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TRANSFORMATION OF THE AMUDARYA RIVER BASIN IN THE CONTEXT OF CLIMATE CHANGE

Abstract. The article assesses the impact of climate change on the water resources of the Amudarya River basin. The Amudarya River is fed by thawed snow and glacial waters. Glaciers have a significant role in the water supply of agriculture, as well as hydropower. Due to the intensive melting of glaciers in the short term, the flow of some rivers will increase. However, in the long term, the runoff will decrease, and some glaciers may disappear altogether. An important task of this study was to take into account the work of researchers working on environmental problems in the Amudarya basin. Since the ecology of the transboundary Amudarya River is in the sphere of national interests of several countries: Tajikistan, Uzbekistan, Turkmenistan and Kazakhstan, certain conditions for cross-border cooperation are being formed. The main problem of cooperation is unstable river regimes, which require continuous planning and negotiations on the allocation of resources, and which are exacerbated by climate change. The main consequences of the influence of climate change on the formation of water resources and water use in the Amudarya River basin are highlighted.

Keywords: Amudarya River, climate change, river runoff, glaciers.

Introduction. The Amudarya is the largest river in Central Asia, with a catchment area of 309,000 km^2 and a length of 2,540 km. On its way, it overcomes the highest mountains and vast deserts, in which it is helped by multiple tributaries. Melting glaciers and snowfields on the slopes of the Hindu Kush and the Vrev Glacier form the Wakhandarya watercourse, which in its turn forms the Panj River. The Amudarya River is formed by the confluence of two main tributaries: the Vakhsh River, originating in the Kyrgyz part of the Pamir Mountains, and the Panj River flowing along the border of Tajikistan and Afghanistan. The Amudarya River is a cross–border river flowing between Afghanistan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan. The main flow of the Amudarya is formed on the territory of Tajikistan (72.8 %), 14.6 % in Afghanistan and 8.5 % in Uzbekistan. Three major tributaries Kafirnigan, Sherabad, and Surkhandarya flow into the Amudarya. The annual flow of the Amudarya is 73.6 km^3, with a water storage volume of 24 billion m^3 [1]. About 80 % of the Amudarya is regulated by more than 35 reservoirs, which capacity is more than 10 million, and Nurek and Tuyamuyun reservoirs are the main reservoirs [1].

The Amudarya River has a significant role for the development of the basin countries. The water resources of the Amudarya River are used mainly for agriculture, power generation, industrial, domestic and drinking purposes, and the lower reaches of the Amudarya are important for fishing. The cities Urgench, Nukus, Termez, as well as the Amudarya Reserve and many dams are situated near the Amudarya. Dams are especially important for Tajikistan because of the country's export of electricity generated by the dams. As it is known, Amudarya waters are fully used for irrigation. The Karakum Canal takes water from the Amudarya and flows through the desert from east to west and is the main source of drinking water and irrigation. The Kizil Canal, which irrigates the central part of Uzbekistan, also flows from the river. Uzbekistan harvests about 10-20 % of the world's cotton through irrigation [2]. Huge fields of cotton and wheat are growing along the Amudarya and its canals in Turkmenistan. However, due to irrigation, most of the river does not reach the Aral Sea, as a consequence of which it is rapidly drying up and decreasing in size. In turn, the lack of water resources is one of the factors limiting the development of the Amudarya basin countries. The world is undergoing intensive climate warming, which leads to melting of glaciers. And glaciers, in turn, are the main sources of fresh water for the river basins of Central Asia.

Another peculiarity of the Amudarya basin is the active manifestation of denudation and erosion processes, which cause a high sediment load of many rivers. The Amudarya is one of the first on the globe in terms of suspended sediment runoff. Excessive water use without knowledge of ecological laws and poor water management create even more difficulties for the functioning of water management systems in the Amudarya river basin. Water consumption and water use are constantly increasing, and the impact of economic activities on the hydrological regime of water flow, especially for irrigation, population and industry, is also increasing significantly. Therefore, today's global problem is the severity, extent of climate change, especially in developing countries.

Materials and methods of research. The main data for this review were publications of scientific articles in journals, anthologies, as well as electronic resources and publications on the Amudarya River Basin. The studies from 2010-2022 were also taken into account. From glaciers to water use of water resources in the basin were analyzed and assessed.

Glaciers as a runoff formation zone. Central Asia is characterized by arid and continental climate. This means that summers are very hot (up to 50 °C in deserts), winters are very cold (up to -60 °C in the mountainous regions of the Pamirs). The average annual temperature ranges from + 14 to + 17 °C, winter temperature – from + 1 to + 2 °C, summer temperature – from + 30 to + 32 °C [3]. It is known that climate change is influencing the temperature rise as well as precipitation patterns. But melting of glaciers is a more worrying consequence of global warming in Central Asia. Currently, glacier losses in Central Asia are about 1 % per year [4]. Small glaciers (less than 0.5 km^2) are already at the stage of complete melting [4]. Due to the intensive melting of glaciers in the short term, the flow of some rivers will increase. However, in the long term, runoff will decrease and some glaciers may disappear completely. According to the reports of the UN Regional Center for Preventive Diplomacy for Central Asia, water reserves in CA glaciers have decreased by more than 25 % [4]. The rapid melting of ice formations in the mountains, as a continuous process, is influenced by several factors. Among the subjective reasons is the widespread human interference in local ecosystems. The objective reason is the impact of global climate warming processes. Taking into account the above-mentioned, in the long term, the Amudarya river flow will decrease. According to foreign experts' assessments, the Amudarya runoff may decrease up to 15 % during 25 years [4]. Such water deficit, as we know, is influenced by melting of glaciers and permafrost, temperature increase and decrease in surface runoff.

Glaciers are sensitive climate indicators, as described above. They primarily respond to inter-annual changes in temperature and precipitation. Recently, there has been a significant increase in glacier melt research using remote sensing. In the paper by Franz Gerlich, Tobias Bolch et al. "More dynamic than expected: an updated survey of surging glaciers in the Pamir" [5] presents an updated list of confirmed rising glaciers in the Pamir, where the Amudarya River originates. This work is based on previous studies and more on a systematic analysis of Landsat image time series (from 1988 to 2018) to detect glacier surges and determine the start, end and their full surge cycle (for example, from the beginning of an active phase year to the beginning of the next active phase) and very high resolution imagery (Corona, Hexagon, Bing Maps, Google Earth). In the framework of this study, glacier pulsation data in the Pamir Mountains confirming temperature spikes were obtained. According to the research, on average, the minimum altitude decreased from 3954 to 3793 m above sea level, but individual glaciers at maximum length reached points more than 800 m lower than that [5]. These results of the study prove the fact that due to climate change glaciers are at the stage of melting and possible disappearance. The list created during this study is available in the supplementary material, which can serve as a basis for further research [5]. Due to the melting of glaciers, it is important to take into account the work of researchers working on environmental problems in the Amudarya basin.

Melting glaciers is a global environmental problem caused by climate warming. The increase in air temperature causes a massive melting of glaciers, making their area gradually decrease and the water level of the basin increase. Over time, the problem will only worsen and could result in an ecological catastrophe.

Ecology in the Amudarya basin. The Amudarya is the most high-water river in Central Asia and throughout its course the water is used for irrigation purposes. Subsequently, drainage water can flow back into the river with organic and chemical pollutants in its composition. In terms of turbidity and the amount of suspended sediment, the Amudarya ranks among the highest in the world. The increase in water

turbidity is explained by the erosion of soils and river banks by significant flow velocities. The composition of river water is affected not only by precipitation and snowmelt, but also by floods and tributaries flowing into the larger river and groundwater. An important objective of this review was to take into account the works of researchers working on environmental problems in the Amudarya basin, because the ecology of the transboundary Amudarya River is in the sphere of national interests of several countries: Tajikistan, Uzbekistan, Turkmenistan and Kazakhstan.

The ecological state of the Amudarya river basin can be characterized by studies of water properties. During the international experiment "NOWRUZ", which involved scientists from Kazakhstan, Kyrgyzstan, Uzbekistan and Tajikistan, the results of processing and interpretation of the database were obtained [6]. The aim of the experiment was to study the radioecological and geochemical purity of the transboundary rivers of Central Asia. The samples were studied by neutron activation analysis (NAA) at the Institute of Nuclear Physics of the Academy of Sciences of the Republic of Kazakhstan (INP of the Academy of Sciences of the Republic of Kazakhstan). Vakhsh, Pyandj and Kafirnigan rivers were selected points of the main tributaries of the Amudarya in the study. According to the results, water in two tributaries of the Amudarya River showed increased mineralization. In the Vakhsh river, the concentration of salts was 650 mg/l, in the Panj River – 520 mg/l. As a result of the study, the neutron activation analysis (NAA) method was used to obtain a quantitative analysis of the presence of metals in the objects with an accuracy better than 10 *(-10) g/g. The obtained data of the provided method allowed to detect the presence of metals in river waters and to show their distribution. In river waters, elements of the 1st hazard class - As and the 2nd hazard class - Co, Na, Sb, U were detected. For comparison, sodium concentration was high in the lower reaches of Pyanj (52000 μg/l) and Vakhsh (70000 μg/l), but lower than maximum permissible concentration (200000 μg/l) [6].

In continuation of the interpretation of previously obtained data on water composition in the Amudarya river basin, the work of D.A. Abdushukurov and Z.V. Kobuliev "Elemental composition of bottom sediments and adjacent soils of the main tributaries of the Amudarya" is dedicated to the processing of the results based on samples collected at the confluence of the three main tributaries of the Amudarya - the Panj, Vakhsh and Kafirnigan rivers. In the course of fieldwork, samples of bottom sediments and adjacent soils were collected at the three locations: on the Panj River; on the Vakhsh River (1 km upstream of the confluence with the Panj); and on the Kafirnigan River (upstream of the confluence with the Amudarya). Sample data were obtained from various laboratories of the Nuclear Physics Institutes of Uzbekistan and Kazakhstan. The methods which have been used (neutron-activation and X-ray fluorescence analyses) have high sensitivity. All in all, concentrations of 38 elements were determined in the samples. The study allowed to identify 6 macroelements and trace elements, including rare-earth elements, among the elements and to reveal radiochemical patterns of element distribution in the rivers [7].

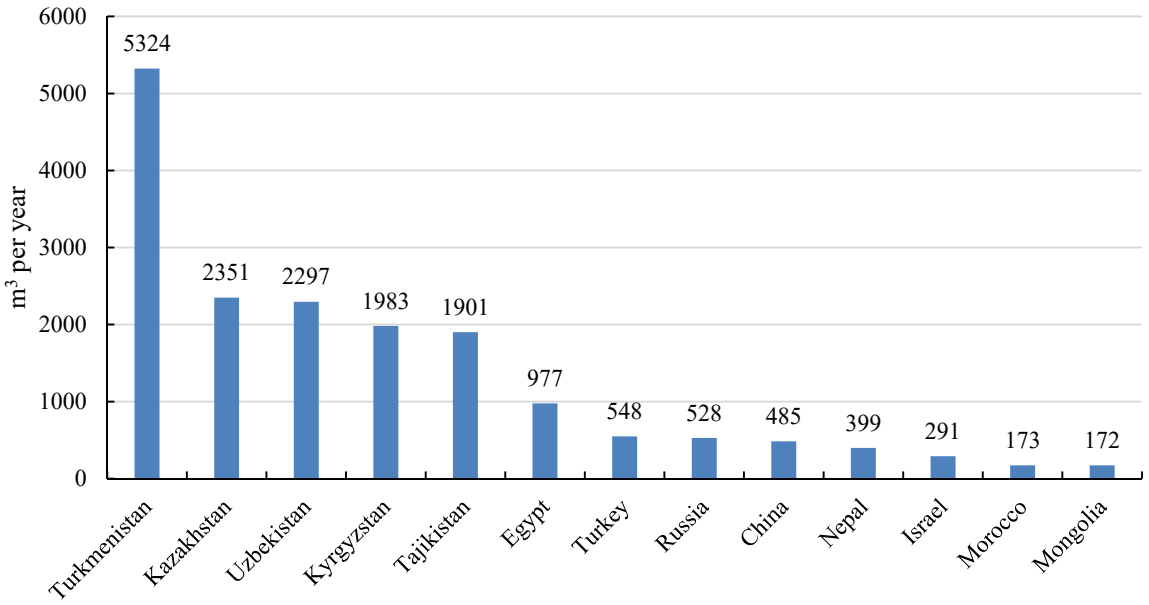
In conclusion, according to the value of water pollution index (WPI), the quality of Amudarya water in all sites complies with the 3rd class of medium polluted waters. On average, the river has a 962.8 mg/dm^3 mineralization [8]. Such increase of river runoff mineralization and, accordingly, deterioration of water quality is caused by general decrease of water availability along the whole length of the river and discharge of return collector water into the river channel from irrigated areas. In places where a large volume of return water is created, it means that excessive water withdrawal from the river and discharge into collectors is made. Therefore, it is necessary to reduce the volume of excessive water withdrawal in the future and thus reduce the volume of return flow and utilize it in small reservoirs and natural depressions. An important task of the joint strategy of Amudarya water resources management in the context of climate change is to balance the interests of the countries in the region between environmental water requirements and water use issues.

Water use and infrastructure. The impact of climate change on the nature of the functioning of water management systems in the Amudarya basin can be expressed both through changes in the conditions for the formation of water resources and through modification of the water consumption regime. Due to the continuous increase in water use, the impact of economic activity on the hydrological regime of water flow, especially for irrigation, for the population and industry, has increased significantly. Only the Karakum canal, with a length of about 1,100 km, annually withdraws about 18 km^3/year of water from the Amudarya and conveys it to the southern part of Turkmenistan, where this water is used in

gravity irrigation systems [9]. The area of irrigated agricultural land in the Kyrgyz part of the basin (Kyzyl Suu sub-basin) is 20,000 ha, while in Afghanistan it is 1,200,000 ha. Groundwater extraction volumes in the Amudarya River basin are estimated at 4.8 km^3/year [10].

Excessive water use without knowledge of environmental laws and poor regulation during the Soviet period caused to the serious environmental consequences that independent countries of Central Asia had to face: 80% of the Aral Sea turned into a desert, and about 90% of the near Aral Sea region is subject to salinization [3]. The decrease in quality has a negative impact on soil fertility and requires additional large volumes of water to leach saline soils. If in the headwaters of the Amudarya river basin, in the feeding zone, the average mineralization delivers 0.35-0.37 g/dm^3, in the middle flow it reaches 0.79 g/dm^3, and in the lower flow, in the accumulation zone – up to 1.1 g/dm^3 [11].

In the lower course of the Syr Darya and Amudarya, in Kyzylorda region in Kazakhstan, Dashoguz region in Turkmenistan, as well as in Khorezm region and Karakalpakstan in Uzbekistan, water is so polluted that it is unsuitable for human drinking or agricultural use. Decades of excessive agricultural water use have created an infrastructure, economic dependency, social structures, habits and traditions of water use that are not easily changed. Therefore, these water use models persist and still have an impact today. Outdated irrigation technologies with high water consumption and high evaporation are still used in the fields. As a consequence, Central Asia has the lowest water use efficiency in the world. According to experts, 50 to 80% of irrigation water is wasted before it reaches the fields [3]. The following figure shows that even compared to countries such as Egypt or Turkey (which are not the most efficient water users), water use in Central Asia per capita is much higher (figure).



Water consumption per capita [4]

Until the 1950s, the demand for irrigation water was relatively low and the Amudarya River flowed continuously to the Aral Sea. However, since the 1960s, excessive irrigation has unbalanced human demand for water against the capacity of the Amudarya and the Aral Sea. Until 1990, enormous amounts of money were invested in the region's water infrastructure: reservoirs, irrigation canals, and drainage networks were built to supply agriculture in the arid steppe and desert areas. In 2005-2010, the area of irrigated land in the Amudarya basin averaged over 5 million ha [12]. The actual irrigated area depends on the climatic conditions of the current year, and the government decides how much land can be irrigated. Uzbekistan has the largest area covered by large-scale irrigation, followed by Turkmenistan, Tajikistan and Afghanistan. In comparison with the other types of water use, irrigation is the main source of water use in the Amudarya basin today.

The following table shows water availability and use by countries (table) [4].

Water availability and use by countries

	Afganistan	Kazakhstan	Kyrgyzstan	Tajikistan	Turkmenistan	Uzbekistan
Domestic freshwater resources per capita (m^3/person) (2007)	1705	5095	8624	9992	273	597
Total freshwater resources per capita (m^3/person) (2007)	2015	7405	3821	2392	4979	1842
Agricultural water use (% of total water use) (2007)	98	82	94	92	98	93
Total irrigation area, ha	3,2 mln	2,3 mln	1 mln	719 200	1,1 mln	4,4 mln
Irrigated lands (% of the total area of arable land)	5,8	15,7	75	84	100	89
The proportion of the irrigated area subjected to salinization, %	–	>33%	11,5%	16%	95,5%	50%
The share of agriculture in GDP (2009), %	29	6	39	22	20	12
Production of electricity from hydro resources (2008)	–	7,5 billion	10,7 billion	15,8 billion	3 mln	11,4 billion
Electricity production from hydroresources (% of total production) (2008)	–	9	90	98	0	23

In addition to water intake, the irrigation agrarian farming involves the discharge of drainage water back to the Amudarya River from irrigation fields in the middle and upstream zone: 3-4 km³ is discharged directly into the river annually [13]. A large amount of drainage water is discharged to deserts and other lands which are deemed unsuitable for farming. In general, drainage water comprises 30 % of the water discharge in the Amudarya basin. Despite the significant volume, collector-drainage water is generally not recognized as a resource. A proportion of irrigation runoff volume is used to supplement irrigation water, especially in dry years, while most of this water is drained and disappears into the desert, and a significant amount flows back to the middle and lower reaches of the Amudarya River, increasing the quantity but significantly reducing the quality of water, making it unsuitable for drinking. It should be noted that much of the agricultural land is not irrigated currently due to the very poor state of the irrigation infrastructure. When these irrigation systems will be restored, water withdrawal from the river will be increased.

The main difficulty such as unstable river regimes that require continuous planning and allocation negotiations is increasing due to climate change with a corresponding increase in flow variability. Therefore, climate change creates even more challenges for transboundary cooperation. The availability of flexible institutions for adaptive management is of paramount importance and, in turn, institutional strengthening is critical. In view of these challenges, in the early 1990s many experts were concerned about the possibility of future tensions between the Central Asian countries due to water issues. After gaining independence, the Central Asian countries began to cooperate more closely to solve water problems. In 1992, an Agreement between the Republics of Kazakhstan, Kyrgyzstan, Uzbekistan, Tajikistan and Turkmenistan on Cooperation in the Joint Management, Use and Protection of Water Resources from Interstate Sources was agreed upon. The reached Agreements and adopted decisions on water problems in Central Asia played a huge role in regulating water issues [14].

Indeed, after gaining independence, due to the need to solve transboundary water management issues, over the last 20 years, multiple agreements have been signed between the Central Asian countries. One of them is the establishment of an organizational structure for regional water management and solving the Aral Sea problem. The main platform for regional cooperation is the International Fund for Saving the Aral Sea (IFAS), which was established in 1993 in Almaty. The members of the Fund are all five former Soviet republics, which have agreed to pay annually 1% of their government expenditures to the Fund.

As noted, the key challenge is increasing due to climate change, making transboundary cooperation even more problematic. However, the Amudarya River Basin exemplifies the possibility of how shared water can encourage cooperation even under challenging conditions. Although the benefits of cooperation remain unsatisfactory, existing institutions serve as a "safety valve" against the emergence of water conflicts. Strong and effective regional organizations, especially IFAS, are a significant support for sustainability in the region.

Conclusion. The main data for this review were publications of scientific articles in journals, collections, as well as electronic resources and publications about the Amudarya River basin. The studies from 2010-2022 were also taken into account. Special attention was devoted to the problems of glacier melting and ecology, as a result of which the river flow decreases. And reduction of river flow, in turn, creates problems for the countries of the region in water use.

Recently, the vulnerability of economies and population to climate change has been studied in detail around the world. Various scenarios of climate change impacts and how to adapt to them are being explored and developed. Based on the results of the studies that served as the basis for this review, it can be concluded that the impact of global climate change on the Amudarya basin countries is significant. If the forecast for rising temperatures and decreasing glacier volumes in Central Asia comes true, a decrease in seasonal runoff can be expected following the increase in seasonal runoff as a result of intensive glacier melting. By the end of the century, the area of glaciers in the region is projected to decrease significantly. The peak of intra-annual river runoff will shift to the early months. And in the summer months the volume of water will be less, which is important for agriculture.

Central Asia is characterized by a variety of climatic conditions, however, the climate has a common similarity - high continentality, characterized by a large amplitude of air temperature fluctuations per year and low precipitation. The main indicator of climate change in Central Asia is the state of glaciers and snow cover, and the growth of desertification in the countries of the region. That is, the transformation of the hydrological regime of rivers is associated with natural climatic changes, and, above all, with the melting of glaciers as a result of climate warming.

Also, the transformation of the Amudarya river basin is affected by the deterioration of the environmental situation in the region. In terms of turbidity and suspended sediment load, the Amudarya ranks among the highest in the world. Therefore, an important objective of this review was to take the work of researchers working on environmental problems in the Amudarya basin into account. The proven increase in river runoff salinity and, consequently, deterioration of water quality is caused by a general decrease in water availability along the entire length of the river and discharge of return collector water into the river channel from irrigated areas. Where a large volume of return water is created, it means that excessive water withdrawal from the river and discharge into collectors is made. Therefore, it is necessary to reduce the volume of excessive water withdrawal and thus reduce the volume of return flow and utilize it in small reservoirs and natural depressions.

Unfortunately, Central Asia has the lowest indicators in the world rankings in terms of water use efficiency. Improving the efficiency of water use, water conservation and water demand management, achieving compromises between the interests of upstream and downstream countries, the needs of water users and ecosystems requires strengthening the cooperation of the Amudarya River Basin countries. Therefore, an important task of the common strategy of water resources management in Central Asia in the context of climate change is joint development of adaptation measures and balancing the interests of the region's countries between environmental water demands, hydropower and irrigated agriculture.

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КЛИМАТТЫҢ ӨЗГЕРУІ ЖАҒДАЙЫНДА АМУДАРИЯ ӨЗЕНІ БАССЕЙНІНІҢ ТРАНСФОРМАЦИЯСЫ

Аннотация. Мақалада климаттың өзгеруінің Амудария өзені бассейнінің су ресурстарына әсері бағаланады. Амудария өзенінің қоректенуі еріген қар мен мұздық сулардан тұрады. Мұздықтар ауыл шаруашылығын сумен қамтамасыз етуде, сондай-ақ гидроэнергетикада маңызды рөл атқарады. Мұздықтардың қарқынды еруіне байланысты қысқа мерзімде кейбір өзендердің ағыны артады. Алайда, ұзақ мерзімді перспективада ағын азаяды, ал кейбір мұздықтар мүлдем жоғалып кетуі мүмкін. Бұл зерттеудің маңызды міндеті Амудария бассейніндегі экологиялық мәселелермен айналысатын зерттеушілердің жұмысын ескеру болды. Амудария трансшекаралық өзенінің экологиясы бірнеше елдердің: Тәжікстан, Өзбекстан, Түрікменстан және Қазақстанның ұлттық мүдделері саласында болғандықтан, трансшекаралық ынтымақтастық үшін белгілі бір жағдайлар қалыптасуда. Ынтымақтастықтың басты проблемасы-климаттың өзгеруіне байланысты кіретін ресурстарды бөлу бойынша үздіксіз жоспарлау мен келіссөздерді қажет ететін өзендердің тұрақсыз режимдері. Амудария өзенінің бассейнінде су ресурстарының қалыптасуына және суды пайдалануға климаттың өзгеруінің әсер етуінің негізгі салдары қамтылған.

Түйін сөздер: Амудария өзені, климаттың өзгеруі, өзен ағыны, мұздықтар.

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ТРАНСФОРМАЦИЯ БАССЕЙНА РЕКИ АМУДАРИЯ В УСЛОВИЯХ ИЗМЕНЕНИЯ КЛИМАТА

Аннотация. Оценивается воздействие изменения климата на водные ресурсы бассейна реки Амудария. Питание реки составляют талые снеговые и ледниковые воды. Ледники играют значимую роль в водоснабжении сельского хозяйства, а также для гидроэнергетики. По причине интенсивного таяния ледников в краткосрочной перспективе сток некоторых рек будет увеличиваться. Однако в долговременной перспективе сток будет сокращаться, а кое-какие ледники могут вовсе исчезнуть. Важной задачей этого исследования было принять во внимание работы по экологическим проблемам в бассейне Амударии. Так как экология трансграничной реки Амудария находится в сфере национальных интересов Таджикистана, Узбекистана, Туркменистана и Казахстана, возникают определенные проблемы для трансграничного сотрудничества. Они усугубляются неустойчивым режимом реки, что требует непрерывного планирования и переговоров по распределению ресурсов. Изучены главные последствия влияния изменения климата на формирование водных ресурсов и водопользование в бассейне реки Амударии.

Ключевые слова: река Амудария, изменение климата, речной сток, ледники.