollutants that could have long-lasting effects on water quality throughout the region. Though some progress has been made in water treatment technologies, there is much left to do to reduce previous and ongoing impacts of wastewater throughout the region. Future research and efforts should focus on exploring sustainable solutions for water quality management and pollution control to assure environmental sustainability and public health. It is recommended to involve different stakeholders, including the scientific community, government, policy makers and non-governmental organizations, to adopt measures to effectively address the identified challenges, such as policies and strategies that encourage efficient water use, promote the reuse of wastewater, support alternative water sources such as rainwater harvesting, and lead to the development of more efficient wastewater treatment technologies. Investments in infrastructure and institutional capacity are also needed to address the water challenges, particularly in rural areas. Finally, it should be highlighted that there is much more information available for Kazakhstan and Kyrgyzstan than for Uzbekistan and Turkmenistan, placing some geographical bias in our conclusions; thus, we suggest that much more work is needed in these countries.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17125370/s1, Table S1. Toxicity Values for Selected CECs. Table S2. Published data on the detection of contaminants in water objects of Central Asia (NA: Not Available, AL: Action level, SDWR: Secondary drinking water regulations). Table S3. Detected pesticide concentrations measured from the Syr Darya sampling sites. "ND": "Not Detected"; "–": "Not Sampled" [70]. References [75–82] are cited in supplementary materials.

Author Contributions: Conceptualization, D.D.S. and M.S.K.; methodology, D.D.S., M.S.K. and H.T.G.; validation, D.D.S. and M.S.K.; writing—original draft preparation, M.S.K., Z.T.T., A.A.K., A.M., S.A.O. and B.S.; writing—review and editing, D.D.S., A.M. and H.T.G.; funding acquisition, D.D.S., M.S.K. and H.T.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research is funded by the Science Committee of the Ministry of Education and Science of the Republic of Kazakhstan (Grant No. BR24992867) and by CIMO (UIDB/00690/2020).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study.

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

References

1. Bimenova, A. Evaluation of water potential in Central Asia in the context of the term interests of Kazakhstan. *Post Sov. Issues* **2015**, *1*, 165–176.
2. Costa, S.I.G.; Ferreira, F.L.; Weschenfelder, S.E.; Fuck, J.V.R.; da Cunha, M.d.F.R.; Marinho, B.A.; Mazur, L.P.; da Silva, A.; de Souza, S.M.A.G.U.; de Souza, A.A.U. Towards the removal of soluble organic compounds present in oilfield produced water by advanced oxidation processes: Critical review and future directions. *Process Saf. Environ. Prot.* **2023**, *174*, 608–626. [CrossRef]
3. Nikulina, S. Petrochemical waste and by-products production-raw materials for organic synthesis. *Chemistry* **1989**, 237.
4. Kimstach, V.A.; Meybeck, M.; Baroudy, E. *A Water Quality Assessment of the Former Soviet Union*; E & FN Spon: London, UK; New York, NY, USA, 1998; p. 640.
5. Chernogaeva, G.M.; Lvov, A.P.; Georgievsky, V.Y. Water Use and the Influence of Anthropogenic Activity. In *A Water Quality Assessment of the Former Soviet Union*; Kimstach, V.A., Meybeck, M., Baroudy, E., Eds.; E & FN Spon: London, UK, 1998; pp. 69–94.
6. Kalmakhanova, M.S.; Diaz de Tuesta, J.L.; Malakar, A.; Gomes, H.T.; Snow, D.D. Wastewater Treatment in Central Asia: Treatment Alternatives for Safe Water Reuse. *Sustainability* **2023**, *15*, 14949. [CrossRef]
7. Satybaldiyev, B.; Ismailov, B.; Nurpeisov, N.; Kenges, K.; Snow, D.D.; Malakar, A.; Taukebayev, O.; Uralbekov, B. Downstream hydrochemistry and irrigation water quality of the Syr Darya, Aral Sea Basin, South Kazakhstan. *Water Supply* **2023**, *23*, 2119–2134. [CrossRef]

8. Tleuova, Z.; Snow, D.D.; Mukhamedzhanov, M.; Ermenbay, A. Relation of Hydrogeology and Contaminant Sources to Drinking Water Quality in Southern Kazakhstan. *Water* **2023**, *15*, 4240. [CrossRef]
9. Severinenko, M.A.; Solodukhin, V.P.; Djenbaev, B.M.; Lennik, S.G.; Zholboldiev, B.T.; Snow, D.D. Occurrence of Radionuclides and Hazardous Elements in the Transboundary River Basin Kyrgyzstan–Kazakhstan. *Water* **2023**, *15*, 1759. [CrossRef]
10. Ospanov, K.; Kuldeyev, E.; Kenzhaliyev, B.; Korotunov, A. Wastewater treatment methods and sewage treatment facilities in Almaty, Kazakhstan. *J. Ecol. Eng.* **2022**, *23*, 240–251. [CrossRef]
11. Tran, N.H.; Reinhard, M.; Gin, K.Y.-H. Occurrence and fate of emerging contaminants in municipal wastewater treatment plants from different geographical regions—A review. *Water Res.* **2018**, *133*, 182–207. [CrossRef]
12. Feng, W.; Deng, Y.; Yang, F.; Miao, Q.; Ngien, S.K. Systematic Review of Contaminants of Emerging Concern (CECs): Distribution, Risks, and Implications for Water Quality and Health. *Water* **2023**, *15*, 3922. [CrossRef]
13. Khalid, S.; Shahid, M.; Natasha; Bibi, I.; Sarwar, T.; Shah, A.H.; Niazi, N.K. A review of environmental contamination and health risk assessment of wastewater use for crop irrigation with a focus on low and high-income countries. *Int. J. Environ. Res. Public Health* **2018**, *15*, 895. [CrossRef] [PubMed]
14. Yi, X.; Lin, C.; Ong, E.J.L.; Wang, M.; Zhou, Z. Occurrence and distribution of trace levels of antibiotics in surface waters and soils driven by non-point source pollution and anthropogenic pressure. *Chemosphere* **2019**, *216*, 213–223. [CrossRef] [PubMed]
15. Kazakhstan. National Report on the State of the Environment and Use of Natural Resources of the Republic of Kazakhstan for 2011–2014. Astana, Kazakhstan. 2023. Available online: https://www.gcedclearinghouse.org/resources/national-report-state-environment-and-use-natural-resources-republic-kazakhstan-2011-2014?language=en (accessed on 31 December 2024).
16. Bekturganov, Z.; Tussupova, K.; Berndtsson, R.; Sharapatova, N.; Aryngazin, K.; Zhanasova, M. Water related health problems in Central Asia—A review. *Water* **2016**, *8*, 219. [CrossRef]
17. OECD. Overview of the Use and Management of Water Resources in Central Asia: A Discussion Document. Available online: https://issuu.com/oecd.publishing/docs/final_report_eng_issuu (accessed on 31 December 2024).
18. Freeworldmaps.net. Central Asia Region with Major Water Resources. Available online: https://www.freeworldmaps.net/asia/central/centralasia-geography-map.jpg (accessed on 31 December 2024).
19. Zhupankhan, A.; Tussupova, K.; Berndtsson, R. Could Changing Power Relationships Lead to Better Water Sharing in Central Asia? *Water* **2017**, *9*, 139. [CrossRef]
20. Meyer, B.; Lundy, L.; Watt, J.; Abdullaev, I.; Capilla Roma, J.E. Risk Management as a Basis for Integrated Water Cycle Management in Kazakhstan. *J. Environ. Geogr.* **2016**, *9*, 33–42. [CrossRef]
21. Yapiyev, V.; Wade, A.J.; Shahgedanova, M.; Saidaliyeva, Z.; Madibekov, A.; Severskiy, I. The hydrochemistry and water quality of glacierized catchments in Central Asia: A review of the current status and anticipated change. *J. Hydrol. Reg. Stud.* **2021**, *38*, 100960. [CrossRef]
22. Liu, Y.; Wang, P.; Gojenko, B.; Yu, J.; Wei, L.; Luo, D.; Xiao, T. A review of water pollution arising from agriculture and mining activities in Central Asia: Facts, causes and effects. *Environ. Pollut.* **2021**, *291*, 118209. [CrossRef]
23. Crosa, G.; Froebrich, J.; Nikolayenko, V.; Stefani, F.; Galli, P.; Calamari, D. Spatial and seasonal variations in the water quality of the Amu Darya River (Central Asia). *Water Res.* **2006**, *40*, 2237–2245. [CrossRef]
24. Murthy, S.L.; Mendikulova, F. Water, Conflict, and Cooperation in Central Asia: The Role of International Law and Diplomacy. *Vt. J. Environ. Law* **2017**, *18*, 400–454.
25. Sagin, J.; Adenova, D.; Tolepbayeva, A.; Poryadin, V. Underground water resources in Kazakhstan. *Int. J. Environ. Stud.* **2017**, *74*, 386–398. [CrossRef]
26. Morris, B.L.; George Darling, W.; Gooddy, D.C.; Litvak, R.G.; Neumann, I.; Nemaltseva, E.J.; Poddubnaia, I. Assessing the extent of induced leakage to an urban aquifer using environmental tracers: An example from Bishkek, capital of Kyrgyzstan, Central Asia. *Hydrogeol. J.* **2006**, *14*, 225–243. [CrossRef]
27. Nurtazin, S.; Pueppke, S.; Ospan, T.; Mukhitdinov, A.; Elebessov, T. Quality of Drinking Water in the Balkhash District of Kazakhstan's Almaty Region. *Water* **2020**, *12*, 392. [CrossRef]
28. Rakhmatullaev, S.; Huneau, F.; Kazbekov, J.; Celle-Jeanton, H.; Motelica-Heino, M.; Coustumer, P.; Jumanov, J. Groundwater resources of Uzbekistan: An environmental and operational overview. *Open Geosci.* **2012**, *4*, 67–80. [CrossRef]
29. Partnerships, G.W. *Gender Aspects of Integrated Water Management*; Global Water Partnership: Tashkent, Uzbekistan, 2004; p. 142.
30. Akhtar, N.; Syakir Ishak, M.I.; Bhawani, S.A.; Umar, K. Various natural and anthropogenic factors responsible for water quality degradation: A review. *Water* **2021**, *13*, 2660. [CrossRef]
31. Irfeey, A.M.M.; Najim, M.M.; Alotaibi, B.A.; Traore, A. Groundwater Pollution Impact on Food Security. *Sustainability* **2023**, *15*, 4202. [CrossRef]
32. Gleeson, T.; Cuthbert, M.; Ferguson, G.; Perrone, D. Global groundwater sustainability, resources, and systems in the Anthropocene. *Annu. Rev. Earth Planet. Sci.* **2020**, *48*, 431–463. [CrossRef]
33. Frenken, K. *Irrigation in Central Asia in Figures: AQUASTAT Survey-2012*; FAO Water Reports; Food and Agriculture Organization of the United Nations (FAO): Roma, Italy, 2013; p. 88.

34. Zhang, P.; Wang, J.; Huang, L.; He, M.; Yang, H.; Song, G.; Zhao, J.; Li, X. Microplastic transport during desertification in drylands: Abundance and characterization of soil microplastics in the Amu Darya-Aral Sea basin, Central Asia. *J. Environ. Manag.* **2023**, *348*, 119353. [CrossRef]
35. Zhan, S.; Wu, J.; Jin, M. Hydrochemical characteristics, trace element sources, and health risk assessment of surface waters in the Amu Darya Basin of Uzbekistan, arid Central Asia. *Environ. Sci. Pollut. Res.* **2022**, *29*, 5269–5281. [CrossRef]
36. Poshtegal, M.K.; Mirbagheri, S.A. Simulation and Modelling of Heavy Metals and Water Quality Parameters in the River. *Sci. Rep.* **2023**, *13*, 3020. [CrossRef]
37. Kalmakhanova, M.; Massalimova, B.K.; Díaz de Tuesta, J.L.; Gomes, H.; Nurlibaeva, A. Novelty pillared clays for the removal of 4-nitrophenol by catalytic wet peroxide oxidation. *News Natl. Acad. Sci. Repub. Kazakhstan Ser. Geol. Tech. Sci.* **2018**, *3*, 12–19.
38. Ullrich, S.M.; Ilyushchenko, M.A.; Tanton, T.W.; Uskov, G.A. Mercury contamination in the vicinity of a derelict chlor-alkali plant: Part II: Contamination of the aquatic and terrestrial food chain and potential risks to the local population. *Sci. Total Environ.* **2007**, *381*, 290–306. [CrossRef] [PubMed]
39. Mukhopadhyay, A.; Duttagupta, S.; Mukherjee, A. Emerging organic contaminants in global community drinking water sources and supply: A review of occurrence, processes and remediation. *J. Environ. Chem. Eng.* **2022**, *10*, 107560. [CrossRef]
40. Malakar, A.; Snow, D.D.; Ray, C. Irrigation Water Quality—A Contemporary Perspective. *Water* **2019**, *11*, 1482. [CrossRef]
41. Van Winckel, T.; Cools, J.; Vlaeminck, S.E.; Joos, P.; Van Meenen, E.; Borregán-Ochando, E.; Van Den Steen, K.; Geerts, R.; Vandermoere, F.; Blust, R. Towards harmonization of water quality management: A comparison of chemical drinking water and surface water quality standards around the globe. *J. Environ. Manag.* **2021**, *298*, 113447. [CrossRef] [PubMed]
42. Allen, D.S.; Kolok, A.S.; Snow, D.D.; Satybaldiyev, B.; Uralbekov, B.; Nystrom, G.S.; Thornton Hampton, L.M.; Bartelt-Hunt, S.L.; Sellin Jeffries, M.K. Predicted aquatic and human health risks associated with the presence of metals in the Syr Darya and Shardara Reservoir, Kazakhstan. *Sci. Total Environ.* **2023**, *859*, 159827. [CrossRef]
43. Amirgaliev, N.A.; Askarova, M.; Opp, C.; Medeu, A.; Kulbekova, R.; Medeu, A.R. Water Quality Problems Analysis and Assessment of the Ecological Security Level of the Transboundary Ural-Caspian Basin of the Republic of Kazakhstan. *Appl. Sci.* **2022**, *12*, 2059. [CrossRef]
44. Salikova, N.S.; Rodrigo-Ilarri, J.; Alimova, K.K.; Rodrigo-Clavero, M.-E. Analysis of the Water Quality of the Ishim River within the Akmola Region (Kazakhstan) Using Hydrochemical Indicators. *Water* **2021**, *13*, 1243. [CrossRef]
45. Alvarado, J.C.; Balsiger, B.; Röllin, S.; Jakob, A.; Burger, M. Radioactive and chemical contamination of the water resources in the former uranium mining and milling sites of Mailuu Suu (Kyrgyzstan). *J. Environ. Radioact.* **2014**, *138*, 1–10. [CrossRef]
46. Li, Y.; Ma, L.; Abuduwaili, J.; Li, Y.; Abdyzhapar uulu, S. Spatiotemporal Distributions of Fluoride and Arsenic in Rivers with the Role of Mining Industry and Related Human Health Risk Assessments in Kyrgyzstan. *Expo. Health* **2022**, *14*, 49–62. [CrossRef]
47. Ma, L.; Abuduwaili, J.; Li, Y.; Abdyzhapar uulu, S.; Mu, S. Hydrochemical characteristics and water quality assessment for the upper reaches of Syr Darya River in Aral Sea Basin, Central Asia. *Water* **2019**, *11*, 1893. [CrossRef]
48. Rzymski, P.; Klimaszyk, P.; Niedzielski, P.; Marszelewski, W.; Borowiak, D.; Nowiński, K.; Baikenzheyeva, A.; Kurmanbayev, R.; Aladin, N. Pollution with trace elements and rare-earth metals in the lower course of Syr Darya River and Small Aral Sea, Kazakhstan. *Chemosphere* **2019**, *234*, 81–88. [CrossRef] [PubMed]
49. Uralbekov, B.M.; Smodis, B.; Burkitbayev, M. Uranium in natural waters sampled within former uranium mining sites in Kazakhstan and Kyrgyzstan. *J. Radioanal. Nucl. Chem.* **2011**, *289*, 805–810. [CrossRef]
50. Ivanova, K.; Stojanovska, Z.; Badulin, V.; Kunovska, B.; Yovcheva, M. Radiological impact of surface water and sediment near uranium mining sites. *J. Radiol. Prot.* **2015**, *35*, 819. [CrossRef] [PubMed]
51. Burkitbayev, M.; Uralbekov, B.; Nazarkulova, S.; Matveyeva, I.; Leon Vintro, L. Uranium series radionuclides in surface waters from the Shu river (Kazakhstan). *J. Environ. Monit.* **2012**, *14*, 1190–1195. [CrossRef]
52. Hofmann, J.; Watson, V.; Scharaw, B. Groundwater quality under stress: Contaminants in the Kharaa River basin (Mongolia). *Environ. Earth Sci.* **2015**, *73*, 629–648. [CrossRef]
53. Różkowski, J.; Rzętała, M. Uzbekistan's Aquatic Environment and Water Management as an Area of Interest for Hydrology and Thematic Tourism. *J. Environ. Manag. Tour.* **2021**, *12*, 642–653. [CrossRef] [PubMed]
54. Zhulidov, A.V.; Emetz, V.M. Heavy Metals, Natural Variability and Anthropogenic Impacts. In *A Water Quality Assessment of the Former Soviet Union*; Kimstach, V.A., Meybeck, M., Baroudy, E., Eds.; E & FN Spon: London, UK; New York, NY, USA, 1998; pp. 179–240.
55. Ogata, R.; Matsuda, K.; Avzal, T.J.; Abe, K. Improvement of water utility management in Tajikistan: Reduction in water wastage using a metered tariff system. *AQUA Water Infrastruct. Ecosyst. Soc.* **2023**, *72*, 221–229. [CrossRef]
56. Papa, E.; Castiglioni, S.; Gramatica, P.; Nikolayenko, V.; Kayumov, O.; Calamari, D. Screening the leaching tendency of pesticides applied in the Amu Darya Basin (Uzbekistan). *Water Res.* **2004**, *38*, 3485–3494. [CrossRef]
57. Khan, S.; Naushad, M.; Govarthanan, M.; Iqbal, J.; Alfadul, S.M. Emerging contaminants of high concern for the environment: Current trends and future research. *Environ. Res.* **2022**, *207*, 112609. [CrossRef]

58. Rogowska, J.; Cieszynska-Semenowicz, M.; Ratajczyk, W.; Wolska, L. Micropollutants in treated wastewater. *Ambio* **2020**, *49*, 487–503. [CrossRef]
59. Martín-Pozo, L.; de Alarcón-Gómez, B.; Rodríguez-Gómez, R.; García-Córcoles, M.T.; Çipa, M.; Zafra-Gómez, A. Analytical methods for the determination of emerging contaminants in sewage sludge samples. A review. *Talanta* **2019**, *192*, 508–533. [CrossRef] [PubMed]
60. Karthe, D.; Abdullaev, I.; Boldgiv, B.; Borchardt, D.; Chalov, S.; Jarsjö, J.; Li, L.; Nittrouer, J.A. Water in Central Asia: An integrated assessment for science-based management. *Environ. Earth Sci.* **2017**, *76*, 690. [CrossRef]
61. Batbayar, G.; Pfeiffer, M.; von Tümpling, W.; Kappas, M.; Karthe, D. Chemical water quality gradients in the Mongolian sub-catchments of the Selenga River basin. *Environ. Monit. Assess.* **2017**, *189*, 420. [CrossRef]
62. Malsy, M.; Flörke, M.; Borchardt, D. What drives the water quality changes in the Selenga Basin: Climate change or socio-economic development? *Reg. Environ. Change* **2017**, *17*, 1977–1989. [CrossRef]
63. Pfeiffer, M.; Batbayar, G.; Hofmann, J.; Siegfried, K.; Karthe, D.; Hahn-Tomer, S. Investigating arsenic (As) occurrence and sources in ground, surface, waste and drinking water in northern Mongolia. *Environ. Earth Sci.* **2015**, *73*, 649–662. [CrossRef]
64. Skripnik, G. In Taraz, They Have Been Solving the Problem of Sewage Treatment for More Than 30 Years. 2023. Available online: https://primeminister.kz/en/news/new-waste-water-treatment-facilities-construction-in-taraz-to-start-as-soon-as-possible-alikhan-smailov-25036 (accessed on 31 December 2024).
65. Gholizadeh, M.H.; Melesse, A.M.; Reddi, L. A Comprehensive Review on Water Quality Parameters Estimation Using Remote Sensing Techniques. *Sensors* **2016**, *16*, 1298. [CrossRef]
66. Silva, G.M.e.; Campos, D.F.; Brasil, J.A.T.; Tremblay, M.; Mendiondo, E.M.; Ghiglieno, F. Advances in Technological Research for Online and in Situ Water Quality Monitoring—A Review. *Sustainability* **2022**, *14*, 5059. [CrossRef]
67. Singh, A.; Chaurasia, D.; Khan, N.; Singh, E.; Chaturvedi Bhargava, P. Efficient mitigation of emerging antibiotics residues from water matrix: Integrated approaches and sustainable technologies. *Environ. Pollut.* **2023**, *328*, 121552. [CrossRef]
68. Jiang, T.; Wu, W.; Ma, M.; Hu, Y.; Li, R. Occurrence and distribution of emerging contaminants in wastewater treatment plants: A globally review over the past two decades. *Sci. Total Environ.* **2024**, *951*, 175664. [CrossRef]
69. Satayeva, A.; Kerim, T.; Kamal, A.; Issayev, J.; Inglezakis, V.; Kim, J.; Arkhangelsky, E. Determination of aspirin in municipal wastewaters of Nur-Sultan City, Kazakhstan. In *Proceedings of the IOP Conference Series: Earth and Environmental Science*; IOP: Bristol, UK, 2022; p. 012067.
70. Snow, D.D.; Chakraborty, P.; Uralbekov, B.; Satybaldiev, B.; Sallach, J.B.; Thornton Hampton, L.M.; Jeffries, M.; Kolok, A.S.; Bartelt-Hunt, S.B. Legacy and current pesticide residues in Syr Darya, Kazakhstan: Contamination status, seasonal variation and preliminary ecological risk assessment. *Water Res.* **2020**, *184*, 116141. [CrossRef]
71. Shen, B.; Wu, J.; Zhan, S.; Jin, M. Residues of organochlorine pesticides (OCPs) and polycyclic aromatic hydrocarbons (PAHs) in waters of the Ili-Balkhash Basin, arid Central Asia: Concentrations and risk assessment. *Chemosphere* **2021**, *273*, 129705. [CrossRef] [PubMed]
72. Amirgaliyev, N.; Opp, C.; Askarova, M.; Ismukhanova, L.; Madibekov, A.; Zhadi, A. Long-Term Dynamics of Persistent Organic Pollutants in Water Bodies of the Aral Sea–Syrdarya Basin. *Appl. Sci.* **2023**, *13*, 11453. [CrossRef]
73. Jin, M.; Wu, J.; Zhang, H.; Zhao, Z.; Alam, M.; Guo, R. Study on the Aral Sea crisis from the risk assessment of polycyclic aromatic hydrocarbons and organochlorine pesticides in surface water of Amu Darya river basin in Uzbekistan. *Front. Earth Sci.* **2023**, *11*, 1295485. [CrossRef]
74. Russell, A.; Ghalaieny, M.; Gazdiyeva, B.; Zhumabayeva, S.; Kurmanbayeva, A.; Akhmetov, K.K.; Mukanov, Y.; McCann, M.; Ali, M.; Tucker, A.; et al. A Spatial Survey of Environmental Indicators for Kazakhstan: An Examination of Current Conditions and Future Needs. *Int. J. Environ. Res.* **2018**, *12*, 735–748. [CrossRef]
75. Past PFOA and PFOS Health Effects Science Documents. Available online: https://www.epa.gov/sdwa/past-pfoa-and-pfos-health-effects-science-documents (accessed on 31 December 2024).
76. Re-Evaluation of the Risks to Public Health Related to the Presence of Bisphenol A (BPA) in Foodstuffs. Available online: https://www.efsa.europa.eu/en/efsajournal/pub/6857 (accessed on 31 December 2024).
77. Di (2-Ethylhexyl)phthalate (DEHP). Available online: https://iris.epa.gov/ChemicalLanding/&substance_nmbr=0014 (accessed on 31 December 2024).
78. Quinoline. Available online: https://www.epa.gov/sites/default/files/2016-09/documents/quinoline.pdf (accessed on 31 December 2024).
79. USEPA. *2018 Edition of the Drinking Water Standards and Health Advisories*; USEPA: Washington, DC, USA, 2018; p. 20.
80. Ayers, R.S.; Westcot, D.W. *Water Quality for Agriculture*; FAO Irrigation and Drainage Paper; FAO: Roma, Italy, 1985; Volume 21, p. 186.

81. Hofmann, J.; Venohr, M.; Behrendt, H.; Opitz, D. Integrated water resources management in central Asia: Nutrient and heavy metal emissions and their relevance for the Kharaa River Basin, Mongolia. *Water Sci. Technol.* **2010**, *62*, 353–363. [CrossRef]
82. Satybaldiyev, B.; Ismailov, B.; Nurpeisov, N.; Kenges, K.; Snow, D.D.; Malakar, A.; Uralbekov, B. Evaluation of dissolved and acid-leachable trace element concentrations in relation to practical water quality standards in the Syr Darya, Aral Sea Basin, South Kazakhstan. *Chemosphere* **2023**, *313*, 137465. [CrossRef]