Spatiotemporal changes in water, land use, and ecosystem services in Central Asia considering climate changes and human activities: Postprint

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Abstract

Central Asia is located in the hinterland of Eurasia, comprising Kazakhstan, Uzbekistan, Kyrgyzstan, Turkmenistan, and Tajikistan; over 93.00% of the total area is dryland. Temperature rise and human activities have severe impacts on the fragile ecosystems. Since the 1970s, nearly half the great lakes in Central Asia have shrunk and rivers are drying rapidly owing to climate changes and human activities. Water shortage and ecological crisis have attracted extensive international attention. In general, ecosystem services in Central Asia are declining, particularly with respect to biodiversity, water, and soil conservation. Furthermore, the annual average temperature and annual precipitation in Central Asia increased by 0.30°C/decade and 6.9 mm/decade in recent decades, respectively. Temperature rise significantly affected glacier retreat in the Tianshan Mountains and Pamir Mountains, which may intensify water shortage in the 21st century. The increase in precipitation cannot counterbalance the aggravation of water shortage caused by the temperature rise and human activities in Central Asia. The population of Central Asia is growing gradually, and its economy is increasing steadily. Moreover, the agricultural land has not been expended in the last two decades. Thus, water and ecological crises, such as the Aral Sea shrinkage in the 21st century, cannot be attributed to agriculture extension any longer. Unbalanced regional development and water interception/transfer have led to the irrational exploitation of water resources in some watersheds, inducing downstream water shortage and ecological degradation. In addition, accelerated industrialization and urbanization have intensified this process. Therefore, all Central Asian countries must urgently reach a consensus and adopt common measures for water and ecological protection.

Full Text

Preamble

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Abstract

Central Asia, located in the Eurasian hinterland and comprising Kazakhstan, Uzbekistan, Kyrgyzstan, Turkmenistan, and Tajikistan, is characterized by drylands covering over 93% of its total area. The region' s fragile ecosystems face severe impacts from rising temperatures and intensifying human activities. Since the 1970s, nearly half of Central Asia' s major lakes have shrunk, and rivers are drying rapidly due to the combined effects of climate change and anthropogenic pressures. These water shortages and ecological crises have attracted extensive international attention, with ecosystem services in Central Asia generally declining, particularly in biodiversity, water resources, and soil conservation. Recent decades have witnessed increases in annual average temperature (0.30°C per decade) and annual precipitation (6.9 mm per decade) across the region. While temperature rise has significantly accelerated glacier retreat in the Tianshan and Pamir Mountains—potentially intensifying water scarcity in the 21st century—the modest precipitation increase cannot offset water shortages exacerbated by warming and human activities. Although Central Asia' s population continues to grow gradually and its economy expands steadily, agricultural land area has not increased over the past two decades. Consequently, 21st-century water and ecological crises, such as the Aral Sea shrinkage, can no longer be attributed to agricultural expansion. Instead, unbalanced regional development and water interception/transfer have led to irrational exploitation of water resources in some watersheds, causing downstream water shortages and ecological degradation—a process further intensified by accelerated industrialization and urbanization. Therefore, all Central Asian countries must urgently reach consensus and adopt

common measures for water resource and ecological protection.

Keywords: water resources; land-use changes; ecosystem services; climate change; human activities; Aral Sea

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1 Introduction

Water resources, land use, and ecosystem services are crucial factors determining the quality of sustainable development in arid regions, all of which are profoundly influenced by climate change and human activities. Central Asia, situated in the Eurasian hinterland, hosts one of the world' s most sensitive and vulnerable ecosystems. Its mountain–oasis–desert system holds global importance, with drylands covering over 93% of the total area. As one of the most water-scarce regions globally, Central Asia exhibits the highest per capita water consumption, and the vulnerability of its water resources has become increasingly prominent in recent years, representing a critical constraint on socioeconomic development (Yu et al., 2020). The Aral Sea crisis exemplifies a typical human-induced environmental catastrophe that demands more detailed research and management interventions.

The region comprises five nations: Kazakhstan, Uzbekistan, Kyrgyzstan, Turkmenistan, and Tajikistan. Its landlocked geography impedes moisture flow, resulting in predominantly arid landscapes with sparse precipitation and harsh environmental conditions. The climate exhibits strong continental characteristics with large annual temperature ranges. Instrumental data from over 300 meteorological stations reveal that the annual mean temperature increased at an average rate of 0.30°C per decade from the 1960s to the 2000s, with an even faster rate in the 21st century (Yu et al., 2020). The complex and diverse terrain makes Central Asia one of the world' s most sensitive areas to climate change (Lioubimtseva and Henebry, 2009). Remote sensing analysis indicates that the total area of major lakes in Central Asia decreased by 49.62% over recent decades (Bai et al., 2011), while rivers such as the Amu Darya and Syr Darya are rapidly drying. These changes stem from both climatic and anthropogenic factors, and their cascading effects will significantly impact regional climate systems and human wellbeing.

The region' s topography follows an east-high, west-low pattern, with nearly 98% of river discharge originating from mountainous areas in the east (Yu et al., 2019). The Tianshan and Pamir Mountains serve as Central Asia' s freshwater towers, with glacier and snowmelt providing the primary water supply for seasonal rivers that exhibit high fluctuations and decreasing trends from upstream to downstream. Studies have documented significant glacier retreat in the eastern mountains (Sorg et al., 2012; Duethmann et al., 2014), which will likely exacerbate water shortages across vast areas of Central Asia in coming decades. Within these mountains lie valleys such as the Fergana and Alay Valleys, rivers including the Amu Darya and Syr Darya, deserts like the Karakum and Kyzylkum, and major lakes such as the Aral Sea, Lake Balkhash, and Lake Issyk-Kul. These lakes are primarily fed by mountain-originating rivers, with substantial evaporation losses during long-distance transport.

Human impacts on the environment encompass greenhouse gas emissions, land-use changes, pollution, water consumption and management, and various effects on biodiversity, forests, and dust dynamics. While summarizing all anthropogenic environmental effects in a single study is challenging, numerous investigations have examined different aspects of human influence, revealing both positive and negative outcomes (Yin et al., 2016; Jiang et al., 2017; Gutman et al., 2020). Central Asia is strongly affected by human activities, with unprecedented changes profoundly impacting land use, water resources, and crops (Sokolik et al., 2020). As public awareness of environmental issues grows, more research findings and conservation efforts are being realized. However, uncertainties remain regarding the achievement of land degradation neutrality by 2030 due to pressures from population growth and water scarcity. Currently, major efforts must be undertaken to guarantee environmental sustainability, making the vulnerability and sensitivity of ecosystems a focal point for regional research and policy discussions.

2 Climate Changes in Central Asia

With intensifying global warming, Central Asia' s climate has changed rapidly. Extensive research reveals that the region experienced significant warming throughout the 20th century, with average temperature increases considerably higher than the global average, particularly since the 1960s (Mannig et al., 2013; Hu et al., 2014; Huang et al., 2017). Over the last five decades, Central Asia' s average temperature has risen significantly, especially since the 1980s (Chen et al., 2011). Instrumental data from more than 300 meteorological stations indicate that the annual mean temperature increased at an average rate of 0.30°C per decade from the 1960s to the 2000s, with continued warming in the 21st century [Figure 1: see original paper]. This warming trend is expected to intensify substantially in the future, accompanied by more extreme climate events. Spatially, warming has been more pronounced in northern Central Asia than in southern areas, with the total area experiencing significant warming increasing considerably (Botterill and Hayes, 2012; Li et al., 2015). This warming trend significantly affects glacier retreat, which will certainly induce water shortages and very likely intensify water and ecological crises in the 21st century.

Precipitation, alongside surface temperature, represents a fundamental meteorological and climate variable. Variations in precipitation directly or indirectly affect water–energy exchange among the atmosphere, biosphere, and lithosphere, thereby controlling freshwater supply, food production, disease outbreaks, floods, and droughts (Yatagai et al., 2012; Hu et al., 2016). Central Asia exhibits substantial precipitation gradients, ranging from over 1000 mm/year in eastern mountainous regions (Yang and Du, 2013; Donat et al., 2016) to 200-400 mm/year in central and northern plains, and below 100 mm/year in western arid basins. Overall precipitation across Central Asia showed an increasing trend of 6.6 mm per decade from 1901 to 2013, with regional annual precipitation displaying multidecadal variations (Hu et al., 2017). Generally, precipitation increases have been greater in mountainous regions than in plains and basins. In recent decades, precipitation has increased by 6.9 mm per decade [Figure 1: see original paper]. The increase in summer precipitation in arid Central Asia has been linked to weakening of the East Asian summer monsoon (Chen et al., 2020), while human activities have also contributed noticeably to summer precipitation increases during 1961-2013 (Peng et al., 2018). In most Central Asian regions, precipitation has increased in both summer (primarily as rainfall) and winter (as snow) (Song et al., 2016). Overall, Central Asia has become wetter over the past century.

3 Socioeconomic Development in Central Asia

Statistical data reveal that Central Asia's population has grown gradually while its economy has increased steadily [Figure 2: see original paper]. Although cotton and other cultivation areas expanded significantly from the 1960s to the 1990s (Yu et al., 2019), total agricultural land area has not increased over the past two decades, and crop production has remained stable according to statistical records. Consequently, agriculture expansion can no longer be blamed for water and ecological crises such as the Aral Sea shrinkage in the 21st century. Instead, unbalanced regional development and water interception/transfer have caused irrational exploitation of water resources in some watersheds, leading to downstream water shortages and ecological crises. This phenomenon is typical in arid river basins, such as the Tarim River Basin in Northwest China (Yu et al., 2017). Effective ecological restoration measures require unified water resources management and conservation at the basin-wide scale, necessitating urgent consensus and coordinated action among stakeholders.

Between 2000 and 2020, Central Asia's population grew steadily, with annual average growth rates of 1.30% in Kazakhstan, 1.94% in Uzbekistan, 1.73% in Kyrgyzstan, 1.68% in Turkmenistan, and 2.67% in Tajikistan. The region remains a vast territory with sparse population density (less than 19 people/km^2), particularly in Kazakhstan (less than 7 people/km^2). The total area of agricultural lands—including cultivated land, pasture, gardens, fishponds, and all facilities used for agricultural production—has remained stable in Kazakhstan and Tajikistan, with slight decreases in Uzbekistan, Kyrgyzstan, and Turkmenistan. Forest areas have increased slightly, particularly in Uzbekistan (1.03% annual increment). Meanwhile, increases in CO_2 emissions and gross domestic product (GDP), coupled with decreases in the GDP added value from agriculture, forestry, and fishing, indicate accelerated industrialization and urbanization across Central Asia. To avoid imbalance between economic development and ecological protection, environmental issues must receive greater attention with increased relevant investment.

4.1 Water Shortage and Land Degradation

Growing populations, agricultural demands, and industrial development have intensified freshwater shortages in Central Asia. Current research on water resources in Central Asian countries has primarily focused on runoff dynamics (Chen et al., 2018), climatic responses (Chen et al., 2017; Kobuliev et al., 2021), and water crisis management (Zhang et al., 2020). Zhang et al. (2014) reported that Turkmenistan faces dramatically increasing water resource pressure due to the water footprint of agriculture and animal husbandry, with ecological security of water resources becoming increasingly crucial. Ma et al. (2021) analyzed spatiotemporal characteristics of crop water footprints in the five Central Asian countries from 1992 to 2017 using crop water footprint assessment methods, revealing that green water footprint changes mirrored cultivation area variations with an overall decreasing trend, while the blue water footprint also tended to decline. They concluded that cereals dominate the green water footprint of crops in Central Asia, while cereals and oil crops constitute the main blue water footprint. Huang and Wang (2021) calculated water footprints, water consumption, and relative state transition probabilities for major food crops in the five Central Asian countries using CROPWAT models, kernel density estimation, and Markov chains, predicting water consumption state transition probabilities through 2042. Their findings identified wheat as the most water-intensive crop across all five countries, with variations in the second-most water-intensive crops.

A structural water transfer scheme has emerged in Central Asia based on remote sensing data and hydrological modeling analysis. While water storage shows an increasing trend in northeastern Kazakhstan, the Aral Sea region exhibits a clear decreasing trend. Remote sensing analysis reveals that the Aral Sea has been shrinking at an average rate of 1,000 km^2 per year over recent decades. Water resources have generally been transferred from west to east and from lower reaches to middle and upper reaches, primarily through river closure (reservoirs) and diversion (irrigation) in upstream areas. This transferred water supports regional agricultural and industrial development while causing downstream water shortages. This pattern suggests that irrational upstream exploitation of water resources has induced downstream ecological crises, indicating unsustainable development across Central Asian countries. The consequences of downstream water shortage and ecological degradation cannot be compensated by economic growth. Increased salt dust, sand dust, and extreme weather events will cause long-term damage to human health. The primary persistent sources of dust storms originate from the Aral Sea region, deserts north of the Caspian Sea, areas south of Lake Balkhash, and southern deserts (Indoitu et al., 2012). These frequent water-scarce regions contain highly sensitive ecosystems that require additional water resources rather than further diversion.

The water crisis is closely linked to land degradation in arid regions. Central Asia has experienced complex land-use changes since the collapse of the Soviet Union, including land abandonment and reclamation (Hamidov et al., 2016). Major land-use conversions include: (1) transformation of farmlands to grasslands or urban areas in some regions, (2) conversion of grasslands to farmlands or urban areas in other regions, and (3) transformation of waterbodies to grasslands or sparsely vegetated areas. In arid regions, vast grazing areas have degraded due to climate change and human activities (Han et al., 2016), particularly in the lower reaches of the Amu Darya and Syr Darya river basins (Djanibekov et al., 2018; Zhou et al., 2019). Generally, no significant changes have occurred in the total areas of cropland, forestland, and grassland across Central Asia in the 21st century. The most severe land degradation has occurred in the Aral Sea Basin and northern Kazakhstan due to regional agricultural reclamation, overgrazing, and water shortages (Han et al., 2018; Li et al., 2019). Soil degradation is also evident in these arid and semi-arid regions due to intensive tillage, irrigation water mismanagement, and cropping practices (Nurbekov et al., 2016). Reducing crop water stress and improving soil quality remain herculean tasks for local farmers, while preventing soil and vegetation degradation represents a crucial responsibility for governments and decision-makers.

4.2 Decline of Ecosystem Services

Ecosystem services form the basis of human survival and development and are crucial for sustainable ecosystem development (Costanza et al., 1997; Daily et al., 2000). They serve as a connection between humans and nature, bridging the gap between scientific research and management decisions (Fu et al., 2013), and are instrumental in maintaining the dynamic balance between Earth' s life support systems and the environment. Optimizing ecosystem services at the regional scale represents a scientific pathway to achieving sustainable development (Fu et al., 2014).

Literature search results indicate that early research on ecosystem services in Central Asia was conducted by Chen et al. (2013), focusing on ecologically vulnerable areas including land use and land cover changes, net primary productivity, actual evapotranspiration, and crop production. Another research group subsequently conducted 11 ecosystem service studies in Central Asia. Based on literature review and change analysis , research outcomes indicate that ecosystem service hotspots primarily focus on land-use changes (Chen et al., 2013; Shan et al., 2013), value assessment (Li et al., 2019), climate change impacts (Li et al., 2020), biodiversity (Thevs et al., 2017), tradeoffs and synergies (Mashizi et al., 2019), and scientific research for decision-making and management (Saraswat et al., 2015).

Table 1 Ecosystem service studies in Central Asia

Study area	Ecosystem type	Category of ES studies	Methodology/Tool	Reference
Central Asia	Mixed ecosystems	Net primary productivity, actual evapotranspiration, and crop production	Global production efficiency model	Chen et al. (2013)
Kyrgyz Republic	Mixed ecosystems	Economic valuation	Evaluation method based on money supply, contribution rate analysis, and sensitivity analysis	Shan et al. (2013)
Turkmenistan	Mixed ecosystems	Economic valuation	Questionnaire	Yao et al. (2014)
Kyrgyz Republic	Mixed ecosystems	Payment of ecosystem services	RapidEye and Landsat satellite images	Saraswat et al. (2015)
Tajikistan	Forest ecosystem	Provisioning, regulating, supporting, and cultural services	GIS, CA-Markov model, and IDRISI	Mislimshoeva et al. (2016)
Ili Delta	Wetland and catchment ecosystems	Provisioning, regulating, habitat, and cultural services	InVEST and ArcGIS	Thevs et al. (2017)
Central Asia	Mixed ecosystems	Service function of vegetation ecosystem	RUSLE, revised wind erosion equation, and CASA	Li et al. (2019)
Baghbazm Basin	Semi-arid watershed	Provisioning, regulating, supporting, and cultural services	InVEST and ArcGIS	Mashizi et al. (2019)
Central Asia	Mixed ecosystems	Forage production, water yield, carbon stock, soil retention, and soil formation	PSO-SOFM	Li et al. (2020)

Study area	Ecosystem type	Category of ES studies	Methodology/Too	Reference
Central Asia	Mixed ecosystems	Soil conservation, sand fixation, and net primary productivity	Revised wind erosion equation and CASA	Yan et al. (2021)

Note: ES, ecosystem service; InVEST, Integrated Valuation of Ecosystem Services and Tradeoffs; RUSLE, Revised Universal Soil Loss Equation; CASA, Carnegie–Ames–Stanford Approach; PSO-SOFM, Particle Swarm Optimization-Self-Organizing Feature Map.

According to Li et al. (2019), waterbodies, croplands, and grasslands accounted for over 90% of Central Asia' s total ecosystem service value from 1995 to 2035. However, water area decreased sharply by 38.34% during this period, resulting in a loss of $64.38 billion. Specifically, from 1995 to 2015, cropland ecosystem service value increased by approximately $67.89 billion. The most crucial ecosystem service functions in Central Asia are biodiversity (40.03% of total value in 2015), food production (29.47%), and water regulation (10.21%). From 1995 to 2015, the ecosystem service value of water regulation declined fastest (-12.70%), followed by gas regulation (-3.00%), while cultural, tourism, and biodiversity services decreased by -3.00%, -3.14%, and -0.29%, respectively. In contrast, the ecosystem service values of grain production, raw materials, climate regulation, soil formation, and waste treatment increased by 4.87%, 7.92%, 12.11%, 12.01%, and 2.91%, respectively (Li et al., 2019).

Spatially, ecosystem service value in Central Asia is typically high in the southeast and low in the northwest, decreasing along the mountain–oasis–desert gradient. All categories of ecosystem services—provisioning, regulating, supporting, and cultural—decreased to varying degrees from 2000 to 2015. Vegetation carbon sequestration and soil conservation areas decreased significantly, accounting for 84.81% and 84.82% of Central Asia' s total area, respectively. Water supply and conservation areas accounted for 69.48%, while biodiversity protection areas accounted for 19.80%, likely related to unreasonable development of regional land resources (Yan et al., 2021).

5 Discussion and Conclusions

Central Asia has become warmer and wetter over the past century. Although climate conditions vary greatly from mountainous regions to plains and basins, the general trend is now clear: annual average temperature and precipitation have increased by 0.30°C per decade and 6.9 mm per decade, respectively, in recent years. Temperature rise has significantly accelerated glacier retreat in the Tianshan and Pamir Mountains, which may intensify water shortages in the 21st century. However, increased precipitation cannot counterbalance water scarcity aggravated by warming and human activities. In vast arid regions, increased precipitation primarily enhances evapotranspiration rather than generating surface runoff. Furthermore, upstream water transfer through river closure and diversion has exacerbated downstream water shortages, resulting in severe soil erosion and ecological crises. Therefore, ecological water requirements must be guaranteed first throughout entire river basins, requiring integrated water resources management across national borders. Typically, ecosystem services in Central Asia are declining, particularly regarding biodiversity, water, and soil conservation.

Central Asia' s population and economy continue to grow gradually in the 21st century, yet total agricultural land area has not expanded. Water interception and transfer have caused downstream water crises and ecological degradation, while accelerated industrialization and urbanization have intensified this process. Thus, regional overexploitation rather than insufficient total water resources has driven the Aral Sea shrinkage. Two perspectives exist regarding this shrinkage. International scholars view it as a severe ecological crisis over the past 60 years, prompting major concerns and criticism. Conversely, some local experts argue that the Aral Sea' s disappearance has minimal impact on animals, plants, and particularly humans in neighboring villages, suggesting that fully utilizing freshwater resources upstream of the Amu Darya and Syr Darya rivers has enabled flourishing agriculture and ecosystems in oases. This raises critical questions: Is diverting freshwater to the Aral Sea wasteful? What will happen if the Aral Sea vanishes? How can we address this dilemma? Our further investigation of ecosystem changes in the Aral Sea region reveals that most ecosystem services are declining, with water-regulated ecosystem service value decreasing most dramatically (-48.07%), followed by recreation, cultural, and tourism services (-15.97%) and waste treatment (-15.78%). The value of ecosystem services in the Aral Sea decreased by $40.54 billion between 1993 and 2018, primarily due to the rapid decline in waterbody proportion. The potential future loss to the ecological environment is difficult to estimate, but evaluating these ecosystem services represents the first step toward determining losses from environmental degradation and planning future actions. Ecological degradation in Central Asia is widespread, long-term, and detrimental, making it unwise and unsustainable to trade ecology for economy.

Ecological disasters such as the Aral Sea shrinkage are directly linked to the lack of motivation and cohesive governance among Central Asian countries. For historical and practical reasons, the parties maintain numerous divergences regarding cross-border water rights. While building a dam to separate the Aral Sea' s waterbody is considerably easier than constructing a wall to divide the regional climate, cooperation remains the only viable solution. Since the beginning of the 21st century, the Chinese Academy of Sciences and Central Asian countries have established a water-ecological monitoring network in Central Asia' s major lakes, constructing over 80 real-time monitoring stations for continuous surveillance of water and ecological conditions in regional watersheds. This network will provide data support for future optimal allocation of water resources and sustainable development of the water-ecology-society nexus across the entire region. Water use efficiency in Central Asia remains generally low, though most researchers and stakeholders agree that developing water-saving irrigation will benefit the entire region. Applications of drip irrigation, seepage control, and other technologies are rapidly advancing, while government management and public awareness are also improving significantly in the 21st century. Additionally, scientific research and local practice must be better integrated to benefit the entire region.

Central Asia has served as a link between East Asia and Europe since ancient times and has now become a pivotal area along the "Silk Road Economic Belt." The region' s environment and development have consistently been major concerns for international organizations, including the Shanghai Cooperation Organization (SCO) and the Alliance of International Science Organizations (ANSO). Coordinated development of society, economy, and environment in Central Asia represents the common goal of all five countries and other stakeholders.

As no integrated hydrological and ecological monitoring system has been established in Central Asia, considerable data remain imperfect due to historical reasons, and relevant research is relatively limited. However, geoscience, economic, and social science studies in Central Asia have recently gained popularity. With increased attention and effort, a path to sustainable development will ultimately be identified and established.

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Note: Figure translations are in progress. See original paper for figures.