Adaptation to climate change in the mountain regions of Central Asia: a systematic literature review

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SYSTEMATIC REVIEW

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Adaptation to climate change in the mountain regions of Central Asia: A systematic literature review

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Abstract

The mountains of Central Asia support many environmental functions and ecosystem services. The mountain environments and their services are affected by climate change and climate change adaptation (CCA) actions are required to increase resilience of regional communities. This paper is a systematic review of the English and Russian-language literature published between 2013 (IPCC AR5) and May 2021 (IPCC AR6) focusing on CCA in the Central Asian mountains. In all, 52 publications have been reviewed. Criteria defining incremental and transformative adaptation were established and the reviewed studies were assigned to one of these approaches. The relatively low number of publications shows that the extent of CCA knowledge represented in academic literature is limited in comparison to other mountainous regions. There is a disparity between the growing body of publications addressing climate change and limited and decreasing number of academic publications focusing on adaptation in the region. Only 11 publications reported transformative adaptation actions. Most of the reviewed papers (55%) focus on water resources and future water availability; 15% focus on land degradation, 10% on changes in vertical zonation of plant species, 7% on loss of plant species, 3% on impacts of hazardous events, and 10% on multiple impacts of climate change. The awareness of the importance of CCA among the regional actors should be improved through closer collaboration between researchers, international organizations focusing on sustainable development and adaptation which have recently become more active in the region, practitioners, and local communities and co-production of knowledge on the development and implementation of CCA.

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KEYWORDS

climate change, incremental and transformative adaptation, Pamir, Tien Shan, water resources

1 | INTRODUCTION

Central Asia, a region accommodating the glacierized mountain systems of the Tien Shan and Pamir and vast arid and semi-arid plains, is a hotspot of the observed (Groisman et al., 2017, 2018; Unger-Shayesteh et al., 2013) and projected (Huang et al., 2014; Jiang et al., 2020; Mannig et al., 2013) climate change. The impacts are particularly notable in the mountains because climatic warming is enhanced at high elevations (Pepin et al., 2015) and because of the vulnerability to climate change of mountain glaciers which occupy approximately 15,400 km^2 in the Tien Shan (Farinotti et al., 2015) and 13,800 km^2 in the Pamir (Mölg et al., 2018). An increase in surface air temperature has been observed in every season at the high-elevation sites (Shahgedanova et al., 2018). The widespread glacier retreat has been observed in the Tien Shan mountains where glaciers lost 18% $\pm$ 6% of area and 27% $\pm$ 15% of mass in 1961–2012 (Farinotti et al., 2015) and there is evidence for permafrost thaw (Marchenko et al., 2007). Although to date glaciers in the western and central Pamir exhibited smaller loss of mass and had balanced budgets in the eastern Pamir (Bolch, Rohrbach, et al., 2019; Bolch, Shea, et al., 2019; Brun et al., 2017), glacier retreat is projected for the whole region in all climate scenarios (Huss & Hock, 2018; Shannon et al., 2019). According to IPCC AR6, there is high confidence in the projected increase in the intensity and frequency of extreme events (including heat waves, droughts, floods, and natural hazards associated with climatic warming and glacier retreat) in the region (Chen et al., 2021; Groisman et al., 2018; Ranasinghe et al., 2021; Seneviratne et al., 2021). Central Asia is an economically developing region including both middle- and low-income countries (Table 1). Its water resources are transboundary and the institutions, regulating both national and international use of water, are not well established (Zhiltsov et al., 2020). The socio-economic, political, and environmental aspects of regional development are strongly linked to the state of its environment and successful adaptation to climate change is of utmost importance given that the region is a hotspot of future climate change and associated risks (Adler et al., 2022).

Changes, observed in the mountains, make a significant impact on both mountain and downstream ecosystems, communities and different socio-economic sectors such as water provision, agriculture, recreation, tourism, and many others (Adler et al., 2019; Huss et al., 2017; IPCC, 2018; Shahgedanova et al., 2021; Vakulchuk et al., 2022). Central Asia is no exception. The region has an arid and semi-arid continental climate (Shahgedanova, 2002) and almost all water is supplied by the mountain snowpack and melting glaciers which provide the key ecosystem services to the densely populated foothills and oases (Figure 1) where arable agriculture will not be viable without irrigation. Kaser et al. (2010) estimated that Central Asia depends on glacial melt for water provision more than any other part of the world. In the 21st Century, water availability will be the key issue for the developing economy of the region (Immerzeel et al., 2020; Karthe et al., 2015). In Central Asia, peak flow is expected to pass by the 2050s (Huss & Hock, 2018; Shahgedanova et al., 2020) putting water provision at risk. At present, runoff is increasing in the high-elevation headwater catchments, which are not affected by water abstraction (Shahgedanova et al., 2018). Increased runoff leads to higher frequency of natural hazards related to glacier retreat, such as an increase in volume and abundance of glacial lakes (Kapitsa et al., 2017), increasing potential for the formation of glacier outburst floods (GLOF), debris flow and landslides (Mamadjanova et al., 2018).

Strong climate change adaptation (CCA) action is required to increase resilience of the local population and avoid competition for and conflicts over the scarce resources in the transboundary catchments. According to IPCC (2022),

TABLE 1 Selected demographic and economic indicators for the CA countries.

Variable	KZ	KG	TJ	TM	UZ
Area, km^2	2.7×10^6	199×10^3	144×10^3	488×10^3	447×10^3
Population in 2020 (10^6)	18.8	6.5	9.5	6.0	33.5
Population density (number of people per km^2, 2018)	6.8	32.9	65.6	12.5	77.5
Population growth rate, (% of total population, 2020)	0.89	0.96	1.52	1.06	0.88
Urban population, (% of total population, 2020)	57.7	36.9	27.5	52.5	50.4
Rate of urbanization (% annual rate of change, 2015–2020)	1.29	2.03	2.62	2.46	1.28
GDP per capita (USD, 2017)	26,700	3700	3200	18,200	6900
GDP growth (%, 2017)	4.0	4.6	7.1	6.5	5.3
GDP—composition, by sector of origin (%, 2017)	Total				
Agriculture	4.7	14.6	28.6	7.4	17.9
Industry	34.1	31.2	25.5	44.9	33.7
Services	61.2	54.2	45.9	47.7	48.5
Human Development Index[a] value, 2018	0.817	0.674	0.656	0.710	0.710
Human Development Rank, 2018	51	122	126	106	106
Population below poverty line, (%, 2016)	2.6	32.1	31.5	0.2	14.0
Employment in (% of total population, 2017)					
Agriculture	18.1	48.0	43.0	48.2	25.9
Industry	20.4	12.5	10.6	14.0	13.2
Services	61.6	39.5	46.4	37.8	60.9
Agricultural land, (% of total land area, 2016)	80.4	55.0	34.1	72.0	62.9
Degraded land, (% of total land area, 2015)	36	24	97	22	29
Irrigated land, (km^2, 2012)	20,660	10,233	7420	19,950	42,150
Access to drinking water sources (% of total population, 2015)					
Improved[b]					
Urban	99.4	96.7	93.1	89.1	98.5
Rural	85.6	86.2	66.7	53.7	80.9
Total	92.9	90.0	73.8	71.1	87.3
Unimproved[c]					
Urban	0.6	3.3	6.9	10.9	1.5
Rural	14.4	13.8	33.3	46.3	19.1
Total	7.1	10.0	26.2	28.9	12.7

[a]Human Development Index (HDI): A composite index measuring average achievement in three basic dimensions of human development—a long and healthy life, knowledge and a decent standard of living (United Nations Development Programme, 2019).
[b]Improved drinking water—use of any of the following sources: piped water into dwelling, yard, or plot; public tap or standpipe; tube well or borehole; protected dug well; protected spring; or rainwater collection.
[c]Unimproved drinking water—use of any of the following sources: unprotected dug well; unprotected spring; cart with small tank or drum; tanker truck; surface water, which includes rivers, dams, lakes, ponds, streams, canals or irrigation channels; or bottled water.
Source: United Nations Development Programme (2019); The World Factbook (2020); Worldometer (2023).

CCA is not only a process of adjustment of environmental and human systems to the negative impacts of the observed and future climate conditions but it is also the ability to use the emerging opportunities. Furthermore, increasing threats posed by the intensifying and cascading risks demand more of transformative rather than incremental adaptation actions (Terzi et al., 2019). IPCC (2014) defines incremental actions as actions that expand or alter existing practices using small steps from a status quo which might be sufficient to reduce impacts. By contrast, transformative actions foster deep structural and socio-economic changes that challenge the status quo and are linked to mitigation (IPCC, 2014; Pelling et al., 2014). Transformative interventions are often implemented on a large scale to reduce

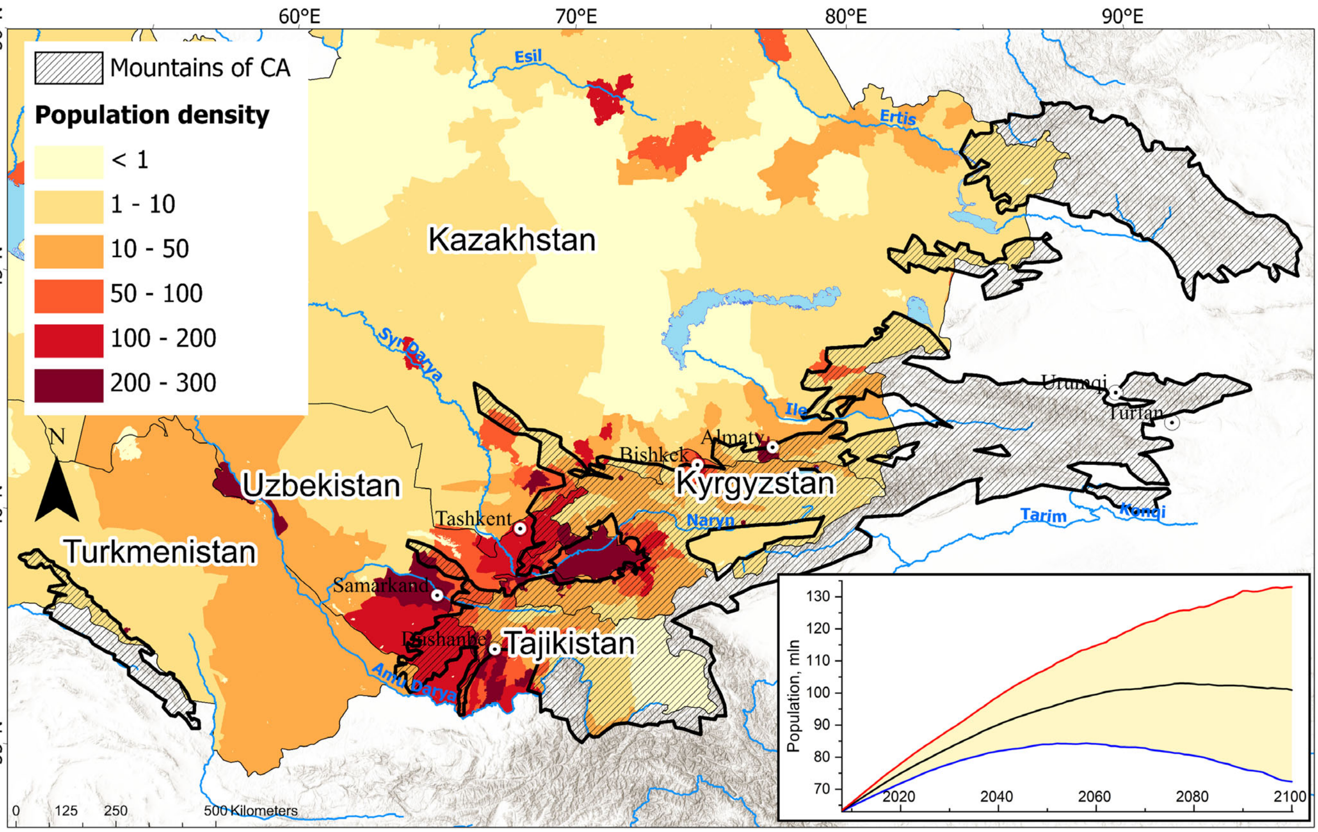

FIGURE 1 Outlines of the Central Asia mountains (Körner et al., 2017) and population density as in 2020 (number of people per km^2; spatial resolution 1 km) (GPW, 2018). The inset figure shows future scenario of population growth in the region (red and blue lines denote 10th and 90th percentiles of confidence interval, respectively; black is mean value) (Lutz et al., 2008).

stronger impacts of climate change. Transformative adaptations have a longer timeframe, a higher price and usually are not supported by existing local institutions (Adler et al., 2022). Transformative adaptation is needed when adaptation limits might be encountered. In mountain regions globally, compound multiple stresses require integrative, informed, and inclusive governance approaches including smart policy mixes; multiscale and transdisciplinary approaches (Díaz et al., 2019; Fedele et al., 2019; McDowell et al., 2021). More specifically, innovative governance solutions are needed in montane Central Asia, which experiences multiple stressors and risks and where environmental, socio-economic, and political problems are closely intertwined at international, national, and regional levels. Therefore, stocktaking of CCA is needed to understand the potential of transformative adaptations of current and planned actions that reduce or close adaptation gaps in the Central Asia mountains (McDowell et al., 2019, 2021).

However, currently, knowledge of any CCA actions in the mountains and mountain-dependent downstream regions of Central Asia is limited in comparison with other mountainous regions of the world (Berrang-Ford et al., 2015; Huggel et al., 2015; McDowell et al., 2019; Payne et al., 2020; Vij et al., 2021). Rasul et al. (2020) discussed adaptation practices related to changes in the mountain cryosphere comparing very limited information about Central Asia with the much more widespread research in the European Alps, Himalayas, and the Andes citing only two publications related to adaptation to water stress and two publications about adapting to the cryosphere-induced hazards. Liu, Liu, and Gao (2020) and Liu, Wang, et al. (2020) reviewed the literature on CCA, published between 1990 and 2019, using the Web of Science Core Collection concluding that while the "gray literature" is available (e.g., eight reports from the World Bank, United Nations Environmental Programme (UNEP), United Nations Development Programme (UNDP), and Central Asia Regional Economic Cooperation (CAREC)), the peer-reviewed literature was very limited and focused on the lowlands. Yapiyev et al. (2017) discussed CCA and mitigation activities as part of the review of endorheic basins and lakes of Central Asia. They identified some international initiatives and pilot projects which are already underway in the region, which usually are disconnected from each other, and intersectoral synergies are lacking. Neither of these publications distinguished between the incremental and transformative adaptation actions in Central Asia.

The aim of this study is to provide a better understanding of the current knowledge of CCA in the mountains of Central Asia using a systematic review methodology of McDowell et al. (2014). The systematic review allows combining, synthesizing and critical assessment of published literature, tracking changes in knowledge over time. The paper aims to compile and analyze the information about the existing CCA projects and related publications in the mountain regions of Central Asia and to identify gaps in adaptation efforts by conducting a systematic assessment of the peer-reviewed literature published in English and Russian languages between 2013 and May 2021. The starting year was identified according to IPCC AR6 because information from the previous years was combined in IPCC AR5. Russian remains the most widely spoken language in Central Asia and is used in academic publications throughout the region as well as by authors across the former Soviet Union (FSU) writing about Central Asia.

The specific objectives of this paper are fourfold (i) to identify the CCA actions taking place across the mountains of Central Asia (see Supplement: Definitions of the keywords); (ii) to establish which impacts of climate change and environmental sectors are prioritized in CCA, (iii) to identify the main actors involved in CCA, and (iv) to synthesize the obtained information to identify gaps in knowledge and suggest directions for future research.

2 | STUDY REGION

In the context of this study, we define Central Asia as five post-Soviet countries (Van den Bosch et al., 2021)—Kazakhstan (KZ), Kyrgyzstan (KG), Tajikistan (TJ), Turkmenistan (TM), and Uzbekistan (UZ)—with a total population of approximately 74.3 million (Table 1). Adaptation extends beyond geographical boundaries and national borders; however, it is rooted in the socio-economic and cultural characteristics. Being a part of the post-Soviet space, the selected countries share these characteristics while other countries bordering the region do not. In particular, Afghanistan and north-western China are geographically a part of Central Asia and their environmental and water management policies affect the region (Britannica, 2024). Examples include the ongoing construction of the Qosh Tepa Canal in Afghanistan designed to divert water from the Amu Darya (Kamil, 2021; Shih, 2023) and construction of multiple reservoirs in the upper reaches of the Ile River in China (Thevs, Nurtazin, et al., 2017; Zhupankhan et al., 2017). Both are the main transboundary rivers in Central Asia. However, Afghanistan and China evolved within different historical, cultural, and socio-economic contexts and, therefore, their responses to adaptation are different. It is for this reason that both countries have been excluded from this assessment despite its overall importance for the region.

Despite the recent deceleration of population growth, the overall population of Central Asia is expected to increase in the 21st Century by more than 100% under the most aggressive population change scenario (Figure 1; Lutz et al., 2008). Currently, the highest population growth is observed in TJ, which is one of the poorest countries of the region (Table 1). There is already pressure on arable land and water resources across most of the region (Aleksandrova et al., 2014; Viviroli et al., 2020) and especially in UZ and TJ where population density is high in the foothills and in mountain and river valleys (Table 1, Figure 1).

National income varies between countries (Table 1). Using the Organization for Economic Co-operation and Development (OECD) definition, KZ is an upper middle income country, KG and UZ are in the lower middle income category, and TJ is in the low income category (The World Bank, 2023). The relatively high GDP in TM, which places it in the upper-middle income group of countries, results from the profits from export of natural resources (primarily, natural gas) and does not reflect real income of the country's population. An important socio-economic characteristic of the region is the prominence of climate-dependent sectors with high requirements for water use in subsistence agriculture in the lower-income countries. The shares of agricultural sector in national GDP vary from 4.7% in KZ to 28.6% in TJ and on average, the sector employs around 35% of the labor force in the region (Table 1). Impacts of climate change, in combination with a lack of agrometeorological support, poor state of the irrigation systems, and inefficient water management compromise water and food security in Central Asia, especially if the contribution of the mountain cryosphere to water balance declines significantly, as expected (Barrett et al., 2017; Hoelzle et al., 2019; Yapiyev et al., 2021).

2.1 | Evidence of climate change in the region

In Central Asia, climate has been warming more rapidly than on average over the globe since the 1950s (IPCC, 2013, 2014). The biggest changes in temperature are observed in winter in the northern part of the region and in the mountains. Hu et al. (2014) showed that regional annual mean surface air temperature increased by 0.36–0.42°C per decade from 1979 to 2011 in Central Asia. The increasing trends are more significant in the cold period of the year—autumn and winter (Unger-Shayesteh et al., 2013). Studies of the future climate change are not numerous in Central Asia, but several studies have analyzed projections from the regional climate models on the scale of the whole region and for more specific areas (Vakulchuk et al., 2022). For example, Schiemann et al. (2008), Mannig et al. (2013), Shahgedanova et al. (2020), and Ozturk et al. (2017) provided regional assessments, using Regional Climate Model (RCM) experiments and showing that temperatures will increase across the region. The most aggressive scenarios (e.g., RCP 8.5) show a strong warming across all seasons with temperature increase reaching 7–8°C in 2100 in comparison with the pre-industrial period (Hayhoe et al., 2017; Mannig et al., 2013; Shahgedanova et al., 2020). The less aggressive scenarios project temperature increase over 4°C for the northern part of the region and 2–3°C for Central Asia as a whole (Huang et al., 2014; Jiang et al., 2020; Mannig et al., 2013).

While all models agree that regional climate will become warmer in the future, there is low confidence about changes in the observed and projected changes in precipitation (Jiang et al., 2020; Reyer et al., 2017; Yu et al., 2018). Uncertainties in the assessments of changes in solid precipitation (forming the mountain snowpack) are particularly high because of the relatively sparse observational networks and time-dependent systematic biases in precipitation records (Groisman et al., 2018). Analysis of the long-term precipitation records, starting before the 1970s (which was a very dry period) showed that there is no significant long-term trend in precipitation in the Tien Shan while decadal variability is strong (Shahgedanova et al., 2018). Future projections vary substantially between regions (most notably north and south of Central Asia) and seasons (Duethmann et al., 2013; Ozturk et al., 2017; Schiemann et al., 2008) (*low confidence*). The multi-model CMIP5 (Coupled Model Intercomparison Project) (Huang et al., 2014) and CMIP6 (Jiang et al., 2020) projections suggest that precipitation *likely* to increase in winter and spring, and decrease in summer across the region. However, high uncertainty between CMIP5 and CMIP6 as well as spatial heterogeneity lend to *low agreement* between the future projections. There is a strong variability between models (*low confidence*) (including not only rate but also signs of trends) in the CMIP5 ensemble (Huang et al., 2014). Overall, CMIP5 projects the strongest rate of increase in annual precipitation (over 3 mm per decade under RCP2.6 and over 6 mm per decade under RCP4.5 and RCP8.5) in the northern part of Central Asia. The results from CMIP6 project are more consistent between models (*higher confidence* relative to CMIP5) (Ranasinghe et al., 2021). CMIP6 projects *likely to* increase in annual precipitation under all scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5) from 4 [2–7]% to 14 [9–21]% by the end of the 21st Century (Jiang et al., 2020). The changes in seasonal precipitation are not homogenous with a wetting trend projected for winter and spring and drying trend for summer. The largest increase in annual mean precipitation is projected by CMIP6 models for the mountains (Jiang et al., 2020).

The mountains of Central Asia are the regional water towers: runoff generated by melting seasonal snowpack and glaciers sustains regional water resources. Hydrographs in natural catchments are characterized by a strong seasonal peak in late spring and summer. In the main river basins—the Amu Darya and Syr Darya—the combined contribution of snow and glacier meltwater accounts for approximately 70% and 80% of annual runoff, respectively. Snow melt accounts for 89% and 65% of the total melt component (Djumaboev et al., 2019). The sub-surface ice also contributes to runoff. Although seasonal snow is the main contributor to runoff in Central Asia and snow cover duration and snow water equivalent (SWE) are important controls over the warm season stream, there are few reliable assessments of changes in snow pack characteristics, and especially SWE, over time (Kraaijenbrink et al., 2021). On average, in the 1986–2008 period, snow cover lasted for 0–30 days on the plains and for more than 240 days above 3000 m a.s.l. with longer duration on the plains of Kazakhstan, in northern, central and eastern Tien Shan (Zhou et al., 2017). The significant change in the duration of snow season timing with shifts toward the earlier onset of snow was identified using MODIS products for 2002–2015 affecting herder livelihoods in Kyrgyzstan (Tomaszewska & Henebry, 2018).

Mean annual glacial mass balance has been negative ranging from −0.3 to −0.8 mm w.e.a^{-1} in the 21 Century (Brun et al., 2017; Gardner et al., 2013) and since the 1960s–1970s (Farinotti et al., 2015; Kapitsa et al., 2020; Pieczonka et al., 2013). Glacier retreat is observed throughout the Tien Shan with the highest area loss rates of 1% a^{-1} in the outer ranges (Hoelzle et al., 2019; Kutuzov & Shahgedanova, 2009; Narama et al., 2010; Severskiy et al., 2016; Sorg et al., 2012; Unger-Shayesteh et al., 2013). Glaciers in the western and central Pamir exhibited lower mass losses (Brun et al., 2017). In all these regions, glacier wastage is projected to continue (Hock et al., 2019). In the eastern Pamir, balanced and slightly positive budgets were observed (Bolch, Rohrbach, et al., 2019; Bolch, Shea, et al., 2019; Brun et al., 2017; Holzer et al., 2015) suggesting that precipitation increases at high-elevations in this region (Hoelzle et al., 2019).

Sporadic permafrost occurs in the Tien Shan between 2600 m a.s.l. and 3200 m a.s.l. and above 3300 m a.s.l. in the Pamir (Tajikistan) although there is less information about its type and distribution (Hoelzle et al., 2019). Gorbunov et al. (1996) estimated that the total volume of ground ice in the Northern Tien Shan was 62% of the surface ice volume.

An increase in permafrost temperature and depth of the active layer has been reported (Marchenko et al., 2007). Rock glaciers are widespread in region but there is no information about their contribution to streamflow (Bolch, Rohrbach, et al., 2019; Bolch, Shea, et al., 2019; Jones et al., 2019).

At present, high air temperatures and low precipitation, observed in summer, do not imply a lack of water in the natural catchments because of the meltwater contribution which is responsible for a strong peak in annual hydrographs in the warm season (Huss et al., 2017; Shahgedanova et al., 2018). However, higher summer flows are not always observed in the lower reaches because almost all rivers of Central Asia are affected by water abstraction for irrigation and are regulated by dams and reservoirs (Grill et al., 2019; Immerzeel et al., 2012). Trends in annual and summer runoff, observed over the last 50–60 years in natural headwater catchments are insignificant and inconsistent (Hoelzle et al., 2019). Analyses of shorter (30–40 year) records show that annual and summer runoff has not declined in the natural catchments but has increased in catchments with higher glacierization, and extent of permafrost and rock glaciers (Duethmann et al., 2015; Krysanova et al., 2015; Kundzewicz et al., 2015; Shahgedanova et al., 2018). The projected reduction in glacier and ground ice volume are likely to result in changes in magnitude and seasonal cycle of runoff (Huss et al., 2017; Shahgedanova et al., 2020) although these changes will strongly depend on the future SWE which is hard to predict given a strong uncertainty in projections of precipitation. Permafrost responds more slowly to climate change than glaciers and its contribution is likely to lag that of the glacier ice (Hoelzle et al., 2019).

The projections of runoff, which explicitly incorporate glacier change scenarios driven by various emission scenario—climate model combinations, are spatially heterogeneous. Reductions in runoff, with a shorter duration of summer peak flow and lower flow are projected to occur by 2050 in the autumn for the Amu Darya and Sur Darya catchments (Immerzeel et al., 2012). In smaller (<600 km^2) natural catchments in the Balkhash-Alakol basin, summer discharge is projected to decline (not change significantly) in basins with lower (higher) glacierization but earlier freshets are predicted (Shahgedanova et al., 2020).

The continuing temperature increase, strong variability in precipitation, changes in land cover and land use (Groisman et al., 2018) will accelerate the deglaciation of the mountains and aridization of the plains and increase exposure of population and ecosystems in the transboundary, densely populated, and otherwise water-deficient catchments.

3 | METHODOLOGY

3.1 | Systematic review approach

The main definitions and keywords used in the literature search are presented in the Supplement. The extent of the considered area is shown as the outlines of the Central Asia mountains in Figure 1. The study area was restricted to the national borders of five Central Asia counties and the natural mountains borders which were extracted from the Global Mountain Biodiversity Assessment (GMBA) Mountain Inventory (Körner et al., 2017). The full list of the considered mountain ranges is presented Table S1.

A systematic review was conducted using the approach based on the Reporting Standards for Systematic Evidence Syntheses (ROSES) in environmental research protocol (Haddaway et al., 2018). This approach is designed to implement a formal, transparent, and standardized analysis of academic literature. Figure 2 shows the sequence of the implementation of the systematic review. Two largest databases of scientific literature were used to select publications in English: Scopus and the Web of Science (WoS). The largest databases of academic literature published in Russian—Scientific Electronic Library (Elibrary)—was used to identify the relevant articles.

The methodology for screening papers used the following criteria (Table S4): (i) peer-reviewed journal articles and book chapters written in English and Russian; (ii) publication between 2013 and May 2021; (iii) explicit focus on CCA in the mountains of Central Asia and foothills where the mountains play a key role in a considered issue; (iv) explanation of adaptation options in an assessed publication; (v) a clear methodology for deriving suitable adaptation options proposed in the publication. The review considered only those papers which reported original research and provided clear evidence of explicit adaptation responses, that is, responses that have been or are in the process of being implemented or are planned. The relevant review papers were examined and used as additional sources of bibliography but were not included in the analysis. To make the selection of publications unbiased, we followed the approach described in papers underwent multiple rounds of reviews and discussion among the authors until agreement was reached for their inclusion or exclusion (Berrang-Ford et al., 2015, 2021; McDowell et al., 2014, 2021).

Based on the main aim and specific objectives of this study, the following research queries were developed to identify relevant articles. Keywords such as "adaptation," "resilience," "mountain", and "climate change," "name of

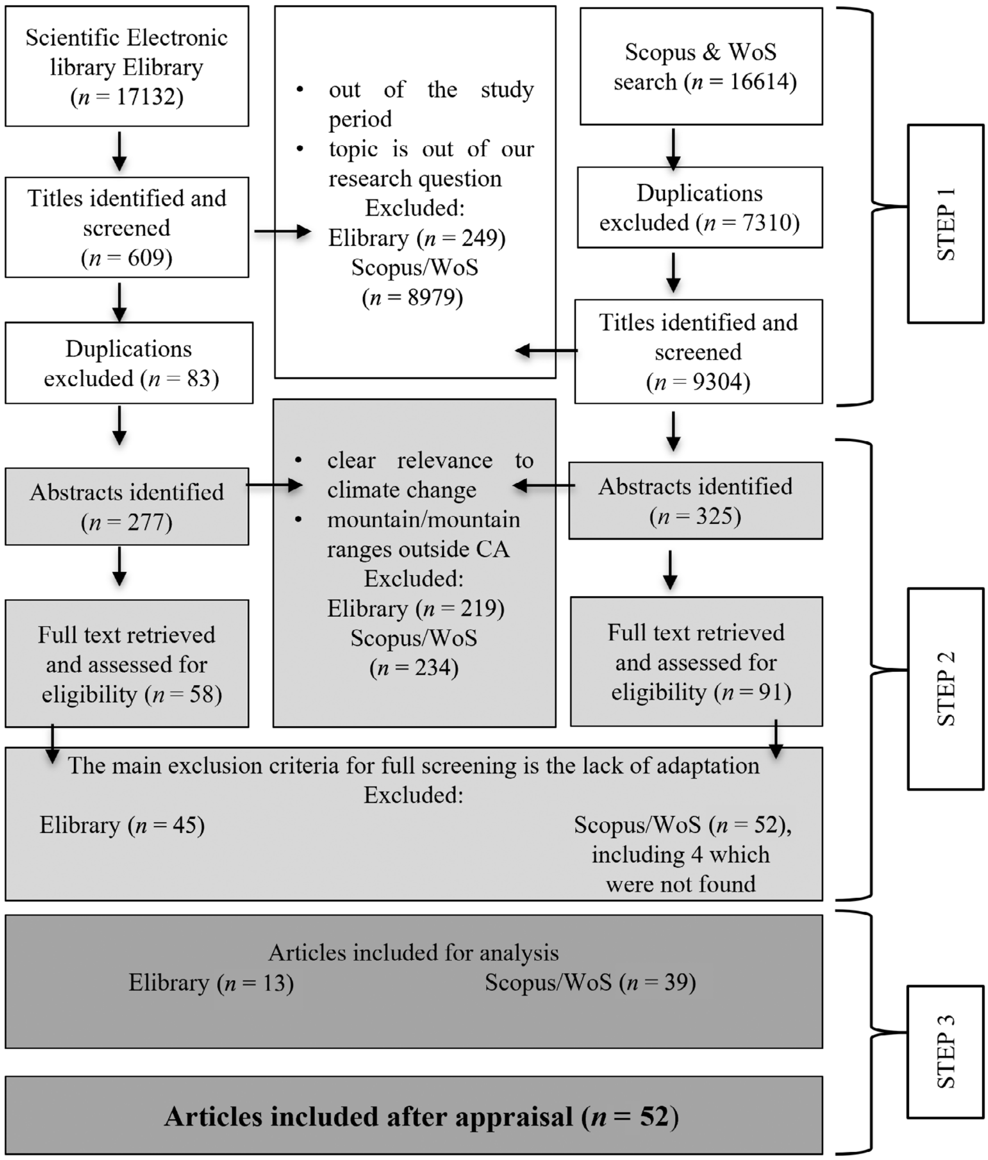

FIGURE 2 Selection procedure for identifying articles following the ROSES protocol where *n* is number of publications. Adapted from Vij et al. (2021).

mountain" and "name of country/countries", "Central Asia" where mountains are geographically located were used to develop the search queries (Table S2). Various combinations of search queries were used in the selected search databases to maximize the capture of relevant literature. Importantly, all queries were applied to full body of article including title, abstract, full text, and references preventing us from missing publications related to the region and the topic. Moreover, mountain ranges often have several names in both English and Russian languages and their transliteration and use varies (e.g., Zailiiskiy Alatau and Ile Alatau). In addition, several regions were renamed recently to reflect national heritage (e.g., Dzhungarskiy (or Jungar) Alatau is currently referred to as Jetisu Alatau). In total, 100 search queries were applied (Table S3).

The search was implemented on 17 May 2021 (Scopus/WoS, $n = 16{,}614$, Elibrary $n = 17{,}132$), and after removing duplicates (Step 1 "Data collection," Figure 2), 9304 (Scopus/WoS) and 516 (Elibrary) articles were used in Step 2 "Screening of publications" (Figure 2). At the second step, titles and keywords were screened according to their relevance and a decision was made about the selection of articles for the next stage of assessment. Abstract screening was performed on 325 (Scopus/WoS) and 277 (Elibrary) articles. After reading the abstracts, 91 (Scopus/WoS) and 58 (Elibrary) articles were included in the full-text screening. The complete texts of the selected articles were checked for compliance with the inclusion criteria (Table S4). Following the examination of the full texts, 52 (Scopus/WoS) and 45 (Elibrary) articles were excluded because they did not match the inclusion criteria (full text of four of these articles were not found). The most frequent reasons for the exclusion were a lack of discussion of adaptation actions and absence of clarity about CCA methodology. Most of the excluded articles mentioned the importance of adaptation or suggested that the outcomes of the study can be used to develop adaptation strategies but stopped short of proposing methodologies for adaptation. The papers that referred indirectly to adaptation (e.g., preparedness, risk management, resilience building, mitigation etc.) were not included for the next step of review. An example is a paper by Kapitsa et al. (2017) discussing the use of GLacier Bed TOPography version 2 (GlabTop2) model to predict the formation of glacial lakes. The paper shows that the model is a useful risk management and adaptation tool, but it does not outline any CCA actions and methodology. The articles focused on CCA in the lowlands of Central Asia were excluded too, unless they discuss the issues related to the mountains, for example, water availability or hazards originating in the mountains. However, the papers where the notion of adaptation was ambiguous, or the paper used analogous terminology were included based on several rounds of consultations and discussions between co-authors.

The critical view step (Step 3, "Critical assess and final analysis" Figure 2) included the screening of all included papers by the authors in the context of the inclusion criteria to make consolidated decisions about selecting papers for final analysis. The third step involved processing data on and analysis of the selected publications ($n = 52$). Data processing consisted of (i) recording metadata such as author(s) name(s), year of publication, journal title, abstract, key words, name of the mountain range/basin/region, and country, and (ii) coding the articles. The articles were coded according to the following categories (Table S5): (i) study area (country); (ii) climate change impact; (iii) environmental sectors; (iv) type of adaptation measure, i.e., incremental or transformative; (v) who adapts. A short description of adaptation actions was included for the subsequent analysis (Table S6).

Two types of adaptation—transformative and incremental—were recognized (See Supplement: Definitions of the keywords). Table 2 summarizes criteria applied to determine the type of adaptation. At least one criterion should be satisfied to attribute the action to transformative adaptation.

4 | RESULTS

4.1 | Scoping results of the peer-reviewed literature: A limited representation of adaptation actions in the region

Following the final approval, 39 (Scopus and WoS) and 13 (Elibrary) publications were analyzed. The structure of the peer-reviewed articles published in English differs from publications in Russian as the latter do not always follow

TABLE 2 Criteria of transformative and incremental adaptations (Fedele et al., 2019; Filho et al., 2022).

N	Criterion	Transformative	Incremental
1	Innovative/Restructuring Is this adaptation new for the region?	Adaptation is implemented or proposed for implementation in the region for the first time (implementation in other part of the world is acceptable)	Adaptation is not new but is an improvement on existing measures.
2	Multiscale/Systemwide Does this adaptation involve large-scale changes?	Large territory, several regions, several countries	Small area, several experimental locations, limited community
3	Path-shifting/ Restructuring Does this adaptation have long- or short-term time of implementation?	Long-term	Short-term
4	Innovative Does it require a big investment?	Yes	No
5	Persistent/Systemwide Does the implementation of this adaptation change (or will change in the future) attributes of a system?	Results of the implementation of this adaptation change or will bring changes at different levels (local, country, region, global), system or part of system (policy, economy, law, socio, environment, etc.), condition of system	Results of the implementation maintain the essence and integrity of the existing technological, institutional, governance, and value systems

the traditional structure ("Introduction," "Study region," "Data and Methods," "Results," "Discussion," "Conclusion"). In particular, many papers, published in Russian, do not follow the standard structure: in some, section "Data and methods" is missing and most do not have "Discussion" section. The journals in English and Russian have different review and citation systems. Some analyses, implemented in this study, are applicable only to the English-language publications other only to those published in Russian. It is for these reasons that we provide separate preliminary analyses of the two groups of publications.

The total number of publications varied between years with lower activity after 2017 (Figure 3). In 42 articles, impacts of climate change were analyzed and followed by a discussion of the CCA actions. The remaining 11 publications focused strictly on adaptation to climate change impacts. Publications focused both on single and multiple impacts.

The main issues, related to climate change, were temperature increase ($n = 35$), degradation of glaciers ($n = 23$), changes in precipitation ($n = 13$), and increase of hazardous events ($n = 7$) (Figure 4a). Three publications (Scopus/WoS) focusing on hazardous events considered increasing awareness of the multi-hazard risks in the region (Lioubimtseva, 2015; Shodieva et al., 2014; Xenarios, Gafurov, et al., 2019; Xenarios, Schmidt-Vogt, et al., 2019). Only Gaisberger et al. (2020) considered specific hazards affecting biodiversity in the mountain areas such as threats of landslides and habitat fragmentation. Despite the strong evidence for increasing frequency of natural hazards and disasters resulting from the observed climatic warming and glacier retreat (Kapitsa et al., 2017; Kattel et al., 2020; Medeu et al., 2020; Petrakov et al., 2020; Piroton et al., 2020; Zheng et al., 2019), only seven of all selected articles mentioned impact of climate change on the increasing hazard potential and risks. Only three articles discussed adaptation actions against increasing hazard potential. These actions included creating early warning system against mudflow and floods (Zamai, 2014), hydraulic engineering activities (Fazilov & Fazilov, 2017), and scientific research (Yuldashev et al., 2015).

The distribution of the articles by the spatial scale of adaptation strategy are present in Figure 4b. The majority of articles are devoted to the transboundary issues ($n = 21$) related to water resources ($n = 15$). The main problem in the transboundary water use is relations between the upstream (Tajikistan, Kyrgyzstan) and downstream (Kazakhstan, Turkmenistan, Uzbekistan) countries. The main concerns of the upstream countries are generation of hydropower and operation of reservoirs while the downstream countries are concerned about irrigation (Jalilov et al., 2013; Zhupankhan et al., 2017). Tajikistan and Kyrgyzstan control about 80% of all surface water reserves in the region which enables them to influence activities in the downstream neighboring countries (Zhiltsov & Bimenova, 2015). Thus, water resources have become a source of existing and potential socio-political, national and transboundary conflicts (Jalilov et al., 2013; Kurtov, 2014; Menga, 2017). Other articles, considering issue of water resources, focused on individual countries: UZ

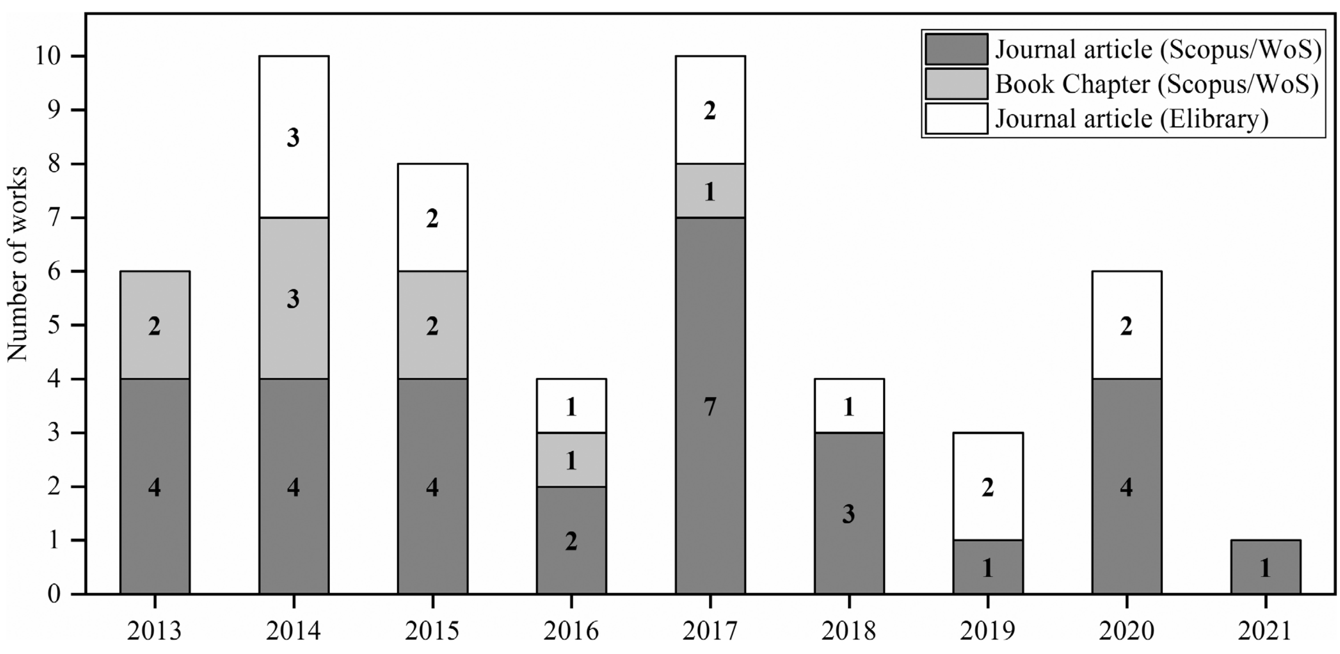

FIGURE 3 Number of publications within the assessment period by year.

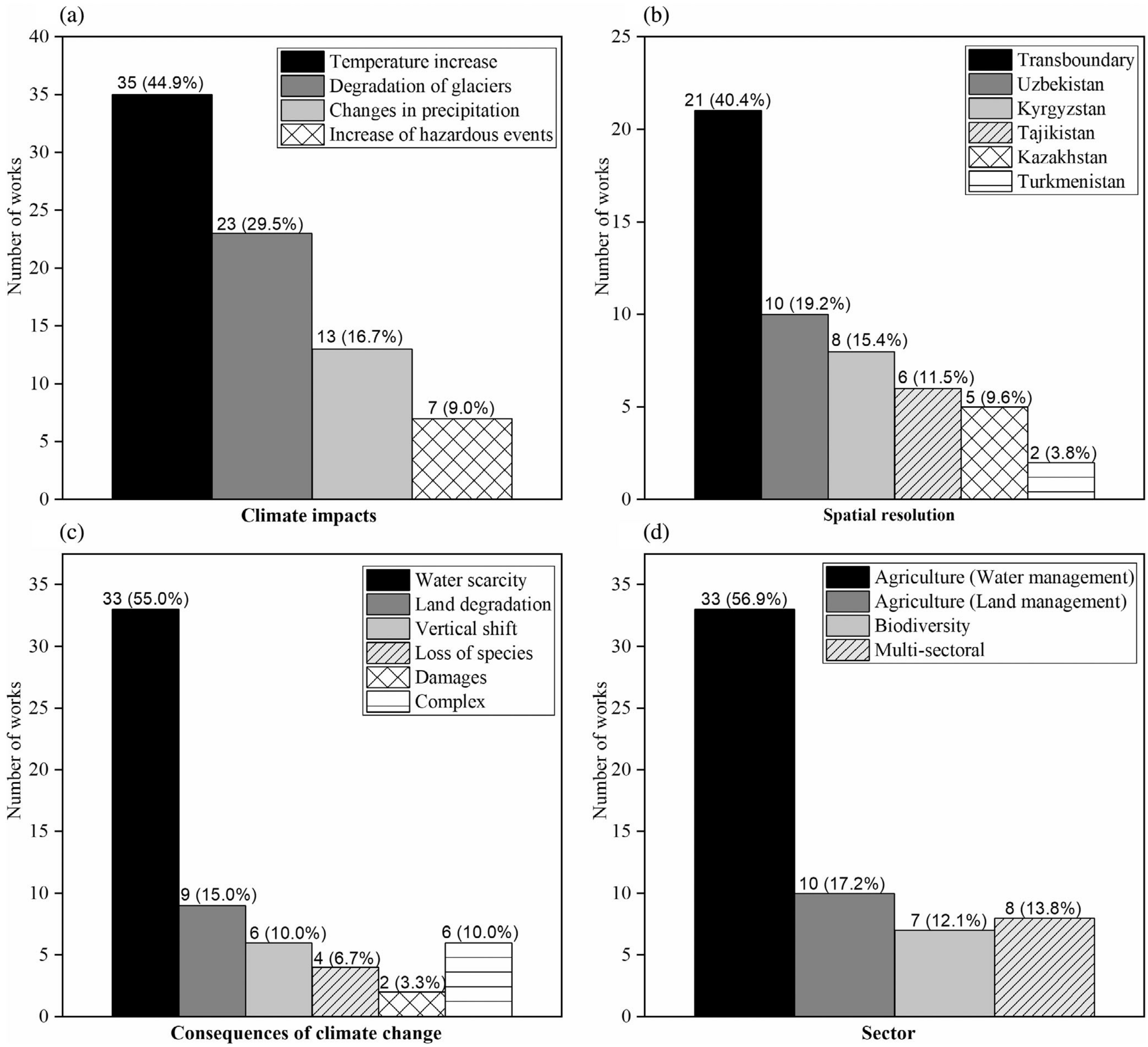

FIGURE 4 Number (percentage) of articles focusing on (a) impacts of climate change; (b) spatial scale of adaptation showing which country or countries (transboundary) were considered in the paper; (c) considered consequences of climate change; (d) sectors targeted by adaptation actions.

($n = 7$), KG ($n = 3$), TJ ($n = 4$), KZ ($n = 2$), and TM ($n = 2$). These articles considered various issues such as a lack of hydrometeorological observations (Klümper et al., 2017; Mukhamedjanov et al., 2021), unsustainable water use (Barrett et al., 2017; Bekchanov & Lamers, 2016; Brody et al., 2020; Kulov, 2020), and the absence of institutional distribution of water resources between the local users (Mosello, 2015; Mukhtarov et al., 2015). The key issue for Central Asia is future water availability (Hock et al., 2019; Xenarios et al., 2021) and this point was confirmed by the analysis of the selected publications: 33 articles focused on water resources (Figure 4c). Adaptation in the Aral Sea basin was addressed by three publications and another four focused on its main rivers, the Syr Darya and Amy Darya. Other publications focused on the CCA in various mountain regions of Central Asia.

Issues other than impacts of climate change on water availability and associated hazards were addressed in 27 publications including land degradation ($n = 9$), vertical shift of plant species ($n = 6$), loss of plant and animal species ($n = 4$), damages from hazard events ($n = 2$) and complex of consequences of climate change impact ($n = 6$). The selected articles focused on such sectors as water management ($n = 33$), land management ($n = 10$), and biodiversity ($n = 7$). In eight publications, adaptation in more than three sectors was addressed (multi-sectoral, $n = 8$) (Figure 4d).

Although there is a clear understanding that there is a pressing need to improve water resource management, most proposed and discussed actions directed toward the improvements in water management were incremental (41 publications) rather than transformative (11 publications). Table 3 presents examples of the transformative and incremental adaptation practices classified using the criteria summarized in Table 2. Here, transformative adaptations were related to measures that are either large-scale, in terms of the amount of time or fund consumption, change the attribute of a system, or were completely new for the region. Some transformative adaptations satisfied two or even all three criteria (Table 2). For example, rangeland restoration using seed isles (Christmann et al., 2015) is a new approach for Central Asia (Criterion 1), requires large-scale seeding (Criterion 2 and 3) and changes the system of grazing (Criterion 5). By contrast, improvement of existing irrigation system is an example of incremental adaptation (Sorg et al., 2013; Criteria 1 and 2) and harmonization of ongoing initiatives (Xenarios, Gafurov et al., 2019; Criteria 1, 4 and 5).

The discussed adaptation actions were implemented at different levels: International (by national governments in the transboundary river basins, $n = 12$), local authorities ($n = 11$), local users ($n = 20$), and academics ($n = 13$). Four publications combine the adaptations which require the efforts of both local scientists and governmental organizations.

4.2 | Representation of the region in international journals: Web of Science and Scopus databases

A relatively small number of the English-language publications (39 in total; 24 publications were in open access) were accepted for the final analysis, including nine book chapters and 30 peer-reviewed articles. The included articles were published in 23 interdisciplinary, social and environmental science journals with a large range of impact factor (IF) values. At the lower end, there were journal that did not yet have an IF such as *Ekonomicheskaya Politika* or had a very low IF, for example, *Asian Journal of Women's Studies* (IF 0.2). *Journal of Cleaner Production* had the highest IF of 7.2. The journals in which more than one article was published included *Water* (IF 2.5, $n = 3$), *Mountain Research and Development* (IF 1.5, $n = 3$), *Journal of Hydrology* (IF 5.7, $n = 2$), *Environmental Science and Policy* (IF 4.8, $n = 2$), *Regional Environmental Change* (IF 3.5, $n = 2$).

In total, 153 authors from various countries contributed to the selected peer-reviewed articles (Figure 5). Most authors (51) had the main affiliation with the Central Asia organizations leading eight publications. Authors with main affiliation with the European Union organizations and Switzerland (37 and 27, respectively) led 10 publications. There were 13 authors from the United States of America (USA) and Canada leading four publications. Authors from China and Australia led two publications each. Authors from the United Kingdom (UK), Azerbaijan, Morocco and Sri Lanka led one publication each.

4.3 | The main focus of the local scientific community: Elibrary database

Only 13 articles were included for the final analysis from the Elibrary database. The second step of the systematic review (Figure 2) showed that 65 articles focused on adaptation to anthropogenic impacts while a much smaller number 13 of publications focused on climate change (Figure 6). The focus of literature in Russian was human activity and its impact on the environment rather than climate change impact.

The most commonly discussed issues were those related to water management including transboundary conflicts of interests and inefficient local use of water resources (implementation and application of outdated or destroyed technologies, planting of crops with high water requirements) with higher prevalence of anthropogenic impact ($n = 35$) relative to climate change ($n = 5$). Biodiversity was the second most relevant topic discussed by 18 publications focusing on the effects of development in mountain areas, increasing livestock and overgrazing, poaching, and uncontrolled deforestation. Eight publications discussed land resources and adaptation to unsustainable grazing and overgrazing, failure to implement crop rotation, salinization of soils and the excessive use of fertilizers. Soil erosion attributed the impacts of climate change was consider in one paper (Yuldashev et al., 2015).

5 | DISCUSSION

Following the screening and subsequent analysis of the selected publications, complying with the specified selection criteria, 52 peer-reviewed articles were analyzed. This number is considerably lower than the publications concerned

TABLE 3 Transformative and incremental adaptation actions in different sectors identified in the selected literature.

Sector	Transformative ($n = 11$)	Incremental ($n = 41$)	References
Water resources	Reservoir development and operation or creating artificial dams and small reservoirs (development hydropower capacity)[1] Tree shelterbelts[2] International investment laws (updated legal framework for managing transboundary water resources)[3] Drip irrigation technology[4] The small-scale, self-organized irrigation governance system, applying the concept of “hydrosocial arrangements”[5]	Integrated approach to water management[6] Improvement of existing irrigation system[7] Introducing more water-efficient crops[8] Institutional changes[9] Economic incentives for local users[10] Investments to improve infrastructure[11] Cooperative water management[12] Market-based management, including water pricing or trading in water rights[13] The harmonization of ongoing initiatives[14] Comprehensive evaluation of irrigation water requirements[15]	[1]Jalilov et al., 2013; Veysov & Khamraev, 2019 [2]Thevs, Strenge, et al., 2017 [3]Boute 2017; Duan et al., 2019 [4]Brody et al., 2020 [5]Dörre & Goibnazarov, 2018 [6]Schlüter et al., 2013; Krutov et al., 2014; Zhupankhan et al., 2017 [7]Sorg et al., 2013 [8]Christmann & Aw-Hassan, 2015 [9]Tischbein et al., 2013; Mukhtarov et al. 2015; Mosello, 2015 [10]Tischbein et al., 2013 [11]Barrett et al., 2017 [12]Stucker & Lopez-Gunn, 2014 [13]Bekchanov & Lamers, 2016 [14]Xenarios, Gafurov et al., 2019 [15]Tian & Zhang, 2020
Land resources	Rangeland restoration using seed isles[1] Triple rotation[2]	Community-based pasture management[3]	[1]Christmann et al. 2014 [2]Ibragimov et al., 2020 [3]Zhumanova et al., 2016
Biodiversity		Effective transboundary landscape-level management of mountain biodiversity[1] Development of criteria for the effective transboundary conservation of terrestrial biodiversity[2] In situ conservation and assisted natural regeneration[3]	[1]Lim, 2013 [2]Lim, 2015 [3]Sultanova et al., 2012; Kasiyev, 2014; Gaisberger et al., 2020
Multi-sectoral	Create a network of small agrometeorological stations[1] Pilot model of an automated system of monitoring and early-warning system of catastrophic mudflows and floods[2]	Multi-scale approach to vulnerability assessment[3] Building capacity[4] Climate corridor analysis[5] Glacier monitoring[6]	[1]Mukhamedjanov et al., 2021 [2]Zamai, 2014 [3]Lioubimtseva, 2015 [4]Shodieva et al., 2014; Williams & Golovnev, 2015 [5]Kohler et al., 2016; Orlowsky et al., 2017 [6]Hoelzle et al., 2017; Nussbaumer et al., 2017

with adaptation in the European Alps, Hindu-Kush – Himalayas, and the Andes (Aggarwal et al., 2021; Payne et al., 2020). Moreover, the number of publications on adaptation in the Central Asia mountains has declined since 2013 (Figure 3). This trend persists despite a strong evidence of escalating impacts of climate change, increasing understanding of the vulnerability of the region to climate change and a growing number of publications on climate and

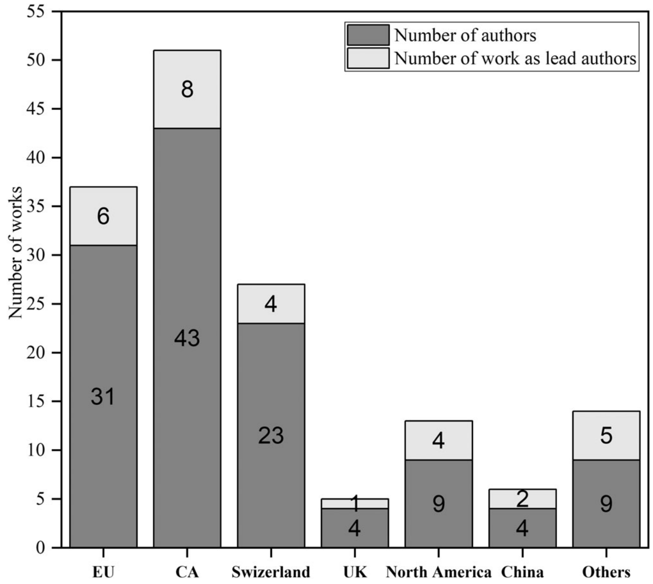

FIGURE 5 The authors' countries of affiliation: Scopus and WoS publications.

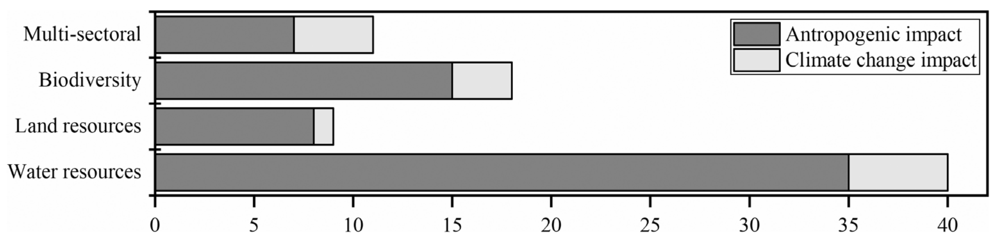

FIGURE 6 Number of publications considering CC and anthropogenic impacts.

environmental change itself (but not on adaptation plans or actions). Vakulchuk et al. (2022) found same tendency for the climate change papers which peaked in 2013 and declined since.

The research is largely focused on the problem of water resources, especially present and future water availability with 55% of the analyzed papers addressing these issues. This result reflects the dependence of the region on runoff from the mountains and the importance of impacts of climate change on mountain cryosphere (Duethmann et al., 2015; Huss & Hock, 2018; Shahgedanova et al., 2020; Xenarios et al., 2021) exacerbated by the aridity of regional climate (Verhagen & Rahman, 2023; Yapiyev et al., 2021). Except in northern and eastern Kazakhstan where large-scale arable agriculture is rain-fed, a very high proportion of agricultural production depends on irrigation sustained by mountain water (Table 1). Many studies focus on water supply (Hoelzle et al., 2019). However, water availability and quality strongly depend on water management especially in Central Asia because of the extensive water abstraction and creation of dams and reservoirs within the region (Church, 2017; Karthe et al., 2015; Yapiyev et al., 2021) and in the bordering states of Afghanistan and China (Kamil, 2021; Shih, 2023; Thevs, Nurtazin, et al., 2017; Zhupankhan et al., 2017).

Currently, natural flow exists only in proglacial headwater zones (Shahgedanova et al., 2018). Downstream, water management and land use including agricultural practices, animal husbandry, forestry, and mining activities (e.g., Allan et al., 2020; Ullah et al., 2019) make greater impact on water availability than changes in supply due to climate change (Yang et al., 2021). However, impacts of poor and unsustainable water management are sometimes wrongly attributed to climate change especially in the Russian-language literature while water governance, which is an important factor affecting water security provision (Assubayeva et al., 2022), is understated. A serious limitation is a lack of information about water supply (including streamflow statistics) and demand and building new monitoring networks is required to implement adaptation especially the transformative actions which often require different types of data with higher temporal and spatial resolution (Mukhamedjanov et al., 2021; Zamai, 2014). An important gap in adaptation of water resources research is that groundwater is under-researched (Gafurov et al., 2019). Many large cities in the region (e.g., Bishkek, Dushanbe, and Almaty) are situated on large aquifers in the piedmont areas and rely on groundwater for potable water supply (Liu, Liu, & Gao, 2020; Liu, Wang, et al., 2020; Morris et al., 2006; Xenarios, Gafurov, et al., 2019; Xenarios, Schmidt-Vogt, et al., 2019). Mountains "subsidize" these areas by recharging groundwater aquifers but this contribution has not been quantified (Jobbágy et al., 2011) thus limiting the sustainable use of groundwater as adaptation instrument (Xenarios, Gafurov, et al., 2019; Xenarios, Schmidt-Vogt, et al., 2019).

The implementation of adaptation strategies in the region occurred relatively recently, resulting in a delay in acting. This delay implies that over the last two decades, the region relied (and still does) on the Soviet heritage and only now does it try to improve the infrastructure and implement new options (Matiiuk et al., 2020; Sehring, 2020). For example, the aged, dilapidated irrigation systems, unproductive agricultural cultivars, and outdated early warning systems are used instead of applying new technologies and approaches (Barrett et al., 2017). Season forecast are not discussed in the academic literature as the method of adaptation in Central Asia, and neither are they delivered directly to farmer communities, although, this method is widely used elsewhere (e.g. Daron et al., 2021). The recently conducted interviews with farmers producing cereal crops in the foothills of the northern Tien Shan, Kazakhstan revealed that farmers do not have timely access to seasonal forecasts although they identified forecast availability as one of their main needs and tools of adaptation to climate change and variability (Salokhiddinov et al., 2020; Suleimenova et al., 2024). One of the new approaches is grassroots or citizen-driven projects for tackling problems for tackling problems with infrastructure, access to expertise and sharing knowledge. Social innovations may represent a way forward for CCA in mountains and beyond (OECD, 2021), thus, international donors are focusing on initiatives to strengthen civil society through collaborations with NGOs and grassroots movements.

Most articles (79%) considered incremental actions (Table 3) which include incremental adaptation measures aiming to improve practices that are already in place. Many of these projects are successful. For example, integrated approach to water management is a common worldwide action for sustainable use of water resources. However, the implementation of incremental adaptation measures does not always alleviate vulnerabilities in the most exposed areas. For example, the improvement of an existing irrigation system is not a reliable measure, and innovative measures should be applied to improve water use. However, as the obtained statistics shows, both research on and actions in transformative adaptation (including that to multiple risks) are lacking in Central Asia (Adler et al., 2022; Christmann et al., 2015; Thevs, Strenge, et al., 2017) due to costs, speed, and difficulties of implementation. We identified only five studies exploring transformative adaptation applying in water sector in the region (Table 3). Although we divided the adaptation into incremental and transformative following IPCC AR6 (2021), we recognize that incremental actions and tackling environmental, socio-economic, governance and technical issues in small steps can lead to the transformational reaction in the socio-economic and environmental field in line with Karl Popper's Piecemeal Social Engineering concept (Shearmur, 1996) applied in other countries of the Global South (e.g., Afisi, 2021; Ezeugwu, 2020).

5.1 | Adaptation strategies gaps in other sectors

There is a predominance toward CCA research in water resources and natural hazards, while adaptation in other sectors is under-represented. Such important issues as biodiversity received little attention, with only six publications. This issue is despite the fact that the mountains of Central Asia are a hotspot of biodiversity (Nowak et al., 2020) and shifts in plant distributions and threat of extinction of some plant species have been reported (Akhmedov et al., 2021; Iegorova et al., 2019; Kohli et al., 2021; Nowak et al., 2020). In contrast to the monitoring of glaciers which expanded recently (Hoelzle et al., 2017; Kapitsa et al., 2020), biota monitoring has declined and the region is not represented in the mountain biota monitoring networks (e.g., Grabherr et al., 2010). Overcoming this problem may be the first step toward development of adaptation studies in biodiversity.

Another important gap is adaptation of animal husbandry and agro-pastoralism to climate change. These sectors are an important part of the rural montane economy in all Central Asian countries but especially in Kyrgyzstan where over 80% of country's agricultural land consists of mountain pastures (Azarov et al., 2024; Kerven et al., 2011). Comprised predominantly by smallholdings with limited adaptive capacity, they face extensive pressures from climate change and rangeland degradation and biodiversity loss due to overgrazing (Azarov et al., 2024). Yet only one paper published within the assessment period disscussed adaptation of the agropastoral systems using the community-based pasture management as adaptation strategy for improvement of pasture condition and decreasing pasture degradation (Zhumanova et al., 2016).

As stated above, there are contrasting trends in the increase in number of publications for Central Asia (Xenarios et al., 2021) and declining number of publications on evidence of climate change and adaptation (Vakulchuk et al., 2022). Many studies of the scientific aspects of climate change and its impacts have been published in the highest-ranking journals, however, they stop short of developing adaptation strategies, programmes and actions and do not demonstrate a clear pathway between the generated knowledge to implementation. A lack of clear instructions on the implications of the results to regional and local stakeholders in adapting to climate change limits the usefulness of the scientific studies. For example, natural hazards and disasters such as GLOF, landslides and debris flows are common in the Central Asia mountains experiencing rapid deglaciation and are comparatively well-researched (Kapitsa et al., 2017; Kattel et al., 2020; Piroton et al., 2020; Mamadjanova et al., 2018; Medeu et al., 2020; Medeu et al., 2022). There are publications about other hazards related to temperature rise such as potential extension of areas affected by wildfires (Zong et al., 2020). These papers, however, do not clearly formulate CCA strategies and actions although the data they present are used in adaptation. The Kazakhstan State Agency for Mudflow Protection implemented knowledge on the expansion of glacial lakes, both observed and projected, provided by Kapitsa et al. (2017, 2023) in lake management aimed at preventing GLOF and issuing recommendations for planning and development in the mountains. These clearly are adaptation actions, but they are not explicitly addressed in publications which limits the awareness of stakeholders and implementation of knowledge in other regions.

This research, however, is a successful example of co-production and implementation of knowledge by scientists and practitioners. In other thematic areas and countries of Central Asia, there is a bigger gap in communication between scientists, governmental and community stakeholders, international development agencies, and other interested parties. This study found that while the work is not described as "adaptation" in publications, actions effectively representing climate change adaptation measures are discussed but are not explicitly connected with climate change and adaptation (Baimoldayev et al., 2018; Hamidov et al., 2015; Hill, 2013; Shigaeva et al., 2016). Implicitly discussing climate change but failing to assign the observed impacts to climate change and failure to understand and apply the concept of CCA is typical of the research culture in the region. Perhaps, this gap is due to the fact that climate adaptation and mitigation are relatively new concepts for Central Asia.

We suggest that developing interdisciplinary studies, connecting scientific findings with practical adaptation actions, is a priority for Central Asia. For example, while the water-energy-food (WEF) nexus approach is discussed globally including Central Asia (Abdullaev & Rakhmatullaev, 2016; Yapiyev et al., 2017), we have not identified any study related to the mountains of Central Asia. In theory, the WEF nexus approach to developing adaptation strategies is very relevant to the mountains with their capacity for hydropower generation and water supply. However, the application of the WEF nexus methodology to policy-making and development of adaptation strategies in competing sectors is very limited (Endo et al., 2020).

5.2 | Limited involvement of local academic community in CCA research

Although the Russian language is the language of communication and science in Central Asia, the systematic review of Elibrary shows a limited number of publications considering CCA. Language barriers and accessibility of publications remain limiting factors. The involvement of local academics and practitioners in international research on adaptation, published in English is limited (Figure 3) while publications in Russian are less accessible to the international community. Most assessed publications were led by international researchers except eight articles, four of which were led by the international experts affiliated with local organizations (Ashley et al., 2016; Christmann et al., 2015; Ibragimov et al., 2020; Mukhamedjanov et al., 2021; Shodieva et al., 2014; Thevs, Strenge, et al., 2017; Xenarios, Schmidt-Vogt et al., 2019; Zhupankhan et al., 2017). Moreover, while researchers are often familiar with the latest CCA approaches applied globally, they do not consider implementation of these approaches at national and regional levels (Sehring, 2020). We attribute this lack of involvement of regional scientists in research on and application of the contemporary approaches to CCA to two factors. Firstly, the Soviet legacy left behind a strong tradition of scientific training but neglected socio-economic knowledge required in adaptation research (Matiiuk et al., 2020). In Central Asia, there is a dominance of "hard" science and engineering approaches to solving the climate and water problems, while human dimension is often neglected or marginalized although it is clear that technologies alone are not sufficient to address pressing water resource issues in Central Asia and improvements in governance and management are required (Yapiyev et al., 2017). Secondly, following the collapse of the Soviet Union, many research institutes and national academies of science, which had established links with decision-makers and end users were closed or lost their status.

Research shifted to universities many of which at present do not prioritize collaboration with stakeholders. There are, however, some good examples of co-production of knowledge and emergence of the impact-oriented research. Research on hazards related to glacier retreat is conducted jointly by research organizations and risk-reduction agencies (e.g. Kapitsa et al., 2023) and those involved in agricultural research have close links with farmer communities. The newly-established universities aim to focus on the reduction of vulnerability of local population to climate change (e.g., Azarov et al., 2024). However, the practice of delivering knowledge to stakeholders and implementing it in adaptation should be expanded considerably to achieve effective CCA (Nabavi, 2022).

5.3 | Limitations of the study

A comprehensive systematic review of the peer-reviewed literature on CCA in the mountains of Central Asia published in English and Russian languages has revealed gaps in academic publications. This, however, does not imply that knowledge about adaptation is not being developed and shared. Adaptation, including concrete steps and measures, is often discussed in gray sources including reports from international, regional and local organizations, research briefs, and materials produced for stakeholders (Berrang-Ford et al., 2021; McDowell et al., 2019). These sources cannot be reviewed in a systematic way according. The exclusion of these sources is, therefore, a limitation of this study as well as other studies based on the methodology of a systematic review.

In Central Asia, a multitude of international agencies and initiatives play vital roles in sustainable development and adaptation to climate change including the World Bank, the Asian Development Bank (ADB), the United Nations Development Programme (UNDP), the Aga Khan Foundation, and regional development organizations such as the Central Asia Regional Economic Cooperation (CAREC) (Liu, Liu, & Gao, 2020; Liu, Wang, et al., 2020). These organizations collaborate with national and regional governments, local communities, and stakeholders to assess impacts of climate change, reduce vulnerability and foster resilience through the development of adaptation policies and practices. Their role is particularly important because practitioners and decision makes often do not engage with academic literature but focus on more practical recommendations instead. Their role is particularly important because practitioners and decision makes often do not engage with academic literature but focus on more practical recommendations instead. The practice of providing policy briefs resulting from the academic projects may also help to fill this gap (e.g. Feola et al., 2017).

6 | CONCLUSIONS

This systematic review assessed the peer-reviewed literature on CCA actions in the mountains of Central Asia using two international databases (WoS and Scopus) and the largest database of the Russian-language literature (Elibrary), for the time period between January 2013 and May 2021. The key finding was a lack of academic publications on adaptation strategies in comparison to other mountain regions despite the growing evidence of climate change impacts and the high vulnerability of Central Asia region. Although impacts of climate change were discussed in many publications, articles made very limited recommendations using the term "adaptation" to formulate prospects of further studies but did not present a clear pathway to CCA or explained how the obtained results can be used for adaptation. Most publications focused on water security and water use in agriculture while other problems were under-represented. There was a lack of publications on adaptation to hazards and disasters related to deglaciation despite a clear focus on the scientific aspects of these problems and their importance for the region and a surprising lack of publications on adaptation of mountain farming and agropastoralism to climate change despite its high importance for the region combined with high vulnerability.

We conclude that advocacy and awareness of CCA actions are required at different levels starting from the transboundary governance to local users. Capacity building among the regional community of academics and practitioners is required to improve their understanding of CCA and its implementation. It was highlighted that the local languages are not prioritized for scientific publications, and, importantly, local knowledge seldom makes its way to scientific publications. Involving local community in international projects would improve understanding of local practices, knowledge and culture. The region requires more expertise in CCA and there are ample opportunities for those who can improve CCA knowledge in subjects such as biodiversity, disaster mitigation, montane farming, and health.

AUTHOR CONTRIBUTIONS

Zarina Saidaliyeva: Formal analysis (lead); methodology (equal); supervision (lead); visualization (lead); writing – original draft (lead). **Veruska Muccione:** Methodology (equal); supervision (equal); writing – review and editing (lead). **Maria Shahgedanova:** Methodology (equal); supervision (equal); writing – review and editing (lead). **Sophie Bigler:** Methodology (supporting); writing – review and editing (supporting). **Carolina Adler:** Methodology (supporting); writing – review and editing (supporting). **Vadim Yapiyev:** Supervision (supporting); writing – review and editing (lead).

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data openly available in a public repository that issues datasets with DOIs.

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Adler, C., Balsiger, J., Huggel, C., Grêt-Regamey, A., Heinimann, A., Weingartner, R., Goss-Durant, G., Thornton, J. M., & Vance, G. (2024). Chapter 22 - Making connections for our changing mountains: The Mountain Research Initiative. In S. Schneiderbauer, P. F. Pisa, J. F. Shroder, & J. Szarzynski (Eds.), *Safeguarding mountain social-ecological systems* (pp. 149–154). Elsevier. https://doi.org/10.1016/B978-0-12-822095-5.00022-X

Kopp, R. E., Gilmore, E. A., Shwom, R. L., Adler, C., Adams, H., Oppenheimer, M., Patwardhan, A., Schmidt, D. N., & York, R. (2024). *"Tipping" points confuse and can distract from urgent climate action*. https://doi.org/10.22541/essoar.170542965.59092060/v1

Muccione, V., Haasnoot, M., Alexander, P., Bednar-Friedl, B., Biesbroek, R., Georgopoulou, E., Le Cozannet, G., & Schmidt, D. N. (2024). Adaptation pathways for effective responses to climate change risks. *Wiley Interdisciplinary Reviews: Climate Change, February*, 1–20. https://doi.org/10.1002/wcc.883

Shahgedanova, M., Afzal, M., Usmanova, Z., Kapitsa, V., Mayr, E., Hagg, W., Severskiy, I., & Zhumabayev, D. (2016). Impacts of climate change on river discharge in the northern Tien Shan: Results from long-term observations and modelling. In A. R. Medeu (Ed.), *Water resources of Central Asia and their use* (pp. 248–258). Institute of Geography.

Yapiyev, V., Sagintayev, Z., Verhoef, A., Kassymbekova, A., Baigaliyeva, M., Zhumabayev, D., Malgazhdar, D., Abudanash, D., Ongdas, N., & Jumassultanova, S. (2017). The changing water cycle: Burabay National Nature Park, Northern Kazakhstan. *Wiley Interdisciplinary Reviews: Water*, *4*(5), 1–14. https://doi.org/10.1002/wat2.1227

REFERENCES

Abdullaev, I., & Rakhmatullaev, S. (2016). Setting up the agenda for water reforms in Central Asia: Does the nexus approach help? *Environmental Earth Sciences*, *75*(10), 870. https://doi.org/10.1007/s12665-016-5409-8

Adler, C., Von Dach, S. W., Mathez-Stiefel, S. L., Zimmermann, A. B., Breu, T., & Molden, D. (2019). Focus issue: Adaptation to climate change and sustainable mountain development—Assessing approaches and understanding implications for the future. *Mountain Research and Development*, *39*(2), 1–3. https://doi.org/10.1659/mrd.3902

Adler, C., Wester, P., Bhatt, I., Huggel, C., Insarov, G., Morecroft, M., Muccione, V., Prakash, A., Alcántara-Ayala, I., Allen, S. K., Bader, M., Bigler, S., Camac, J., Chakraborty, R., Sanchez, A. C., Cuvi, N., Drenkhan, F., Hussain, A., Maharjan, A., … Werners, S. (2022). Cross-chapter paper 5: Mountains. In *Climate change 2022: Impacts, adaptation and vulnerability—working group II contribution to the sixth assessment report of the intergovernmental panel on climate change* (pp. 2273–2318). Cambridge University Press. https://doi.org/10.1017/9781009325844.022

Afisi, O. T. (2021). Karl Popper's social engineering: Piecemeal or 'many-pieces-at-once'? In *Karl popper and Africa: Knowledge, politics and development* (pp. 31–42). Springer International Publishing. https://doi.org/10.1007/978-3-030-74214-0_3

Aggarwal, A., Frey, H., McDowell, G., Drenkhan, F., Nüsser, M., Racoviteanu, A., & Hoelzle, M. (2021). Adaptation to climate change induced water stress in major glacierized mountain regions. *Climate and Development*, *14*(2), 1–13. https://doi.org/10.1080/17565529.2021.1971059

Akhmedov, A., Rog, I., Bachar, A., Shomurodov, H., Nasirov, M., & Klein, T. (2021). Higher risk for six endemic and endangered Lagochilus species in Central Asia under drying climate. *Perspectives in Plant Ecology, Evolution and Systematics*, *48*, 125586. https://doi.org/10.1016/j.ppees.2020.125586

Aleksandrova, M., Lamers, J. P. A., Martius, C., & Tischbein, B. (2014). Rural vulnerability to environmental change in the irrigated lowlands of Central Asia and options for policy-makers: A review. *Environmental Science and Policy*, *41*, 77–88. https://doi.org/10.1016/j.envsci.2014.03.001

Allan, R. P., Barlow, M., Byrne, M. P., Cherchi, A., Douville, H., Fowler, H. J., Gan, T. Y., Pendergrass, A. G., Rosenfeld, D., Swann, A. L. S., Wilcox, L. J., & Zolina, O. (2020). Advances in understanding large-scale responses of the water cycle to climate change. *Annals of the New York Academy of Sciences*, *1472*(1), 49–75. https://doi.org/10.1111/NYAS.14337

Ashley, L., Zhumanova, M., Isaeva, A., & Dear, C. (2016). Examining changes in local adaptive capacity resulting from climate change adaptation programming in rural Kyrgyzstan. *Climate and Development*, *8*(3), 281–287. https://doi.org/10.1080/17565529.2015.1034230

Assubayeva, A., Xenarios, S., Li, A., & Fazli, S. (2022). Assessing water security in Central Asia through a Delphi method and a clustering analysis. *Frontiers in Environmental Science*, *10*, 1–15. https://doi.org/10.3389/fenvs.2022.970633

Azarov, A., Sidle, R. C., Darr, D., Verner, V., & Polesny, Z. (2024). A proposed typology of farming systems for assessing sustainable livelihood development pathways in the Tien Shan Mountains of Kyrgyzstan. *Land*, *13*(2), 126. https://doi.org/10.3390/land13020126

Baimoldayev, T. A., Kassenov, M. K., Mussina, A. K., & Raimbekova, Z. T. (2018). Spatial-temporal analysis of the mudflow phenomena distribution and ways of preventing and reducing their destructive effects in mountainous and foothill areas of Kazakhstan (in Russian). *Debris Flows: Disasters, Risk, Forecast, Protection*, *1*, 262–270.

Barrett, T., Feola, G., Khusnitdinova, M., & Krylova, V. (2017). Adapting agricultural water use to climate change in a post-soviet context: Challenges and opportunities in Southeast Kazakhstan. *Human Ecology*, *45*(6), 747–762. https://doi.org/10.1007/s10745-017-9947-9

Bekchanov, M., & Lamers, J. P. A. (2016). Economic costs of reduced irrigation water availability in Uzbekistan (Central Asia). *Regional Environmental Change*, *16*(8), 2369–2387. https://doi.org/10.1007/s10113-016-0961-z

Berrang-Ford, L., Pearce, T., & Ford, J. D. (2015). Systematic review approaches for climate change adaptation research. *Regional Environmental Change*, *15*(5), 755–769. https://doi.org/10.1007/s10113-014-0708-7

Berrang-Ford, L., Siders, A. R., Lesnikowski, A., Fischer, A. P., Callaghan, M. W., Haddaway, N. R., Mach, K. J., Araos, M., Shah, M. A. R., Wannewitz, M., Doshi, D., Leiter, T., Matavel, C., Musah-Surugu, J. I., Wong-Parodi, G., Antwi-Agyei, P., Ajibade, I., Chauhan, N., Kakenmaster, W., … Abu, T. Z. (2021). A systematic global stocktake of evidence on human adaptation to climate change. *Nature Climate Change*, *11*(11), 989–1000. https://doi.org/10.1038/s41558-021-01170-y

Bolch, T., Rohrbach, N., Kutuzov, S., Robson, B. A., & Osmonov, A. (2019). Occurrence, evolution and ice content of ice-debris complexes in the Ak-Shiirak, Central Tien Shan revealed by geophysical and remotely-sensed investigations. *Earth Surface Processes and Landforms*, *44*(1), 129–143.

Bolch, T., Shea, J. M., Liu, S., Azam, F. M., Gao, Y., Gruber, S., Immerzeel, W. W., Anil Kulkarni, H. L., Tahir, A. A., Zhang, G., & Zhang, Y. (2019). Status and change of the cryosphere in the extended Hindu Kush Himalaya region. In *The Hindu Kush Himalaya Assessment* (pp. 211–245). Springer. https://doi.org/10.1007/978-3-319-92288-1_7

Boute, A. (2017). Water management in Central Asia: The role of energy, trade, and investment law. In J. Chaisse (Ed.), *The regulation of the global water services market* (pp. 335–358). CUP. https://doi.org/10.1017/9781316678442.015

Britannica. (2024). Central Asia. Encyclopedia Britannica. The Editors of Encyclopaedia. https://www.britannica.com/place/Central-Asia

Brody, M., Eshchanov, B., & Golub, A. (2020). Approaches to optimize Uzbekistan's Investment in Irrigation Technologies. *Economic Policy*, *15*(2), 136–147. https://doi.org/10.18288/1994-5124-2020-2-136-147

Brun, F., Berthier, E., Wagnon, P., Kääb, A., & Treichler, D. (2017). A spatially resolved estimate of High Mountain Asia glacier mass balances from 2000 to 2016. *Nature Geoscience*, *10*(9), 668–673. https://doi.org/10.1038/ngeo2999

Chen, D., Rojas, M., Samset, B. H., Cobb, K., Niang, A. D., Edwards, P., Emori, S., Faria, S. H., Hawkins, E., Hope, P., Huybrechts, P., Meinshausen, M., Mustafa, S. K., Plattner, G.-K., & Tréguier, A.-M. (2021). Framing, context, and methods. In *Climate change 2021—The physical science basis* (pp. 147–286). Cambridge University Press. https://doi.org/10.1017/9781009157896.003

Christmann, S., Aw-Hassan, A., Rajabov, T., & Rabbimov, A. (2015). Collective action for common rangelands improvement: A climate change adaptation strategy in Uzbekistan. *Society & Natural Resources*, *28*(3), 280–295. https://doi.org/10.1080/08941920.2014.933927

Christmann, S., & Aw-Hassan, A. A. (2015). A participatory method to enhance the collective ability to adapt to rapid glacier loss: The case of mountain communities in Tajikistan. *Climatic Change*, *133*(2), 267–282. https://doi.org/10.1007/s10584-015-1468-1

Church, J. M. (2017). Soft power of Tajikistan on the water agenda: Cross-scale dynamics. In S. S. Zhiltsov, I. S. Zonn, A. G. Kostianoy, & A. V. Semenov (Eds.), *Water resources in Central Asia: International context. The handbook of in environmental chemistry* (vol. 85). Springer. https://doi.org/10.1007/698_2017_130

Daron, J., Allen, M., Bailey, M., Ciampi, L., Cornforth, R., Costella, C., Fournier, N., Graham, R., Hall, K., Kane, C., Lele, I., Petty, C., Pinder, N., Pirret, J., Stacey, J., & Ticehurst, H. (2021). Integrating seasonal climate forecasts into adaptive social protection in the Sahel. *Climate and Development*, *13*(6), 543–550. https://doi.org/10.1080/17565529.2020.1825920

Díaz, S., Settele, J., Brondízio, E. S., Ngo, H. T., Agard, J., Arneth, A., Balvanera, P., Brauman, K. A., Butchart, S. H. M., Chan, K. M. A., Garibaldi, L. A., Ichii, K., Liu, J., Subramanian, S. M., Midgley, G. F., Miloslavich, P., Molnár, Z., Obura, D., Pfaff, A., & Zayas, C. N. (2019). Pervasive human-driven decline of life on earth points to the need for transformative change. *Science*, *366*(6471), 1–10. https://doi.org/10.1126/science.aax3100

Djumaboev, K., Anarbekov, O., Holmatov, B., Hamidov, A., Gafurov, Z., Murzaeva, M., Sušnik, J., Maskey, S., Mehmood, H., & Smakhtin, V. (2019). Surface water resources. In *The Aral Sea basin: Water for sustainable development in Central Asia* (pp. 25–38). Taylor and Francis. https://doi.org/10.4324/9780429436475-3

Dörre, A., & Goibnazarov, C. (2018). Small-scale irrigation self-governance in a mountain region of Tajikistan. *Mountain Research and Development*, *38*(2), 104–113. https://doi.org/10.1659/MRD-JOURNAL-D-17-00085.1

Duan, W., Chen, Y., Zou, S., & Nover, D. (2019). Managing the water-climate- food nexus for sustainable development in Turkmenistan. *Journal of Cleaner Production*, *220*, 212–224. https://doi.org/10.1016/j.jclepro.2019.02.040

Duethmann, D., Bolch, T., Farinotti, D., Kriegel, D., Vorogushyn, S., Merz, B., Pieczonka, T., Jiang, T., Su, B., & Gunter, A. (2015). Attribution of streamflow trends in snow and glacier melt-dominated catchments of the Tarim River, Central Asia. *Water Resources Research*, *51*, 4727–4750. https://doi.org/10.1002/2014WR016716

Duethmann, D., Zimmer, J., Gafurov, A., Güntner, A., Kriegel, D., Merz, B., & Vorogushyn, S. (2013). Evaluation of areal precipitation estimates based on downscaled reanalysis and station data by hydrological modelling. *Hydrology and Earth System Sciences*, *17*(7), 2415–2434. https://doi.org/10.5194/hess-17-2415-2013

Endo, A., Yamada, M., Miyashita, Y., Sugimoto, R., Ishii, A., Nishijima, J., Fujii, M., Kato, T., Hamamoto, H., Kimura, M., Kumazawa, T., & Qi, J. (2020). Dynamics of water–energy–food nexus methodology, methods, and tools. *Current Opinion in Environmental Science and Health*, *13*, 46–60. https://doi.org/10.1016/j.coesh.2019.10.004

Ezeugwu, E. C. (2020). The applicability of Karl Popper's piecemeal social engineering in Nigeria: Prospects and challenges. *Philosophia*, *26/2020*, 106–125. https://philosophia-bg.com/archive/philosophia-26-2020/the-applicability-of-karl-poppers-piecemeal-social-engineering-in-nigeria-prospects-and-challenges/

Farinotti, D., Longuevergne, L., Moholdt, G., Duethmann, D., Mölg, T., Bolch, T., Vorogushyn, S., & Güntner, A. (2015). Substantial glacier mass loss in the Tien Shan over the past 50 years. *Nature Geoscience*, *8*(9), 716–722. https://doi.org/10.1038/ngeo2513

Fazilov, A., & Fazilov, V. (2017). Hydraulic activities mudflows regulation in the conditions of climate change (in Russian). *Bulletin of the Don State Agrarian University*, *2–1*(24), 105–113. http://www.nutricion.org/publicaciones/pdf/prejuicios_y_verdades_sobre_grasas.pdf%0Ahttps://www.colesterolfamiliar.org/formacion/guia.pdf%0Ahttps://www.colesterolfamiliar.org/wp-content/uploads/2015/05/guia.pdf

Fedele, G., Donatti, C. I., Harvey, C. A., Hannah, L., & Hole, D. G. (2019). Transformative adaptation to climate change for sustainable social-ecological systems. *Environmental Science & Policy*, *101*, 116–125. https://doi.org/10.1016/j.envsci.2019.07.001

Feola, G., Barrett, T., Khusnitdinova, M., & Krylova, V. (2017). Agricultural water use in Southeast Kazakhstan: current challenges and adaptations to water stress. https://dspace.library.uu.nl/bitstream/handle/1874/361295/20170428_CCKAZ_Research_Brief_English.pdf?sequence=1

Filho, W. L., Wolf, F., Moncada, S., Salvia, A. L., Balogun, A. L. B., Skanavis, C., Kounani, A., & Nunn, P. D. (2022). Transformative adaptation as a sustainable response to climate change: Insights from large-scale case studies. *Mitigation and Adaptation Strategies for Global Change*, *27*(3), 1–26. https://doi.org/10.1007/s11027-022-09997-2

Gafurov, A., Yapiyev, V., Ahmed, M., Sagin, J., Haghighi, A. T., Akylbekova, A., & Kløve, B. (2019). Groundwater resources. In *The Aral Sea basin* (pp. 39–51). Routledge. https://doi.org/10.4324/9780429436475-4

Gaisberger, H., Legay, S., Andre, C., Loo, J., Azimov, R., Aaliev, S., Bobokalonov, F., Mukhsimov, N., Kettle, C., & Vinceti, B. (2020). Diversity under threat: Connecting genetic diversity and threat mapping to set conservation priorities for Juglans regia L. Populations in Central Asia. *Frontiers in Ecology and Evolution*, *8*, 1–18. https://doi.org/10.3389/fevo.2020.00171

Gardner, A. S., Moholdt, G., Cogley, J. G., Wouters, B., Arendt, A. A., Wahr, J., Berthier, E., Hock, R., Pfeffer, W. T., & Kaser, G. (2013). A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009. *Science*, *340*(6134), 852–857.

Gorbunov, A. P., Seversky, E. V., & Titkov, S. N. (1996). *Geocriologicheskie Usloviya Tyan-Shanya i Pamira (Geocryological conditions of the Tien Shan and Pamir)*. Permafrost Institute. *[in Russian]*.

GPW. (2018). Gridded population of the world, version 4 (GPWv4): Population density adjusted to match 2015 revision UN WPP country totals, revision 11. NASA Socioeconomic Data and Applications Center (SEDAC) https://doi.org/10.7927/H4F47M65

Grabherr, G., Gottfried, M., & Pauli, H. (2010). Climate change impacts in alpine environments. *Geography Compass*, *4*(8), 1133–1153. https://doi.org/10.1111/j.1749-8198.2010.00356.x

Grill, G., Lehner, B., Thieme, M., Geenen, B., Tickner, D., Antonelli, F., Babu, S., Borrelli, P., Cheng, L., Crochetiere, H., Ehalt Macedo, H., Filgueiras, R., Goichot, M., Higgins, J., Hogan, Z., Lip, B., McClain, M. E., Meng, J., Mulligan, M., … Zarfl, C. (2019). Mapping the world's free-flowing rivers. *Nature*, *569*(7755), 215–221. https://doi.org/10.1038/s41586-019-1111-9

Groisman, P., Bulygina, O., Henebry, G., Speranskaya, N., Shiklomanov, A., Chen, Y., Tchebakova, N., Parfenova, E., Tilinina, N., Zolina, O., Dufour, A., Chen, J., John, R., Fan, P., Mátyás, C., Yesserkepova, I., & Kaipov, I. (2018). Dryland belt of northern Eurasia: Contemporary environmental changes and their consequences. *Environmental Research Letters*, *13*(11), 115008. https://doi.org/10.1088/1748-9326/aae43c

Groisman, P., Shugart, H., Kicklighter, D., Henebry, G., Tchebakova, N., Maksyutov, S., Monier, E., Gutman, G., Gulev, S., Qi, J., Prishchepov, A., Kukavskaya, E., Porfiriev, B., Shiklomanov, A., Loboda, T., Shiklomanov, N., Nghiem, S., Bergen, K., Albrechtová, J., … Zolina, O. (2017). Northern Eurasia future initiative (NEFI): Facing the challenges and pathways of global change in the twenty-first century. *Progress in Earth and Planetary Science*, *4*(1), 1–48. https://doi.org/10.1186/s40645-017-0154-5

Haddaway, N. R., Macura, B., Whaley, P., & Pullin, A. S. (2018). ROSES reporting standards for systematic evidence syntheses: Pro forma, flow-diagram and descriptive summary of the plan and conduct of environmental systematic reviews and systematic maps. *Environmental Evidence*, *7*(1), 4–11. https://doi.org/10.1186/s13750-018-0121-7

Hamidov, A., Thiel, A., & Zikos, D. (2015). Institutional design in transformation: A comparative study of local irrigation governance in Uzbekistan. *Environmental Science and Policy*, *53*, 175–191. https://doi.org/10.1016/j.envsci.2015.06.012

Hayhoe, K. J., Kopp, R. E., LeGrande, A. N., Sanderson, B. M., Wehner, M. F., & Wuebbles, D. J. (2017). Climate models, scenarios, and projections. In *Climate science special report: Fourth National Climate Assessment* (pp. 133–160). U.S. Global Change Research Program, I. https://doi.org/10.7930/J0WH2N54.U.S

Hill, J. (2013). The role of Authority in the Collective Management of Hill irrigation Systems in the Alai (Kyrgyzstan) and Pamir (Tajikistan). *Mountain Research and Development*, *33*(3), 294–304. https://doi.org/10.1659/mrd-journal-d-12-00127.1

Hock, R., Rasul, G., Adler, C., Cáceres, B., Gruber, S., Hirabayashi, Y., Jackson, M., Kääb, A., Kang, S., & Kutuzov, S. (2019). High Mountain areas. In *IPCC special report on the ocean and cryosphere in a changing climate*. The Intergovernmental Panel on Climate Change (IPCC).

Hoelzle, M., Azisov, E., Barandun, M., Huss, M., Farinotti, D., Gafurov, A., Hagg, W., Kenzhebaev, R., Kronenberg, M., Machguth, H., Merkushkin, A., Moldobekov, B., Petrov, M., Saks, T., Salzmann, N., Schöne, T., Tarasov, Y., Usulbajev, R., Vorogushyn, S., … Zemp, M. (2017). Re-establishing a monitoring programme for glaciers in Kyrgyzstan and Uzbekistan, Central Asia. *Geoscientific Instrumentation, Methods and Data Systems*, *6*, 397–418. https://doi.org/10.5194/gi-6-397-2017

Hoelzle, M., Barandun, M., Bolch, T., Fiddes, J., Gafurov, A., Muccione, V., Saks, T., & Shahgedanova, M. (2019). The status and role of the alpine cryosphere in Central Asia. *The Aral Sea Basin: Water for Sustainable Development in Central Asia*, *2*, 100–121. https://doi.org/10.4324/9780429436475-8

Holzer, N., Vijay, S., Yao, T., Xu, B., Buchroithner, M., & Bolch, T. (2015). Four decades of glacier variations at Muztagh Ata (eastern Pamir): A multi-sensor study including hexagon KH-9 and Pléiades data. *The Cryosphere*, *9*, 2071–2088. https://doi.org/10.5194/tc-9-2071-2015

Hu, Z., Zhang, C., Hu, Q., & Tian, H. (2014). Temperature changes in central Asia from 1979 to 2011 based on multiple datasets. *Journal of Climate*, *27*(3), 1143–1167. https://doi.org/10.1175/JCLI-D-13-00064.1

Huang, A., Zhou, Y., Zhang, Y., Huang, D., Zhao, Y., & Wu, H. (2014). Changes of the annual precipitation over central Asia in the twenty-first century projected by multimodels of CMIP5. *Journal of Climate*, *27*(17), 6627–6646. https://doi.org/10.1175/JCLI-D-14-00070.1

Huggel, C., Scheel, M., Albrecht, F., Andres, N., Calanca, P., Jurt, C., Khabarov, N., Mira-Salama, D., Rohrer, M., Salzmann, N., Silva, Y., Silvestre, E., Vicuña, L., & Zappa, M. (2015). A framework for the science contribution in climate adaptation: Experiences from science-policy processes in the Andes. *Environmental Science and Policy*, *47*, 80–94. https://doi.org/10.1016/j.envsci.2014.11.007

Huss, M., Bookhagen, B., Huggel, C., Jacobsen, D., Bradley, R. S., Clague, J. J., Vuille, M., Buytaert, W., Cayan, D. R., Greenwood, G., Mark, B. G., Milner, A. M., Weingartner, R., & Winder, M. (2017). Toward mountains without permanent snow and ice. *Earth's Future*, *5*(5), 418–435. https://doi.org/10.1002/2016EF000514

Huss, M., & Hock, R. (2018). Global-scale hydrological response to future glacier mass loss. *Nature Climate Change*, *8*(2), 135–140. https://doi.org/10.1038/s41558-017-0049-x

Ibragimov, N., Djumaniyazova, Y., Khaitbaeva, J., Babadjanova, S., Ruzimov, J., Akramkhanov, A., & Lamers, J. (2020). Simulating crop productivity in a triple rotation in the semi-arid area of the Aral Sea basin. *International Journal of Plant Production*, *14*(2), 273–285. https://doi.org/10.1007/s42106-019-00083-3

Iegorova, L. V., Gibbs, J. P., Mountrakis, G., Bastille-Rousseau, G., Paltsyn, M. Y., Ayatkhan, A., Baylagasov, L. V., Robertus, Y. V., & Chelyshev, A. V. (2019). Rangeland vegetation dynamics in the Altai mountain region of Mongolia, Russia, Kazakhstan and China: Effects of climate, topography, and socio-political context for livestock herding practices. *Environmental Research Letters*, *14*(10), 104017. https://doi.org/10.1088/1748-9326/ab1560

Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., Hyde, S., Brumby, S., Davies, B. J., Elmore, A. C., Emmer, A., Feng, M., Fernández, A., Haritashya, U., Kargel, J. S., Koppes, M., Kraaijenbrink, P. D. A., Kulkarni, A. V., Mayewski, P. A., … Baillie, J. E. M. (2020). Importance and vulnerability of the world's water towers. *Nature*, *577*(7790), 364–369. https://doi.org/10.1038/s41586-019-1822-y

Immerzeel, W. W., Lutz, A. F., & Droogers, P. (2012). *Climate change impacts on the upstream water resources of the Amu and Syr Darya River basins*. FutureWater, 116.

IPCC. (2013). Summary for policymakers. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P. M. Midgley (Eds.), *Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change*. Cambridge University Press.

IPCC. (2014). Climate change 2014: Synthesis report. In Core Writing Team, R. K. Pachauri, & L. A. Meyer (Eds.), *Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change* (p. 151). IPCC.

IPCC. (2018). Summary for policymakers. In V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, & T. Waterfield (Eds.), *Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* (pp. 3–24). Cambridge University Press. https://doi.org/10.1017/9781009157940.001

IPCC. (2022). Summary for policymakers. In H.-O. Pörtner, D. C. Roberts, E. S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama (Eds.), *Climate change 2022: Impacts, adaptation, and vulnerability. Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change* (pp. 3–33). Cambridge University Press. https://doi.org/10.1017/9781009325844.001

Jalilov, S. M., Amer, S. A., & Ward, F. A. (2013). Reducing conflict in development and allocation of transboundary rivers. *Eurasian Geography and Economics*, *54*(1), 78–109. https://doi.org/10.1080/15387216.2013.788873

Jiang, J., Zhou, T., Chen, X., & Zhang, L. (2020). Future changes in precipitation over Central Asia based on CMIP6 projections. *Environmental Research Letters*, *15*(5), 1–8. https://doi.org/10.1088/1748-9326/ab7d03

Jobbágy, E. G., Nosetto, M. D., Villagra, P. E., & Jackson, R. B. (2011). Water subsidies from mountains to deserts: Their role in sustaining groundwater-fed oases in a sandy landscape. *Ecological Applications*, *21*(3), 678–694. https://doi.org/10.1890/09-1427.1

Jones, D. B., Harrison, S., Anderson, K., & Whalley, W. B. (2019). Rock glaciers and mountain hydrology: A review. *Earth-Science Reviews*, *193*, 66–90. https://doi.org/10.1016/j.earscirev.2019.04.001

Kamil, I. (2021). Afghanistan, the Amu Darya basin and regional treaties. *Chinese Journal of Environmental Law*, *5*(1), 37–62. https://doi.org/10.1163/24686042-12340063

Kapitsa, V., Shahgedanova, M., Kasatkin, N., Severskiy, I., Kasenov, M., Yegorov, A., & Tatkova, M. (2023). Bathymetries of proglacial lakes: A new data set from the northern Tien Shan, Kazakhstan. *Frontiers in Earth Science*, *11*(1192719), 1–17. https://doi.org/10.3389/feart.2023.1192719

Kapitsa, V., Shahgedanova, M., Machguth, H., Severskiy, I., & Medeu, A. (2017). Assessment of evolution and risks of glacier lake outbursts in the Djungarskiy Alatau, Central Asia, using Landsat imagery and glacier bed topography modelling. *Natural Hazards and Earth System Sciences*, *17*(10), 1837–1856. https://doi.org/10.5194/nhess-17-1837-2017

Kapitsa, V., Shahgedanova, M., Severskiy, I., Kasatkin, N., White, K., & Usmanova, Z. (2020). Assessment of changes in mass balance of the Tuyuksu Group of Glaciers, northern Tien Shan, between 1958 and 2016 using ground-based observations and Pléiades satellite imagery. *Frontiers in Earth Science*, *8*, 1–14. https://doi.org/10.3389/feart.2020.00259

Karthe, D., Chalov, S., & Borchardt, D. (2015). Water resources and their management in central Asia in the early twenty first century: Status, challenges and future prospects. *Environmental Earth Sciences*, *73*(2), 487–499. https://doi.org/10.1007/s12665-014-3789-1

Kaser, G., Großhauser, M., & Marzeion, B. (2010). Contribution potential of glaciers to water availability in different climate regimes. *Proceedings of the National Academy of Sciences*, *107*(47), 20223–20227. https://doi.org/10.1073/pnas.1008162107

Kasiyev, K. (2014). Forecast of the development of vegetation cover in Kyrgyzstan during global warming (in Russian). *Bulletin of the Kyrgyz National Agrarian University Named after K.I. Scriabin*, *13*, 395–402.

Kattel, D. B., Mohanty, A., Daiyrov, M., Wang, W., Mishra, M., Kulenbekov, Z., & Dawadi, B. (2020). Evaluation of Glacial Lakes and catastrophic floods on the northern slopes of the Kyrgyz range. *Mountain Research and Development*, *40*(3), 37–47. https://doi.org/10.1659/MRD-JOURNAL-D-19-00068.1

Kerven, C., Steimann, B., Ashley, L., Dear, C., & Kerven, C. (2011). Pastoralism and farming in Central Asia's Mountains: A research review. In C. Kerven, B. Steimann, L. Ashley, C. Dear, & I. Rahim (Eds.), *MSRC Background Paper No. 1* (Vol. 1). University of Central Asia. https://doi.org/10.5167/uzh-52730

Klümper, F., Herzfeld, T., & Theesfeld, I. (2017). Can water abundance compensate for weak water governance? Determining and comparing dimensions of irrigation water security in Tajikistan. *Water*, *9*(4), 286. https://doi.org/10.3390/w9040286

Kohler, T., Wehrli, A., Batjargal, E., Kanyamibwa, S., Maselli, D., & Wiesmann, U. (2016). The science-policy dialogue for climate change adaptation in mountain regions. In *Climate change adaptation strategies—An upstream-downstream perspective* (pp. 271–292). Springer. https://doi.org/10.1007/978-3-319-40773-9_15

Kohli, M., Mijiddorj, T. N., Suryawanshi, K. R., Mishra, C., Boldgiv, B., & Sankaran, M. (2021). Grazing and climate change have site-dependent interactive effects on vegetation in Asian montane rangelands. *Journal of Applied Ecology*, *58*(3), 539–549. https://doi.org/10.1111/1365-2664.13781

Körner, C., Jetz, W., Paulsen, J., Payne, D., Rudmann-Maurer, K., Spehn, M., & Spehn, E. M. (2017). A global inventory of mountains for bio-geographical applications. *Alpine Botany*, *127*(1), 1993–1996. https://doi.org/10.1007/s00035-016-0182-6

Kraaijenbrink, P. D. A., Stigter, E. E., Yao, T., & Immerzeel, W. W. (2021). Climate change decisive for Asia's snow meltwater supply. *Nature Climate Change*, *11*(7), 591–597. https://doi.org/10.1038/s41558-021-01074-x

Krutov, A., Rahimov, S., & Kamolidinov, A. (2014). Republic of Tajikistan: Its role in the management of water resources in the Aral Sea basin. In V. R. Squires, H. M. Milner, & K. A. Daniell (Eds.), *River Basin Management in the Twenty-First Century* (pp. 325–345). Semantic Scholar. https://doi.org/10.1201/b17168-18

Krysanova, V., Wortmann, M., Bolch, T., Merz, B., Duethmann, D., Walter, J., Huang, S., Tong, J., Buda, S., & Kundzewicz, Z. W. (2015). Analysis of current trends in climate parameters, river discharge and glaciers in the Aksu River basin (Central Asia). *Hydrological Sciences Journal*, *60*(4), 566–590.

Kulov, K. (2020). Technologies of rational use of land and water resources taking into account the climate change under the Kyrgyz Republic context (in Russian). *Materials of the International Scientific and Practical Internet Conference*, *1*, 40–49.

Kundzewicz, Z. W., Merz, B., Vorogushyn, S., Hartmann, H., Duethmann, D., Wortmann, M., Huang, S., Su, B., Jiang, T., & Krysanova, V. (2015). Analysis of changes in climate and river discharge with focus on seasonal runoff predictability in the Aksu River basin. *Environmental Earth Sciences*, *73*(2), 501–516.

Kurtov, A. (2014). More terrible than the afghan threat: Water as a source of conflicts in Central Asia (in Russian). *Ezhegodnik IMI*, *1*(7), 96–115.

Kutuzov, S., & Shahgedanova, M. (2009). Glacier retreat and climatic variability in the eastern Terskey-Alatoo, inner Tien Shan between the middle of the 19th century and beginning of the 21st century. *Global and Planetary Change*, *69*(1–2), 59–70. https://doi.org/10.1016/j.gloplacha.2009.07.001

Lim, M. (2013). Transboundary conservation of mountain biodiversity in a climate change impacted world: Governance perspectives from Central Asia and the Island of Borneo. In *Biodiversity and climate change* (pp. 268–302). Edward Elgar Publishing. https://doi.org/10.4337/9781782546894.00021

Lim, M. (2015). Governance criteria for effective transboundary biodiversity conservation. *International Environmental Agreements: Politics, Law and Economics*, *16*(6), 797–813. https://doi.org/10.1007/s10784-015-9296-3

Lioubimtseva, E. (2015). A multi-scale assessment of human vulnerability to climate change in the Aral Sea basin. *Environmental Earth Sciences*, *73*(2), 719–729. https://doi.org/10.1007/s12665-014-3104-1

Liu, W., Liu, L., & Gao, J. (2020). Adapting to climate change: Gaps and strategies for Central Asia. *Mitigation and Adaptation Strategies for Global Change*, *25*(8), 1439–1459. https://doi.org/10.1007/s11027-020-09929-y

Liu, Y., Wang, P., Ruan, H., Wang, T., Yu, J., Cheng, Y., & Kulmatov, R. (2020). Sustainable use of groundwater resources in the transboundary aquifers of the five central Asian countries: Challenges and perspectives. *Water*, *12*(8), 2101. https://doi.org/10.3390/w12082101

Lutz, W., Sanderson, W., & Scherbov, S. (2008). IIASA's 2007 Probabilistic World Population Projections, IIASA World Population Program Online Data Base of Results. https://webarchive.iiasa.ac.at/Research/POP/proj07/index.html?sb=6

Mamadjanova, G., Wild, S., Walz, M. A., & Leckebusch, G. C. (2018). The role of synoptic processes in mudflow formation in the piedmont areas of Uzbekistan. *Natural Hazards and Earth System Sciences*, *18*(11), 2893–2919. https://doi.org/10.5194/nhess-18-2893-2018

Mannig, B., Müller, M., Starke, E., Merkenschlager, C., Mao, W., Zhi, X., Podzun, R., Jacob, D., & Paeth, H. (2013). Dynamical downscaling of climate change in Central Asia. *Global and Planetary Change*, *110*, 26–39. https://doi.org/10.1016/j.gloplacha.2013.05.008

Marchenko, S. S., Gorbunov, A. P., & Romanovsky, V. E. (2007). Permafrost warming in the Tien Shan Mountains, Central Asia. *Global and Planetary Change*, *56*(3–4), 311–327. https://doi.org/10.1016/j.gloplacha.2006.07.023

Matiiuk, Y., Poškus, M. S., & Liobikienė, G. (2020). The implementation of climate change policy in post-soviet countries achieving long-term targets. *Sustainability*, *12*(11), 4558. https://doi.org/10.3390/su12114558

McDowell, G., Huggel, C., Frey, H., Wang, F. M., Cramer, K., & Ricciardi, V. (2019). Adaptation action and research in glaciated mountain systems: Are they enough to meet the challenge of climate change? *Global Environmental Change*, *54*, 19–30. https://doi.org/10.1016/j.gloenvcha.2018.10.012

McDowell, G., Stephenson, E., & Ford, J. (2014). Adaptation to climate change in glaciated mountain regions. *Climatic Change*, *126*(1–2), 77–91. https://doi.org/10.1007/s10584-014-1215-z

McDowell, G., Stevens, M., Lesnikowski, A., Huggel, C., Harden, A., DiBella, J., Morecroft, M., Kumar, P., Joe, E. T., Bhatt, I. D., & the Global Adaptation Mapping Initiative. (2021). Closing the adaptation gap in mountains. *Mountain Research and Development*, *41*(3), A1–A10. https://doi.org/10.1659/MRD-JOURNAL-D-21-00033.1

Medeu, A. P., Blagovechshenskiy, V. P., Kasatkin, N. E., Kapitsa, V. P., Kasenov, M. K., & Raymbekova, Z. T. (2020). Glacial debris flows in Zailiysky Alatau over the past 120 years. *Ice and Snow*, *60*(2), 213–224. https://doi.org/10.31857/S2076673420020035

Medeu, A. R., Popov, N. V., Blagovechshenskiy, V. P., Askarova, M. A., Medeu, A. A., Ranova, S. U., Kamalbekova, A., & Bolch, T. (2022). Moraine-dammed glacial lakes and threat of glacial debris flows in South-East Kazakhstan. *Earth-Science Reviews*, *229*, 103999. https://doi.org/10.1016/j.earscirev.2022.103999

Menga, F. (2017). *Power and water in Central Asia*. Routledge.

Mölg, N., Bolch, T., Rastner, P., Strozzi, T., & Paul, F. (2018). A consistent glacier inventory for Karakoram and Pamir derived from Landsat data: Distribution of debris cover and mapping challenges. *Earth System Science Data*, *10*, 1807–1827.

Morris, B. L., Darling, W. G., Gooddy, D. C., Litvak, R. G., Neumann, I., Nemaltseva, E. J., & Poddubnaia, I. (2006). Assessing the extent of induced leakage to an urban aquifer using environmental tracers: An example from Bishkek, capital of Kyrgyzstan, Central Asia. *Hydrogeology Journal*, *14*(1–2), 225–243. https://doi.org/10.1007/s10040-005-0441-x

Mosello, B. (2015). How to deal with climate change?: Institutional adaptive capacity as a means to promote sustainable water governance. In *How to deal with climate change?: Institutional adaptive capacity as a means to promote sustainable water governance*. Springer. https://doi.org/10.1007/978-3-319-15389-6

Mukhamedjanov, S., Mukhomedjanov, A., Sagdullaev, R., & Khasanova, N. (2021). Adaptation to climate change in irrigated agriculture in Uzbekistan*. *Irrigation and Drainage*, *70*(1), 169–176. https://doi.org/10.1002/ird.2529

Mukhtarov, F., Fox, S., Mukhamedova, N., & Wegerich, K. (2015). Interactive institutional design and contextual relevance: Water user groups in Turkey, Azerbaijan and Uzbekistan. *Environmental Science & Policy*, *53*, 206–214. https://doi.org/10.1016/j.envsci.2014.10.006

Nabavi, E. (2022). Who speaks for water in times of crisis? A case for co-production of engineering and governance. *Frontiers in Communication*, *7*, 1–14. https://doi.org/10.3389/FCOMM.2022.810266

Narama, C., Kääb, A., Duishonakunov, M., & Abdrakhmatov, K. (2010). Spatial variability of recent glacier area changes in the Tien Shan Mountains, Central Asia, using Corona (∼ 1970), Landsat (∼ 2000), and ALOS (∼ 2007) satellite data. *Global and Planetary Change*, *71*(1–2), 42–54. https://doi.org/10.1016/j.gloplacha.2009.08.002

Nowak, A., Świerszcz, S., Nowak, S., Hisorev, H., Klichowska, E., Wróbel, A., Nobis, A., & Nobis, M. (2020). Red list of vascular plants of Tajikistan—The core area of the mountains of Central Asia global biodiversity hotspot. *Scientific Reports*, *10*(1), 6235. https://doi.org/10.1038/s41598-020-63333-9

Nussbaumer, S. U., Hoelzle, M., Hüsler, F., Huggel, C., Salzmann, N., & Zemp, M. (2017). Glacier monitoring and capacity building: Important ingredients for Sustainable Mountain development. *Mountain Research and Development*, *37*(1), 141–152. https://doi.org/10.1659/MRD-JOURNAL-D-15-00038.1

OECD. (2021). Social innovation—OECD.

Orlowsky, B., Calanca, P., Ali, I., Ali, J., Hilares, A. E., Huggel, C., Khan, I., Neukom, R., Nizami, A., Qazi, M. A., Robledo, C., Rohrer, M., Salzmann, N., Schmidt, K., Khan, I., Neukom, R., Nizami, A., Qazi, M. A., & Robledo, C. (2017). Climate corridors for strategic adaptation planning. *International Journal of Climate Change Strategies and Management*, *9*(6), 811–828.

Ozturk, T., Turp, M. T., Türkeş, M., & Kurnaz, M. L. (2017). Projected changes in temperature and precipitation climatology of Central Asia CORDEX region 8 by using RegCM4.3.5. *Atmospheric Research*, *183*, 296–307. https://doi.org/10.1016/j.atmosres.2016.09.008

Payne, D., Snethlage, M., Geschke, J., Spehn, E. M., & Fischer, M. (2020). Nature and people in the Andes, east African Mountains, European Alps, and Hindu Kush Himalaya: Current research and future directions. *Mountain Research and Development*, *40*(2), R1–R14. https://doi.org/10.1659/MRD-JOURNAL-D-19-00075.1

Pelling, M., O'Brien, K., & Matyas, D. (2014). Adaptation and transformation. *Climatic Change*, *133*(1), 113–127. https://doi.org/10.1007/s10584-014-1303-0

Pepin, N., Bradley, R. S., Diaz, H. F., Baraer, M., Caceres, E. B., Forsythe, N., Fowler, H., Greenwood, G., Hashmi, M. Z., Liu, X. D., Miller, J. R., Ning, L., Ohmura, A., Palazzi, E., Rangwala, I., Schöner, W., Severskiy, I., Shahgedanova, M., Wang, M. B., … Yang, D. Q. (2015). Elevation-dependent warming in mountain regions of the world. *Nature Climate Change*, *5*(5), 424–430. https://doi.org/10.1038/nclimate2563

Petrakov, D. A., Chernomorets, S. S., Viskhadzhieva, K. S., Dokukin, M. D., Savernyuk, E. A., Petrov, M. A., Erokhin, S. A., Tutubalina, O. V., Glazyrin, G. E., Shpuntova, A. M., & Stoffel, M. (2020). Putting the poorly documented 1998 GLOF disaster in Shakhimardan River valley (Alay range, Kyrgyzstan/Uzbekistan) into perspective. *Science of the Total Environment*, *724*, 138287. https://doi.org/10.1016/j.scitotenv.2020.138287

Pieczonka, T., Bolch, T., Junfeng, W., & Shiyin, L. (2013). Heterogeneous mass loss of glaciers in the Aksu-Tarim catchment (central Tien Shan) revealed by 1976 KH-9 hexagon and 2009 SPOT-5 stereo imagery. *Remote Sensing of Environment*, *130*, 233–244.

Piroton, V., Schlögel, R., Barbier, C., & Havenith, H.-B. (2020). Monitoring the recent activity of landslides in the Mailuu-Suu Valley (Kyrgyzstan) using radar and optical remote sensing techniques. *Geosciences*, *10*(5), 164. https://doi.org/10.3390/geosciences10050164

Ranasinghe, R., Ruane, A. C., Vautard, R., Arnell, N., Coppola, E., Cruz, F. A., Dessai, S., Islam, A. S., Rahimi, M., Carrascal, D. R., Sillmann, J., Sylla, M. B., Tebaldi, C., Wang, W., & Zaaboul, R. (2021). Climate change information for regional impact and for risk assessment. In *Climate change 2021—The physical science basis* (pp. 1767–1926). Cambridge University Press. https://doi.org/10.1017/9781009157896.014

Rasul, G., Pasakhala, B., Mishra, A., & Pant, S. (2020). Adaptation to mountain cryosphere change: Issues and challenges. *Climate and Development*, *12*(4), 297–309. https://doi.org/10.1080/17565529.2019.1617099

Reyer, C. P., Otto, I. M., Adams, S., Albrecht, T., Baarsch, F., Cartsburg, M., Coumou, D., Eden, A., Ludi, E., Marcus, R., Mengel, M., Mosello, B., Robinson, A., Schleussner, C.-F., Serdeczny, O., & Stagl, J. (2017). Climate change impacts in Central Asia and their implications for development. *Regional Environmental Change*, *17*(6), 1639–1650. https://doi.org/10.1007/s10113-015-0893-z

Salokhiddinov, A., Boirov, R., Ismailov, M., Mamatov, S., Khakimova, P., & Rakhmatullaeva, M. (2020). Climate change effects on irrigated agriculture: Perspectives from agricultural producers in eastern Uzbekistan. *IOP Conference Series: Earth and Environmental Science*, *612*(1), 012058. https://doi.org/10.1088/1755-1315/612/1/012058

Schiemann, R., Lüthi, D., Vidale, P. L., & Schär, C. (2008). The precipitation climate of Central Asia—Intercomparison of observational and numerical data sources in a remote semiarid region. *International Journal of Climatology*, *28*(3), 295–314. https://doi.org/10.1002/joc.1532

Schlüter, M., Khasankhanova, G., Talskikh, V., Taryannikova, R., Agaltseva, N., Joldasova, I., Ibragimov, R., & Abdullaev, U. (2013). Enhancing resilience to water flow uncertainty by integrating environmental flows into water management in the Amudarya River, Central Asia. *Global and Planetary Change*, *110*, 114–129. https://doi.org/10.1016/j.gloplacha.2013.05.007

Sehring, J. (2020). Unequal distribution: Academic knowledge production on water governance in Central Asia. *Water Security*, *9*, 100057. https://doi.org/10.1016/j.wasec.2019.100057

Seneviratne, S. I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., di Luca, A., Ghosh, S., Iskandar, I., Kossin, J., Lewis, S., Otto, F., Pinto, I., Satoh, M., Vicente-Serrano, S. M., Wehner, M., & Zhou, B. (2021). Weather and climate extreme events in a changing climate. In *Climate change 2021—The physical science basis* (pp. 1513–1766). Cambridge University Press. https://doi.org/10.1017/9781009157896.013

Severskiy, I., Vilesov, E., Armstrong, R., Kokarev, A., Kogutenko, L., & Usmanova, Z. (2016). Changes in glaciation of the Balkhash - Alakol basin over the past decades. *Annals of Glaciology*, *57*(71), 382–394. https://doi.org/10.3189/2016AoG71A575

Shahgedanova, M. (2002). In: The physical geography of northern Eurasia: Russia and Neighbouring states. In *Climate at present and in the historical past* (pp. 70–102). Oxford University Press.

Shahgedanova, M., Adler, C., Gebrekirstos, A., Grau, R. H., Huggel, C., Marchant, R., Pepin, N., Vanacker, V., Viviroli, D., & Vuille, M. (2021). Mountain observatories: Status and prospects to enhance and connect a global community. *Mountain Research and Development*, *41*(2), 1–15. https://doi.org/10.1659/MRD-JOURNAL-D-20-00054.1

Shahgedanova, M., Afzal, M., Severskiy, I., Usmanova, Z., Saidaliyeva, Z., Kapitsa, V., Kasatkin, N., & Dolgikh, S. (2018). Changes in the mountain river discharge in the northern Tien Shan since the mid-20th century: Results from the analysis of a homogeneous daily streamflow data set from seven catchments. *Journal of Hydrology*, *564*, 1133–1152. https://doi.org/10.1016/j.jhydrol.2018.08.001

Shahgedanova, M., Afzal, M., Hagg, W., Kapitsa, V., Kasatkin, N., Mayr, E., Rybak, O., Saidaliyeva, Z., Severskiy, I., Usmanova, Z., Wade, A., Yaitskaya, N., & Zhumabayev, D. (2020). Emptying water towers? Impacts of future climate and glacier change on river discharge in the northern Tien Shan, Central Asia. *Water*, *12*(3), 627. https://doi.org/10.3390/w12030627

Shannon, S., Smith, R., Wiltshire, A., Payne, T., Huss, M., Betts, R., Caesar, J., Koutroulis, A., Jones, D., & Harrison, S. (2019). Global glacier volume projections under high-end climate change scenarios. *The Cryosphere*, *l*, 325–350.

Shearmur, J. (1996). *The political thought of Karl popper*. Routledge. https://doi.org/10.4324/9780203212820

Shigaeva, J., Hagerman, S., Zerriffi, H., Hergarten, C., Isaeva, A., Mamadalieva, Z., & Foggin, M. (2016). Decentralizing governance of Agropastoral Systems in Kyrgyzstan: An assessment of recent pasture reforms. *Mountain Research and Development*, *36*(1), 91–101. https://doi.org/10.1659/mrd-journal-d-15-00023.1

Shih, G. (2023). Taliban bringing water to Afghanistan's parched plains via massive canal. *The Washington Post* https://www.washingtonpost.com/world/2023/08/20/afghanistan-taliban-canal-amu-darya/

Shodieva, D., Vakhitova, N., & Abbazova, L. (2014). Promoting women's capacity building to adapt to climate change in Uzbekistan. *Asian Journal of Women's Studies*, *20*(3), 132–144. https://doi.org/10.1080/12259276.2014.11666194

Sorg, A., Mosello, B., Shalpykova, G., Allan, A., Hill Clarvis, M., & Stoffel, M. (2013). Coping with changing water resources: The case of the Syr Darya river basin in Central Asia. *Environmental Science & Policy*, *43*, 68–77. https://doi.org/10.1016/j.envsci.2013.11.003

Sorg, A., Bolch, T., Stoffel, M., Solomina, O., & Beniston, M. (2012). Climate change impacts on glaciers and runoff in Tien Shan (Central Asia). *Nature Climate Change*, *2*(10), 725–731. https://doi.org/10.1038/nclimate1592

Stucker, D., & Lopez-Gunn, E. (2014). In D. Stucker & E. Lopez-Gunn (Eds.), *Adaptation to climate change through water resources management*. Routledge. https://doi.org/10.4324/9780203085875

Suleimenova, S., Lukac, M., & Shahgedanova, M. (2024). *Modelling of soybean yield under different irrigation scenarios in South East Kazakhstan and stakeholder engagement*. PhD Students Symposium. University of Reading.

Sultanova, B. M., Dimeyeva, L. A., & Islamgulova, A. F. (2012). Botanical diversity of the South Altai mountains under conditions of climate change (in Russian), *588*, 219–223.

Terzi, S., Torresan, S., Schneiderbauer, S., Critto, A., Zebisch, M., & Marcomini, A. (2019). Multi-risk assessment in mountain regions: A review of modelling approaches for climate change adaptation. *Journal of Environmental Management*, *232*, 759–771. https://doi.org/10.1016/j.jenvman.2018.11.100

The World Factbook. (2020). The World Factbook. https://www.cia.gov/library/publications/the-world-factbook/

Thevs, N., Nurtazin, S., Beckmann, V., Salmyrzauli, R., & Khalil, A. (2017). Water consumption of agriculture and natural ecosystems along the Ili River in China and Kazakhstan. *Water*, *9*(3), 207. https://doi.org/10.3390/w9030207

Thevs, N., Strenge, E., Aliev, K., Eraaliev, M., Lang, P., Baibagysov, A., & Xu, J. (2017). Tree shelterbelts as an element to improve water resource management in Central Asia. *Water (Switzerland)*, *9*(11), 1–11. https://doi.org/10.3390/w9110842

Tian, J., & Zhang, Y. (2020). Detecting changes in irrigation water requirement in Central Asia under CO2 fertilization and land use changes. *Journal of Hydrology*, *583*, 124315. https://doi.org/10.1016/j.jhydrol.2019.124315

Tischbein, B., Manschadi, A. M., Conrad, C., Hornidge, A.-K., Bhaduri, A., Ul Hassan, M., Lamers, J. P. A., Awan, U. K., & Vlek, P. L. G. (2013). Adapting to water scarcity: Constraints and opportunities for improving irrigation management in Khorezm, Uzbekistan. *Water Supply*, *13*(2), 337–348. https://doi.org/10.2166/ws.2013.028

Tomaszewska, M. A., & Henebry, G. M. (2018). Changing snow seasonality in the highlands of Kyrgyzstan. *Environmental Research Letters*, *13*(6), 065006. https://doi.org/10.1088/1748-9326/aabd6f

Ullah, I. I. T., Chang, C., & Tourtellotte, P. (2019). Water, dust, and agro-pastoralism: Modeling socio-ecological co-evolution of landscapes, farming, and human society in southeast Kazakhstan during the mid to late Holocene. *Journal of Anthropological Archaeology*, *55*, 101067. https://doi.org/10.1016/J.JAA.2019.101067

Unger-Shayesteh, K., Vorogushyn, S., Farinotti, D., Gafurov, A., Duethmann, D., Mandychev, A., & Merz, B. (2013). What do we know about past changes in the water cycle of central Asian headwaters? A review. *Global and Planetary Change*, *110*, 4–25. https://doi.org/10.1016/j.gloplacha.2013.02.004

United Nations Development Programme. (2019). *Human Development Report 2019: Beyond income, beyond averages, beyond today*. 366. http://hdr.undp.org/sites/default/files/hdr2019.pdf

Vakulchuk, R., Daloz, A. S., Overland, I., Sagbakken, H. F., & Standal, K. (2022). A void in Central Asia research: Climate change. *Central Asian Survey*, *1–20*, 1–20. https://doi.org/10.1080/02634937.2022.2059447

Van den Bosch, J., Fauve, A., & De Cordier, B. (2021). *European handbook of central Asian studies history, politics, and societies*. ibidem Verlag. http://hdl.handle.net/1854/LU-8723294

Verhagen, F., & Rahman, J. (2023). *GCA*. Making water central to climate action: A message for the UN 2023 Water Conference. https://gca.org/making-water-central-to-clim

Veysov, S. K., & Khamraev, G. O. (2019). Impact of climate change on water resources of Turkmenistan (in Russian). *Science, New Technologies and Innovations of Kyrgyzstan*, *4*, 31–35. https://doi.org/10.1007/978-81-322-2157-9_21

Vij, S., Biesbroek, R., Adler, C., & Muccione, V. (2021). Climate Change Adaptation in European Mountain Systems : A Systematic Mapping of Academic Research Climate Change Adaptation in European Mountain Systems: A Systematic Mapping of Academic. 41(May).

Viviroli, D., Kummu, M., Meybeck, M., Kallio, M., & Wada, Y. (2020). Increasing dependence of lowland populations on mountain water resources. *Nature Sustainability*, *3*, 917–928. https://doi.org/10.1038/s41893-020-0559-9

Williams, C., & Golovnev, I. (2015). Pamiri women and the melting glaciers of Tajikistan: A visual knowledge exchange for improved environmental governance. In S. Buechler & A.-M. Hanson (Eds.), *A political ecology of women, water and global environmental change*. Routledge. https://doi.org/10.4324/9781315796208

World Bank. (2023). *World Bank*. World Development Indicators | DataBank. https://databank.worldbank.org/reports.aspx?source=2&series=EN.POP.DNST&country=KAZ,KGZ,TJK,TKM,UZB#

Worldometer. (2023). *Worldometer* (*Population of Central Asia*). https://www.worldometers.info/world-population/central-asia-population/

Xenarios, S., Gafurov, A., Schmidt-Vogt, D., Sehring, J., Manandhar, S., Hergarten, C., Shigaeva, J., & Foggin, M. (2019). Climate change and adaptation of mountain societies in Central Asia: Uncertainties, knowledge gaps, and data constraints. *Regional Environmental Change*, *19*(5), 1339–1352. https://doi.org/10.1007/s10113-018-1384-9

Xenarios, S., Assubayeva, A., Xie, L., Sehring, J., Amirkhanov, D., Sultanov, A., & Fazli, S. (2021). A bibliometric review of the water security concept in Central Asia. *Environmental Research Letters*, *16*(1), 013001. https://doi.org/10.1088/1748-9326/abc717

Xenarios, S., Schmidt-Vogt, D., Qadir, M., Janusz-Pawletta, B., & Abdullaev, I. (2019). The Aral Sea basin. In *Water for sustainable development in Central Asia*. Routledge. https://doi.org/10.4324/9780429436475

Yang, Y., Roderick, M. L., Yang, D., Wang, Z., Ruan, F., McVicar, T. R., Zhang, S., & Beck, H. E. (2021). Streamflow stationarity in a changing world. *Environmental Research Letters*, *16*(6), 064096. https://doi.org/10.1088/1748-9326/AC08C1

Yapiyev, V., Sagintayev, Z., Inglezakis, V. V. J. V., Samarkhanov, K., & Verhoef, A. (2017). Essentials of endorheic basins and lakes: A review in the context of current and future water resource management and mitigation activities in Central Asia. *Water*, *9*(10), 798. https://doi.org/10.3390/w9100798

Yapiyev, V., Wade, A. J., Shahgedanova, M., Saidaliyeva, Z., Madibekov, A., & Severskiy, I. (2021). The hydrochemistry and water quality of glacierized catchments in Central Asia: A review of the current status and anticipated change. *Journal of Hydrology: Regional Studies*, *38*, 100960. https://doi.org/10.1016/j.ejrh.2021.100960

Yu, X., Zhao, Y., Ma, X., Yao, J., & Li, H. (2018). Projected changes in the annual cycle of precipitation over central As ia by CMIP5 models. *International Journal of Climatology*, *38*, 5589–5604.

Yuldashev, A., Nigmatov, I., & Mamaraculova, M. (2015). The influence of climatic disasters on the land reclamation state in the conditions of Central Asia (in Russian). *Russian Electronic Scientific Journal*, *4*(18), 45–53.

Zamai, B. (2014). Problems of monitoring mudflow hazard in mountainous regions of Kazakhstan (in Russian). *Automation and Control Problems*, *2*(27), 72–81.

Zheng, G., Bao, A., Li, J., Zhang, G., Xie, H., Guo, H., Jiang, L., Chen, T., Chang, C., & Chen, W. (2019). Sustained growth of high mountain lakes in the headwaters of the Syr Darya River, Central Asia. *Global and Planetary Change*, *176*, 84–99. https://doi.org/10.1016/j.gloplacha.2019.03.004

Zhiltsov, S. S., & Bimenova, A. (2015). Policy of the central Asian countries in the field of water resources use of transboundary Rivers (in Russian). *Central Asia and Caucasus*, *18*(1), 90–100.

Zhiltsov, S. S., Zonn, I. S., Orlovsky, N. S., & Semenov, A. V. (2020). Main problems of water resources use in Central Asia. *Handbook of Environmental Chemistry*, *105*, 77–98. https://doi.org/10.1007/698_2020_601

Zhou, H., Aizen, E., & Aizen, V. (2017). Seasonal snow cover regime and historical change in Central Asia from 1986 to 2008. *Global and Planetary Change*, *148*, 192–216. https://doi.org/10.1016/j.gloplacha.2016.11.011

Zhumanova, M., Wrage-Mönnig, N., & Darr, D. (2016). Farmers' decision-making and land use changes in Kyrgyz Agropastoral systems. *Mountain Research and Development*, *36*(4), 506–517. https://doi.org/10.1659/MRD-JOURNAL-D-16-00030.1

Zhupankhan, A., Tussupova, K., & Berndtsson, R. (2017). Could changing power relationships lead to better water sharing in Central Asia? *Water (Switzerland)*, *9*(2), 1–17. https://doi.org/10.3390/w9020139

Zong, X., Tian, X., & Yin, Y. (2020). Impacts of climate change on wildfires in Central Asia. *Forests*, *11*(8), 802. https://doi.org/10.3390/f11080802

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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