Ecological Problems and Ecological Restoration Zoning of the Aral Sea Postprint

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Date: 2024-03-13T00:00:00+00:00

Abstract

The Aral Sea was the fourth largest lake in the world but it has shrunk dramatically as a result of irrational human activities, triggering the “Aral Sea ecological crisis” . The ecological problems of the Aral Sea have attracted widespread attention, and the alleviation of the Aral Sea ecological crisis has reached a consensus among the five Central Asian countries (Kazakhstan, Uzbekistan, Tajikistan, Kyrgyzstan, and Turkmenistan). In the past decades, many ecological management measures have been implemented for the ecological restoration of the Aral Sea. However, due to the lack of regional planning and zoning, the results are not ideal. In this study, we mapped the ecological zoning of the Aral Sea from the perspective of ecological restoration based on soil type, soil salinity, surface water, groundwater table, Normalized Difference Vegetation Index (NDVI), land cover, and aerosol optical depth (AOD) data. Soil salinization and salt dust are the most prominent ecological problems in the Aral Sea. We divided the Aral Sea into 7 first-level ecological restoration subregions (North Aral Sea catchment area in the downstream of the Syr Darya River (Subregion I); artificial flood overflow area in the downstream of the Aral Sea (Subregion II); physical/chemical remediation area of the salt dust source area in the eastern part of the South Aral Sea (Subregion III); physical/chemical remediation area of severe salinization in the central part of the South Aral Sea (Subregion IV); existing water surface and potential restoration area of the South Aral Sea (Subregion V); Aral Sea vegetation natural recovery area (Subregion VI); and vegetation planting area with slight salinization in the South Aral Sea (Subregion VII)) and 14 second-level ecological restoration subregions according to the ecological zoning principles. Implementable measures are proposed for each ecological restoration subregion. For Subregion I and Subregion II with lower elevations, artificial flooding should be carried out to restore the surface of the Aral Sea. Subregion III and Subregion IV have severe salinization, making it difficult for vegetation to grow. In these subregions, it is recommended to cover and pave the areas with green biomatrix coverings and environmentally sustainable bonding materials. In Subregion V located in the central and western parts of the South Aral Sea, surface water recharge should be increased to ensure that this subregion can maintain normal water levels. In Subregion VI and Subregion VII where natural conditions are suitable for vegetation growth, measures such as afforestation and buffer zones should be implemented to protect vegetation. This study could provide a reference basis for future comprehensive ecological management and restoration of the Aral Sea.

Full Text

Preamble

Ecological Problems and Ecological Restoration Zoning of the Aral Sea

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Abstract: The Aral Sea was once the world' s fourth-largest lake but has shrunk dramatically due to irrational human activities, triggering the "Aral Sea ecological crisis." This crisis has attracted widespread international attention, and alleviating it has become a consensus among the five Central Asian countries (Kazakhstan, Uzbekistan, Tajikistan, Kyrgyzstan, and Turkmenistan). Over the past decades, numerous ecological management measures have been implemented for Aral Sea restoration. However, the lack of regional planning and zoning has yielded unsatisfactory results. This study mapped ecological restoration zones for the Aral Sea based on soil type, soil salinity, surface water, groundwater table, Normalized Difference Vegetation Index (NDVI), land cover, and aerosol optical depth (AOD) data. Soil salinization and salt dust storms represent the most prominent ecological problems. We divided the Aral Sea into seven first-level ecological restoration subregions: (I) North Aral Sea catchment area in the downstream of the Syr Darya River; (II) artificial flood overflow area in the downstream of the Aral Sea; (III) physical/chemical remediation area of the salt dust source area in the eastern part of the South Aral Sea; (IV) physical/chemical remediation area of severe salinization in the central part of the South Aral Sea; (V) existing water surface and potential restoration area of the South Aral Sea; (VI) Aral Sea vegetation natural recovery area; and (VII) vegetation planting area with slight salinization in the South Aral Sea. These were further subdivided into 14 second-level subregions according to ecological zoning principles. Implementable measures are proposed for each subregion. For Subregions I and II with lower elevations, artificial flooding should restore the Aral Sea surface. Subregions III and IV suffer severe salinization that inhibits vegetation growth; these areas should be covered with green biomatrix coverings and environmentally sustainable bonding materials. In Subregion V, located in the central and western South Aral Sea, surface water recharge should be increased to maintain normal water levels. In Subregions VI and VII, where natural conditions favor vegetation growth, afforestation and buffer zones should protect existing vegetation. This study provides a reference basis for future comprehensive ecological management and restoration of the Aral Sea.

Keywords: ecological restoration zoning; salt and dust storms; soil salinization; ecological crisis; Aral Sea; Central Asia

Citation: BAO Anming, YU Tao, XU Wenqiang, LEI Jiaqiang, JIAPAER Guli, CHEN Xi, Tojibaev KOMILJON, Shomurodov KHABIBULLO, Xabibullaev B SAGIDULLAEVICH, Idirisov KAMALATDIN. 2024. Ecological problems and ecological restoration zoning of the Aral Sea. *Journal of Arid Land*, 16(3): 315-330. https://doi.org/10.1007/s40333-024-0055-6

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1 Introduction

The Aral Sea lies in the arid region of Central Asia. Its name derives from the Turkish word "aral," meaning island (Glantz, 2007). The Aral Sea region was part of the ancient Silk Road, facilitating trade and cultural exchange between East and West. The area has a long history of irrigated agriculture, and ancient civilizations such as Ferghana and Bukhara developed closely alongside irrigation culture (Andrianov and Mantellini, 2016). Once the world' s fourth-largest lake (Micklin, 2010), the Aral Sea has experienced dramatic shrinkage since the 1960s due to land reclamation and water diversion from the Karakum Canal for desert irrigation, creating the globally recognized "Aral Sea ecological crisis" (Micklin, 1988; Indoitu et al., 2015).

Currently, the Aral Sea' s area has shrunk by approximately 90%, and the ecological crisis continues to worsen (Micklin, 2007; Yang et al., 2020). Ecosystem destruction has reduced soil and water conservation capacity and caused significant vegetation degradation (Xu et al., 2016; Jiang et al., 2020). Reduced water volume has increased salinity, causing mass mortality and extinction of aquatic organisms (Qadir et al., 2009). Between 1961 and 1978, as salinity rose sharply, carp catches plummeted from 9,940 to 100 tonnes (Ermakhanov et al., 2012), and when salinity exceeded 18 g/L, the Aral Sea completely lost its fishery (Ermakhanov et al., 2012). Worse still, accumulated salts and high winds have transformed the dried seabed into a source of salt and dust storms, seriously endangering local residents' health and livelihoods (Indoitu et al., 2015; Chen et al., 2022; Wang et al., 2022). In Turkmenistan, 50% of reported childhood illnesses are respiratory, potentially linked to Aral Sea salt dust (UNDP, 1995). Effective ecological management requires restoration zoning and targeted, implementable plans.

The Aral Sea' s environmental deterioration has drawn widespread international attention, and alleviating the crisis has become a priority for Central Asian countries (Kotlyakov, 1991; Horst et al., 2005; Micklin and Aladin, 2008; Wang et al., 2023a). Over recent decades, numerous ecological management measures have been implemented. In 2008, the German Agency for Technical Cooperation (GTC) collaborated with Uzbekistan' s Forestry Research Institute to plant black saxaul (*Haloxylon aphyllum*) in the central dry regions to reduce dust (Xenarios et al., 2019). Kazakhstan built the Kok-Aral dam to restore the North Aral Sea and developed measures to reduce industrial effluent discharge (Micklin, 2016; Rzymski et al., 2019). However, previous measures failed to consider spatial variability of ecological problems and lacked regional planning, resulting in continued environmental deterioration. Effective management requires ecological restoration zoning with targeted, implementable plans.

Ecological restoration zoning is part of ecological zoning, first proposed by Bailey (1976) in the United States. Since then, researchers worldwide have extensively discussed zoning principles, indicators, and methods (Fischer et al., 2021; Xu et al., 2022). Ecological zoning research has evolved rapidly, shifting from issue-oriented approaches based on natural zoning and ecological problem severity to restoration zoning for specific issues (Liu et al., 2017; Xu et al., 2022). Ecological restoration zoning emphasizes identifying key ecological problems and proposing restoration measures based on ecosystem degradation status and restoration potential. With advances in remote sensing and GIS technologies, spatial analysis and mapping have been widely applied to ecological restoration zoning for salinization control and desertification restoration (Akbari et al., 2020), providing technical support for regional ecological management.

This study maps the Aral Sea' s ecological governance regions to provide a reference for the Aral Sea and similar regions worldwide. Using remote sensing and GIS technologies combined with satellite imagery, surface water, groundwater table, soil salinity, soil type, vegetation distribution, land cover, and aerosol optical depth (AOD) data, we mapped ecological restoration subregions and proposed implementable measures for each. The results aim to provide scientific guidance for future Aral Sea ecological governance and restoration.

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2 Study Area

The Aral Sea lies between Kazakhstan and Uzbekistan (43°13 –46°56 N, 57°56 – 62°18 E) and is primarily fed by the Amu Darya and Syr Darya rivers [Figure 1: see original paper]. As the terminal lake of both rivers, it is Asia's second-largest inland saltwater lake after the Caspian Sea (Micklin, 2010). The region has a typical continental climate with annual precipitation below 100 mm. February temperatures average -12°C in the north and -6°C in the south, while July temperatures average 23°C in the north and 26°C in the south (Boomer et al., 2000; Shibuo et al., 2007). Until the 1960s, evaporation approximately equaled inflow (Cretaux et al., 2013; Wang et al., 2023b). Currently, most of the Aral Sea has disappeared, splitting into the South Aral Sea in Uzbekistan and the North Aral Sea mainly in Kazakhstan. In 1993, the five Central Asian countries established the Interstate Commission for Water Coordination (ICWC) and the International Fund for Saving the Aral Sea (IFAS) to manage the crisis.

3.1 Data Sources

The Aral Sea' s most prominent ecological problems involve soil salinization and salt-dust storms in arid regions (Abuduwaili et al., 2010; Shen et al., 2016). Salt-dust storms relate to both soil salinization and soil type, as dry sandy soils are more prone to dust emission (Stulina and Sektimenko, 2004). Groundwater table critically affects vegetation growth; declining water tables cause vegetation degradation or death and represent a prerequisite for vegetation recovery. This study' s data therefore included soil salinity, soil type, groundwater table, land cover, and field survey data. Soil salinity, soil type, and groundwater table were obtained by vectorizing thematic maps from the United Nations Environment Programme (UNEP) in 2008 (Dukhovny et al., 2008). Land cover data (30-m resolution) for 1990 and 2018, along with field survey data (salinization, vegetation type, etc.) from 2018–2019, were obtained from the Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences. Twenty field samples from two survey sites investigated the ecological environment status. Land use types were classified into six categories: shrubland, grassland, wetland, bare land, salt marsh, and water body (Shen et al., 2016; Yu et al., 2021). MODIS AOD data (1-km resolution) from 2000 and 2018 revealed salt dust spatial distribution. Landsat TM and OLI imagery calculated NDVI and Normalized Difference Water Index (NDWI). Areas with NDVI<0.2 were defined as lacking vegetation cover, and NDVI$ $0.2 as having vegetation cover (Sobrino et al., 2001; Momeni and Saradjian, 2007). NDWI determined existing water surfaces. The digital elevation model (DEM) was generated from ZiYuan-3 satellite data. Data details are listed in Table 1 .

3.2 Principles of Zoning

Ecological restoration zoning should follow established principles to ensure rationality and effectiveness. Widely used principles include geographical unit integrity, dominant factors, and consistency of control strategies (Allen et al., 2002; Wang et al., 2020). The geographical unit integrity principle emphasizes high similarity in ecological problem occurrence and development within the same unit, helping effectively identify regional ecological problems. The dominant factor principle requires clarifying the primary drivers of ecological problems in each region to formulate targeted restoration measures. The consistency of control strategies principle demands relatively uniform governance measures within each zoning unit, ensuring zoning rationality and practicality.

3.3 Methods of Zoning

This study divided the Aral Sea into two hierarchical levels of ecological restoration subregions. First, indicators reflecting ecological status were selected based on previous research (Di et al., 2008, 2009), including salinization, vegetation cover (via NDVI), sand-dust storms, existing water surface (via NDWI), land cover, and soil type. Using GIS spatial analysis and referencing previous zoning methods (Zhao et al., 2013), we visualized and overlaid these indicator layers to identify dominant ecological problem factors through visual interpretation. Following zoning principles and regional dominant factors, we determined and adjusted boundaries to form first-level subregions. Since the Aral Sea is a transboundary lake shared by Uzbekistan and Kazakhstan, we further subdivided first-level zones into second-level zones along the national boundary to reduce conflicts of interest.

4.1 Main Ecological Problems in the Aral Sea

The Aral Sea is primarily supplied by the Amu Darya and Syr Darya rivers. Irrational water usage accounts for 86% of the sea' s retreat, while climate change contributes only 14% (Bekzod et al., 2021). During the Soviet era, numerous reservoirs, hydroelectric stations, and aqueducts were built on both rivers. The Karakum Canal, Turkmenistan' s "lifeblood," is the largest diversion project on the Amu Darya, serving 60% of Turkmenistan' s population. It withdraws 19.0$×10^{9}$ m^{3} annually—approximately 33% of the Amu Darya' s total volume (Spoor, 1998). Additionally, the Karshi Irrigation Canal diverts 3.3$×10$^{\{9\}-5.25\times10}${9}$ m^{3} yearly. Figure 2 [Figure 2: see original paper] shows the Aral Sea' s area declining from 57.0$×10^{3}$ to 9.29$×10^{3}$ km^{2} between 1974-2020, averaging -1.04$×10^{3}$ km^{2}/a. Dramatic changes concentrated in the South Aral Sea (Fig. 2a) because the central water area remains dynamically unstable. Currently stabilized water areas include the North Aral Sea in northern Kazakhstan and a small portion of the South Aral Sea in western Uzbekistan. Excessive water diversion during 1974-2020 left the Syr Darya and Amu Darya deltas with no surplus water, causing their deltaic networks to gradually disappear and 95% of marshes and wetlands to degrade into saline deserts (Rudenko and Lamers, 2010; Jiang et al., 2019).

Over the past 60 years, drying areas have experienced vegetation succession, with dominant vegetation shifting from hydrophytic to xerophytic types (Liliya, 2015; Shomurodov et al., 2021). Land cover changes from 1990–2018 (Figs. 3a and 3b [Figure 3: see original paper]) show that despite grassland area increases, most dry areas degraded to salt marsh (26.81$×10^{3}$ km^{2}) and bare land (23.40$×10^{3}$ km^{2}). NDVI patterns indicate high vegetation coverage in the Amu Darya delta in the southern Aral Sea (Figs. 3c and 3d), where grassland dominates (Figs. 3a and 3b). Compared to 1990, the lower dry region of the North Aral Sea evolved into a vegetation-suitable area by 2018, with sparse vegetation distribution.

Vegetation distribution and succession closely relate to hydrological regime changes and soil salinity (Liliya, 2015). We generated a soil salinity map (Fig. 4a [Figure 4: see original paper]) using FAO salinity classification criteria (FAO, 2005) and 2008 UNEP survey data (Dukhovny et al., 2008). Severe salinization and salt soils occur mainly in the central Aral Sea’ s low-lying terrain (Fig. 4b), where salt soil and salt marsh dominate (Fig. 4c). Slight salinization areas concentrate in the southern North Aral Sea’ s higher terrain, where meadow soil prevails. Non-salinized areas occur in the southern and northern Aral Sea, specifically in the Amu Darya and Syr Darya delta downstreams. Soil salinization correlates closely with groundwater table; shallower groundwater generally means greater salinization. Figure 4d shows shallow groundwater (0.0–1.0 m) in the central Aral Sea and deeper groundwater (>5.0 m) in the east.

Aral Sea drying increased water salinity from 9 g/L in 1957 to over 70 g/L in 2003 (Micklin, 2010). The dried seabed became saline wasteland and a new sand-dust source. Wind-driven salt-sand (dust) storms dispersed large salt quantities into surrounding areas, causing gradual desertification around the Aral Sea. This desertification led to land function loss and wind transport of toxic salt dust to deltas, exacerbating Central Asian agricultural land salinization (Indoitu et al., 2015; Issanova et al., 2015; Liu et al., 2020). Salt- and toxic-element-laden dust storms disrupted livestock and agricultural production, increasing respiratory disease risks in the Amu Darya delta (Crighton et al., 2011; Jiang et al., 2020). Higher AOD indicates more frequent sand-dust storms. Figure 5 [Figure 5: see original paper] shows AOD spatial distributions for 2000 and 2018, revealing a significant increasing trend. In 2018, high AOD values occurred mainly in the central Aral Sea, where saline and desert soils are distributed (Figs. 4c and 5b).

Declining water levels, shrinking surfaces, and substrate changes affected water-heat exchange and weakened the Aral Sea’ s climate-regulating function. Regional climate conditions have changed, with summers becoming shorter, drier, and hotter, and winters longer and colder (He et al., 2022). Groundwater table decline has further exacerbated drought. Extensive irrigation caused land salinization, while pesticides and fertilizers polluted drainage systems, degrading surface and groundwater quality. This polluted water enters local residents’ drinking water systems through various pathways, endangering human health

(Kulmatov et al., 2021). Species diversity has also suffered, with six animal species or subspecies disappearing, over 20 becoming rare, and 30 bird species vanishing from the Amu Darya delta between 1960-2000 (Zadereev et al., 2020).

4.2 First-Level Zoning of Ecological Restoration

First-level zoning divided the study area into seven subregions (Fig. 6 [Figure 6: see original paper]). The largest are the Aral Sea vegetation natural recovery area (Subregion VI, 22.06×10^{3} km^{2}) and the existing water surface and potential restoration area in the South Aral Sea (Subregion V, 12.16×10^{3} km^{2}). Next are the artificial flood overflow area (Subregion II, 9.26×10^{3} km^{2}), North Aral Sea catchment area (Subregion I, 7.54×10^{3} km^{2}), and vegetation planting area with slight salinization (Subregion VII, 7.18×10^{3} km^{2}). The smallest are the physical/chemical remediation areas: salt dust source area in the eastern South Aral Sea (Subregion III, 5.19×10^{3} km^{2}) and severe salinization area in the central South Aral Sea (Subregion IV, 4.32×10^{3} km^{2}).

4.3 Second-Level Zoning of Ecological Restoration

Based on first-level zoning, we further divided the Aral Sea into 14 second-level subdivisions. Following national boundaries, Subregion II split into Subregion II-1 (Kazakhstan, 6.23×10^{3} km^{2}) and II-2 (Uzbekistan, 3.02×10^{3} km^{2}) (Table 2). Subregion III-1 (Kazakhstan) covers 4.21×10^{3} km^{2}, while III-2 (Uzbekistan) is smaller (0.98×10^{3} km^{2}). Subregion IV divided into IV-1 (Kazakhstan) and IV-2 (Uzbekistan), with IV-2 being larger (4.16×10^{3} km^{2}), indicating more severe salinization in Uzbekistan' s Aral Sea region. Subregion V split into V-1 (Uzbekistan) and V-2 (Kazakhstan). Subregion VI divided into three subdivisions: VI-1 (Kazakhstan) and VI-2 (Uzbekistan) are high-topography sandy areas that have been dry long-term but still preserve some desert vegetation according to field surveys and NDVI monitoring; VI-3 (Uzbekistan) lies in the Amu Darya downstream with abundant water resources and good vegetation growth. Subregion VII divided into two subdivisions, primarily in Uzbekistan (VII-2), with a smaller area in Kazakhstan (VII-1).

4.4 Ecological Restoration Measures

Drawing from desertification control experience in China' s Tarim River Basin (Yu et al., 2022) and considering local hydrological conditions, salinization degree, and vegetation distribution in each second-level subregion, we propose the following zonal restoration measures (Fig. 7 [Figure 7: see original paper]).

Subregion I (North Aral Sea catchment area in the Syr Darya downstream) receives Syr Darya recharge in the north, has slight salinization, and high vegetation coverage. Recent water storage dam construction in Kazakhstan has restored North Aral Sea surfaces (Wang et al., 2023b). We recommend using artificial floods to recharge Subregion II-1 while maintaining current North Aral Sea water levels.

Subregion II (artificial flood overflow area in the Aral Sea downstream) lies mainly in the southern North Aral Sea and southern South Aral Sea, with low topography and high vegetation coverage. Numerous depressions intercept surface runoff from the lower Amu Darya and Syr Darya, severely reducing Aral Sea inflow. This subregion can be restored through artificial flooding. Subregion II-1 (Kazakhstan) still contains small water bodies and wetlands in the Syr Darya downstream, restorable through Syr Darya water diversion or flood irrigation. Subregion II-2 (Uzbekistan) has extensive wetlands and tributary systems in the lower Amu Darya; artificial flood relief could protect these deltaic water networks. Artificial flooding should occur during water-abundant periods to minimize conflicts with irrigated agriculture.

Subregion III (physical/chemical remediation area of the salt dust source area in the eastern South Aral Sea) lies mainly in the eastern South Aral Sea with severe soil salinization, featuring both dried saline-alkali soil and dry sandy soil. Dried saline-alkali soil easily generates extremely harmful salt dust. High soil salinity prevents vegetation growth, classifying this as a physical/chemical technical restoration area (Kim et al., 2020). We recommend covering surfaces with green bio-matrix coverings and environmentally sustainable bonding materials; soybean-derived urease adsorbents can absorb salt dust while being soil-degradable (Wu et al., 2020).

Subregion IV (physical/chemical remediation area of severe salinization in the central South Aral Sea) lies mainly in the lakeshore area with shallow groundwater and high soil salinity. Predominantly saline-alkali soil prevents vegetation growth, making this a physical/chemical technology remediation area. The second-level subdivisions (IV-1 in Kazakhstan and IV-2 in Uzbekistan) could be physically covered with high-density gravels to prevent salt dust formation as saline soils dry.

Subregion V (existing water surface and potential restoration area of the South Aral Sea) lies mainly in the central and western South Aral Sea. The western part still contains large, relatively stable water surfaces, while the central part has some water surface but experiences considerable groundwater and surface water dynamics (Yang et al., 2020; Huang et al., 2022). Surrounding exposed areas have extremely high soil salinity that prevents vegetation survival, classifying this as a potential water surface restoration area. Buffer zones could be established in Subregion V-1 (Kazakhstan) and V-2 (Uzbekistan) to minimize human activity disturbance (e.g., tourism) to water surface restoration. Surface water recharge should increase during drought years to maintain normal water levels.

Subregion VI (Aral Sea vegetation natural recovery area) lies mainly in the eastern and southeastern Aral Sea Basin. This high-topography area was the first to dry up and has low salinization (Bekzod et al., 2021; Wang et al., 2021). Vegetation coverage is higher in Subregions VI-1 (Kazakhstan), VI-2 (Uzbekistan), and VI-3 (Uzbekistan). Therefore, Subregion VI can be designated for natural vegetation restoration. In VI-1 and VI-2, forest belts with barrier effects can be established for natural conservation. To address desert water shortage, groundwater can replace surface water for vegetation irrigation, reducing secondary salinization and ensuring vegetation growth. Subregion VI-3 has abundant water resources, allowing localized groundwater extraction to sustain vegetation.

Subregion VII (vegetation planting area with slight salinization in the South Aral Sea) lies mainly in the central South Aral Sea with high topography, low salinization, and shallow groundwater. Soil types are primarily residual meadow soil and swampy salt soil. Although some vegetation exists, coverage is low. In Subregions VII-1 (Kazakhstan) and VII-2 (Uzbekistan), some salt-tolerant desert species can be planted.

4.5 Implications and Initiatives

Since the 1960s, rapid agricultural development in the Aral Sea Basin has caused pronounced declines in water depth, area, and volume (Boomer et al., 2000), leading to ecological deterioration such as Amu Darya delta degradation (Yu et al., 2019) and increased soil salinization and desertification (Jiang et al., 2019; Yu et al., 2021). The Aral Sea’ s ecological problems represent “the most worrying ecological disaster” in Central Asia, serving as a warning for sustainable development in arid regions. Northwest China and the Aral Sea Basin are both arid/semi-arid regions with similar climates and ecosystems extremely sensitive to climate change and human activities. During water resource development in China’ s inland river basins, attention should be paid to the Aral Sea Basin’ s ecological problems and management experience, adhering to sustainable development concepts. Full consideration must be given to ecological water requirements in inland river basins, rationally allocating and adjusting regional productive and ecological water structures to follow sustainable development pathways.

This study delineated Aral Sea environmental restoration areas at a regional scale, providing a reference for sustainable management. Future work should obtain more detailed data to construct reasonable, comprehensive indicators to guide restoration zoning implementation. The Aral Sea’ s ecological evolution affects the health and stability of the entire Aral Sea Basin and Central Asian ecosystem. However, comprehensive restoration remains a long-term endeavor requiring joint efforts from all Central Asian countries and the international community. As direct managers, Kazakhstan and Uzbekistan have implemented several restoration measures. Future cooperation should reference the overall ecological balance framework to reduce management conflicts and discrepancies. As a major Shanghai Cooperation Organization promoter, China should uphold the "community with a shared future for humankind" concept, actively implement the Belt and Road Initiative, and promote Green Silk Road construction. China should extend its technologies and successful experiences in water resources restoration, desertification control, ecological restoration, and remote sensing monitoring, demonstrating its contribution to ecological and environmental protection along the Silk Road Economic Belt. It is imperative to provide Chinese technologies and solutions for Central Asian ecological and environmental protection to help achieve the UN Sustainable Development Goals by 2030.

5 Conclusions

The Aral Sea Basin' s ecological problems threaten regional ecosystem stability and sustainable social development in Central Asian countries. This study identified the Aral Sea's main ecological problems and mapped ecological restoration zones based on soil type, soil salinity, surface water, groundwater table, NDVI, land cover, and AOD data. Soil salinization and salt dust are the most prominent issues, with severely salinized areas and high-frequency salt-dust storms mainly distributed in the central Aral Sea. The downstream North Aral Sea and Amu Darya delta have low salinization and high vegetation coverage.

To manage these problems, we divided the region into seven first-level and 14 second-level subregions. The largest first-level subregions are Subregion VI (22.06$×10^{3}$ km^{2}) and Subregion V (12.16$×10^{3}$ km^{2}). Based on second-level zoning, we proposed appropriate restoration measures. Water level restoration is crucial for maintaining ecological balance, requiring artificial irrigation in Subregions I and II. Artificial irrigation must minimize conflicts with agricultural water use to avoid further resource depletion. In Subregions III and IV, we recommend covering areas with green bio-matrix coverings and environmentally sustainable bonding materials. Subregion V should receive increased surface water recharge to maintain normal water levels. For Subregions VI and VII, afforestation and buffer zones should protect vegetation.

This study proposes a framework for future Aral Sea ecological governance but has limitations. First, lacking species richness data, we could not include biodiversity indicators in restoration zoning. Second, we did not consider human activity impacts such as agricultural irrigation on restoration zoning. These limitations will be addressed in future work to better support sustainable Aral Sea management.

References

Abuduwaili J, Liu D W, Wu G Y. 2010. Saline dust storms and their ecological impacts in arid regions. *Journal of Arid Land*, 2(2): 144–150.

Akbari M, Shalamzari M J, Memarian H, et al. 2020. Monitoring desertification processes using ecological indicators and providing management programs regions of Iran. *Ecological Indicators*, 111: 106011, doi: 10.1016/j.ecolind.2019.106011.

Allen C D, Savage M, Falk D A, et al. 2002. Ecological restoration of southwestern ponderosa pine ecosystems: A broad perspective. *Ecological Applications*, 12(5): 1418–1433.

Andrianov N, Mantellini S. 2016. *Ancient Irrigation Systems of the Aral Sea Area: The History, Origin, and Development of Irrigated Agriculture*. Oxford: University of Oxford, 95–98.

Bailey R. 1976. *Ecoregions of the United States*. Scale 1:7,500,000. Ogden, UT, USA: USDA (United States Department of Agriculture) Forest Service.

Bekzod A, Habibullo S, Fan L, et al. 2021. Transformation of vegetative cover on the Ustyurt Plateau of Central Asia as a consequence of the Aral Sea shrinkage. *Journal of Arid Land*, 13(1): 71–87.

Boomer I, Aladin N, Plotnikov I, et al. 2000. The palaeolimnology of the Aral Sea: A review. *Quaternary Science Reviews*, 19(13): 1259–1278.

Chen Z, Gao X, Lei J Q. 2022. Dust emission and transport in the Aral Sea region. *Geoderma*, 428: 116177, doi: 10.1016/j.geoderma.2022.116177.

Cretaux J F, Letolle R, Bergé-Nguyen M. 2013. History of Aral Sea level variability and current scientific debates. *Global and Planetary Change*, 110: 99–113.

Crighton E J, Barwin L, Small I, et al. 2011. What have we learned? A review of the literature on children' s health and the environment in the Aral Sea area. *International Journal of Public Health*, 56(2): 125–138.

Di B F, Cui P, Ai N S. 2008. The study of regionalization on ecological restoration in China. *Advanced Engineering Sciences*, 40(5): 32–37. (in Chinese)

Di B F, Cui P, Ai N S, et al. 2009. Study of building measures on ecological restoration in China. *Advanced Engineering Sciences*, 41(2): 64–69. (in Chinese)

Dukhovny V A, Navratil P, Rusiev I, et al. 2008. *Comprehensive Remote Sensing and Ground Based Studies of the Dried Aral Sea Bed*. Tashkent: Scientific-Information Center Interstate Commission for Water Coordination in Central Asia (SIC ICWC).

Ermakhanov Z K, Plotnikov I S, Aladin N, et al. 2012. Changes in the Aral Sea ichthyofauna and fishery during the period of ecological crisis. *Lakes &*

Reservoirs: Research & Management, 17(1): 3-9.

FAO (Food and Agriculture Organization of the United Nations). 2005. *Global Network on Integrated Soil Management for Sustainable Use of Salt-Affected Soils*. Rome: FAO Land and Plant Nutrition Management Service.

Fischer G, Nachtergaele F O, van Velthuizen H, et al. 2021. *Global Agro-ecological Zones (GAEZ v4)-Model Documentation*. Food and Agriculture Organization of the United Nations (FAO) & International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria; Rome, Italy.

Glantz M H. 2007. Aral Sea Basin: a sea dies, a sea also rises. *Ambio*, 36(4): 323-327.

He H, Hamdi R, Luo G, et al. 2022. Numerical study on the climatic effect of the Aral Sea. *Atmospheric Research*, 268: 105977, doi: 10.1016/j.atmosres.2021.105977.

Horst M, Shamutalov S S, Pereira L, et al. 2005. Field assessment of the water saving potential with furrow irrigation in Fergana, Aral Sea Basin. *Agricultural Water Management*, 77(1-3): 210-231.

Huang S, Chen X, Chang C, et al. 2022. Impacts of climate change and evapotranspiration on shrinkage of Aral Sea. *Science of the Total Environment*, 845: 157203, doi: 10.1016/j.scitotenv.2022.157203.

Indoitu R, Kozhoridze G, Batyrbaeva M, et al. 2015. Dust emission and environmental changes in the dried bottom of the Aral Sea. *Aeolian Research*, 17: 101-115.

Issanova G, Abuduwaili J, Galayeva O, et al. 2015. Aeolian transportation of sand and dust in the Aral Sea region. *International Journal of Environmental Science and Technology*, 12(10): 3213-3224.

Jiang L L, Jiapaer G, Bao A M, et al. 2019. Assessing land degradation and quantifying its drivers in the Amu Darya River delta. *Ecological Indicators*, 107: 105595, doi: 10.1016/j.ecolind.2019.105595.

Jiang L L, Jiapaer G, Bao A M, et al. 2020. The effects of water stress on croplands in the Aral Sea Basin. *Journal of Cleaner Production*, 254: 120114, doi: 10.1016/j.jclepro.2020.120114.

Kim J, Song C, Lee S, et al. 2020. Identifying potential vegetation establishment areas on the dried Aral Sea floor using satellite images. *Land Degradation & Development*, 31(18): 2749-2762.

Kotlyakov V M. 1991. The Aral Sea Basin: a critical environmental zone. *Environment: Science and Policy for Sustainable Development*, 33(1): 4-38.

Kulmatov R, Mirzaev J, Taylakov A, et al. 2021. Quantitative and qualitative assessment of collector-drainage waters in Aral Sea Basin: trends in Jizzakh region, Republic of Uzbekistan. *Environmental Earth Sciences*, 80(3): 122, doi: 10.1007/s12665-021-09406-y.

Liliya D. 2015. Natural and anthropogenic dynamics of vegetation in the Aral Sea Coast. *American Journal of Environmental Protection*, 4: 136–142.

Liu W, Ma L, Abuduwaili J. 2020. Historical change and ecological risk of potentially toxic elements in the lake sediments from North Aral Sea, Central Asia. *Applied Sciences-Basel*, 10(16): 5623, doi: 10.3390/App10165623.

Liu X H, Liu L, Peng Y. 2017. Ecological zoning for regional sustainable development using an integrated modeling approach in the Bohai Rim, China. *Ecological Modelling*, 353: 158–166.

Micklin P. 2007. The Aral Sea disaster. *Annual Review of Earth and Planetary Sciences*, 35: 47–72.

Micklin P, Aladin N V. 2008. Reclaiming the Aral Sea. *Scientific American*, 298(4): 64–71.

Micklin P. 2010. The past, present, and future Aral Sea. *Lakes & Reservoirs: Research & Management*, 15(3): 193–213.

Micklin P. 2016. The future Aral Sea: hope and despair. *Environmental Earth Sciences*, 75(9): 844, doi: 10.1007/s12665-016-5614-5.

Micklin P P. 1988. Desiccation of the Aral Sea: A water management disaster in the Soviet Union. *Science*, 241: 1170–1176.

Momeni M, Saradjian M R. 2007. Evaluating NDVI-based emissivities of MODIS bands 31 and 32 using emissivities derived by Day/Night LST algorithm. *Remote Sensing of Environment*, 106(2): 190–198.

Qadir M, Noble A D, Qureshi A S, et al. 2009. Salt-induced land and water degradation in the Aral Sea Basin: A challenge to sustainable agriculture in Central Asia. *Natural Resources Forum*, 33(2): 134–149.

Rudenko I, Lamers J P A. 2010. *The Aral Sea: An Ecological Disaster*. New York: Cornell University, 14.

Rzymski P, Klimaszyk P, Niedzielski P, et al. 2019. Pollution with trace elements and rare-earth metals in the lower course of Syr Darya River and Small Aral Sea, Kazakhstan. *Chemosphere*, 234: 81–88.

Shen H, Abuduwaili J, Samat A, et al. 2016. A review on the research of modern aeolian dust in Central Asia. *Arabian Journal of Geosciences*, 9(13): 625, doi: 10.1007/s12517-016-2646-9.

Shibuo Y, Jarsjö J, Destouni G. 2007. Hydrological responses to climate change and irrigation in the Aral Sea drainage basin. *Geophysical Research Letters*, 34(21): L21406, doi: 10.1029/2007GL031465.

Shomurodov Kh, Rakhimova T, Adilov B, et al. 2021. Current state of vegetation of the dried bottom of the Aral Sea. *IOP Conference Series: Earth and Environmental Science*, 629: 012085, doi: 10.1088/1755-1315/629/1/012085.

Sobrino J, Raissouni N, Li Z L. 2001. A comparative study of land surface emissivity retrieval from NOAA data. *Remote Sensing of Environment*, 75(2): 256–266.

Spoor M. 1998. The Aral Sea Basin crisis: Transition and environment in former soviet Central Asia. *Development and Change*, 29(3): 409–435.

Stulina G, Sektimenko V. 2004. The change in soil cover on the exposed bed of the Aral Sea. *Journal of Marine Systems*, 47(1–4): 121–125.

UNDP (United Nations Development Programme). 1995. *General Human Development Report: Turkmenistan 1995*. [2023-06-25]. https://hdr.undp.org/content/general-human-development-report-turkmenistan-1995.

Wang J, Liu D W, Ma J L, et al. 2021. Development of a large-scale remote sensing ecological index in arid areas and its application in the Aral Sea Basin. *Journal of Arid Land*, 13(1): 40–55.

Wang L, Zhao Z, Shomurodov K, et al. 2023a. Address the Aral Sea crisis with cooperation. *Science*, 380(6650): 1114, doi: 10.1126/science.adi2199.

Wang M, Chen X, Cao L Z, et al. 2023b. Correlation analysis between the Aral Sea shrinkage and the Amu Darya River. *Journal of Arid Land*, 15(7): 757–778.

Wang N, Cheng W M, Wang B X, et al. 2020. Geomorphological regionalization theory system and division methodology of China. *Journal of Geographical Sciences*, 30(2): 212–232.

Wang W, Samat A, Abuduwaili J, et al. 2022. Temporal characterization of sand and dust storm activity and its climatic and terrestrial drivers in the Aral Sea region. *Atmospheric Research*, 275: 106242, doi: 10.1016/j.atmosres.2022.106242.

Wu M Y, Hu X M, Zhang Q, et al. 2020. Preparation and performance evaluation of environment-friendly biological dust suppressant. *Journal of Cleaner Production*, 273: 123162, doi: 10.1016/j.jclepro.2020.123162.

Xenarios S, Schmidt-Vogt D, Qadir M, et al. 2019. *The Aral Sea Basin: Water for Sustainable Development in Central Asia*. London: Routledge, 100–121.

Xu H J, Wang X P, Zhang X X. 2016. Decreased vegetation growth in response to summer drought in Central Asia from 2000 to 2012. *International Journal of Applied Earth Observation and Geoinformation*, 52: 390–402.

Xu Z H, Peng J, Dong J Q, et al. 2022. Spatial correlation between the changes of ecosystem service supply and demand: An ecological zoning approach. *Landscape and Urban Planning*, 217: 104258, doi: 10.1016/j.landurbplan.2021.104258.

Yang X, Wang N, He J, et al. 2020. Changes in area and water volume of the Aral Sea in the arid Central Asia over the period of 1960-2018 and their causes. *Catena*, 191: 104566, doi: 10.1016/j.catena.2020.104566.

Yu T, Bao A M, Xu W Q, et al. 2019. Exploring variability in landscape ecological risk and quantifying its driving factors in the Amu Darya Delta. *International Journal of Environmental Research and Public Health*, 17(1): 79, doi: 10.3390/ijerph17010079.

Yu T, Jiapaer G, Bao A M, et al. 2021. Using synthetic remote sensing indicators to monitor the land degradation in a salinized area. *Remote Sensing*, 13(15): 2851, doi: 10.3390/rs13152851.

Yu X, Lei J Q, Gao X. 2022. An over view of desertification in Xinjiang, Northwest China. *Journal of Arid Land*, 14(11): [page numbers].

Zadereev E, Lipka O, Karimov B, et al. 2020. Overview of past, current, and future ecosystem and biodiversity trends of inland saline lakes of Europe and Central Asia. *Inland Waters*, 10(4): 438-452.

Zhao Y, Wang Z G, Sun B P, et al. 2013. A study on scheme of soil and water conservation regionalization in China. *Journal of Geographical Sciences*, 23(4): 721-734.

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