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Sustainable Use of Groundwater Resources in the Transboundary Aquifers of the Five Central Asian Countries: Challenges and Perspectives

Yu Liu [1], Ping Wang [2,3,*], Hongwei Ruan [2,3], Tianye Wang [2,3], Jingjie Yu [2,3], Yanpei Cheng [4] and Rashid Kulmatov [5]

1 Linköping University-Guangzhou University Research Center on Urban Sustainable Development, School of Environmental Science and Engineering, Guangzhou University, Guangzhou 510006, China; liuyu@gzhu.edu.cn
2 Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, 11A, Datun Road, Chaoyang District, Beijing 100101, China; ruanhw.17b@igsnrr.ac.cn (H.R.); wangty.16b@igsnrr.ac.cn (T.W.); yujj@igsnrr.ac.cn (J.Y.)
3 University of Chinese Academy of Sciences, Beijing 100049, China
4 Institute of Hydrogeology and Environmental Geology, Chinese Academy of Geological Sciences, Shijiazhuang 050061, China; yanpeicheng@tom.com
5 Department of Biology and Soil Science, National University of Uzbekistan, Tashkent 100170, Uzbekistan; rashidkulmatov46@gmail.com
* Correspondence: wangping@igsnrr.ac.cn

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Abstract: Groundwater is critical for supporting socioeconomic development but has experienced gradual decreases in recent decades due to rapid population growth and economic development throughout the world. In recent years, the utilization of transboundary groundwater resources has received extensive attention globally. Because transboundary aquifers do not follow borders and are concealed, neighboring countries are prone to experiencing conflicts over the use of these transboundary groundwater resources. Therefore, an accurate and comprehensive assessment of the development potential of groundwater resources in these transboundary aquifers is necessary for the rational and fair use of those groundwater resources. Transboundary groundwater resources are an important water source for life, production, and ecological water use in Central Asia, which has a distinctive continental arid and semi-arid climate, and surface water resources in this region are relatively scarce. Considering the existing problems related to the utilization of groundwater resources in the transboundary aquifers in this region, we propose developing strategies for on-demand water abstraction, enhancing the ecological protection of transboundary aquifers, and strengthening international cooperation. This paper summarizes the distribution of 34 transboundary aquifers in Central Asia and analyzes the status and potential of groundwater resource uses in these transboundary aquifers.

Keywords: Central Asia; groundwater resources; transboundary aquifers; sustainable development

1. Introduction

Global systematic research on transboundary aquifers (TBAs) began in 2000 with the International Shared Aquifer Resource Management Plan (ISARM), which was initiated by the UNESCO International Hydrological Project [1]. In general, a TBA (or TBA system) refers to the same aquifer (system) located in different administrative units, including trans-administrative aquifers and cross-border

aquifers [2]; the TBAs referred to in this article are all of the latter type. Statistically, a total of 592 TBAs have been identified globally, including 72 in Africa, 73 in the Americas, 129 in Asia and Oceania, and 318 in Europe (including 226 transboundary "groundwater bodies", as defined in the EU Water Framework Directive) [3]. By definition, a TBA does not follow borders, has a high degree of exploitability, and is concealed. Research on TBAs has been performed in many fields, such as natural sciences (hydrogeology), law, socioeconomics, and environmental science [4–6], because these aquifers play extremely important roles in providing drinking water, producing food, and supporting the development and survival of millions of people around the world [7–9].

Due to the connectivity of a groundwater system, one-sided overexploitation of a TBA can change the groundwater flow field, resulting in the loss of groundwater resources outside the boundary (i.e., in neighboring countries); for this reason, competition for water resources is inevitable and can lead to conflicts among affected neighboring countries [10].

However, the construction of water conservancy projects can replenish the water resources of TBAs. For example, the world's largest irrigation canal, the 42 km-long All-American Canal, caused a rise in regional groundwater level as a result of river leakage; this increase caused groundwater to flow into Mexico through the Mexicali Valley aquifer [11]. At present, increasing numbers of studies are beginning to focus on the comprehensive risk assessment and management of TBA resources, as well as on the sustainable use and protection of these resources [12–15]. Moreover, in the context of climate change, as the degree of drought further intensifies [16] and as rapid population growth continues, groundwater exploitation in arid areas is becoming increasingly intense; consequently, the development and protection of groundwater resources in a TBA are met with greater risks and challenges [17,18]. Therefore, clarifying the formation, distribution, development, and utilization of TBA water resources and accurately assessing the amount of available water resources form the bases for scientific planning and determining of the rational use of groundwater resources in TBAs.

Central Asia comprises five countries, namely, Kazakhstan, Kyrgyzstan, Tajikistan, Uzbekistan, and Turkmenistan, which are located in the middle of the Central Eurasian plate in the core area of the Silk Road Economic Belt [19]. The terrain in this region gradually decreases in elevation from east to west, transitioning from high mountains to plains and deserts. Precipitation also gradually decreases from east to west. The water resources in the upstream mountainous areas are relatively abundant, whereas those in the downstream plains and desert areas are extremely scarce [19–24]. In addition, Central Asia is facing severe challenges related to ecological degradation [25], including environmental issues such as deterioration of land and vegetation, surface water shortages and pollution, declines in the volume and quality of terminal lakes, reductions in groundwater levels, and increased groundwater pollution. By evaluating both the distribution and the development of transboundary groundwater resources in Central Asia, this manuscript discusses the prospects for the development of TBAs and proposes preliminary suggestions to alleviate the contradiction between the supply and demand of water resources in this region.

2. Study Area

The five Central Asian countries (46°45′~87°21′ E, 35°5′~52°33′ N) are located in the middle of the Eurasian plate and border China to the east, Iran and Afghanistan to the south, and Azerbaijan to the west; across the Caspian Sea, the northern part of the region is adjacent to Russia (Figure 1) [26]. The total area of Central Asia is approximately 4 million km^2, of which Kazakhstan's land area accounts for 68.06% (2.7249 million km^2); furthermore, Turkmenistan (480,800 km^2) and Uzbekistan (444,700 km^2) account for 12.19% and 11.18%, respectively, and Kyrgyzstan (19.99 million km^2) and Tajikistan (1431,000 km^2) are relatively small, accounting for 8.57% of the total area of the region combined [26].

The five Central Asian countries are located in an arid region of the Northern Hemisphere. The southeastern portion of this region features the Tianshan and Pamir-Alai Mountains [26], where elevation is high and there is more precipitation, with obvious vertical zonation.

The southwestern part of Central Asia includes the Turan Plain, which includes the Karakum Desert and the Kyzyl Kum Desert, which are characterized by low elevation, strong evapotranspiration, and sparse precipitation [27]. There is a vast trough in the western Central Asian basin, which contains thick sedimentary rock layers and forms an internally drained system, in which the Aral Sea acts as a drainage basin [28].

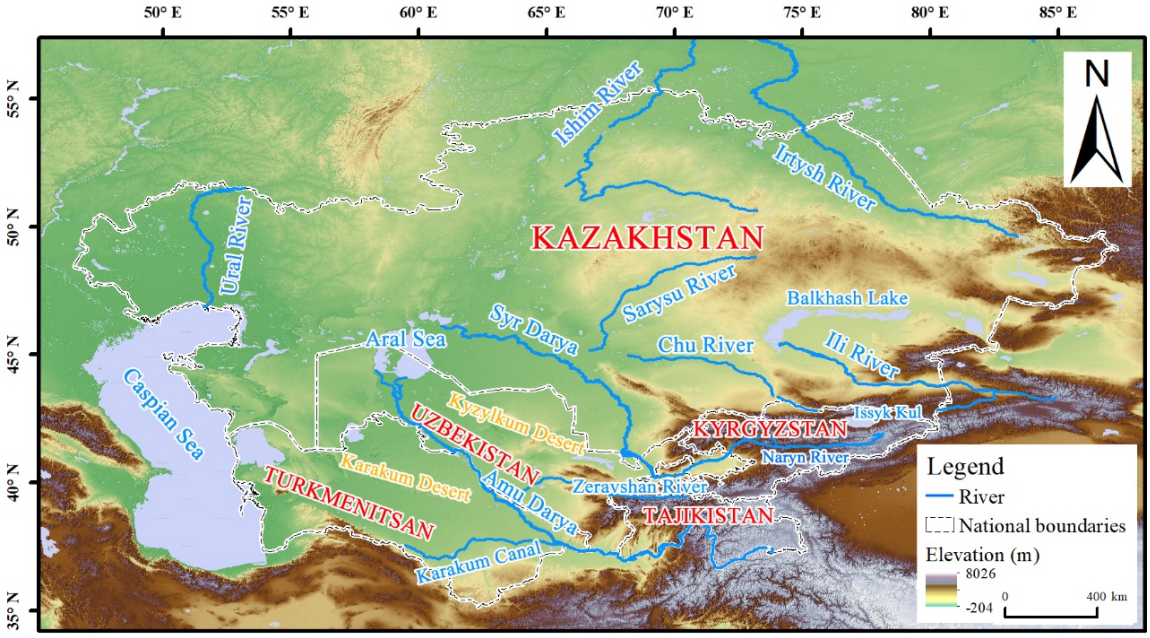

Figure 1. Map of the geographical location of the five Central Asian countries [26].

Northeastern Kazakhstan and the mountains and plateaus of Kyrgyzstan and Tajikistan are adjacent to each other (Figure 1). The melting of glaciers and snow is the source of many rivers and lakes, creating a runoff and groundwater formation area in Central Asia. In terms of the distribution of water resources, Tajikistan and Kyrgyzstan, which are located upstream of other countries, control 90% of the surface water resources in Central Asia [29].

The water area of Tajikistan accounts for only 2% of the national land area, or approximately 2862 km^2; this region represents the runoff formation area of the Amu Darya River. Similarly, the water area of Kyrgyzstan accounts for 4.4% of the country's land area, or approximately 8796 km^2. The main lakes and rivers are Issyk-Kul Lake and the upper reaches of the Syr Darya River, including the Naryn River, Karadarya River, and Chu River [27].

In contrast, the total water area of Kazakhstan is 25,200 km^2, which includes numerous lakes and rivers, such as the Ural River and the Emba River, which flow into the Caspian Sea; the Syr Darya River, which flows into the Aral Sea; the Ili River, which flows into Balkhash Lake; the Irtysh River and its tributaries, such as the Ishim River and the Tobol River, which flow into the Arctic Ocean [29].

The total water area of Uzbekistan represents 1.8% of the country's territory, or approximately 8053.2 km^2, and the main rivers include the Zeravshan River, the Syr Darya River, and the Amu Darya River, which flow into the Aral Sea. Ninety-five percent of Turkmenistan's surface water is formed in neighboring countries, and 88% of it comes from the Amu Darya [28].

3. Methodology

The classification of hydrogeological units for TBAs in Central Asia used in this paper is based on the Transboundary Aquifers of the World map (UNESCO-IGRAC, 2015), supplemented by previously published studies in the literature.

As shown on the TBA map, there are thirty-four major TBAs in Central Asia, 30 of which are partially located in Uzbekistan. Numerous TBAs exist in the runoff formation zones in southeastern Kazakhstan, Kyrgyzstan, and Tajikistan. As shown in Figure 2, 24 of the TBAs in the study area (AS36, AS45, AS46, AS47, AS48, AS49, AS50, AS51, AS52, AS53, AS56, AS57, AS58, AS59, AS60, AS61, AS62, AS63, AS64, AS65, AS66, AS67, AS68, and AS69) are located within the Syr Darya River basin, whereas six TBAs (AS37, AS40, AS41, AS42, AS43, and AS70) are located within the Amu Darya River basin, and only two aquifers (AS54 and AS55) are located in the Talas River basin. Additionally, the Zeravshan River basin and the Chu River basin each have only one aquifer, AS44 and AS71, respectively.

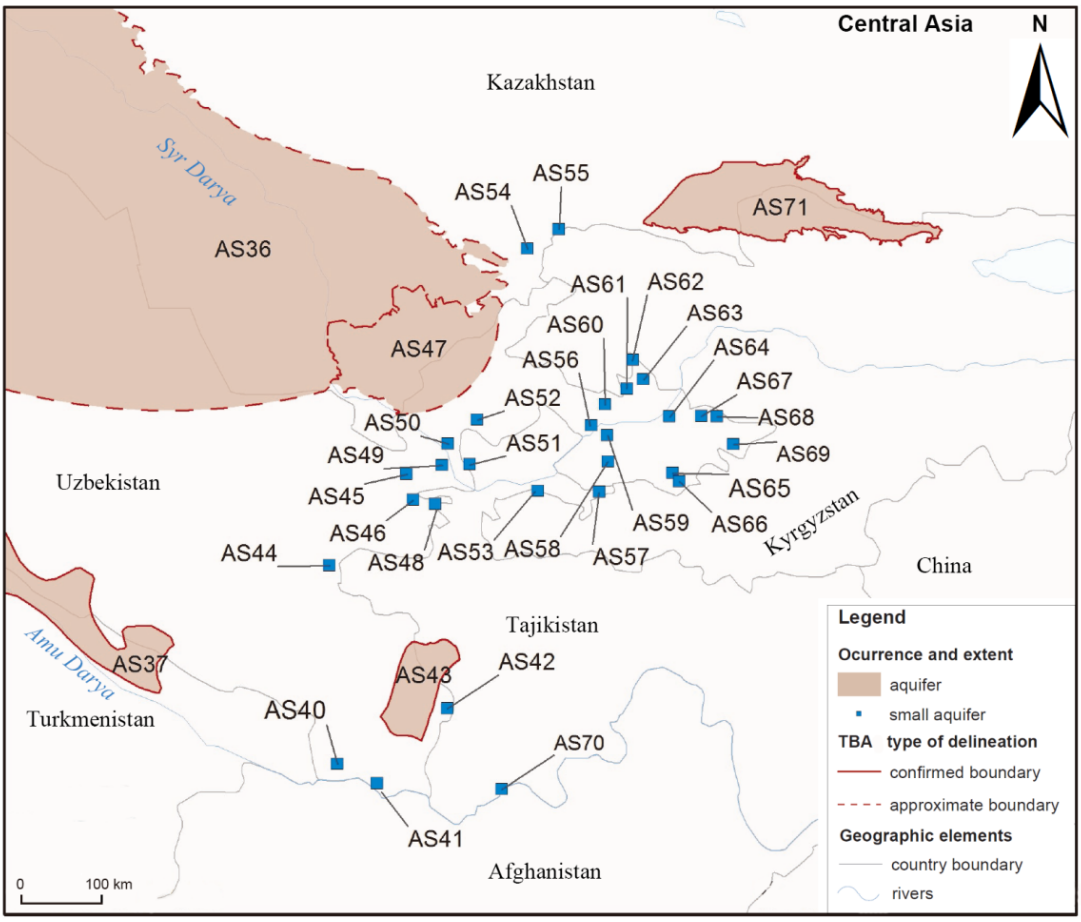

Figure 2. Spatial distribution of transboundary aquifers in Central Asia [3].

The classification of hydrogeological units is based on geological characteristics, such as geological formations, lithological features, porosity, permeability, and water quality.

Most of the 34 TBAs in the five Central Asian countries are present in the Quaternary and Neogene strata, although some are in the Cretaceous strata (Table 1).

Table 1. Distribution of transboundary aquifers in Central Asia [3].

Label	Aquifer Name	Geologic Age [30,31]	Sharing Countries	Area (km^2)
AS36	Syr Darya	Pliocene–Holocene, Paleogene, Cretaceous	Kazakhstan, Uzbekistan	408,988
AS37	Birata-Urgench	Paleogene-Quaternary, Cretaceous, Jurassic, Triassic, Permian	Uzbekistan, Turkmenistan	80,150
AS40	Sherabad	Quaternary	Uzbekistan, Turkmenistan	699
AS41	Amudaryia	Quaternary	Afghanistan, Tajikistan, Uzbekistan	1481
AS42	Kofarnihon Aquifer	Quaternary	Tajikistan, Uzbekistan	404
AS43	Karatag/North-Surhandarya Aquifer	Quaternary	Tajikistan, Uzbekistan	6413
AS44	Zeravshan Aquifer	Quaternary	Tajikistan, Uzbekistan	3995
AS45	Dustlik	Quaternary	Tajikistan, Uzbekistan, Kazakhstan	1915
AS46	Havost	Quaternary	Tajikistan, Uzbekistan	735
AS47	Pretashkent Aquifer	Cenomanian	Kazakhstan, Uzbekistan	21,472
AS48	Zafarobod Aquifer	Quaternary	Tajikistan, Uzbekistan	1191
AS49	Syr-Darya 3	Quaternary, Cenomanian	Tajikistan, Uzbekistan	812
AS50	Kokaral	Quaternary, Cenomanian	Tajikistan, Uzbekistan	892
AS51	Dalverzin Aquifer	Quaternary, Cenomanian	Tajikistan, Uzbekistan	2063
AS52	Ahangaran	Quaternary	Tajikistan, Uzbekistan	1312
AS53	Sulyukta-Batken-Nau-Isfara Aquifer	Quaternary	Tajikistan, Uzbekistan	3904
AS54	South Talas Aquifer	Quaternary Pliocene	Kazakhstan, Kyrgyzstan	1838
AS55	North Talas Aquifer	Neogene–Quaternary	Kazakhstan, Kyrgyzstan	1352
AS56	Chust-Pap Aquifer	Paleogene–Quaternary	Tajikistan, Uzbekistan	589
AS57	Shorsu Aquifer	Quaternary	Tajikistan, Kyrgyzstan, Uzbekistan	344
AS58	Sokh Aquifer	Quaternary	Kyrgyzstan, Uzbekistan	2389
AS59	Syr-Darya 2	Quaternary	Tajikistan, Uzbekistan	1601
AS60	Almos-Vorzik Aquifer	Quaternary	Kyrgyzstan, Uzbekistan	635
AS61	Kasansay Aquifer	Quaternary	Kyrgyzstan, Uzbekistan	136
AS62	Nanay	Quaternary	Kyrgyzstan, Uzbekistan	64
AS63	Iskovat-Pishkaran Aquifer	Quaternary	Kyrgyzstan, Uzbekistan	583
AS64	Naryn Aquifer	Quaternary	Kyrgyzstan, Uzbekistan	1885
AS65	Yarmazar	Quaternary	Kyrgyzstan, Uzbekistan	407
AS66	Chimion-Aval	Quaternary	Kyrgyzstan, Uzbekistan	690
AS67	Maylusu Aquifer	Quaternary	Kyrgyzstan, Uzbekistan	505
AS68	Karaungur	Quaternary	Kyrgyzstan, Uzbekistan	167
AS69	Osh-Aravan Aquifer	Quaternary	Kyrgyzstan, Uzbekistan	1704
AS70	Vakhsh Aquifer	Quaternary	Afghanistan, Tajikistan	154
AS71	Chu Basin	Quaternary	Kyrgyzstan, Kazakhstan	18,575

In terms of hydrogeological units, TBAs AS40–AS43 belong to the Surhandarya artesian basin. The AS43 Karatag/North-Surhandarya aquifer of the Amu Darya River basin belongs to both Tajikistan and Uzbekistan, which have equal shares of the aquifer area. Furthermore, groundwater runoff flows from Tajikistan to Uzbekistan. The groundwater runoff direction of the AS42 Kofarnihon aquifer is the same as that of the AS43 Karatag/North-Surhandarya aquifer, the area of which in Uzbekistan is 343 km^2, accounting for 84.9% of the total aquifer area. The maximum thickness of the AS43 Karatag/North-Surhandarya aquifer and the AS42 Kofarnihon aquifer is 100 m. The AS44 Zeravshan aquifer is located in the Zeravshan artesian basin, which is affiliated with Tajikistan and Uzbekistan, and the aquifer area in Tajikistan is 383 km^2, accounting for 9.6% of the total aquifer area; this aquifer has an average thickness of 36 m and a maximum thickness of 110 m [32]. A common feature of TBAs AS40–AS43 is that they are all located in the alluvial fan area of the river.

TBAs AS45–AS52 are located in the Pretashkent artesian basin. The AS45 Dustlik aquifer is located in a synclinal zone in Tajikistan, Uzbekistan, and Kazakhstan. The AS46 Havost and AS48 Zafarobod aquifers are located in a synclinal area crossed by an east–west trending anticline. AS49 Syr-Darya 3 is located on the left bank of the Syr Darya River, while the AS50 Kokaral and AS51 Dalverzin aquifers are located on the right bank of the Syr Darya River. TBAs AS49–AS51 all exist in the same Cenomanian

strata (except for one Quaternary aquifer) as AS47 [31]. The AS52 Ahangaran aquifer is located in the alluvial fan area of the Ahangaran River.

TBAs AS53 and AS56–AS69 are located in the Ferghana artesian basin. Differences in geological structure and hydrogeological conditions divide the Fergana artesian basin into the following hydrogeological regions: a fractured water basin, an artesian basin in the low foothill zone, and an artesian basin in the central plain zone [31]. The AS62 Nanay aquifer is located in the fractured water basin; the AS56 Chust-Pap, AS60 Almos-Vorzik, AS61 Kasansay, AS63 Iskovat-Pishkaran, AS65 Yarmazar, AS66 Chimion-Aval, and AS69 Osh-Aravan aquifers are located in the artesian basin in the low foothill zone; the AS57 Shorsu, AS58 Sokh, AS59 Syr-Darya 2, AS64 Naryn, AS67 Maylusu, and AS68 Karaungur aquifers are located in the artesian basin in the central plain zone.

The AS70 Vakhsh aquifer is the main TBA in the area of the Vakhsh River and is located in Afghanistan and Tajikistan. The Vakhsh River is one of the main tributaries of the Amu Darya, and its upstream area extends into the territory of Kyrgyzstan, while most of the drainage area (31,200 km^2) is located in Tajikistan. The Vakhsh River basin provides an average of 13.48 km^3 of groundwater resources to Tajikistan every year [32].

The hydrogeological parameters of several representative aquifers from among the 34 TBAs are shown in Table 2.

Table 2. Hydrogeological parameters of representative TBAs in Central Asia [30].

Label	Aquifer Type	Number of Aquifer Layers	Average Transmissivity (m^2/d)	Total Groundwater Volume (km^3)	TDS (mg/L)
AS36	Multiple layers, hydraulically connected	3	3300	9920	100–70,000
AS37	Multiple layers, hydraulically connected	5	-	-	1000–50,000
AS43	Multiple layers, hydraulically connected	3	-		1000–70,000
AS47	Single layer	1	-	1.35	200–35,000
AS54	Multiple layers, hydraulically connected	2	1923	24	-
AS55	Single layer	1	2400	10.2	-
AS71	Single layer/Multiple layers, hydraulically connected	1/2	1500	300	140–500

The AS36 Syr Darya aquifer has the largest area among all the TBAs studied and is located on the border between Kazakhstan and Uzbekistan in the Syr Darya River basin. The area of this TBA in Kazakhstan is 189,000 km^2, accounting for 46.2% of the total area of the aquifer. Additionally, the aquifer thickness varies between 0.5 and 40 m. AS36 is a three-layered hydraulically connected system with a total groundwater volume of 9900 km^3. The average transmissivity is 3300 m^2/d [30]. The underground runoff direction of this aquifer is basically the same as that of the Syr Darya River.

The AS47 Pretashkent aquifer is the second largest TBA system in the Syr Darya River basin and is located on the border between Uzbekistan and Kazakhstan. The area of this TBA in Kazakhstan is approximately 10,840 km^2, accounting for 13.5% of the total area of the aquifer, and the average thickness is 200 m. The total groundwater volume in Kazakhstan is estimated to be 1.35 km^3. As shown in Figure 3, the AS47 Pretashkent aquifer is distributed mainly in the Cenomanian strata of the Upper Cretaceous, with its surface exposed at the foot of the mountain. The aquifer thickness varies from 41 to 254 m, with an average thickness of 179 m [33], and it has a weak hydraulic connection with surface water.

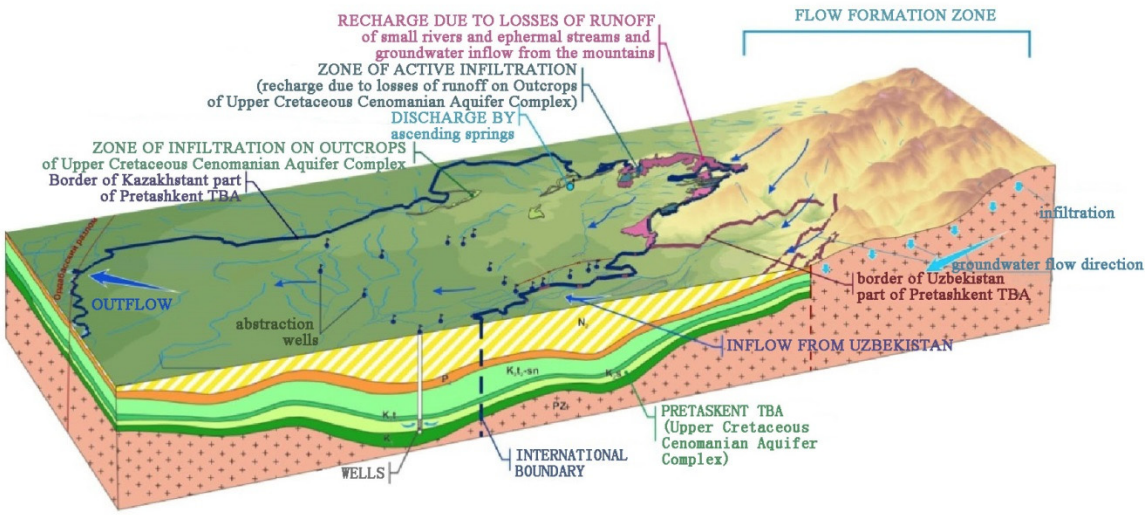

Figure 3. Conceptual hydrogeological map of the AS47 Pretashkent aquifer [34].

The groundwater resources of the Amu Darya River basin account for 58% of the total in the Aral Sea basin [35]. The AS37 Birata-Urgench aquifer in the Amu Darya River basin is a multilayered aquifer system that includes multiple aquifers in the Quaternary, Neogene, Paleogene, Cretaceous, and Jurassic strata [36]. The aquifer thickness varies widely (1.5–100 m); the central thickness exceeds 300 m and gradually thins towards the edges [30].

The AS54 South Talas aquifer spans the border between Kyrgyzstan and Kazakhstan; its territory in Kazakhstan spans approximately 1160 km^2, representing more than 60% of the total aquifer area. Additionally, the aquifer has an average thickness of 50 m and a maximum thickness of 500 m. The groundwater runoff flows from southern Kyrgyzstan to northern Kazakhstan [32]. The average transmissivity is 1900 m^2/d, the total water volume of the aquifer is approximately 24 km^3, and the average annual recharge is 220 mm^3 [30].

The AS55 North Talas aquifer is located in Kyrgyzstan and Kazakhstan. The area in Kazakhstan reaches approximately 689 km^2, accounting for 37.5% of the total aquifer area. Additionally, the average thickness is 25 m, with a maximum thickness of 98 m. The groundwater runoff direction of the AS55 North Talas aquifer is the same as that of the AS54 South Talas aquifer and is closely related to the surface hydraulics [32]. The average transmissivity is 2400 m^2/d; the total water volume of this aquifer is approximately 10 km^3, and the annual recharge is 510 mm^3 [30].

The AS71 Chu aquifer, located in the Chu River basin, has an area of approximately 7516 km^2 in Kazakhstan, accounting for 40.5% of the total aquifer area. The average aquifer thickness is between 250 and 300 m, and the maximum thickness is 500 m [32].

The Zharkent aquifer and Tekes aquifer are located on the China–Kazakhstan border in the Ili River basin. The area of the Zharkent aquifer in Kazakhstan is 12,080 km^2, accounting for 9.6% of the total aquifer area. The average thickness of this aquifer is 1300 m, and the maximum thickness is 2830 m. The area of the Tekes aquifer in Kazakhstan is 1876 km^2, the average thickness of the aquifer is 25 m, and the maximum thickness is 50 m. In addition, the groundwater flows from west to east (i.e., from Kazakhstan to China) and is closely related to the surface hydraulics [32].

The TBAs (TBA systems) in Central Asia are generally composed of a single aquifer or several hydraulically connected aquifers. According to the simplified conceptual diagram of a TBA shown in Figure 4 [32,37], the 34 TBAs and TBA systems in the study area can be divided into three typical types. In Type A aquifers, the surface water and groundwater areas are separated by a national border, with recharge occurring in one country and discharge occurring in adjacent countries; examples include the AS43 Karatag/North-Surhandarya aquifer, AS48 Zafarobod aquifer, and AS51 Dalverzin aquifer. In Type B aquifers, the national border corresponds to a major river or lake, the alluvial aquifer is connected to the river, and there is little transboundary flow; one example is the AS37 Birata-Urgench

aquifer. In Type C aquifers, which are large and deep, recharge occurs far from the border, and there is no connection between the local surface water and groundwater; examples include the AS44 Zeravshan and AS47 Pretashkent aquifers.

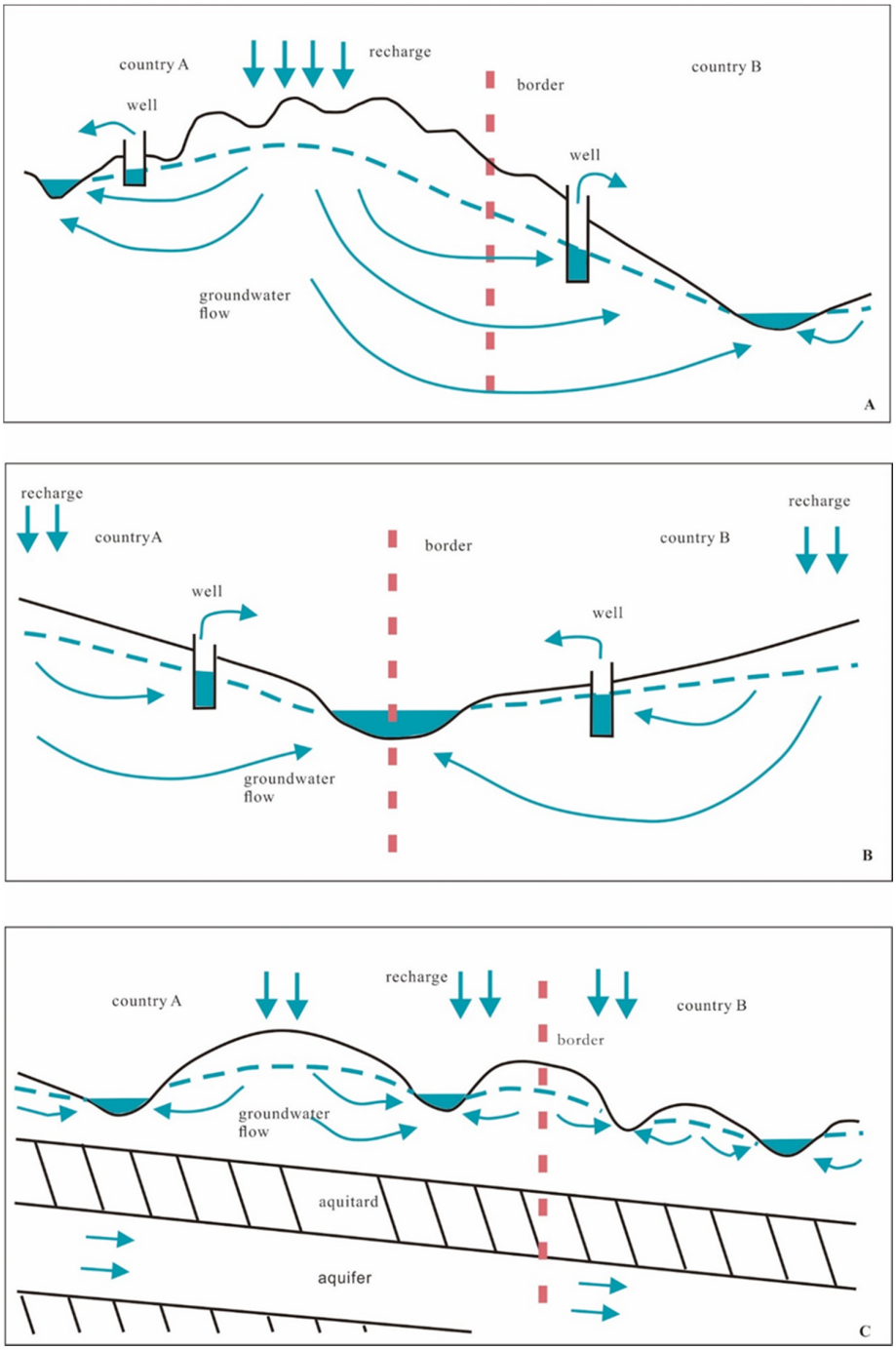

Figure 4. Simplified conceptual illustrations of the three transboundary aquifer types [37]. (**A**) Surface water and groundwater are divided separately from the national border; recharge occurs in one country and discharge occurs in adjacent areas. (**B**) The national border follows a major river or lake; the alluvial aquifer is connected to rivers and there is little transboundary flow. (**C**) Large and deep aquifers that are recharged far from the national borders, and the local surface water and groundwater are not connected.

4. Groundwater and its Utilization in TBAs

4.1. Groundwater Resources in TBAs

The groundwater resources in the five Central Asian countries are closely related to the amount of surface water resources. Kyrgyzstan and Tajikistan, as countries with relatively abundant surface water resources, use relatively few groundwater resources. In addition, Turkmenistan's groundwater resources are relatively limited, but only 2.5% of its total water resources are exploited. The groundwater resources in these three countries are mainly used for domestic purposes. In contrast, Kazakhstan and Uzbekistan, which are located in the downstream reaches of river basins, have relatively scarce surface water resources and a relatively high dependence on groundwater. Irrigation accounts for approximately 50% of the groundwater extracted in Kazakhstan, and approximately two-thirds of Uzbekistan's water demand depends on groundwater.

The groundwater resources associated with a given TBA may have different uses in different countries; for example, the AS47 Pretashkent aquifer is used mainly for drinking water in Kazakhstan, but is used only as a source of mineral water in Uzbekistan [37]. For the AS71 Chu aquifer in Kazakhstan, 40% of the extracted groundwater is used for drinking water and 60% is used for agricultural irrigation; however, in Kyrgyzstan, the groundwater from this aquifer is widely used for drinking water, agricultural irrigation, industrial mining, livestock feeding, and hot spring fishery needs [32].

The reserves of fresh groundwater available in Kyrgyzstan are equal to 650 km^3, of which the Chu River basin provides 300 km^3 and the Taras River basin supplies 75 km^3 [38]. At present, Kyrgyzstan has identified more than 250 mineral water sources. Based on the mineralization and hydrochemical composition of the groundwater therein, the mineral water in Kyrgyzstan can be classified as saltwater, brine, carbonate-rich mineral water, silicate-rich hot spring water, mineral water containing radon, sulfate-rich mineral water, iron-rich mineral water, iodine- and bromine-rich mineral water, and other types [39]. The annual available groundwater resources in Kyrgyzstan are 11.11 km^3, and 3.85 km^3 of groundwater resources is approved for exploitation each year, accounting for approximately 35% of the total groundwater resources [40]. These fresh groundwater resources are used mainly for purposes related to residential uses and agricultural production, while groundwater is used mostly in the capital and economically developed areas.

The groundwater in the mountainous area of Tajikistan exists mostly in fissures or pores. The groundwater depth is approximately 100–150 m, but the water table in the mountainous basin in the southwestern part of the country is relatively shallow at approximately 10–100 m. Tajikistan contains an estimated 18.70 $km^3 \cdot a^{-1}$ of groundwater resources, and the permitted groundwater exploitation level is 3.0 $km^3 \cdot a^{-1}$, of which 1.24 $km^3 \cdot a^{-1}$ is permitted in the Syr Darya River basin. The total groundwater use in the country is 0.8 $km^3 \cdot a^{-1}$ [41], mainly for purposes related to residential uses and industrial uses, and agricultural irrigation water accounts for approximately 40%.

The groundwater resources in Turkmenistan are equal to 1.3 $km^3 \cdot a^{-1}$, of which 0.44 $km^3 \cdot a^{-1}$ is mineralized groundwater [42]. The groundwater in this area is formed mainly in mountainous areas [43]. More than 130 groundwater sources have been identified, and groundwater is extracted annually at rates of 0.47–0.67 $km^3 \cdot a^{-1}$, of which 45% is for drinking water and 30% is for irrigation and livestock [44]. In Turkmenistan, groundwater accounts for 50% of the total water consumed and originates mainly from the AS37 Birata-Urgench aquifer [37].

Kazakhstan, on average, annually exploits 64.28 km^3 of groundwater resources, and the exploitable groundwater is composed as follows: 40.44 km^3 contains mineralization of less than 1 $g \cdot l^{-1}$, 16.40 km^3 contains mineralization of 1–3 $g \cdot l^{-1}$, and 7.44 km^3 contains mineralization of 3–10 $g \cdot l^{-1}$ [45]. The hydrogeological conditions of Kazakhstan vary widely, with 50% of the country's groundwater resources concentrated in the south, 30% located in the central, northern, and eastern regions, and less than 20% located in the western region [46]. As of 2015, the average annual amount of groundwater extracted in Kazakhstan was 15.6 km^3, of which approximately 86% (13.19 km^3) was

fresh water, while domestic consumption accounted for 6.07 $km^3 \cdot a^{-1}$, industrial uses accounted for 1.1 $km^3 \cdot a^{-1}$, and agricultural irrigation accounted for 8.41 $km^3 \cdot a^{-1}$ [45]. Eighty percent of the water used in urban areas in Kazakhstan is drawn from groundwater resources.

In Uzbekistan, groundwater is an important water resource that provides 60% of the country's tap water demand [47]. There are more than 25,000 groundwater wells in Uzbekistan, and the amount of groundwater resources containing mineralization of less than 1 $g \cdot l^{-1}$ is 9.13–9.49 $km^3 \cdot a^{-1}$ [47]. Numerous TBAs are partially located in Uzbekistan and almost all of the TBAs in the Syr Darya and Amu Darya River basins belong to Uzbekistan. The 2016 report of the United Nations Environment Programme classified the aquifers in the Syr Darya River basin as "groundwater crowding" (i.e., groundwater aggregation). Specifically, according to this report, the groundwater development stress index is 20%, the groundwater dependence index is 50%, and the groundwater resources per capita are 558 $m^3 \cdot a^{-1} \cdot cap^{-1}$ [36]. In some TBAs in Uzbekistan, such as the AS37 Birata-Urgench, AS51 Dalverzin, AS58 Sokh, AS60 Almos-Vorzik, AS67 Maylusu, and AS69 Osh-Aravan aquifers, drinking water use accounts for less than 50% of all extracted groundwater. In contrast, drinking water use in the AS36 Syr Darya, AS43 Karatag/North-Surhandarya, AS44 Zeravshan, and AS47 Pretashkent aquifers accounts for more than 75% of all extracted groundwater [37].

4.2. Groundwater Resource Utilization of TBAs in the Aral Sea Basin

The Aral Sea basin flows through most of Central Asia, covering the two major river systems in Central Asia, namely, the Amu Darya and the Syr Darya. The cooperative development of transboundary water resources in this basin is the key to solving the cross-border water problem in Central Asia.

In 2018, the annual runoff of the Aral Sea basin was 97.5 km^3, of which the Amu Darya River accounted for 62.2 km^3 and the Syr Darya River accounted for 35.3 km^3. In 2018, the amount of surface water supplied from the Syr Darya River to the North Aral Sea was 3.03 km^3, and the surface runoff from the Amu Darya River into the South Aral Sea reached 1.32 km^3 [48]. The Aral Sea basin contains approximately 31.17 $km^3 \cdot a^{-1}$ of groundwater reserves, of which 14.7 $km^3 \cdot a^{-1}$ is located in the Amu Darya River basin and 16.4 $km^3 \cdot a^{-1}$ is located in the Syr Darya River basin [35]. The total actual groundwater use in the five Central Asian countries in the Aral Sea basin accounts for approximately 42% of the total groundwater resources; this water is used mainly for drinking water and agricultural irrigation. Nevertheless, the groundwater resources within these five countries differ significantly throughout the Aral Sea basin, and their groundwater uses also vary (Table 3). Among them, Uzbekistan has the highest reserves of groundwater resources in the Aral Sea basin ($18{,}455 \cdot 10^6$ $m^3 \cdot a^{-1}$), far exceeding the reserves of the other four countries. However, the actual groundwater utilization rate of Uzbekistan is as high as 99.4%; approximately 43.5% of the groundwater resources are used for residential drinking water and 27.8% of the resources are used for agricultural irrigation.

Table 3. Groundwater reserves and uses in the five countries within the Aral Sea basin (million m^3 per year) [35].

Country	Estimated Regional Groundwater Reserves	Reserves Confirmed for Extraction	Total Actual Extraction	Including Different Users and Purposes					
				Domestic Water Supply	Industry	Irrigation	Vertical Drainage Wells	Groundwater Pumping	Other
Kazakhstan	1846	1224	420	288	120	0	0	0	12
Kyrgyzstan	862	670	407	43	56	308	0	0	0
Tajikistan	6650	2200	990	335	91	550	0	0	14
Uzbekistan	3360	1220	457	210	36	150	60	1	0.15
Turkmenistan	18,455	7796	7749	3369	715	2156	1349	120	40
Total Aral Sea basin	31,173	13,110	10,023	4245	1018	3164	1409	121	66

Kyrgyzstan has the fewest groundwater reserves in the Aral Sea basin at only 862×10^6 $m^3 \cdot a^{-1}$. The actual utilization rate is 60.7%, ranking second among the Central Asian countries, and most of the water is used for agricultural irrigation. Tajikistan has the second highest amount of groundwater

reserves in the Aral Sea basin and has an actual utilization rate of 45%, ranking third among the five countries; in total, 55.6% of the water is used for irrigation. The groundwater reserves in the Aral Sea basin available to Kazakhstan and Turkmenistan are basically equivalent (exceeding 1200×10^6 $m^3 \cdot a^{-1}$), with actual utilization rates of 34.3% and 37.5%, respectively, and the extracted water is allocated mainly to domestic water use.

In addition to being used as drinking water, the groundwater resources of the TBAs in the Aral Sea basin are used for agricultural irrigation, industrial development, mining, and livestock. The groundwater uses of some TBAs in Central Asian countries are shown in Table 4 [37].

Table 4. Uses of groundwater from typical transboundary aquifers in the Aral Sea basin.

Types of Use	Groundwater Extraction Percentage (%)			
	<25%	25–50%	50–75%	>75%
Drinking water	AS37, AS51	AS53, AS58, AS69	AS48, AS60	AS43, AS44, AS47
Irrigation	AS37, AS69	AS53, AS60	AS48	AS51
Industry	AS37, AS53, AS60			
Mining	AS69			
Spa	AS37			
Livestock	AS37, AS60, AS69			

5. Challenges Associated with Groundwater Exploitation in TBAs

Differences in the climatic conditions, topography, surface water distribution, and groundwater burial conditions among the five Central Asian countries lead to the uneven distribution of groundwater resources throughout the region. At present, the development and uses of groundwater from TBAs in Central Asian countries have affected the quantity and quality of groundwater, resulting in groundwater overexploitation and water quality deterioration.

5.1. Groundwater Overexploitation and Water Level Decline

In agricultural irrigation areas, groundwater overexploitation has resulted in a continuous decline in the groundwater levels of TBAs in Central Asia. The groundwater level of the AS47 Pretashkent aquifer, which crosses the border between Kazakhstan and Uzbekistan, has dropped by 5–14 m in the agricultural irrigation area during irrigation seasons [30].

Due to the climatic and geological conditions of Central Asia, the groundwater recharge conditions are relatively poor. Some TBAs receive little precipitation because most precipitation experiences evapotranspiration before percolating to the water table [49]. Groundwater isotope studies in the 1980s indicated that the groundwater age of the AS47 Pretashkent aquifer is 6000 years [33] and that the natural seepage velocity of the groundwater in this aquifer is 1.5 $m \cdot a^{-1}$. Hence, the groundwater in the AS47 Pretashkent aquifer can be regarded as a non-renewable resource.

In the AS71 Chu aquifer on the border between Kazakhstan and Kyrgyzstan, the groundwater level in Kyrgyzstan is declining at a rate of 0.4 $m \cdot a^{-1}$ [30].

5.2. Groundwater Pollution

The groundwater quality in Central Asian TBAs differs depending on the climate, geological media, and human activities [8]. The national economies of the five Central Asian countries are dominated by agriculture and animal husbandry. Kazakhstan, Tajikistan, Uzbekistan, and Turkmenistan have developed their agricultural sectors, including cotton planting, while Kyrgyzstan has long focused on animal husbandry.

The surface pollution caused by agriculture and animal husbandry affects not only the surface water quality but also the groundwater quality [50]. In addition, the five Central Asian countries are rich in natural resources; for example, Kazakhstan, Uzbekistan, and Turkmenistan are rich in oil and natural gas resources, while Tajikistan and Kyrgyzstan are rich in non-ferrous metals and coal resources [51]. The exploitation of these natural resources also impacts the groundwater environment, particularly

as a result of oil spills, the accumulation of tailings, wastewater processing, and other unreasonable exploitation and utilization phenomena. The types of groundwater pollution in the Central Asian countries include the following main categories: nitrogen-containing substances, pesticides, heavy metals, pathogens, organic compounds, and hydrocarbons [37].

The groundwater of the AS36 Syr Darya aquifer in the Syr Darya River basin has high salinity levels in Kazakhstan; the total dissolved solid (TDS) concentration increases from 100 $mg{\cdot}l^{-1}$ near the river to 70,000 $mg{\cdot}l^{-1}$ in non-irrigated areas [30]. The AS37 Birata-Urgench and AS71 Vakhsh aquifers have natural brackish water, while the salinities of the AS53 Sulyukta-Batken-Nau-Isfara and AS58 Sokh aquifers have increased due to agricultural irrigation, with groundwater TDS concentrations of 1000–3000 $mg{\cdot}l^{-1}$. The AS71 Chu aquifer in Kyrgyzstan has been partially affected by a series of human activities, such as people's lives, municipal administration, agricultural production, and mining. These factors have contaminated the groundwater with nitrates, pesticides, heavy metals, and organic compounds [30].

Pesticides and nitrogen-containing substances have been found in the AS37 Birata-Urgench, AS43 Karatag/North-Surhandarya, AS53 Sulyukta-Batken-Nau-Isfara, AS60 Almos-Vorzik, and AS69 Osh-Aravan aquifers. These compounds originate mainly from regional agricultural activities. The TDS concentration in the groundwater of the AS43 Karatag/North-Surhandarya aquifer is 1000–70,000 $mg{\cdot}l^{-1}$, which fluctuates seasonally and is affected by agricultural irrigation [30]. In addition, the AS37 Birata-Urgench, AS60 Almos-Vorzik, and AS69 Osh-Aravan aquifers exhibit heavy metal pollution, organic compounds, and hydrocarbon pollution. The hydrocarbon concentration of the AS37 Birata-Urgench aquifer ranges from 0.0015 to 0.2 $mg{\cdot}l^{-1}$ and is derived mainly from industrial production, such as ore mining. Studies have shown that the AS51 Dalverzin, AS60 Almos-Vorzik, and AS69 Osh-Aravan aquifers are also contaminated with radioactive elements [30].

In addition to the impacts of the abovementioned human activities on the water quality of TBAs, the excessive extraction of deep pressurized water indirectly leads to a continuous decline in the groundwater level. In turn, the brackish water and saline water that has formed via pollution in the upper levels of the aquifer can infiltrate downward and directly affect the water quality of the TBA. The AS47 Pretashkent aquifer, which is shared by Kazakhstan and Turkmenistan, can be used as an example.

Cretaceous Cenomanian aquifer K_{2s} in the region of the AS47 Pretashkent aquifer provide 1464 and 2044 $m^3{\cdot}d^{-1}$ of groundwater resources to Saryagash [33]. The mineralization of the groundwater is equal to 0.4–1.5 $g{\cdot}l^{-1}$ [34]. Thus, the groundwater can be classified as $HCO_3{\cdot}Cl{-}Ca{\cdot}Mg$-type, $HCO_3{\cdot}Cl{-}Na$-type, and $HCO_3{-}Na$-type groundwater, and the chemical compositions are as follows:

$$M_{0.4-0.67}\frac{HCO_3 45 Cl 36 SO_4 19}{Ca45 Mg43 (Na+K)12}\, M_{0.58-1.5}\frac{HCO_3 47 Cl 25 SO_4 5-13}{(Na+K)55-95 Ca2-24 Mg1-20} M_{0.8-1.2}\frac{HCO_3 50-77 Cl 16-24 SO_4 1-25}{(Na+K)97 Ca2-5 Mg1-5}$$

With the exception of Cretaceous Cenomanian aquifer K_{2s}, the aquifers in the region of the AS47 Pretashkent aquifer are not TBAs. Guseva N.V. analyzed 144 groundwater samples from aquifers in Uzbekistan and found that the groundwater in Quaternary aquifers contained mainly bicarbonate, with a TDS concentration of less than 1 $g{\cdot}l^{-1}$ [52]. Sulfate groundwater appeared only in some areas, and the TDS concentration in these areas reached 5.68 $g{\cdot}l^{-1}$.

Nitrates have been found in aquifers in agriculturally irrigated areas with a maximum content of 86 $mg{\cdot}l^{-1}$ [52]. The AS47 Pretashkent aquifer experiences mountain-front atmospheric precipitation recharge, strong surface runoff, and upper-level infiltration recharge. As a result, pollutants caused by human activities can enter the TBA directly through the exposed surface at the mountain-front, and contaminated surface water or Quaternary groundwater can also enter deep TBAs through downward leakage due to the decline in water levels caused by excessive extraction of groundwater.

6. Comparative Assessment of the TBAs in Central Asia

6.1. Issues of Scale and Number

On the Transboundary Aquifers of the World map (UNESCO-IGRAC, 2015), 34 TBAs can be identified among the five Central Asian countries; of these aquifers, nearly four-fifths span an area of less than 1000 km^2. The difference between the numbers of aquifers identified in Central Asia and those identified in Africa and the Americas reflects, in part, the small size of the TBAs. Densely distributed areas of TBAs in Central Asia are often concentrated in transboundary river basins, which is similar to other regions in the world. Hence, TBAs may have yet to be discovered in less well-mapped parts of Central Asia.

6.2. Groundwater Indicators

The Transboundary Waters Assessment Programme (TWAP Groundwater) in the Global Groundwater Information System (GGIS) collected data from 7 of the 34 TBAs in the five Central Asian countries (Table 2), all of which are relatively large TBAs in size. The amount of data available for these seven aquifers in TWAP Groundwater ranges from 0 to 69%. Nevertheless, only five TBAs in Central Asia were described using 8–14 indicators by combining various data, while in the rest of the world, TBAs were described using, at most, 20 indicators in TWAP Groundwater. In addition to the most basic physiography and climate information, these indicators also include hydrogeological characteristics and environmental and socioeconomic aspects. Regarding the limited data and indicators for Central Asia, the investigation and research of TBAs in this area evidently remain very lacking, which is one of the main challenges facing the proper governance of TBAs.

6.3. Case Studies

This section compares three case studies of TBAs in different parts of the world: the Pretashkent aquifer in Central Asia, the Stamprient aquifer in southern Africa, and the Trifinio aquifer in Central America.

The Pretashkent TBA is located within a continental arid climate, characterized by a lack of precipitation. Therefore, the recharge of the TBA is very limited and the Pretashkent TBA resources are virtually non-renewable. This TBA is representative of medium-sized, deeply buried artesian aquifers with negligible recent recharge [53]. The natural background groundwater quality of the Pretashkent TBA is moderate. However, the potential degradation of the groundwater quality is a major issue, including the gradual decline in the groundwater level in Pretashkent TBA, which may trigger the intrusion of saline water and brine from overlying strata.

The Stampriet TBA system covers a large arid region without permanent surface water and receives negligible recharge. The system contains two confined aquifers and overlying unconfined aquifer units. The mean annual groundwater recharge of the TBA is very low. The natural background groundwater quality is high. However, pollution may cause the groundwater quality to decline. While the confined aquifers are relatively invulnerable to pollution, the shallower and usually phreatic aquifers are vulnerable to pollution from agricultural irrigation and other aspects [53].

The Trifinio TBA is composed of two relatively productive and laterally disjunct aquifer zones, which are considered to be representative of the groundwater setting in small alluvial valleys in mountainous areas around the globe [53]. The long-term average groundwater recharge of the Trifinio TBA is moderate to high. Moreover, the natural background groundwater quality is high, which satisfies local drinking water standards. However, pollution presents a major water resource management challenge in the area. The alluvial aquifer is not threatened by groundwater quantity problems (such as declining water levels and exhaustion), but it is directly exposed to the environment and is extremely vulnerable to pollution. Without effective pollution control, the groundwater will inevitably become increasingly polluted as time passes.

Groundwater is very important for the domestic water supply in all three of these areas. In comparison, the Pretashkent TBA in Central Asia and the Stamprient TBA in southern Africa have relatively low recharges, while the Trifinio TBA in Central America has very high recharge. The natural background quality of the Pretashkent TBA in Central Asia is worse than that of the Stamprient TBA in southern Africa and of the Trifinio TBA in Central America. The groundwater recharge capacity and natural background quality determine the vulnerability to pollution to a certain extent. A transboundary legal framework for these TBAs is missing [53], but in the Stamprient TBA of southern Africa and the Trifinio TBA of Central America, there are international bodies that could be entrusted with a mandate for TBA management.

Ultimately, the development of TBA cooperation in Central Asia requires an improved assessment of the status of shared groundwater resources. Entrusting an international body to manage these TBAs may be the first step in developing TBA cooperation in Central Asia.

7. Strategies for the Further Development of Water Resources in TBAs

The International Water Resources Law (Convention on the Protection and Use of Transboundary Watercourses and International Lakes) (Helsinki, 1992), Convention on the Law on the Non-Navigational Use of International Watercourses (New York, 1997), and Draft Articles on Transboundary Aquifers Law (United Nations General Assembly, 63/124, 66/104, Resolutions 68/118 and 71/150) established the basic requirements for TBA cooperation, namely, the reasonable and equitable use of groundwater resources in TBAs, the prevention of significant damage to TBAs, the enhanced regular exchange of data and information, and the encouragement of bilateral and regional agreements. The reasonable and equitable use of groundwater resources in TBAs forms the basis of TBA cooperation. Accordingly, Brooks and Linton suggested that the application of this principle considers giving precedence to future needs over current uses [54].

Rapid population growth, uneven economic development, the extremely uneven spatiotemporal distribution of water resources, and different degrees of use of groundwater resources in different countries all contribute to a series of problems regarding the use of transboundary water resources. The fundamental reason for the discrepancies in the development of the groundwater resources of TBAs is that TBA systems are connected, and when a country extracts too much groundwater, it will decrease the amount of groundwater resources available for consumption in neighboring countries. In the context of global climate change, rapid population growth, and water shortages, cooperation regarding the use of TBAs in Central Asia is essential.

7.1. Reasonable and Equitable use of Groundwater Resources

Central Asian countries need to reach a long-term cooperative agreement on the development and utilization of transboundary water resources, define quotas for exploitation and utilization, and find the best mutually beneficial cooperation strategy to rationally exploit groundwater resources to meet the needs of people's lives and socioeconomic development.

The rational exploitation of groundwater resources in TBAs requires that the following factors be comprehensively considered: (1) the natural properties of aquifer systems, (2) the formation and sources of recharge of aquifer systems, (3) the existing and potential uses of aquifer systems, (4) the actual and potential consequences of the development and utilization of aquifer systems, (5) the protection and development of aquifer systems, and (6) the ecological environment under the influence of aquifer systems. The equitable use of TBAs should not only enable countries with TBAs to benefit equitably from their groundwater resources, but also maximize the benefits of using those TBAs. To ensure the sustainable use of transboundary groundwater resources, the total amount of groundwater extracted from an aquifer in neighboring countries should not exceed the recharge of the system.

Regarding the development and utilization of groundwater resources in TBAs, the five Central Asian countries must produce a development strategy for on-demand water collection in the vicinity of

the water source system and for monitoring groundwater resources. In addition, countries with aquifers should actively seek alternative sources of water while considering current and future water needs.

7.2. Ecological Protection of Transboundary Aquifers

The problems and challenges faced by the five Central Asian countries in relation to the exploitation of groundwater resources are two-fold. On the one hand, challenges arise from global and regional climate change, which will lead to a reduction in the total amount of water resources in Central Asia. On the other hand, with the socioeconomic development of various countries, groundwater resource pollution is becoming increasingly serious, and the sustainable use of groundwater resources is seriously threatened.

In view of the abovementioned problems, the first step is to conserve the use of water resources and employ groundwater recharge technology to reasonably compensate for the use of groundwater in TBAs. With the warming temperatures in Central Asia, the glacial melting rate in the mountains of Central Asia has accelerated, resulting in increased surface runoff in a short period of time.

Nevertheless, due to the large amount of surface evaporation and the extensive use of surface water resources, especially the consumption of water for agricultural irrigation, plain areas still experience constant shortages of surface water resources, and the exploitation and utilization of groundwater resources have increased. To protect TBA systems, Central Asian countries should recharge groundwater in a timely manner to mitigate the annual decline in transboundary groundwater resources.

Water quality safety is another important aspect of an integrated management plan for groundwater resources. With the development of industry and agriculture, surface water pollution is becoming increasingly serious and is causing groundwater pollution. The self-purification processes of groundwater are far more complex and occur on longer timescales than those of surface water. Central Asian countries should take appropriate measures to protect TBA systems and to prevent or reduce further damage to TBAs during the extraction and recharge processes. At the same time, measures should be taken to protect the relevant ecological environments of TBAs and TBA systems to ensure groundwater quality. The Central Asian countries should conduct joint monitoring of the water levels and water quality of TBA systems and exchange monitoring data on a regular basis. On this basis, a numerical model of groundwater flow and water quality in TBAs should be constructed, predictions and analyses of the water quantities and water quality changes in aquifer systems should be simulated, and future change scenarios should be analyzed.

7.3. Strengthening Dialogue and International Cooperation

The five Central Asian countries should strengthen international dialogue and cooperation regarding the use of groundwater resources in TBAs, including (1) developing and implementing appropriate TBA management plans and creating collaborative management mechanisms; (2) strengthening exchanges and cooperation in terms of water-saving technologies; (3) establishing mechanisms for protecting the ecological environment of transboundary waters, reducing the pollution of water bodies in the basin, and controlling and preventing further deterioration of the ecological environment and declines in water quality.

In summary, improving the effective utilization rate of water resources is a serious problem affecting the five Central Asian countries. Hence, these countries should continue to strengthen their cooperation related to the rehabilitation and improvement of shared water conservancy facilities and water-saving irrigation technology.

8. Concluding Remarks

Central Asia is an inland arid region and most current water resource issues are concerned with the distribution of surface water resources in the Syr and Amu Darya River basins. Affected by climate change, the Tianshan Mountains in the upstream source area are rich in snow and ice runoff, but as ice and snow resources subside, the water resources dispute in this area will revolve around the

groundwater in TBAs. The reasonable development and utilization of transboundary groundwater resources is conducive to alleviating the current conflicts related to regional water supply and demand. A total of 34 TBAs have been identified in the area, and groundwater exploitation has become an important source of water for agricultural irrigation and domestic use throughout the region. However, due to the unmanaged and unchecked exploitation of groundwater, some TBAs risk experiencing a decline in water levels and the deterioration of water quality.

Facing the severe water security situation in Central Asia, it is vital to develop and protect transboundary surface water and groundwater resources in a rational manner. The novelty of this study is the revealing of the spatial distribution of transboundary aquifers and the potential for groundwater resource development and to provide a scientific basis for solving the water crisis in Central Asia under threat from climate warming.

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