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Review Article

Reframing the collapse of the Aral Sea through the principles of ecotoxicology: a critical synthesis of toxicological governance, environmental justice, and restoration

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The degradation of the Aral Sea is among the most severe man-made environmental catastrophes of the 20th and 21st centuries. In this article, the tenets of ecotoxicology, namely, i) Source–Pathway–Receptor, ii) Dose–Response, iii) Bioavailability, iv) Accumulation, v) Mode of Action, vi) Ecological Relevance, vii) Mixture Toxicity, viii) Community Effects, ix) Toxicokinetics, and x) Risk Assessment, are used to reinterpret the toxicological perspective of the ecological degradation of the Aral Sea. This article calls for an expansive historical-ecological synthesis of the manner in which cumulative exposure to toxics, desertification, and systematic water mismanagement have inflicted irreversible damage upon biotic and human communities by synthesizing ecological data, health indicators, remote sensing studies, and governance investigations. Every theme manifests serious gaps in monitoring, risk communication, and regulatory reaction, thus highlighting the lack of integrated toxicological governance in reducing environmental and public health issues. The research shows that ecotoxicology is a framework for ethical and multidisciplinary environmental action and a discipline for assessing chemical risks. The Aral Sea disaster therefore demonstrates how oversight of the toxicological foundations of ecosystem failure can exacerbate health crises, social disintegration, and environmental irreversibility. This article supports the integration of ecotoxicological concepts into regional policy, restoration planning, and resilience-enhancement at the community level. Eventually, the implementation of these concepts may bring about more equitable, science-based, and sustainable futures for previously marginalized ecosystems.

Keywords: *aral sea, ecotoxicology, environmental collapse, toxicological governance, restoration ethics*

Introduction

Having been among the world's largest inland bodies of water, the Aral Sea now serves as a symbol of tremendous environmental destruction due to human abuse. Mass-scale Amu Darya and Syr Darya river diversion for Soviet agricultural expansion desiccated the sea, resulting in the Aralkum Desert, notable microclimatic changes, and profound socio-environmental effects (Liu et al., 2024; Lloyd et al., 2023; Lopes et al., 2020). Although routinely addressed by hydrology and climatology, such a situation is better comprehended as an entirety by ecotoxicology, which is a science concerned with the fate and impact of toxic substances in ecosystems (Walker et al., 2016); Ma et al., 2024; Mayar et al., 2024). Ecotoxicology is a suite of ideas from source–pathway–receptor dynamics to risk assessment that collectively describe how contaminants act in associating with the environment and with living organisms. Beasley & Levengood (2007, 2012) express these ideas as key to diagnosing ecological stressors and to informing regulatory response. Typically applied to industrial pollution and anthropogenic chemicals, ecotoxicology has come to encompass broader applications like evaluating effects at the ecosystem level from multi-stressor environments, land degradation, and air pollution (Gagné, 2014; Truhaut, 1977). More recent initiatives extended ecotoxicology to include ethical and cooperative aspects, promoting open data-sharing and integration approaches that link science and social issues (Muñoz et al., 2023; Pastorino et al., 2024). In politically sensitive or ecologically disputatious contexts in particular, the European Food Safety Authority (EFSA PPR Panel, 2006) and research like Harris et al. (2014) have particularly highlighted the need for scientifically reliable and open examination. These events resonate with the Aral Sea case, where historical pollution, airborne toxins, and environmental degradation converge with human disease and local government collapse. Moreover, the toxic environment of the Aral Sea—defined by salt storms, bioavailable heavy metals, and destruction of ecosystems—offers an in vivo test site for testing and developing ecotoxicological principles (Moiseenko, 2008; Turzhova et al., 1993). The bioaccumulation evidence among animals and plants, community structure perturbation, and changes in trophic interaction fit paradigms that have been addressed in ecotoxicological research (Levengood & Beasley, 2007; Ford, 2017). Ecotoxicology is thus not only significant for scientific explanation but also adaptive policy and moral environmental management. Moreover, the case of the Aral Sea provides rich ground for Lopes et al. (2020) proposed problem-based learning of ecotoxicology. Real-world problems related to environmental justice, socio-economic dislocation, and long-lasting ecosystem resilience demand interdisciplinary education and stakeholder involvement. Ecotoxicology provides an ethical compass and a diagnostic tool set since the discipline is moving from collapse to partial rehabilitation, hence planning future activities towards sustainability. Thus, within this study, the 10 overall ecotoxicology concepts provide an essential framework through which to re-consider the Aral Sea disaster. Building on the science foundation developed by influential books (Walker et al., 2016; Beasley & Levengood, 2012; Harris et al., 2014), it responds to current demands for more varied, evidence-based, and ethical environmental science (Pastorino et al., 2024; Muñoz et al., 2023). With this reframing, we suggest a historical-ecological synthesis that shifts the Aral Sea from an ecological disaster to a case study in applied toxicological ethics, resilience, and planetary health.

Applying the ten principles of ecotoxicology to the Aral Sea collapse

Source–pathway–receptor

Figure 1 depicts the source-pathway-receptor model in Aral Sea basin due to the desiccation environmental issue. The diversion of the Amu Darya and Syr Darya rivers' irrigation was the principal source of hydrological perturbation in the Aral Sea Basin. The construction of extensive canal systems such as the Karakum Canal diverted fresh water flow to large monoculture cotton fields, causing systematic changes in water availability and quality (Ahn et al., 2024; Akramkhanov et al., 2022). This alteration of hydrological pathways cut short the natural linkage between inflow rivers and the Aral Sea, effectively separating the basin's ecological feedback loops.

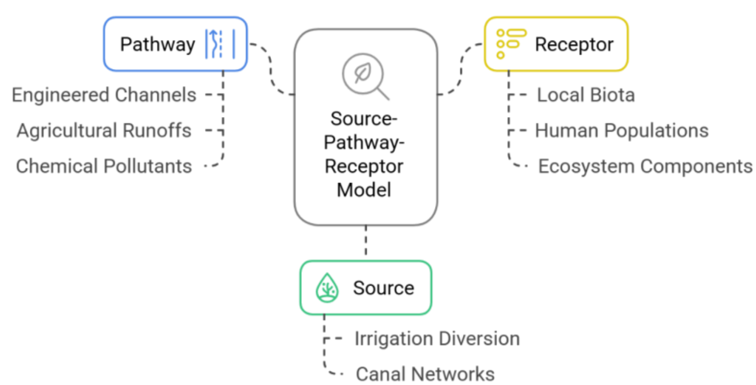

Figure 1. The model of source-pathway-receptor in Aral Sea basin due to the desiccation environmental problem

The channel—formed by artificial canals, agricultural runoffs, and secondary water networks was not just utilized for the diversion of freshwater but also acted as a vehicle for chemical contaminants, including pesticides, fertilizers, and salts, to adjacent ecosystems (Amirgaliyev et al., 2023; Andrulionis et al., 2025). These inputs gradually piled up in water reservoirs and soils, inducing salinization and toxification processes. Turzhova et al. (1993) noted that rapid techniques for determining biological expression can be critical in such dynamic ecotoxicological systems, where biological indicators respond directly to contaminant fluxes.

The receptors—local biota, human settlements, and ecosystem components were subjected to multiscalar impacts including desiccation, habitat destruction, salt toxicity, and airborne dust exposure from the newly formed Aralkum Desert (Kim et al., 2023; Alikhanova & Bull, 2023). Dust storms, now frequent with exposed seabeds, are airborne vectors of residual agrochemicals and pathogens, expanding the ecological footprint of contamination (Asadov et al., 2023; Aslan et al., 2023). Walker et al., (2016) point out that the source-pathway-receptor relationship is key to the science of ecotoxicology insofar as it allows the determination of vulnerable organisms and points of intervention. Failure to control these vectors has resulted in continuous environmental degradation in the form of biodiversity losses, fisheries declines, and worsening public health indicators across the region (Alieva et al., 2023; Alikhanova et al., 2024). Nature-based solutions have since been proposed to cut off these toxic pathways, however, on an ad hoc basis (Alikhanova & Bull, 2023).

Dose–response

Figure 2. depicts the dose-response relationship in Aral Sea crisis instigated by the environmental problem of desiccation. The exposure to increasing intensity of inhalation of air-dust laden with salts, pesticides, and heavy metals has resulted in measurable physiological and public health impacts on the population of the Aral Sea (Suleimen et al., 2024; Erkudov et al., 2023). These effects include heightened respiratory disease incidence, immune dysfunction, cardiovascular disease, and skin disease, particularly in children and the elderly. The severity and incidence of these effects illustrate the classic dose–response relationship: greater exposure intensity is correlated strongly with increased disease incidence and morbidity.

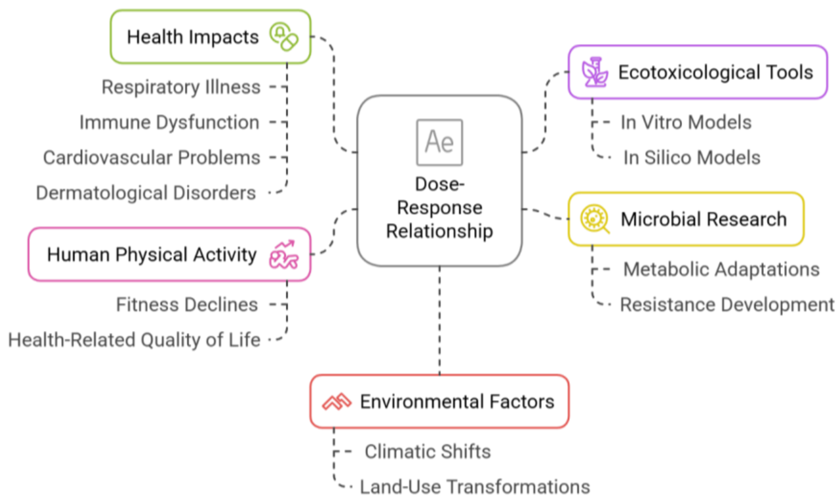

Figure 2. The relationship of dose-response in Aral Sea crisis due to the desiccation environmental problem

In ecotoxicology, the dose–response relationship is applied to determine toxicity levels, establish no-observed-effect levels (NOELs), and define safe thresholds (Truhaut, 1977; Walker et al., 2016). Chronic exposure to low-to-moderate doses of environmental pollutants that have resulted in cumulated health loads with time is exemplified by the Aral Sea disaster. New ecotoxicological tools, including in vitro and in silico models, offer ethical and precise alternatives to assessing such effects and allow for the construction of a green ecotoxicology paradigm (Pastorino et al., 2024). Microbial analysis in the region reported changes in native populations, including metabolic change and resistance development, as signs of long-term biological stress from continuous toxic input (Chernyh et al., 2024). Flora and vegetation in the soil within the Aral region, including antifungal bacteria, have shown shifts in activity, possibly a result of prolonged duration of exposure to pollutants (Aytenov et al., 2024).

In addition, human physical activity assessment in the exposed regions shows lower fitness and health-related quality of life, further confirming the systemic physiological impact of toxic environmental exposure (Baspakova et al., 2024). The cumulative effects of atmospheric toxicants, combined with ongoing climatic alterations and land-cover transformations, underscore the need for integrated risk assessment that includes ecological, chemical, and biomedical data (Bao et al., 2024; Berdimbetov et al., 2024). The temporality of exposure and its intersection with socio-environmental transformation, as theorized in cultural studies and ecological reconstruction, emphasizes that the Aral Sea catastrophe is not an isolated incident of history but a living toxicological state (Bespalova, 2023; Boymirzaev et al., 2024). Therefore, it is essential to have a nuanced appreciation of the dose–response relationship so that effective future mitigation, policy, and ecosystem rehabilitation can be formulated.

Bioavailability

Figure 3. represents the overall concept of bioavailability of pollutants in the Aral Sea region due to the desiccation environmental problem. Bioavailability of pollutants such as heavy metals and persistent organic pollutants (POPs) of the Aralkum Desert aerosol has been confirmed in human biomonitoring studies and field studies on ecosystems (Amirgaliyev et al., 2023). These toxins become progressively available for uptake via seasonal winds and dust storms, particularly when fine particulate matter is inhaled or deposited on water bodies and soil and mobilized. Seasonal resuspension of harmful dust has made the Aral Sea region a chronic hotspot of exposure, particularly impacting communities, farmers, and wildlife in the region (Erkudov et al., 2023; Duan et al., 2024).

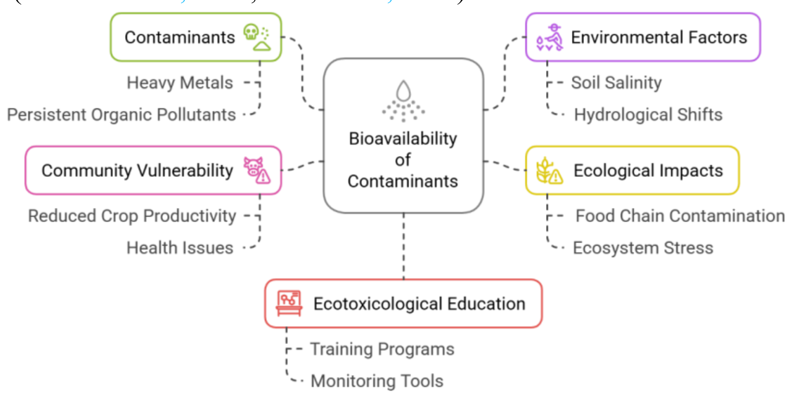

Figure 3. The overall concept of bioavailability of contaminants in Aral Sea region due to the desiccation environmental problem

Bioavailability in ecotoxicology refers to that fraction of a substance that is accessible to an organism's biological systems to be absorbed and interact at the target site (Walker et al., 2016; Moiseenko, 2008). The term is central in assessing environmental health risks since it measures real levels of exposure and not the presence of pollutants. Soil salinization, hydrological transformation, and ecosystem degradation in the Aral Sea basin have altered the physicochemical properties of the landscape to favor the mobilization and assimilation of pollutants (Duan et al., 2024; Cui et al., 2023). Existing studies depict how bioavailable pollutants get uptaken by plants and microorganisms and, therefore, introduce long-term ecological risks into the food web. For instance, native soil microbials and fungal populations exhibit adaptive biochemical responses characteristic of long-term low-dose exposure that undercut their ecological function and resilience (Aytenov et al., 2024). This is a timely process in dryland ecosystems already threatened by unpredictable climate oscillation (Féaux de la Croix & Samakov, 2024). The environmental vulnerability of Karakalpakstan and Khorezm agricultural societies demonstrates the real effects of bioavailable toxins. Farmers regularly record lower crop yields and livestock health concerns, reflecting both indirect and direct exposure pathways (Djumaboev et al., 2024; Fomenko & Fomenko, 2023). This environmental stress falls under the general paradigm of system feedback dynamics, where land degradation induced by bioavailable pollutants is compounded by social vulnerability and food insecurity (Edwin et al., 2024). Training and capacity development in ecotoxicology should therefore emphasize the importance of measuring and modelling bioavailability, particularly in the arid regions with intricate hydrology and land use histories. Lopes et al. (2020) favor problem-based learning curricula in ecotoxicology education that would equip local scientists and practitioners within the Aral Sea region to develop region-specific monitoring tools and interventions. Hence, bioavailability is a more dynamic than static factor and is controlled by climatic, hydrological, and anthropogenic variables. The Aral Sea example illustrates how bioavailability information is essential in following sources of entry of toxicants into ecosystems and human systems, both shaping scientific investigation and policy action.

Accumulation

Figure 4 represents the overall concept of accumulation of toxicants/contaminants in Aral Sea region because of the desiccation environmental problem. Cumulative air toxicant exposure in the Aral Sea region has resulted in widespread bioaccumulation in a number of environmental compartments including human tissues, vegetation, animals, and aquatic and groundwater systems. These long-lasting contaminants, such as heavy metals, polycyclic aromatic hydrocarbons (PAHs), and organochlorine pesticides (OCPs), continue to get accumulation in biological systems through inhalation, dermal absorption, ingestion, and environmental exposure, particularly during dust storm seasons and annual flooding events (Jiemuratova et al., 2024; Erkudov et al., 2023). Such cumulative exposure translates to long-term and progressive accumulation and is particularly harmful to sensitive populations such as children, pregnant women, and outdoor workers, and is associated with immune dysfunctions, growth retardation, and reproductive abnormalities.

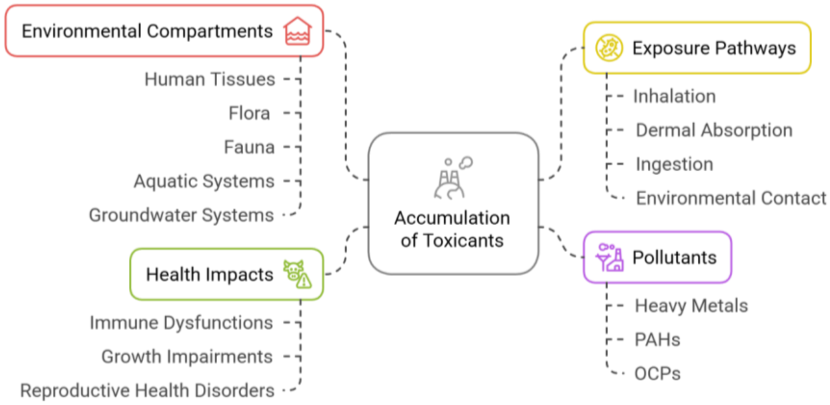

Figure 4. **The overall concept of accumulation of toxicants/contaminants in Aral Sea region due to the desiccation environmental problem**

Bioaccumulation in ecotoxicological research is the mechanism by which pollutants are stored increasingly within organisms directly from the environment or through trophic transmission (Levengood & Beasley, 2007; Harris et al., 2014). Both bioaccumulation and biomagnification have occurred in regards to the Aral Sea. Aquatic life in residual basins, terrestrial vegetation such as Xylosalsola richteri, and even microbial populations in the soil have shown aberrant biochemical profiles, reflecting pollutant deposition (Karlybaeva et al., 2024). The deposition is augmented with water deficiencies in the environment, which accumulate pollutants in reduction water bodies and dust-emitting desertified territories (Han et al., 2024; Huang, Ochoa, & Guo, 2023). The historical path of pollutant accumulation in the Aral Basin is also made more complex by the record of infectious disease control with chemical agents. For example, retrospective molecular evidence for plague epidemics occurring during the mid-20th century suggests environmental pathways of contamination potentially leading to long-term pathogen-pollutant interactions (Karapetyan et al., 2024). These historical and ongoing exposures synergize with each other, underpinning chronic disease burdens in human populations and wildlife as well. Hydrological and remote sensing studies confirm the persistence and accumulation of contaminants in the still water regions of the residual North Aral Sea and bordering terminal lakes (Huang et al., 2023; Izhitskiy & Ayzel, 2023). Lower freshwater inflows under climatic uncertainty lead to lower flushing rates, thus speeding up the accumulation process in sediment and benthic fauna (He et al., 2024). Also, recent risk assessment of the Amu Darya River Basin revealed high levels of PAHs and OCPs, highlighting the transboundary nature of pollution loading and the capacity to accumulate on a regional scale (Jin et al., 2023). These findings underscore the need for robust monitoring programs to quantify pollutant burdens in abiotic and biotic matrices. Robust ecotoxicology, according to Harris et al. (2014), requires integrating long-term data sets and multilevel bioindicators to be in a position to effectively capture the dynamics of accumulation. Ongoing reliance on satellite monitoring and geospatial modelling while beneficial must be supplemented with in situ sampling to monitor contaminant burdens at molecular and ecological levels (Han et al., 2024). Thus, the process of accumulation is more of a systemic indicator of ecological disintegration than a biological process. It is a measure of the severity and longevity of environmental stress and demands interaggregated intervention involving hydrology, toxicology, and public health interventions.

Mode of action

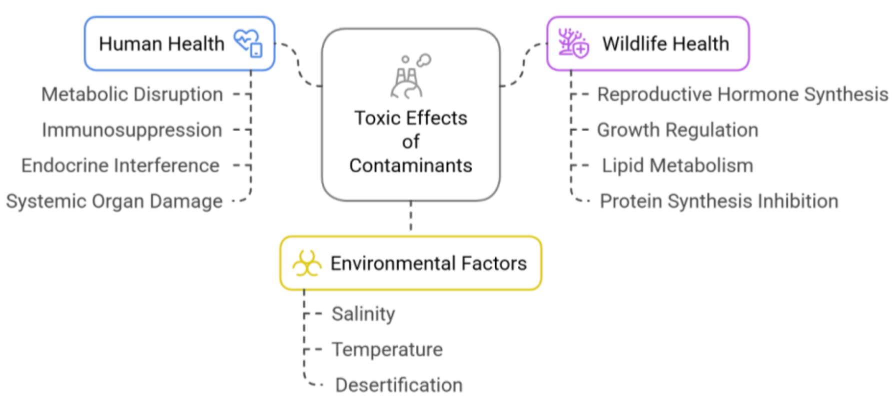

Figure 5. The overall toxic effects of contaminants in Aral Sea region due to the desiccation environmental problem

Figure 5 shows the overall toxic effect of pollutants in Aral Sea region as a result of desiccation environmental problem. The contaminants in the Aral Sea catchment area exert their toxic effects via specific biochemical and physiological pathways that impact both wildlife and the health of human beings. Documented mechanisms of action are metabolic disturbance, immunosuppression, endocrine disruption, and damage to systemic organs (Sokolova et al., 2024; Boymirzaev et al., 2024). These effects are mediated by such pollutants as heavy metals, polycyclic aromatic hydrocarbons (PAHs), and organochlorine pesticides that gain entry into biological systems through inhalation, ingestion, or dermal exposure and then interfere with cellular signaling, gene expression, and enzymatic activity. Biochemical ecotoxicology revealed that xenobiotics are able to strike mitochondrial respiration, oxidative stress mechanisms, and hormone control, leading to a chain of pathological effects (Gagné, 2014). For example, chronic exposure to airborne pollutants in the Aral Sea basin has been linked with disruption of hematological parameters, impaired physical performance, and sexual delayed maturation among children and adolescents (Boymirzaev et al., 2024). These findings are indicative of classic biomarkers of toxic mechanism of action, including disruption of hypothalamic–pituitary–gonadal axis signalling and immune cell dysfunction (Harris et al., 2014). Parallel disruptions also have been observed in wildlife, in fish in the remaining Small Aral Sea, where bioaccumulated toxins interfere with the synthesis of reproductive hormones, growth regulation, and lipid metabolism (Kulikov et al., 2024). In crops such as Sorghum bicolor, cultivated under salinity conditions in the Aral region, stress responses indicate the inhibition of protein synthesis through toxicity and osmotic imbalance (Khaitov et al., 2023). These effects at the species level are reflective of an overall ecosystem instability, wherein individual-level physiological disruption widens into diminished fertility, population decline, and trophic imbalance. The process of action also depends largely on abiotic aspects of the environment such as salinity, temperature, and desertification that may increase the uptake and toxicity of contaminants (Kayiranga et al., 2024; Kim et al., 2024). Degrading topsoil and altering the geomorphology of the ex-seabed modify the mobility and reactivity of contaminants, rendering them bioavailable and hence biologically active (Kurbanov et al., 2024). This modulational component of environmental toxicity is testimony to the significance of local chemical behavior and interaction evaluation, especially within highly perturbed ecosystems. Persistence of certain toxicants within sediments and dust, along with seasonally windborne transport, ensures repeated exposure and thus an expanded window of toxic action (Kim et al., 2023; Kuzmichyova, 2023). Recently developed satellite and remote sensing techniques offer useful means for correlating trends in land degradation with regions of likely biological stress, but these must be integrated with field-based physiological and biochemical monitoring to realistically map toxic action (Kayiranga et al., 2024; Kitov & Al Farabi, 2024). It is therefore necessary to understand how environmental pollutants act in the Aral Sea basin both for diagnostic and preventative purposes. As Harris et al. (2014) emphasize, credible ecotoxicological assessments must not only identify pollutants but inform how they functionally impair organisms. It is only by mapping these pathways that we can create mitigation measures, restore damaged systems, and prevent long-term public health and ecological disasters.

Ecological relevance

Figure 6 depicts the overall ecological impacts of the Aral Sea disaster due to the desiccation environmental problem. The ecological impacts of the Aral Sea disaster are severe and pervasive, evidencing clear violations of the principle of ecological relevance—a fundamental tenet of ecotoxicology emphasizing the cruciality of assessments and models in representing actualized environmental reality and organismal reaction (Ford, 2017; EFSA PPR Panel, 2006). In the Aral Sea Basin, drying up of water bodies, and mobilization of toxic sediments have led to fisheries collapse, loss of aquatic biodiversity, and drastic alterations of terrestrial and microbial assemblages within the newly formed Aralkum Desert (Chernyh et al., 2024).

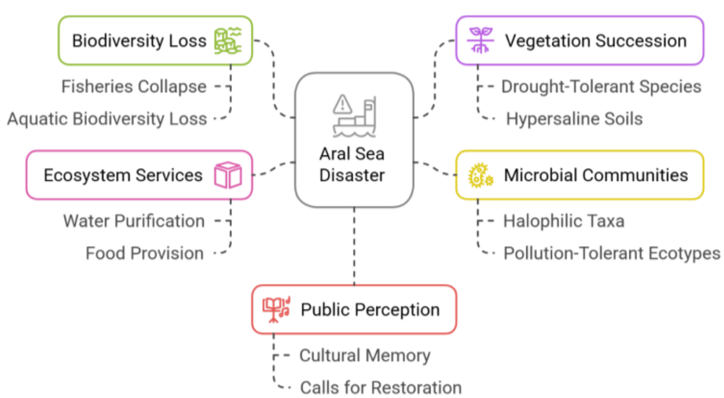

Figure 6. The overall ecological impacts of the Aral Sea disaster due to the desiccation environmental problem

Regional biodiversity loss is most directly connected to the clearing of aquatic habitats, specifically in the river delta provinces of the Amu Darya and Syr Darya. Changes in salinity and toxic runoff have rendered vast territories uninhabitable for native fish, bird, and invertebrate organisms. In addition, the increasing salt dust aerosols of the arid seabed regionally transported by the winds also accelerate degradation of nearby vegetation and soil microbiomes, thereby accelerating ecosystem collapse (Liu et al., 2025; Novikova et al., 2023). Vegetation succession across the ancient seabed has low ecological resilience. While a variety of drought-tolerant crops like Pennisetum glaucum (African millet) have been tried as part of ecological restoration (Nurgaliyev et al., 2024), various native and foreign plant species are unable to survive on the hypersaline, nutrient-deficient soils (Li et al., 2024). This constraint further restricts re-development of functional food webs and compromises efforts at natural or assisted revegetation (Ma et al., 2024). Microbial communities have adapted to extreme abiotic fluctuations through experiencing compositional and functional changes and dominance by halophilic and extremophilic groups (Chernyh et al., 2024). These communities are typical of pollution-tolerant ecotypes, which, while being under acclimation to the new stressors of the environment, are not as diverse and ecologically advantageous as the native assemblages. The resulting loss of ecosystem functionality also extends to biogeochemical cycles, primary productivity, and trophic interactions.

At the system level, the altered form and function of the ecosystem have affected other ecosystem services such as water filtration, supply of food, and climate control (Mayar et al., 2024; Liu et al., 2024). Not only do these ecological changes disown sustainability but also have spillover effects on people's livelihoods, local economies, and long-term food security. The common perception of these changes, documented in sociocultural narratives and ecopoetic framings, again highlights the recognition of ecological disintegration as a felt and witnessed phenomenon (Lloyd et al., 2023; Munisov & Borowy, 2023). Such narratives form part of an extended story of ecological relevance, placing destruction of nature in cultural memory and informing stewardship demands for full rehabilitation. Therefore, the Aral Sea represents a textbook case of ecological irrelevance where environmental mismanagement ignores feedback loops as well as long-term systemic health. Restoration of ecological integrity not only involves biophysical recovery but also adherence to scientifically sound and ecologically appropriate paradigms of measure and action (EFSA PPR Panel, 2006; Ford, 2017).

Mixture toxicity

Figure 7 presents the large body of knowledge on mixture toxicities of toxicants/contaminants in the Aral Sea catchment area due to the desiccation environmental problem. Mixture toxicity i.e., the joint action of multiple contaminants acting simultaneously or sequentially is one of the most critical problems in environmental risk assessment, especially in complex, degraded environments like the Aral Sea Basin. In this case, the environment is contaminated by a combination of salt dust, chemical residues (e.g., fertilizers, pesticides, heavy metals), particulate matter in the air, and biological contaminants such as pathogens and allergens. These contaminants combine by additive, synergistic, or antagonistic mechanisms, typically generating amplified toxicological effects over those of individual contaminants (Jin et al., 2023; Beasley & Levengood, 2007).

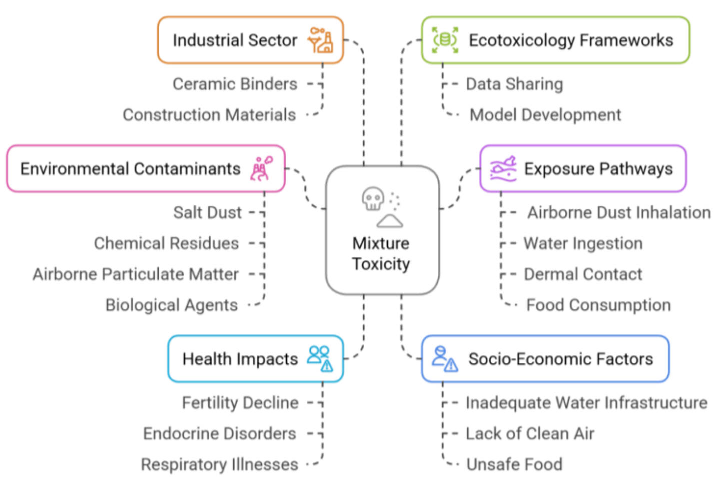

Figure 7. The overall understanding on the mixture toxicities of contaminants/toxicants in the Aral Sea basin due to the desiccation environmental problem

One of the most significant impacts of mixture toxicity is the inability to forecast toxic thresholds. This is especially critical in the Aral Sea where cumulative exposures to toxins occur through multiple environmental pathways air-borne dust inhalation, ingestion of water, dermal contact with soil, and ingestion of contaminated food crops (Satybaldiyev et al., 2023b). These interactions bewilder toxicokinetic and toxicodynamic modeling, frustrating scientists and policymakers in their efforts to derive safe levels of exposure or perform single-target remediation. Chemical mixtures in the Syr Darya and Amu Darya river systems i.e., elevated levels of dissolved and acid-leachable trace elements show high variability and water quality standard exceedances, especially in areas receiving agricultural and industrial runoff (Satybaldiyev et al., 2023a, 2023b). In sediments, the co-occurrence of heavy metals, metalloids, and organic residues also alters bioavailability and enhances long-term accumulation, with risk to aquatic and benthic biota (Plotnikov et al., 2023; Ramazonov et al., 2024). Moreover, socio-economic conditions exacerbate the exposure to multi-pollutant mixtures. Environmental injustice in the form of poor water infrastructure and lack of access to clean air and safe food characterizes the plight of the inhabitants of the Aral Sea region. Reduced fertility, endocrine disruption, and respiratory infections are now prevalent and are due to long-term exposure to overlapping contaminants (Saidmamatov et al., 2024a, 2024b). These are, in ecotoxicological parlance, cumulative stressors that target multiple endpoints reproductive, developmental, and immunological across generations. Raw material utilization within the Aral Sea's industrial economy also raises pollutant mobilization and exposure issues. For instance, ceramic binders and construction materials manufactured from locally derived clays and sediment can sequester trace contaminants, forming secondary sources of environmental exposure (Ruzmetova et al., 2023). Additionally, Pleistocene-era sediment studies refer to long-term pollutant legacies sequestered within geological strata, with implications of legacy mixture toxicity profiles spanning time (Panin et al., 2024). To address these challenges, there is a growing need for open-access, community ecotoxicology platforms with broad data sharing and model construction. The ATTAC concepts proposed by Muñoz et al. (2023) emphasize the integration of wildlife toxicology data, exposure modeling, and mixture evaluation tools as the foundation for effective environmental management. These are particularly needed in areas like the Aral Sea Basin where traditional single-chemical evaluations are not able to capture the extent of environmental interactions. Finally, mixture toxicity reflects not only scientific intricacy but also sociopolitical intertwinings of environmental collapse, food insecurity, and public health deterioration. Restoration efforts and policy responses must consider the systemic character of contaminant interaction and privilege interdisciplinary, multi-stressor risk analysis for sustainable rehabilitation.

Community effects

Figure 8 depicts the overall community impacts of Aral Sea collapse as a result of the desiccation environmental problem. The Aral Sea's ecosystem collapse has triggered a cascade of adverse community effects at various levels, from livelihood loss and mass migration to cultural degradation and poor public health. These effects not only reflect the social costs of environmental degradation but also the chronic toxicological stress of ongoing exposure to pollutants, degraded resources, and disrupted environmental services (Rustamova et al., 2023; Berdimbetov et al., 2024).

Figure 8. The overall community effects of Aral Sea collapse due to the desiccation environmental problem

Destabilization of rural livelihoods is arguably the most severe community effect. As fisheries collapsed and agriculture became ever more impossible due to salinization and dust pollution, thousands of families were forced to abandon ancestral occupations and migrate in search of basic economic stability (Beasley & Levengood, 2007, 2012). The migration destabilized long-established social structures and undercut local knowledge systems related to land and water management. The intensive desertification of the dried bed of the Aral Sea and the rising dust-salt storms have significantly worsened the air quality across the region, resulting in an increase in respiratory diseases, particularly among children and the elderly (Shukurov et al., 2024; Suleimen et al., 2024). Extreme levels of airborne pathogens, heavy metals, and fine particulate matter are not only environmental hazards but direct causes of community-level toxic exposure that drive systemic health decline and reduce life expectancy (Sokolova et al., 2024). There have been mental health implications as well stemming from chronic ecological loss and ongoing uncertainty. Communities coping with drought, land degradation, and the visible contraction of the sea report heightened stress, depression, and trauma associated with environmental grief. These sorts of psychosocial costs, less quantifiable as they are, constitute compelling indicators of ecological failure in the form of societal disempowerment (Song et al., 2024; Timur, 2023).

Moreover, social cohesion has been eroded by fragmented adaptation responses. Some communities have attempted reforestation of the dried seabed to halt wind erosion, but microbial and fungal contamination of new plantations introduces new biological risks (Sherimbetov et al., 2024; Šimonovičová et al., 2024). Similarly, climate change variability, such as shifting precipitation and temperature extremes, continues to undermine resilience strategies, making cohesive community response ever more difficult (Sultonov & Pant, 2023; Timur, 2023). At the cultural level, the collapse has jeopardized traditional ecological knowledge and species utilization. For example, the degradation of wild edible plants like Asparagus L. in the southern Aral Sea area not only limits local food security but also destabilizes ethnobotanical relationships and intergenerational knowledge transmission (Tejetdinova et al., 2023). As climate change intensifies and ecosystem changes persist, such cultural-ecological linkages are at risk of irreparable disruption. Lastly, the Aral Sea disaster demonstrates how ecotoxicological stressors—particularly when combined with socio-economic and climatic vulnerabilities can rend the very fabric of human community. The impact on community requires an integrated, place-based response that intertwines environmental restoration with health infrastructure, social equity, and local empowerment. As Beasley & Levengood (2007, 2012) have emphasized, ecotoxicology must extend beyond laboratory assessment to include these real-world, population-level ramifications for effective environmental and public health practice.

Toxicokinetics

Figure 9 displays the general toxico-kinetics in the Aral Sea region due to the desiccation environmental problem. Toxicokinetics is the internal fate of contaminants in biological systems—more specifically, how toxins are absorbed, distributed, metabolized, and eliminated. In the Aral Sea region, toxicokinetic studies are critical to explaining health outcomes in populations that are chronically exposed to wind-blown dust, contaminated soil, and contaminated water systems. Recent biomonitoring of farm workers and children revealed high levels of heavy metals and endocrine-disrupting chemicals, indicating high absorption rates and low excretion rates, which result in long biological half-lives (Asadov et al., 2023; Jiemuratova et al., 2024).

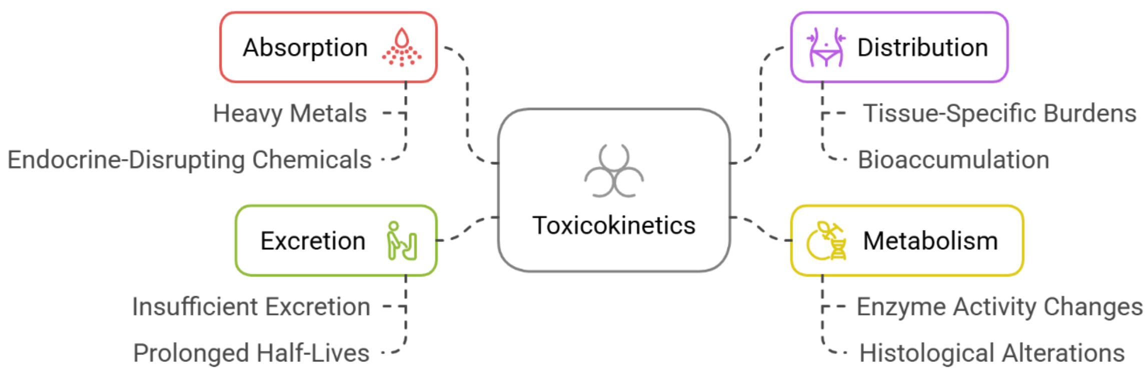

Figure 9. The overall toxico-kinetics in the Aral Sea region due to the desiccation environmental problem

Toxicokinetics is important in ecotoxicology for establishing thresholds of exposure and intervention levels based on health (Truhaut, 1977; Beasley & Levengood, 2007). Such internal events allow for determination of important biomarkers such as shifts in enzyme activity, bioaccumulation levels of metals, and tissue-specific burdens reflecting systemic toxic stress. For instance, animal experiments in the region demonstrate histological and cellular alterations in immune and reproductive organs due to long-term exposure to salt-dust aerosols and polycontaminant loads (Suleimen et al., 2024). Environmental context is also an essential modifier of toxicokinetics. The arid environment of the Aral Sea and widespread desertification increase the chances of re-aerosolization of the pollutants, leading to more chronic exposure through respiratory routes (Yang et al., 2024; Zhang et al., 2023). Additionally, decades of decline in the Amu Darya inflows have concentrated the pollutants in aquatic habitats and sediments, increasing contact frequency and concentration of exposure (Yue et al., 2024). Soil degradation, as is also the case with desertification areas like the Aralkum Desert, also causes redistribution of pollutants. Microplastic, organic pollutant, and trace metal transfer along the desiccation gradient opens up new avenues of exposure to land and microbial organisms, most of which are bioindicators of human health risks (Wicaksono et al., 2023; Turzhova et al., 1993). They also highlight the importance of how toxicokinetic responses must be studied together with environmental forces so as to adequately assess health risks in multi-component ecosystems (Zhou et al., 2024). In addition, post-Soviet studies of population health evidence a clear linkage of toxicokinetic burdens and socio-environmental vulnerability. Disparities in access to healthcare, occupational exposure, and nutrition change metabolic response to pollutants, potentially increasing retention and toxicity (Wheeler, 2021; Wu et al., 2023). It is difficult to distinguish between timing of exposure, quantifying body burden, or planning targeted interventions without systematic toxicokinetic profiling. In addition to this, modern remote sensing and satellite-based assessment have enabled it to become possible to correlate spatial pollutant distribution with risk areas. Such technologies enable more capability in exposure "hotspot" prediction, which can be superimposed on toxicokinetic data in order to inform spatially sensitive public health planning (Zhou et al., 2024; Wen et al., 2023). Therefore, understanding toxicokinetics in the Aral Sea region involves something greater than detection of contaminants it involves an integrated process that includes both internal biological response as well as external environmental transformation. As Truhaut (1977) emphasized and later reaffirmed in further ecological regulation practices (Wu et al., 2023), toxicokinetics remains at the center of predictive modeling, diagnosis, and prevention of ecotoxicological damage in this particularly problematic and historically heavily encumbered environment.

Risk assessment

Figure 10. presents the overall issues of the risk assessment of toxic/contaminant in the Aral Sea basin due to the desiccation environmental problem. Risk assessment in the Aral Sea Basin remains a critical but underemphasized component of public and environmental health management. Where local and international stakeholders have led in developing metrics for quantifying ecological dangers, practice is frustrated by fragmented governance systems, limited inter-agency cooperation, and a lack of reliable ongoing monitoring processes (Andrulionis et al., 2025). As such, environmental and health risks continue to be addressed in post facto, rather than holistic, proactive manner.

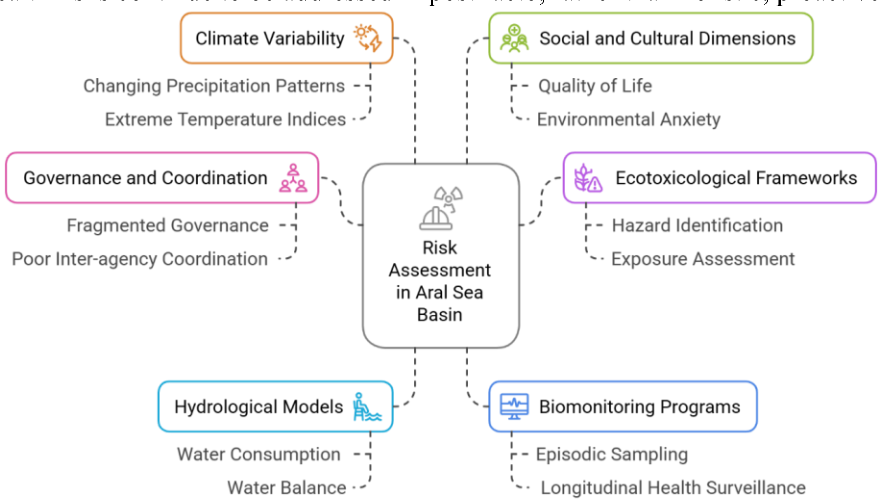

Figure 10. The overall challenges of risk assessments of contaminant/toxicants in the Aral Sea basin due to the desiccation environmental problem

Proven and tested ecotoxicological paradigms emphasize the need for hazard identification, exposure assessment, dose–response analysis, and risk characterization—factors that are still patchily considered in the Aral Sea region (Truhaut, 1977; Turzhova et al., 1993). For instance, although remote sensing and hydro-ecological modeling have been employed to track salinization and water withdrawal trends (Wang et al., 2024; Wen et al., 2023), there are typically few studies that translate these data into quantified human health or ecosystem-level risk levels in a systematic way. Recent hydrological modeling, such as the physically based scheme of Touge et al. (2024), has developed our understanding of water balance and consumption in the basin to the point of making integrated risk prediction possible. Such tools, however, have yet to be used widely by national or regional authorities in planning for actual intervention, and this is in part a matter of limitations of cross-border water governance and competing national interests (Sultonov & Pant, 2023).

In addition, the lack of extensive biomonitoring programs is a severe hindrance to effective risk assessment. Current programs have an intense focus on episodic sampling of environmental parameters without any longitudinal health monitoring or tissue-based contaminant monitoring in humans, livestock, or indicator species (Tejetdinova et al., 2023; Turdimambetov et al., 2024). The absence of real-time, biologically integrated data greatly impedes early warning sign detection and adaptive intervention. Climatic variation also complicates risk prediction because, with altered patterns of precipitation, evaporation rates, and extreme temperature indices, dynamic introduction of changes in exposure pathways and pollutant mobility is brought about (Timur, 2023; Wang et al., 2023a, 2023b). The shrinkage of the Aral Sea not only has concentrated toxicants but created new desert surfaces like the Aralkum Desert, which are active emission zones for air-borne pollutants (Wang et al., 2023a, 2023b). These changing spatial and temporal exposure scales demand flexible, scalable risk assessment models.

Social and cultural dimensions of risk remain under-addressed too. Despite evidence of deteriorating quality of life and environmental concern in vulnerable communities, these are rarely included in official risk frameworks (Wheeler, 2021; Turdimambetov et al., 2024). This disparity reduces trust and adoption of risk reduction measures among communities, highlighting the necessity for participatory and inclusive approaches. Looking forward, strengthening risk analysis in the

Aral Sea Basin must be supported by the institutionalization of regularized biomonitoring programs, transboundary data sharing, and stakeholder-involved forecasting mechanisms. As noted in both ecological and hydro-social studies (Wang et al., 2023b), risk governance must bring together hydrology, toxicology, governance, and social equity in an integrated framework. Without such integration, there will continue to be piecemeal and reactive responses that fail to prevent future health and environmental crises.

Integrated Toxicological Framework: Synthesizing Toxicological Governance, Environmental Justice, and Restoration

Figure 11 presents the overall integrated toxicological framework in for Aral Sea restoration due to the desiccation environmental problem. The destruction of the Aral Sea is not merely an environmental or hydrological anomaly; it is a collapse of toxicological governance in its broadest sense where lackadaisical institutional response, delayed scientific intervention, and asymmetrical policy enforcement allowed incremental toxic pressure to ravage ecosystems and communities with equal ferocity (Andrulionis et al., 2025; Truhaut, 1977). To address this complexity, an integrated toxicological framework is necessary—one that unites the scientific rigor of ecotoxicology with the ethical imperatives of environmental justice and the strategic foresight of ecological restoration.

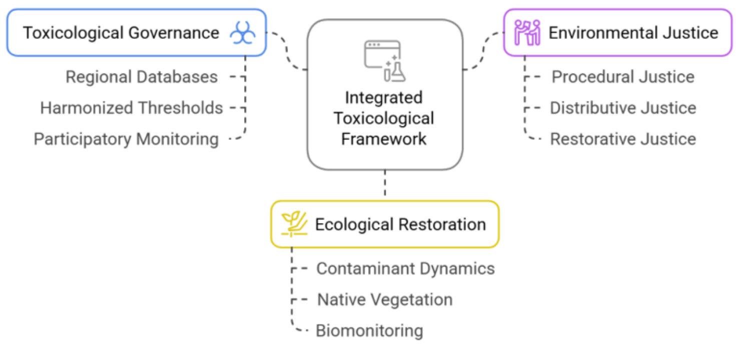

Figure 11. The overall integrated toxicological framework in for Aral Sea restoration due to the desiccation environmental problem

Toxicological management is the process by which scientific knowledge of contaminants and exposure is converted into policy, standards, and enforcement. Historically reactive, uneven, and local in the Aral Sea Basin, it has involved little transboundary coordination (Sultonov & Pant, 2023). The risk avoidance and defense of health continue to be unrealised without biomonitoring infrastructure and warning systems (Turzhova et al., 1993; Wang et al., 2024). The institutionalisation of regional toxicology databases, harmonised exposure standards, and bottom-up participatory monitoring systems that allow communities to co-produce environmental data are recommended in this article (Wu et al., 2023). Aral Sea environmental justice has to contend with unequal environmental load burdens. Rural and peripheral groups, especially women, children, and agricultural workers, experience uneven exposure to air pollutants, polluted water, and eroded soils (Turdimambetov et al., 2024; Jiemuratova et al., 2024). An integrated approach requires procedural justice through participatory decision-making, distributive justice through fair prevention of risk, and restorative justice that recognizes previous neglect and gives first order priority to remediation (Wheeler, 2021). Even framed classically in terms of reforestation or hydrological engineering, ecological restoration needs to be re-imagined as a toxicological activity. Restoration project success depends on an awareness of contaminant dynamics in biota, water, and soil. Restoration activities in the Aralkum Desert, for example, must account for internal contaminant uptake dynamics and sediment mobility (Wicaksono et al., 2023; Yue et al., 2024). Local salt-tolerant flora like Asparagus L. and Pennisetum glaucum proved effective to suppress soil dust mobility and stabilize damaged areas (Tejetdinova et al., 2023; Ramazonov et al., 2024). Effectiveness and safety of such projects should be evaluated based on toxicokinetic knowledge and long-term biomonitoring. Accordingly, the toxicology system introduced herein underscores that a single approach will not usher in long-term recovery of the Aral Sea basin. Instead, it calls for a synergic process that incorporates scientific examination, implementation by policy, and societal adaptive ability. The process offers an iterative model for addressing environmental crises in other post-industrial and climate-vulnerable areas by synthesizing ecotoxicological principles into a justice-focused governance system seeking long-term recovery (Truhaut, 1977).

Conclusion

This paper presents a new historical-ecological synthesis between environmental science, public health, and governance by recasting the Aral Sea collapse in light of ecotoxicology's ten basic principles. From Source-Pathway-Receptor to Risk Assessment, each principle demonstrates not only the biophysical dynamics of decline but also the socio-political deficits that permitted a regional ecological disaster develop into a long-term humanitarian disaster. Specifically, ecotoxicology standards are ethical imperatives that involve foresightful stewardship, organized responsibility, and long-term resilience planning rather than just being instruments of scientific diagnosis. Ecological deterioration in combination with poor toxicological control, disjointed structures of monitoring, and poor risk communication in the Aral Sea case conditions taken as a whole attacking environmental integrity and human health. This study emphasizes the imperative need for cross-sectoral interventions including holistic biomonitoring, adaptive water management, participatory risk assessment, and climate-resilient restoration practices by placing the Aral Sea disaster in an integrated toxicological framework. Finally, when employed holistically, ecotoxicology represents a means toward environmental justice, sustainability, and ethical rehabilitation of hitherto disadvantaged ecosystems and people rather than simply measurements and models.

Author contributions

All authors contributed significantly to the development of this manuscript. CKY conceptualized the study and led the project administration. CKY, MAT, WMS, and NAB performed the experiments and collected the data. NAAW and RN were responsible for data analysis and interpretation. [Author 6] contributed to the writing original draft preparation. CKY, ADS and KAA reviewed and edited the manuscript. All authors read and approved the final version of the manuscript.

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Conflict of interest

The authors declare no conflict of interest. The manuscript has not been submitted for publication in other journal.

Ethics approval

Not applicable.

AI tool usage declaration

The authors not used any AI and related tools to write this manuscript.

References

Ahn, Y.-J., Kamalov, B., & Juraev, Z. (2024). Revisiting the Aral Sea crisis: A geographical perspective. *International Journal of Environmental Studies, 81*(6), 2381–2398. https://doi.org/10.1080/00207233.2024.2422695

Akramkhanov, A., Akbarov, A., Umarova, S., & Le, Q. B. (2022). Agricultural Livelihood Types and Type-Specific Drivers of Crop Production Diversification: Evidence from Aral Sea Basin Region. *Sustainability*, *15*(1), 65. https://doi.org/10.3390/su15010065

Alieva, D., Usmonova, G., Shadmanov, S., & Aktamov, S. (2023). Fishery culture, sustainable resources usage and transformations needed for local community development: The case of Aral Sea. *Frontiers in Marine Science, 10*, 1285618. https://doi.org/10.3389/fmars.2023.1285618

Alikhanova, S., & Bull, J. W. (2023). Review of nature-based solutions in dryland ecosystems: The Aral Sea case study. *Environmental Management, 72*(3), 457–472. https://doi.org/10.1007/s00267-023-01822-z

Alikhanova, S., Milner-Gulland, E. J., & Bull, J. W. (2024). Exploring the human-nature nexus towards effective nature-based solutions: The Aral Sea case. *Land Use Policy, 139*, 107073. https://doi.org/10.1016/j.landusepol.2024.107073

Amirgaliyev, N., Opp, C., Askarova, M., Ismukhanova, L., Madibekov, A., & Zhadi, A. (2023). Long-term dynamics of persistent organic pollutants in water bodies of the Aral Sea–Syrdarya basin. *Applied Sciences*, *13*(20), 11453. https://doi.org/10.3390/app132011453

Andrulionis, N. Y., Izhitskiy, A. S., Savvichev, A. S., & Zavialov, P. O. (2025). Recent changes in physical and biogeochemical state in residual basins of the Aral Sea. *Aquatic Geochemistry, 31*(1), 1. https://doi.org/10.1007/s10498-024-09436-5

Asadov, D. A., Khamraev, A. K., & Yuldashev, G. K. (2023). Ethnogeographic features of tuberculosis incidence in the South Aral Sea region [Этногеографические особенности заболеваемости туберкулезом в зоне Южного Приаралья]. *Tuberculosis and Lung Diseases, 101*(4), 6–12. https://doi.org/10.58838/2075-1230-2023-101-4-6-12

Aslan, G., De Michele, M., Raucoules, D., Renard, F., Dehls, J., Penna, I., Hermanns, R., & Çakir, Z. (2023). Dynamics of a giant slow landslide complex along the coast of the Aral Sea, Central Asia. *Turkish Journal of Earth Sciences, 32*(6), 819–832. doi:10.55730/1300-0985.1876

Aytenov, I. S., Bozorov, T. A., Zhang, D., Samadiy, S. A., Muhammadova, D. A., Isokulov, M. Z., Murodova, S. M., Zakirova, O. R., Chinikulov, B. K., & Sherimbetov, A. G. (2024). Uncovering the antifungal potential of plant-associated cultivable bacteria from the Aral Sea region against phytopathogenic fungi. *Pathogens, 13*(7), 585. https://doi.org/10.3390/pathogens13070585

Bao, A., Yu, T., Xu, W., Lei, J., Jiapaer, G., Chen, X., Tojibaev, K., Shomurodov, K., Xabibullaev, B., & Kamalatdin, I. (2024). Ecological problems and ecological restoration zoning of the Aral Sea. *Journal of Arid Land, 16*(3), 315–330. doi:10.1007/s40333-024-0055-6

Baspakova, A., Aldanova, A., Zinalieva, A., Umbetova, A., Makhashbay, A., & Rakhmanov, Y. (2024). Aral Sea environmental disasters area population's physical activity level assessment – The first step for targeted health promotion. *Polski Merkuriusz Lekarski, 52*(3), 268–276. https://doi.org/10.36740/Merkur202403102

Beasley, V. R., & Levengood, J. M. (2007). Principles of ecotoxicology. In R. C. Gupta (Ed.), *Veterinary toxicology: Basic and clinical principles* (pp. 689–708). Academic Press. https://doi.org/10.1016/B978-012370467-2/50154-1

Beasley, V. R., & Levengood, J. M. (2012). Principles of ecotoxicology. In R. C. Gupta (Ed.), *Veterinary toxicology: Basic and clinical principles* (pp. 831–855). Academic Press. https://doi.org/10.1016/B978-0-12-385926-6.00077-6

Berdimbetov, T., Pushpawela, B., Murzintcev, N., Nietullaeva, S., Gafforov, K., Tureniyazova, A., & Madetov, D. (2024). Unraveling the intricate links between the dwindling Aral Sea and climate variability during 2002–2017. *Climate, 12*(7), 105. https://doi.org/10.3390/cli12070105

Berdimbetov, T., Shelton, S., Pushpawela, B., Rathnayake, U., Koshim, A. G., Yegizbayeva, A., & Nietullaeva, S. (2024). Use of intensity analysis and transfer matrix to characterize land conversion in the Aral Sea Basin under changing climate. *Modeling Earth Systems and Environment, 10*(4), 4717–4729. https://doi.org/10.1007/s40808-024-02019-x

Bespalova, K. (2023). On ruins, debris, and ghosts: The temporality of disaster in the film "Aral, Fishing in the Invisible Sea." *Apparatus, 2023*(17), 1. doi:10.17892/app.2023.00017.334

Boymirzaev, A. S., Berdimbetova, G. E., & Karlybaeva, B. P. (2024). Exclusion liquid chromatography of carboxymethylchitin and carboxymethylchitosan from crustacean *Artemia parthenogenetica* of the Aral Sea. *Proceedings of the National Academy of Sciences of Belarus, Chemical Series, 60*(1), 45–52. https://doi.org/10.29235/1561-8331-2024-60-1-45-52

Chernyh, N. A., Merkel, A. Y., Kondrasheva, K. V., Alimov, J. E., Klyukina, A. A., Bonch-Osmolovskaya, E. A., Slobodkin, A. I., & Davranov, K. D. (2024). At the shores of a vanishing sea: Microbial communities of Aral and Southern Aral Sea region. *Microbiology (Russian Federation), 93*(1), 1–13. https://doi.org/10.1134/S0026261723602944

Cui, M., Zheng, X., Li, Y., & Wang, Y. (2023). Analysis of NDVI trends and driving factors in the buffer zone of the Aral Sea. *Water (Switzerland), 15*(13), 2473. https://doi.org/10.3390/w15132473

Djumaboev, K., Amirova, I., Primov, A., & Ishchanov, J. (2024). Farmers on the front line: Perceptions, practices and discrepancies from the Aral Sea's Karakalpakstan and Khorezm regions. *Irrigation and Drainage, 73*(3), 1102–1118. https://doi.org/10.1002/ird.2922

Duan, Z., Afzal, M. M., Liu, X., Chen, S., Du, R., Zhao, B., Yuan, W., & Awais, M. (2024). Effects of climate change and human activities on environment and area variations of the Aral Sea in Central Asia. *International Journal of Environmental Science and Technology, 21*(2), 1715–1728. https://doi.org/10.1007/s13762-023-05072-8

Duan, Z., Wang, X., Sun, L., Zhou, M., & Luo, Y. (2024). An insight into effect of soil salinity on vegetation dynamics in the exposed seafloor of the Aral Sea. *Science of the Total Environment, 951*, 175615. https://doi.org/10.1016/j.scitotenv.2024.175615

Edwin, I. E., Chukwuka, O., Ochege, F. U., Ling, Q., Chen, B., Nzabarinda, V., Ajaero, C., Hamdi, R., & Luo, G. (2024). Quantifying land change dynamics, resilience and feedback: A comparative analysis of the Lake Chad Basin in Africa and Aral Sea Basin in Central Asia. *Journal of Environmental Management, 361*, 121218. doi:10.1016/j.jenvman.2024.121218

EFSA PPR Panel (EFSA Panel on Plant Protection Products and their Residues (PPR)). (2006). Opinion of the Scientific Panel on Plant Protection Products and their Residues (PPR) on the scientific principles in the assessment and guidance provided in the area of environmental fate, exposure, ecotoxicology, and residues between 2003 and 2006. *EFSA Journal, 4*(6), Article 360. https://doi.org/10.2903/j.efsa.2006.360

Erkudov, V. O., Rozumbetov, K. U., González-Fernández, F. T., Pugovkin, A. P., Nazhimov, I. I., Matchanov, A. T., & Ceylan, H. İ. (2023). The effect of environmental disasters on endocrine status, hematology parameters, body composition, and physical performance in young soccer players: A case study of the Aral Sea region. *Life, 13*(7), 1503. https://doi.org/10.3390/life13071503

Erkudov, V. O., Rozumbetov, K. U., Pugovkin, A. P., Matchanov, A. T., Esimbetov, A. T., Arachchi, S., & Rathnayake, U. (2023). Assessment of youth fitness under long-term exposure to toxic environmental conditions due to pesticides: Case from Aral Sea region. *Case Studies in Chemical and Environmental Engineering, 8*, 100504. https://doi.org/10.1016/j.cscee.2023.100504

Féaux de la Croix, J., & Samakov, A. (2024). Moving beyond the framing impasse in the Aral Sea Delta: Vernacular knowledge of salinization and its potential for social learning towards sustainability. *Sustainability (Switzerland), 16*(19), 8605. https://doi.org/10.3390/su16198605

Fomenko, G., & Fomenko, M. A. (2023). Evaluating measures to support dryland rural populations under high climatic uncertainty and risk: The example of the Aral Sea region. *Reliability: Theory and Applications, 18*(Special Issue 5), 231–237. doi:10.24412/1932-2321-2023-575-231-237

Ford, A. T. (2017). Comment on "Principles of sound ecotoxicology." *Environmental Science & Technology, 51*(19), 11493–11495. https://doi.org/10.1021/acs.est.7b03385

Gagné, F. (2014). *Biochemical ecotoxicology: Principles and methods* (pp. 1–257). Elsevier. https://doi.org/10.1016/C2012-0-07586-2

Han, Y., Ma, X., Yan, W., & Wang, Y. (2024). Windbreak and sand fixation service flow simulation in the terminal lake basin of inland rivers in arid regions: A case study of the Aral Sea basin. *Science of the Total Environment, 945*, 174047. https://doi.org/10.1016/j.scitotenv.2024.174047

Harris, C. A., Scott, A. P., Johnson, A. C., Panter, G. H., Sheahan, D., Roberts, M., & Sumpter, J. P. (2014). Principles of sound ecotoxicology. *Environmental Science & Technology, 48*(6), 3100–3111. https://doi.org/10.1021/es4047507

He, J., Yu, Y., Sun, L., Li, C., Zhang, H., Malik, I., Wistuba, M., & Yu, R. (2024). Spatiotemporal variations of ecosystem services in the Aral Sea Basin under different CMIP6 projections. *Scientific Reports, 14*(1), 12237. https://doi.org/10.1038/s41598-024-62802-9

Huang, F., Ochoa, C. G., & Guo, L. (2023). Estimating environmental water requirements for terminal lakes under varying meteorological conditions: A case study of the Big Aral Sea, Central Asia. *Journal of Hydrology, 621*, 129660. https://doi.org/10.1016/j.jhydrol.2023.129660

Izhitskiy, A., & Ayzel, G. (2023). Water balance of the regulated arid lake as an indicator of climate change and anthropogenic impact: The North (Small) Aral Sea case study. *Water (Switzerland), 15*(8), 1464. doi:10.3390/w15081464

Jiemuratova, G. K., Aripova, T. U., Kamalov, Z. S., & Mambetkarimov, G. A. (2024). Interrelations between iron content and immune dysfunctions in frequently ill children of the Aral Sea region. *Russian Journal of Immunology, 27*(2), 281–286. https://doi.org/10.46235/1028-7221-16661-IBI

Jin, M., Wu, J., Zhang, H., Zhao, Z., Alam, M., & Guo, R. (2023). Study on the Aral Sea crisis from the risk assessment of polycyclic aromatic hydrocarbons and organochlorine pesticides in surface water of Amu Darya river basin in Uzbekistan. *Frontiers in Earth Science, 11*, 1295485. https://doi.org/10.3389/feart.2023.1295485

Karapetyan, L. A., Balykova, A. N., Chervyakova, N. S., Fedorov, A. V., Eroshenko, G. A., Abramova, E. G., Germanchuk, V. G., Kuklev, E. V., & Toporkov, V. P. (2024). Retrospective molecular investigation of plague outbreaks in the Northern Aral Sea Region in the mid-20th century [Ретроспективная молекулярная экспертиза вспышек чумы в Северном Приаралье в середине XX века]. *Problemy Osobo Opasnykh Infektsii*, (4), 94–106. https://doi.org/10.21055/0370-1069-2024-4-94-106

Karlybaeva, M.A., Rakhimova, Sh. Kh., Azamatov, A.A., Mezhlumyan, L.G., Baltabaev, M.T., Adilov, B.A., & Abdullaev, N.D. (2024). Amino-acid composition of proteins from *Xylosalsola richteri* growing in Northwestern Kyzylkum and under southern Aral-Sea conditions. *Chemistry of Natural Compounds*, *60*(5), 1000–1002. https://doi.org/10.1007/s10600-024-04505-1

Kayiranga, A., Chen, X., Ingabire, D., Liu, T., Li, Y., Nzabarinda, V., Ochege, F. U., Hirwa, H., Duulatov, E., & Nthangeni, W. (2024). Anthropogenic activities and the influence of desertification processes on the water cycle and water use in the Aral Sea Basin. *Journal of Hydrology: Regional Studies, 51*, 101598. https://doi.org/10.1016/j.ejrh.2023.101598

Khaitov, B., Karimov, A., Kodirov, A., Yuldasheva, R., & Kim, Y. C. (2023). Identification, characterization and domestication of new sorghum (*Sorghum bicolor* L.) genotypes to saline environments of the Aral Sea regions. *Plant Science Today, 10*(1), 48–56. https://doi.org/10.14719/pst.1797

Kim, G., Ahn, J., Chang, H., An, J., Khamzina, A., Kim, G., & Son, Y. (2024). Effect of vegetation introduction versus natural recovery on topsoil properties in the dried Aral Sea bed. *Land Degradation and Development, 35*(13), 4121–4132. https://doi.org/10.1002/ldr.5209

Kim, T., Yun, Y., Park, S., Oh, J., & Han, Y. (2023). Change detection over the Aral Sea using relative radiometric normalization based on deep learning. *Remote Sensing Letters, 14*(8), 821–832. https://doi.org/10.1080/2150704X.2023.2242589

Kitov, E. P., & Al farabi, O. (2024). Aral Sea Saka tribes study based on Egistic Mausoleum materials [Саки Приаралья по палеоантропологическим материалам из мавзолея Егистик]. *Ufa Archaeological Herald, 24*(2), 373–387. https://doi.org/10.31833/uav/2024.24.2.022

Kulikov, Y., Sambayev, N., Pavlenko, A., Isbekov, K., & Barakbayev, T. (2024). Ways of optimizing the fishery in the Small Aral Sea, taking into account the biotopic distribution of fish fauna. *AACL Bioflux, 17*(4), 1749–1761.

Kurbanov, D., Mylsamy, S., Zhou, B., Babayev, Z., Bazarbayev, R., Allaniyazov, A., Balakumar, S., Zeng, G., Yakubov, K., & Karazhanov, S. (2024). Investigation of the composition and morphology of raw materials from the Aral Sea region. *Zeitschrift für Physikalische Chemie, 238*(11), 2055–2074. https://doi.org/10.1515/zpch-2023-0401

Kuzmichyova, T. F. (2023). On filling of the eastern part of the former Aral Sea due to water discharge through the Kokaral Dam from analysis of Aqua/Terra satellite images [О заполнении восточной части бывшего Аральского моря за счёт сброса вод через Кокаральскую плотину на основе анализа снимков, полученных со спутников

Aqua/Terra]. *Sovremennye Problemy Distantsionnogo Zondirovaniya Zemli iz Kosmosa, 20*(2), 205–215. https://doi.org/10.21046/2070-7401-2023-20-2-205-215

Levengood, J. M., & Beasley, V. R. (2007). Principles of ecotoxicology. In R. C. Gupta (Ed.), *Veterinary toxicology: Basic and clinical principles* (pp. 689–708). Academic Press. https://doi.org/10.1016/B978-012370467-2/50154-1

Li, Y., Saparov, G., Zeng, T., Abuduwaili, J., & Ma, L. (2024). Geochemical behavior of rare earth elements in agricultural soils along the Syr Darya River within the Aral Sea Basin. *Environmental Monitoring and Assessment, 196*(5), 493. https://doi.org/10.1007/s10661-024-12647-6

Liu, J., Ding, J., Liu, B., Wu, S., & Han, Z. (2025). Characteristics of salt dust aerosols and their transport implications in the Aral Sea. *Scientific Reports, 15*(1), 3002. https://doi.org/10.1038/s41598-025-86880-5

Liu, S., Long, A., Luo, G., Wang, H., Yan, D., & Deng, X. (2024). What drives the distinct evolution of the Aral Sea and Lake Balkhash? Insights from a novel CD-RF-FA method. *Journal of Hydrology: Regional Studies, 56*, 102014. https://doi.org/10.1016/j.ejrh.2024.102014

Lloyd, S., Nakamura, T., & Masuda, S. (2023). Public perceptions of the Aral Sea disaster in Uzbekistan. *Journal of Disaster Research, 18*(7), 783–795. https://doi.org/10.20965/jdr.2023.p0783

Lopes, R. M., Hauser-Davis, R. A., Oliveira, M. M., Pierini, M. F., de Souza, C. A. M., Cavalcante, A. L. M., Santos, C. R. D., Comarú, M. W., & da Fonseca Tinoca, L. A. (2020). Principles of problem-based learning for training and professional practice in ecotoxicology. *Science of the Total Environment, 702*, Article 134809. https://doi.org/10.1016/j.scitotenv.2019.134809

Ma, X., Huang, S., Huang, Y., Wang, X., & Luo, Y. (2024). Evaporation from the hypersaline Aral Sea in Central Asia. *Science of the Total Environment, 908*, 168412. https://doi.org/10.1016/j.scitotenv.2023.168412

Mayar, M. A., Hamidov, A., Akramkhanov, A., & Helming, K. (2024). Consideration of the environment in water–energy–food nexus research in the Aral Sea Basin. *Water, 16*(5), 658. https://doi.org/10.3390/w16050658

Moiseenko, T. I. (2008). Aquatic ecotoxicology: Theoretical principles and practical application. *Water Resources, 35*(5), 530–541. https://doi.org/10.1134/S0097807808050047

Munisov, Z., & Borowy, I. (2023). A narrative analysis: Tragic images of the Aral Sea in the Russophone ecopoems. *Central Asian Survey, 42*(2), 238–253. https://doi.org/10.1080/02634937.2022.2154315

Muñoz, C., Charles, S., McVey, E. A., & Vermeiren, P. (2023). The ATTAC guiding principles to openly and collaboratively share wildlife ecotoxicology data. *MethodsX, 10*, Article 101987. https://doi.org/10.1016/j.mex.2022.101987

Novikova, N. M., Kuz'mina, Z. V., & Mamutov, N. K. (2023). Desertification of the Amu Darya River Delta and vegetation dynamics in the conditions of the Aral Sea crisis. *Arid Ecosystems, 13*(4), 371–385. https://doi.org/10.1134/S2079096123040108

Nurgaliyev, N., Tokhetova, L., Demesinova, A., Zhalbyrov, A., Zhapparbekov, N., & Shalabaeva, G. (2024). Assessment of African millet (*Pennisetum glaucum* L.) germplasm in the Aral Sea region, Kazakhstan. *SABRAO Journal of Breeding and Genetics, 56*(6), 2260–2272. https://doi.org/10.54910/sabrao2024.56.6.8

Panin, A. V., Ludikova, A. V., Sapelko, T. V., Uspenskaya, O. N., Borisova, O. K., Zagorulko, V. A., & Utkina, A. O. (2024). New data on the Pleistocene history of the Aral Sea-Lake. *Limnology and Freshwater Biology, 7*(4), 568–573. https://doi.org/10.31951/2658-3518-2024-A-4-568

Pastorino, P., Prearo, M., & Barceló, D. (2024). Ethical principles and scientific advancements: In vitro, in silico, and non-vertebrate animal approaches for a green ecotoxicology. *Green Analytical Chemistry, 8*, Article 100096. https://doi.org/10.1016/j.greeac.2024.100096

Plotnikov, I. S., Aladin, N. V., Zhakova, L. V., Mossin, J., & Høeg, J. T. (2023). Past, present and future of the Aral Sea—A review of its fauna and flora before and during the regression crisis. *Zoological Studies, 62*, 19. https://doi.org/10.6620/ZS.2023.62-19

Ramazonov, B., Mutalov, K., Egamberdiyeva, L., Atabayeva, D., Abdurashitova, Y., & Allanazarova, I. (2024). Growing salt-resistant flora under natural conditions of the Kyzyl-Kum Desert and arid bed of Aral Sea, Uzbekistan. *SABRAO Journal of Breeding and Genetics, 56*(5), 1895–1905. https://doi.org/10.54910/sabrao2024.56.5.13

Rustamova, I., Primov, A., Karimov, A. [Aziz], Khaitov, B., & Karimov, A. [Akmal]. (2023). Crop diversification in the Aral Sea region: Long-term situation analysis. *Sustainability, 15*(13), 10221. https://doi.org/10.3390/su151310221

Ruzmetova, A., Babaev, Z., & Yunusov, M. (2023). Preparation and investigation of a heat-resistant binder with a metakaolin additive made of Aral Sea raw materials. *Refractories and Industrial Ceramics, 64*(4), 383–387. https://doi.org/10.1007/s11148-024-00857-x

Saidmamatov, O., Saidmamatov, O., Sobirov, Y., Marty, P., Ruzmetov, D., Berdiyorov, T., Karimov, J., Ibadullaev, E., Matyakubov, U., & Day, J. (2024a). Nexus between life expectancy, CO_2 emissions, economic development, water, and agriculture in Aral Sea Basin: Empirical assessment. *Sustainability (Switzerland), 16*(7), 2647. https://doi.org/10.3390/su16072647

Saidmamatov, O., Sobirov, Y., Makhmudov, S., Marty, P., Yusupova, S., Ibadullaev, E., & Toshnazarova, D. (2024b). Dynamics of human fertility, environmental pollution, and socio-economic factors in Aral Sea Basin. *Economies, 12*(10), 272. https://doi.org/10.3390/economies12100272

Satybaldiyev, B., Ismailov, B., Nurpeisov, N., Kenges, K., Snow, D. D., Malakar, A., Taukebayev, O., & Uralbekov, B. (2023a). Downstream hydrochemistry and irrigation water quality of the Syr Darya, Aral Sea Basin, South Kazakhstan. *Water Supply, 23*(5), 2119–2134. https://doi.org/10.2166/ws.2023.114

Satybaldiyev, B., Ismailov, B., Nurpeisov, N., Kenges, K., Snow, D. D., Malakar, A., & Uralbekov, B. (2023b). Evaluation of dissolved and acid-leachable trace element concentrations in relation to practical water quality standards in the Syr Darya, Aral Sea Basin, South Kazakhstan. *Chemosphere, 313*, 137465. https://doi.org/10.1016/j.chemosphere.2022.137465

Sherimbetov, A., Sherimbetov, S., Adilov, B., Ruzmetov, D., & Shavkiev, J. (2024). Rapid detection of *Alternaria* spp. by PCR in the newly created forest plantations on the drained bottom of the Aral Sea. *Regulatory Mechanisms in Biosystems, 15*(2), 361–366. https://doi.org/10.15421/022451

Shukurov, I. S., Shukurova, L. I., & Marakulina, S. P. (2024). Problems of desertification and dustiness of atmospheric air in arid cities of the Aral Sea region. *Arid Ecosystems, 14*(3), 369–375. https://doi.org/10.1134/S207909612470032X

Šimonovičová, A., Pauditšová, E., Nosalj, S., Oteuliev, M., Klištincová, N., Maisto, F., Kraková, L., Pavlović, J., Šoltys, K., & Pangallo, D. (2024). Fungal and prokaryotic communities in soil samples of the Aral Sea dry bottom in Uzbekistan. *Soil Systems, 8*(2), 58. https://doi.org/10.3390/soilsystems8020058

Sokolova, E. A., Sadullaev, O. K., Samandarova, B. S., & Ilinskaya, O. N. (2024). The structure of the incidence of acute intestinal infections in children of the Southern Aral Sea region and bioimmune correction of intestinal microbiocenosis in shigellosis [Структура заболеваемости острыми кишечным инфекциями детей Южного Приаралья и биоиммунная коррекция микробиоценоза кишечника при шигеллёзе]. *Kazan Medical Journal, 105*(2), 205–213. https://doi.org/10.17816/KMJ108941

Song, Y., Xun, X., Zheng, H., Chen, X., Bao, A., Liu, Y., Luo, G., Lei, J., Xu, W., Liu, T., Hellwich, O., & Guan, Q. (2024). Modeling and locating the wind erosion at the dry bottom of the Aral Sea based on an InSAR temporal decorrelation decomposition model. *Remote Sensing, 16*(10), 1800. https://doi.org/10.3390/rs16101800

Suleimen, A., Rakhimova, B., Jangildinova, S., Aitkulov, A., Yessilbayeva, B., Dyussenbekova, B., Danilenko, M., & Beygam, N. (2024). Assessment of the influence of dust-salt aerosols of the Aral Sea on the morphological characteristics of the tissue of the epididymis of rats in the experiment. *OnLine Journal of Biological Sciences, 24*(4), 739–746. https://doi.org/10.3844/ojbsci.2024.739.746

Sultonov, Z., & Pant, H. K. (2023). Potential impacts of climate change on water management in the Aral Sea Basin. *Water Resources Management, 37*(14), 5743–5757. https://doi.org/10.1007/s11269-023-03627-5

Tejetdinova, D. M., Esemuratova, R. X., Saitova, A. K., & Begdullaeva, G. S. (2023). A synopsis of the genus *Asparagus* L. in the territory of the southern Aral Sea. *Iranian Journal of Botany, 29*(1), 40–46. https://doi.org/10.22092/ijb.2023.129426

Timur, B. (2023). Spatio-temporal variations of climate variables and extreme indices over the Aral Sea Basin during 1960–2017. *Trends in Sciences, 20*(12), 5664. https://doi.org/10.48048/tis.2023.5664

Touge, Y., Kobayashi, G., Khujanazarov, T., & Tanaka, K. (2024). Reproduction of historical water balance in the Aral Sea Basin: The physically-based framework to quantify water consumption components in endorheic lake. *Journal of Hydrology, 640*, 131711. https://doi.org/10.1016/j.jhydrol.2024.131711

Truhaut, R. (1977). Ecotoxicology: Objectives, principles and perspectives. *Ecotoxicology and Environmental Safety, 1*(2), 151–173. https://doi.org/10.1016/0147-6513(77)90033-1

Turdimambetov, I., Murgaš, F., Victor, F., Oteuliev, M., Madreimov, A., Shamuratova, G., Atabayev, S., & Reymov, A. (2024). Measurement of environmental indicators of the quality of life in a region with extreme climatic conditions: Evidence from around the Aral Sea. *Geojournal of Tourism and Geosites*, *57*, 1941–1951. https://doi.org/10.30892/gtg.574spl08-1361

Turzhova, E. B., Sorokoletova, E. F., Popov, V. B., Sukhov, Y. Z., & Bakina, V. N. (1993). Main methodological principles of biological express assessment in ecotoxicology. *Meditsina Truda i Promyshlennaya Ekologiya*, (7–8), 40–43.

Walker, C. H., Sibly, R. M., Hopkin, S. P., & Peakall, D. B. (2016). *Principles of ecotoxicology* (4th ed., pp. 1–353). CRC Press. https://doi.org/10.1201/b11767

Wang, M., Chen, X., Cao, L., Kurban, A., Shi, H., Wu, N., Eziz, A., Yuan, X., & De Maeyer, P. (2023a). Correlation analysis between the Aral Sea shrinkage and the Amu Darya River. *Journal of Arid Land, 15*(7), 757–778. https://doi.org/10.1007/s40333-023-0062-z

Wang, X., Zhang, J., Wang, S., Ge, Y., Duan, Z., Sun, L., Meadows, M. E., Luo, Y., Fu, B., Chen, X., Huang, Y., Ma, X., & Abuduwaili, J. (2023b). Reviving the Aral Sea: A hydro-eco-social perspective. *Earth's Future*, *11*(11), e2023EF003657. https://doi.org/10.1029/2023EF003657

Wang, X., Cui, B., Chen, Y., Feng, T., Li, Z., & Fang, G. (2024). Dynamic changes in water resources and comprehensive assessment of water resource utilization efficiency in the Aral Sea Basin, Central Asia. *Journal of Environmental Management*, *353*, 120198. https://doi.org/10.1016/j.jenvman.2024.120198

Wen, Z., Jiang, D., Jing, Y., & Liu, G. (2023). Remote sensing classification approach to large-scale crop cultivation identification: A case study of the Aral Sea Basin. *Transactions in GIS, 27*(8), 2278–2296. https://doi.org/10.1111/tgis.13120

Wheeler, W. 2021. *Environment and Post-Soviet Transformation in Kazakhstan's Aral Sea Region: Sea changes*. London: UCL Press. https://doi.org/10.14324/111.9781800080331

Wicaksono, W. A., Egamberdieva, D., Cernava, T., & Berg, G. (2023). Viral community structure and potential functions in the dried-out Aral Sea Basin change along a desiccation gradient. *mSystems, 8*(1). https://doi.org/10.1128/msystems.00994-22

Wu, M., Qiao, J., Zhang, Y., Tian, C., Li, Y., Hao, Y., Zhang, X., Wang, L., & He, J. (2023). Ecological governance of Aral Sea: Important way to deepen scientific and technological cooperation with Central Asia. *Bulletin of Chinese Academy of Sciences, 38*(6), 917–931. https://doi.org/10.16418/j.issn.1000-3045.20221103003

Yang, S., Sun, L., He, J., Li, C., & Yu, Y. (2024). Evolution of the Aral Sea: Crisis and present situation. *Arid Land Geography, 47*(2), 181–191.

Yue, B., Chen, X., Li, S., Du, Z., Wilson, J., Yang, J., Jiao, Y., Huang, S., & Zhou, C. (2024). A four-band index for both liquid and solid water and its applications in the Aral Sea Basin. *Science China Earth Sciences, 67*(3), 769–788. https://doi.org/10.1007/s11430-023-1252-9

Zhang, P., Wang, J., Huang, L., He, M., Yang, H., Song, G., Zhao, J., & Li, X. (2023). Microplastic transport during desertification in drylands: Abundance and characterization of soil microplastics in the Amu Darya–Aral Sea Basin, Central Asia. *Journal of Environmental Management, 348*, 119353. https://doi.org/10.1016/j.jenvman.2023.119353

Zhou, J., Ke, L., Ding, X., Wang, R., & Zeng, F. (2024). Monitoring spatial–temporal variations in river width in the Aral Sea Basin with Sentinel-2 imagery. *Remote Sensing, 16*(5), 822. https://doi.org/10.3390/rs16050822