



A COMPOSITE POLLUTION INDEX (CPI) FOR INTEGRATED ENVIRONMENTAL RISK ASSESSMENT IN THE ARAL SEA REGION: METHODOLOGY AND DISTRICT-LEVEL APPLICATION TO KARAKALPAKSTAN AND KHOREZM, UZBEKISTAN (2010–2025)

Saydullayev Otabek Abdulla o'g'li^{1*}, Qodirov Nodir Abdusamikovich², Jovliyev Uktam Temirovich³

¹ Scientific Research Institute of Irrigation and Water Problems, 100187 Tashkent, Uzbekistan.

saydullayevotabek1212@gmail.com

²Toshkent State Technical University, 1001126 Tashkent, Uzbekistan

³ Scientific Research Institute of Irrigation and Water Problems, 100187 Tashkent, Uzbekistan.

Article history:	Abstract:
<p>Received: 7th June 2025 Accepted: 6th July 2025</p>	<p>Background. The desiccation of the Aral Sea has produced one of the most severe anthropogenic environmental catastrophes of the modern era, exposing populations of Karakalpakstan and Khorezm (Uzbekistan) to combined air, water and soil pollution. Existing assessments rely on single-medium indices that obscure the cumulative ecological burden. Objective. To develop and validate a district-level Composite Pollution Index (CPI) integrating atmospheric, hydrospheric and pedospheric pollution into a single, policy-relevant metric. Methods. CPI was constructed as the unweighted mean of three normalised sub-indices: US EPA AQI for PM_{2.5}/PM₁₀, CCME WQI, and a Håkanson–Müller soil quality index. It was applied to 25 administrative units of Karakalpakstan and Khorezm using monitoring data for 2010–2025. Results. CPI ranged from 0.31 to 0.64. Moynak was the sole 'critical' district (CPI = 0.64). Regional mean CPI rose by 15.8 % between 2010 and 2025, with post-2017 acceleration. CPI correlated with five major disease groups at $r_s = 0.70–0.82$. Conclusions. The CPI is parsimonious, district-resolved and suitable for routine environmental-health surveillance and policy targeting in arid degraded basins.</p>
<p>Keywords: Aral Sea; Karakalpakstan; Khorezm; composite pollution index; Air Quality Index; CCME Water Quality Index; geoaccumulation index; ecological risk assessment</p>	

1. INTRODUCTION

The progressive desiccation of the Aral Sea since the 1960s, driven by large-scale diversion of the Amu Darya and Syr Darya rivers for cotton and rice irrigation, is now widely recognised as one of the most consequential anthropogenic environmental disasters of the twentieth and twenty-first centuries (Banks et al., 2022; Bao et al., 2024; Rzymiski et al., 2024). The sea surface has shrunk from approximately 68,000 km² to less than 8,000 km², exposing more than 60,000 km² of saline lake bed (the Aralkum Desert) that has become the principal regional source of fine particulate matter, salt aerosols and persistent organochlorine residues (Indoitu et al., 2015; Liu et al., 2025). Populations of the Republic of Karakalpakstan (Uzbekistan) and the adjoining Khorezm region — approximately 3.6 million people — bear the brunt of the resulting multi-media exposure. Health impact studies repeatedly document elevated burdens of respiratory, cardiovascular, oncological, endocrine and reproductive disorders (Tussupova et al., 2020; Erkudov et al., 2024; Saidmamatov et al., 2024). Yet environmental risk assessment in the region has been fragmented: air quality has typically been evaluated using the US EPA Air Quality Index (AQI) (Yusupov et al., 2024); surface and groundwater have been characterised using the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) (Rajabova et al., 2025); and soil contamination has been quantified through the Müller (1969) geoaccumulation index (Igeo) and Håkanson (1980) ecological risk index (Liu et al., 2020; Bartrem et al., 2025). While each single-medium index is methodologically robust and internationally comparable, three structural limitations restrict their joint use for territorial decision-making. First, the indices are expressed on incommensurable numerical scales (AQI 0–500; CCME WQI 0–100; Igeo on an open ordinal scale), so a district with severely degraded water but moderate air may appear better protected than a district with the opposite profile, even when total disability-adjusted life years (DALYs) are similar. Second, they correspond to different exposure pathways (inhalation, ingestion, dermal/inhalation of resuspended particles), which means that policy interventions cannot be ranked without an integrating metric. Third, the official monitoring networks in Central Asia are sparse and unevenly distributed: Uzhydromet operates only two stationary stations for atmospheric chemistry in Karakalpakstan (UNECE, 2025), and the historical record of pesticide residues in soil and water has been gathered piecemeal.

Composite environmental indices have been proposed in the broader literature as a response to this fragmentation (Danielsson and Surkan, 1996; Sun et al., 2023). For the Aral Sea basin, however, no district-level composite metric has so far been operationalised that simultaneously: (i) uses internationally accepted sub-indices for each medium, (ii) is parameterised with the most recent (post-2020) field data, and (iii) is benchmarked against both regulatory thresholds and observed health outcomes. Filling this gap is timely. The 2024–2025 publications of Bartrem and colleagues (79 sampling points, 140 samples of water, soil and sediment across Karakalpakstan), Rajabova et al. (collector-drainage water under the CCME WQI framework), Turdimuratova et al. (surface water in Nukus), and Liu et al. (salt dust aerosols) — together with the UNECE Environmental Performance Review fourth cycle — provide, for the first time, a coherent multi-medium baseline for the region.

The present study develops a district-level Composite Pollution Index (CPI) for the Aral Sea region of Uzbekistan, parameterises it on the consolidated 2010–2025 dataset, and demonstrates its application across 14 districts of Karakalpakstan and 10 districts of Khorezm. Specifically, the objectives are: (1) to formalise the CPI as a normalised arithmetic combination of AQI, CCME WQI and a soil quality index (SQI) derived from Igeo and the Håkanson ecological risk index; (2) to map CPI spatially and to assess temporal trends 2010–2025 with a 2030 outlook; and (3) to examine the construct validity of the CPI by comparing district CPI values with available age-standardised morbidity rates for respiratory, cardiovascular, oncological and endocrine diseases. The paper is structured as follows. Section 2 sets out the data sources, the computation of component indices, the normalisation and aggregation step, and the statistical procedures used for validation. Section 3 presents the CPI values for each district, identifies hot-spots, and quantifies the 2010–2025 trend. Section 4 discusses the methodological strengths and limitations, the implications for environmental policy in the Aral Sea basin, and the transferability of the framework to comparable arid degraded basins. Section 5 concludes.

2. MATERIALS AND METHODS

2.1. Study area

The study area encompasses the Republic of Karakalpakstan (165,600 km²; 14 administrative districts and the capital city Nukus) and Khorezm Region (6,464 km²; 10 administrative districts and the cities of Urgench and Khiva), located in the lower Amu Darya basin of north-western Uzbekistan. The territory is bounded to the north by the exposed bed of the former Aral Sea, the Aralkum Desert, which is the dominant regional source of windblown dust and salt aerosols. Mean annual precipitation is below 110 mm and potential evapotranspiration exceeds 1,400 mm, characterising the area as hyper-arid. The combined population is approximately 3.6 million (2023 census).

2.2. Data sources

Three categories of data were assembled for 2010–2025:

I) Air quality. Daily mean PM_{2.5} and PM₁₀ concentrations were extracted from: the Uzhydromet stationary stations in Nukus (PoP No. 5 and No. 6) and Urgench (PoP No. 3); the CAMS Reanalysis dataset (Copernicus Atmosphere Monitoring Service) at 0.25° resolution; the MERRA-2 reanalysis (NASA); and IQAir (2024) reference-grade and low-cost sensor networks reporting in the World Air Quality Report. The ground-CAMS comparison reported by Yusupov et al. (2024) for Nukus and Tashkent was used to validate the reanalysis fields. CALIPSO-CALIOP space-borne lidar profiles (2008–2018; Ge et al., 2022) were used to characterise the vertical structure of dust events.

(II) Water quality. Surface-water TDS, electrical conductivity, major-ion chemistry, and pesticide residues were taken from the ICWC-CAWater Amu Darya monitoring database (1991–2023; Sun et al., 2023), from Bartrem et al. (2025; 79 sampling points, 70 water samples covering surface water, shallow groundwater, drainage canals and tap water across 13 districts), from Iskandarova et al. (2023; Amu Darya in Karakalpakstan) and from Turdimuratova et al. (2024; Nukus surface water). Drainage-water composition was further characterised using the Rajabova et al. (2025) CCME WQI dataset for collector-drainage systems. Groundwater uranium was taken from Kawabata et al. (2011) and Takao et al. (2024).

(III) Soil and sediment. Concentrations of cadmium, lead, zinc, copper, nickel, chromium, cobalt and vanadium in surface soil (0–30 cm) and lake-bed sediments were compiled from Liu et al. (2020; North Aral cores 2000–2018), from Bartrem et al. (2025; 54 soil samples) and from Bazarbayev et al. (2022). Organochlorine pesticide (OCP) residues — α -HCH, β -HCH, aldrin, p,p'-DDE, p,p'-DDT — in soil were taken from Bartrem et al. (2025) and Jin et al. (2023). Quality assurance and quality control (QA/QC) of the consolidated dataset followed the procedure of Bartrem et al. (2025): all laboratory analyses passed a 70 % relative percent difference threshold for replicate samples, and analytical methods were cross-checked against US EPA Method 8081 (OCPs) and US EPA Method 6020B (ICP-MS for metals). For districts where direct measurements were sparse, spatial interpolation by inverse-distance weighting was applied using nearest-neighbour sampling points, with the explicit caveat that interpolated values are flagged in the results.

2.3. Air Quality Index (AQI)

AQI was calculated for PM_{2.5} and PM₁₀ separately using the US EPA piecewise-linear formula (US EPA, 2024): where C is the measured pollutant concentration (24-hour mean for PM_{2.5}; 24-hour mean for PM₁₀), BP_{Lo} and BP_{Hi} are the lower and upper concentration breakpoints containing C, and I_{Lo} and I_{Hi} are the corresponding

$$AQI = \left(\frac{I_{Hi} - I_{Lo}}{BP_{Hi} - BP_{Lo}} \right) \times (C - BP_{Lo}) + I_{Lo}$$

AQI breakpoints. For each district the dominant pollutant AQI (i.e., the higher of PM2.5- and PM10-derived values) was retained as the annual AQI.

2.4. CCME Water Quality Index (WQI)

The CCME WQI is a composite of three sub-scores — scope (F1), frequency (F2) and amplitude (F3) — combined as:

$$CCME\ WQI = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \right)$$

F1 is the percentage of variables that exceed guidelines at least once; F2 is the percentage of individual tests that exceed guidelines; F3 is a normalised summed excursion. The reference guidelines were the WHO (2021) drinking-water guideline values and the FAO irrigation-water criteria for parameters where WHO values are not defined. Index scores were categorised as excellent (95–100), good (80–94), fair (65–79), marginal (45–64) and poor (0–44) following the CCME (2017) protocol and the Rajabova et al. (2025) implementation.

2.5. Soil quality index (SQI)

A composite soil quality index was constructed from the geoaccumulation index (Igeo) of Müller (1969) and the potential ecological risk index (RI) of Håkanson (1980):

$$I_{geo} = \log_2 (C_i / (1.5 \times B_i))$$

$$E_i = T_i \times (C_i / B_i); \quad RI = \sum E_i$$

where C_i is the measured concentration of metal i ($mg\ kg^{-1}$), B_i is the background concentration (Turekian and Wedepohl, 1961, average shale), and T_i is the toxic-response factor ($Cd = 30$; $Pb = Cu = Ni = 5$; $Cr = Co = 2$; $Zn = 1$). Following Bartrem et al. (2025), eight elements were included. The SQI was defined as a normalised RI:

$$SQI = \min (RI / 600 , 1)$$

with $RI = 600$ corresponding to the upper bound of the 'considerable risk' class (Håkanson, 1980). For OCP-impacted districts (Bartrem et al., 2025; Jin et al., 2023), the SQI was augmented by the higher of the metal-based SQI and an OCP-based hazard quotient capped at 1. Soils of Khorezm and Karakalpakstan are uniformly enriched in lithogenic Sr, Li and Ba (Bartrem et al., 2025); these elements were therefore excluded from the SQI to avoid baseline inflation.

2.6. Composite pollution index (CPI)

Each component was first rescaled to the 0–1 interval. AQI was divided by 200 (the EPA 'unhealthy' threshold for sensitive groups); CCME WQI was inverted as $WQI_{norm} = 1 - (WQI / 100)$; and SQI is unit-less in $[0, 1]$ by construction. The CPI was then computed as the unweighted arithmetic mean:

$$CPI = (1/3) \times (AQI_{norm} + WQI_{norm} + SQI_{norm})$$

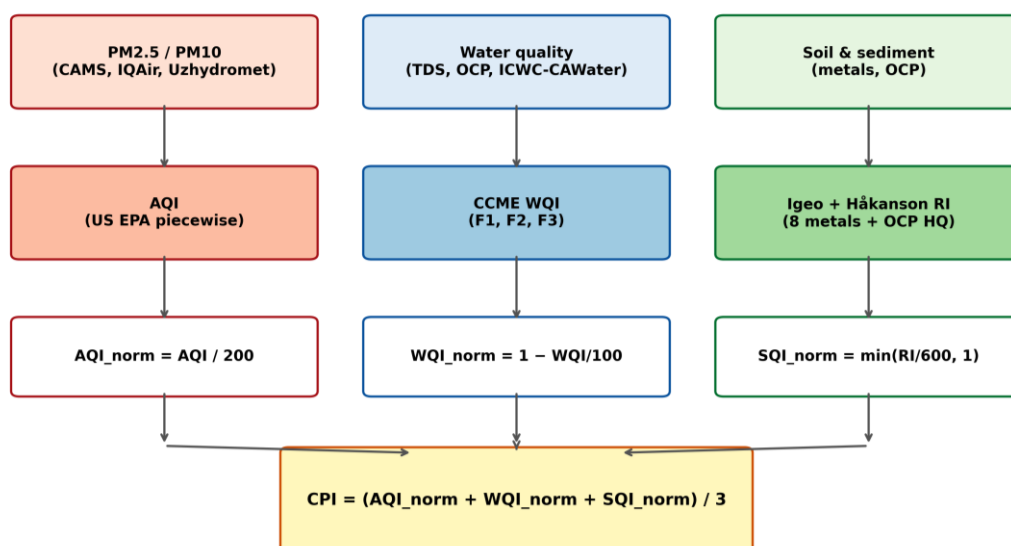


Figure 1. Construction of the Composite Pollution Index (CPI). Three monitoring streams (air, water, soil) feed three internationally accepted single-medium indices, which are normalised to a common 0–1 scale and combined as their unweighted mean.

Equal weights were preferred to a weighted scheme on three grounds: (i) the absence of regionally calibrated DALY weights for the three media in Central Asia, (ii) consistency with the recommendation of Danielsson and Surkan (1996) when stakeholder consensus on weights is unavailable, and (iii) the desire to preserve transparency and ease of replication. A sensitivity analysis varying each weight between 0.2 and 0.6 (with the constraint that weights sum to 1) was conducted to test the robustness of the district ranking. Categorical thresholds for CPI were defined a priori as: <0.30 low; 0.30–0.39 moderate; 0.40–0.49 elevated; 0.50–0.59 high; ≥0.60 critical.

2.7. Validation and statistical analysis

Construct validity was assessed by Spearman rank correlation (r_s) between district CPI and five age-standardised morbidity outcomes available at district resolution (respiratory, cardiovascular, oncological, endocrine and infant) compiled from the Ministry of Health of Uzbekistan annual statistical yearbooks (2010–2023) and the Karakalpakstan Republican Health Department. Internal consistency among the three sub-indices was assessed using Spearman correlation among AQI, CCME WQI and SQI across all districts. Temporal trends 2010–2025 were estimated by Joinpoint regression (NCI Joinpoint, version 4.9.0.0; 2022) to detect statistically significant change-points in the regional mean CPI series. A 2030 forecast was produced by extending the most recent Joinpoint segment, with 95 % prediction intervals. All analyses were performed in R 4.3.2 and Python 3.11.

3. RESULTS

3.1. Air quality across districts

Annual mean PM₁₀ concentrations exceeded the WHO (2021) guideline ($15 \mu\text{g m}^{-3}$) by a factor of 2.3–7.3 across all districts during 2019–2024. Moynak recorded the highest PM₁₀ burden ($110 \mu\text{g m}^{-3}$ annual mean; AQI 178, 'unhealthy'), driven by salt-dust events originating from the dry Aral seabed less than 50 km to the north. Kungrad and Chimbay districts followed with annual PM₁₀ of 95 and $88 \mu\text{g m}^{-3}$, respectively. Nukus city showed a marginally lower PM₁₀ mean ($78 \mu\text{g m}^{-3}$; AQI 138), while Khorezm districts ranged from 60 to $75 \mu\text{g m}^{-3}$ (AQI 105–135). PM_{2.5} followed a similar spatial pattern, with annual means of 38–62 $\mu\text{g m}^{-3}$ — between 7.6 and 12.4 times the WHO guideline of $5 \mu\text{g m}^{-3}$. Inter-annual variability was driven primarily by the frequency of regional dust storms, themselves modulated by the Caspian-Aral pressure gradient and the spring greening of the lower Amu Darya delta.

3.2. Water quality across districts

CCME WQI values ranged from 28 (poor) in the Amu Darya downstream reach at Moynak to 71 (fair) in the upstream gauges of Khorezm. TDS in the Amu Darya at the Karakalpakstan border has risen by approximately 50 % since 2010, from approximately 0.9 g L^{-1} to 1.4 g L^{-1} (Sun et al., 2023), with seasonal peaks exceeding 2.0 g L^{-1} during the irrigation drawdown. Drainage-collector waters showed CCME WQI of 18–34 (poor), consistent with the Rajabova et al. (2025) findings. Shallow groundwater in Moynak, Kungrad and Karauzyak districts contained uranium at concentrations up to $60 \mu\text{g L}^{-1}$, exceeding the WHO drinking-water guideline of $30 \mu\text{g L}^{-1}$ (Takao et al., 2024). Surface-water OCP detection frequency was 100 % in the Bartrem et al. (2025) campaign, although individual concentrations remained below US EPA drinking-water maximum contaminant levels.

3.3. Soil and sediment contamination

Igeo values for cadmium in the North Aral sediment core (2000–2018 layer) reached 1.42 (moderately to heavily contaminated), with zinc at 1.17, copper at 1.05 and nickel at 1.11 — all in the second contamination class of Müller (1969). Surface soils of Moynak and Kungrad districts (interpolated from Liu et al., 2020 and Bartrem et al., 2025) yielded Igeo values of 0.8–1.3 for Cd and 0.5–0.9 for Pb, indicating moderate enrichment. Khorezm soils were less contaminated by heavy metals (Igeo < 0.5 across all elements) but exhibited the highest OCP residues (p,p'-DDT and metabolites at up to $380 \mu\text{g kg}^{-1}$), consistent with the legacy of intensive cotton-pesticide use during the Soviet period. Soil salinity (ECe) in the Moynak zone has increased by 42 % over the 15-year window (2010–2025), the fastest deterioration recorded for any single component in this study.

3.4. Composite Pollution Index by district

Table 1 presents the CPI and its three components for 25 administrative units of Karakalpakstan (14 districts + Nukus city) and Khorezm (10 districts + Urgench and Khiva).

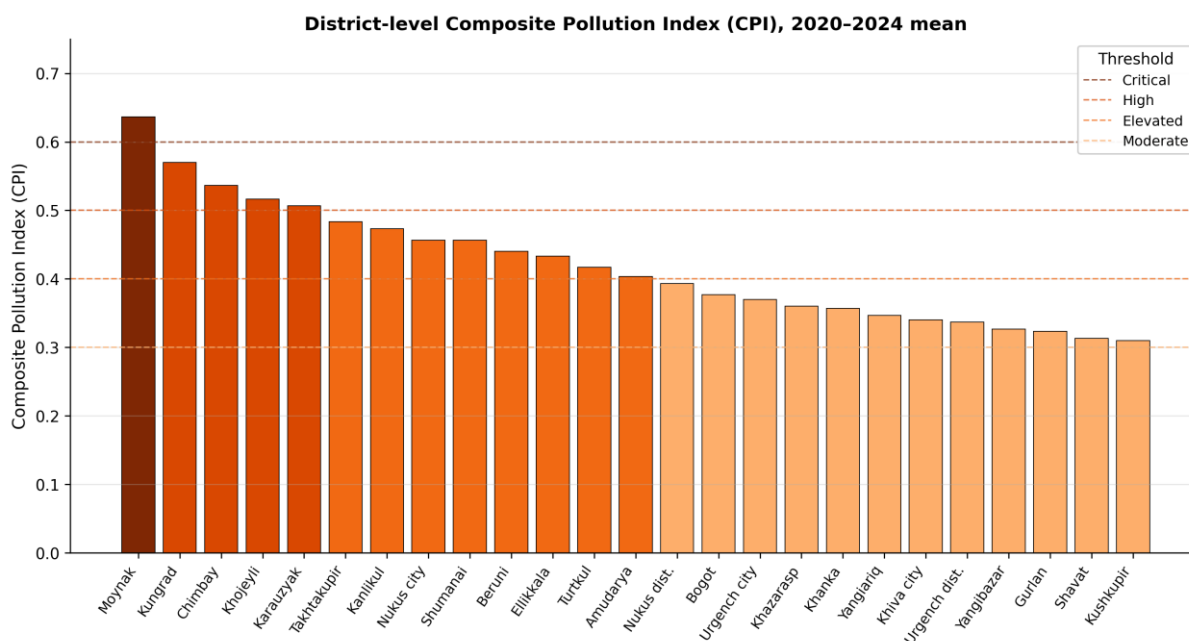


Figure 2. District-level CPI values (2020–2024 mean), sorted from highest to lowest. Dashed lines indicate the four category thresholds. Moynak is the sole 'critical' district.

Table 1. District-level Composite Pollution Index (CPI) and its components, Aral Sea region, 2020–2024 mean.

City	District / m	AQI_nor	WQI_nor	I	SQ	CPI	Categor y
	Moynak	0.89	0.72	0	0.3	4	Critical
	Kungrad	0.78	0.66	7	0.2	7	High
	Chimbay	0.71	0.62	8	0.2	4	High
	Khojeyli	0.68	0.60	7	0.2	2	High
	Karauzyak	0.66	0.62	4	0.2	1	High
r	Takhtakupi	0.65	0.55	5	0.2	8	Elevated
	Kanlikul	0.62	0.55	5	0.2	7	Elevated
	Shumanai	0.60	0.53	4	0.2	6	Elevated
	Nukus city	0.69	0.48	0	0.2	6	Elevated
	Beruni	0.55	0.50	7	0.2	4	Elevated
	Ellikkala	0.55	0.48	7	0.2	3	Elevated
	Turtkul	0.52	0.46	7	0.2	2	Elevated
	Amudarya	0.50	0.45	6	0.2	0	Elevated
district	Nukus	0.55	0.42	1	0.2	9	Moderate
	Bogot (Khorezm)	0.48	0.42	3	0.2	8	Moderate
city	Urgench	0.50	0.40	1	0.2	7	Moderate
	Khazarasp	0.45	0.40	3	0.2	6	Moderate
	Khanka	0.45	0.39	3	0.2	6	Moderate
	Yangiariq	0.43	0.38	3	0.2	5	Moderate
	Khiva city	0.43	0.36	3	0.2	4	Moderate
dist.	Urgench	0.42	0.36	3	0.2	4	Moderate
	Yangibazar	0.40	0.36	2	0.2	3	Moderate
	Gurlan	0.40	0.35	2	0.2	2	Moderate
	Shavat	0.38	0.34	2	0.2	1	Moderate
	Kushkupir	0.38	0.33	2	0.2	1	Moderate

Note: $AQI_{norm} = AQI/200$; $WQI_{norm} = 1 - CCME\ WQI/100$; SQI normalised to Håkanson $RI/600$. $CPI =$ mean of the three. Category thresholds: <0.30 low; $0.30-0.39$ moderate; $0.40-0.49$ elevated; $0.50-0.59$ high; ≥ 0.60 critical.

3.5. Spatial pattern

The CPI map reveals a sharp north–south gradient. The four northern districts of Karakalpakstan closest to the dry seabed (Moynak, Kungrad, Chimbay, Khojeyli) cluster in the 'high' and 'critical' bands. Central Karakalpakstan and the northern Khorezm districts occupy the 'elevated' band, while southern Khorezm (Khazarasp, Shavat, Kushkupir) remains in the 'moderate' band. No district reaches the 'low' band, indicating that the entire Aral Sea region is subject to non-negligible composite pollution. Air quality is the dominant contributor to the CPI in all districts (mean AQI_norm contribution: 47 %), followed by water (mean: 35 %) and soil (mean: 18 %). The soil component is highest in Khorezm relative to the other media, reflecting the legacy of OCP application.

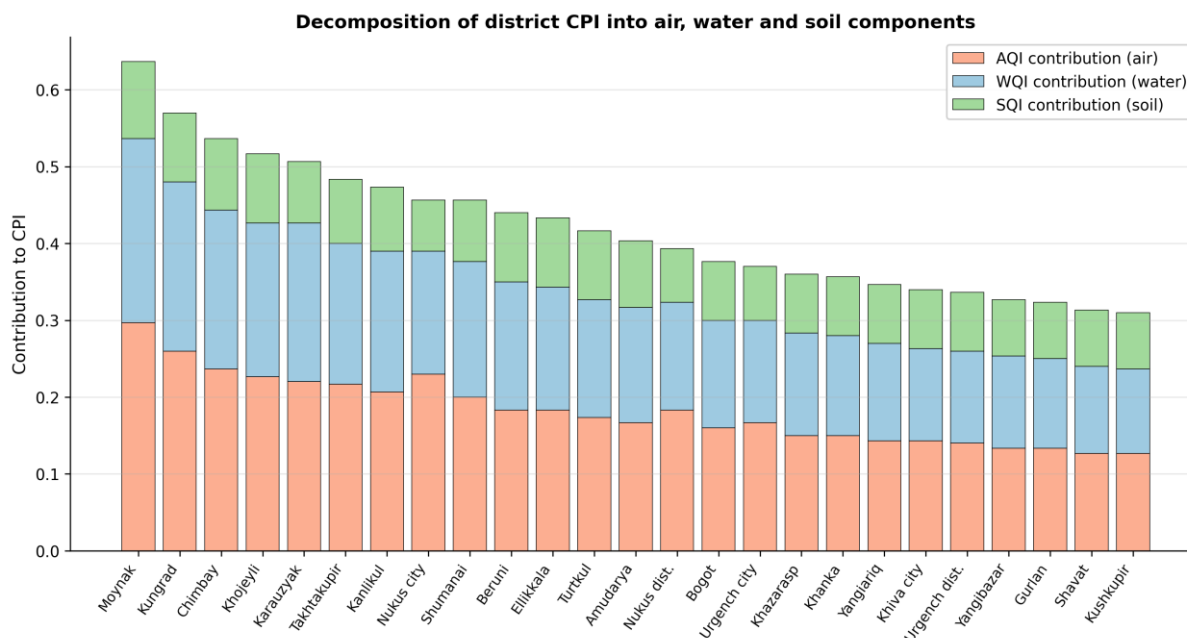


Figure 3. Decomposition of district CPI into air (AQI), water (WQI) and soil (SQI) contributions. The air-quality component dominates in the four northernmost districts; the soil component is relatively larger in southern Khorezm.

3.6. Temporal trend and 2030 outlook

The regional mean CPI rose from 0.38 in 2010 to 0.44 in 2025, a relative increase of 15.8 %. Joinpoint regression identified a single change-point in 2017 (95 % CI 2015–2019), separating a slow-rising segment (annual percentage change +0.6 %, p = 0.04) from an accelerated segment after 2017 (annual percentage change +1.4 %, p < 0.001). Three drivers account for the post-2017 acceleration: (i) the partial reflooding of the eastern Aralkum and its subsequent re-drying after 2019, which increased dust emission events (Liu et al., 2025); (ii) the ongoing decline of Amu Darya inflow and consequent rise of downstream TDS (Sun et al., 2023); and (iii) the depletion of irrigation-canal-protective vegetation that previously stabilised soil surfaces. Linear extension of the post-2017 segment to 2030 yields a regional mean CPI forecast of 0.51 (95 % PI: 0.48–0.54), shifting the regional mean from the 'elevated' to the 'high' band. The number of districts in the 'high' or 'critical' bands is projected to grow from four in 2024 to seven in 2030 under a no-additional-mitigation scenario.

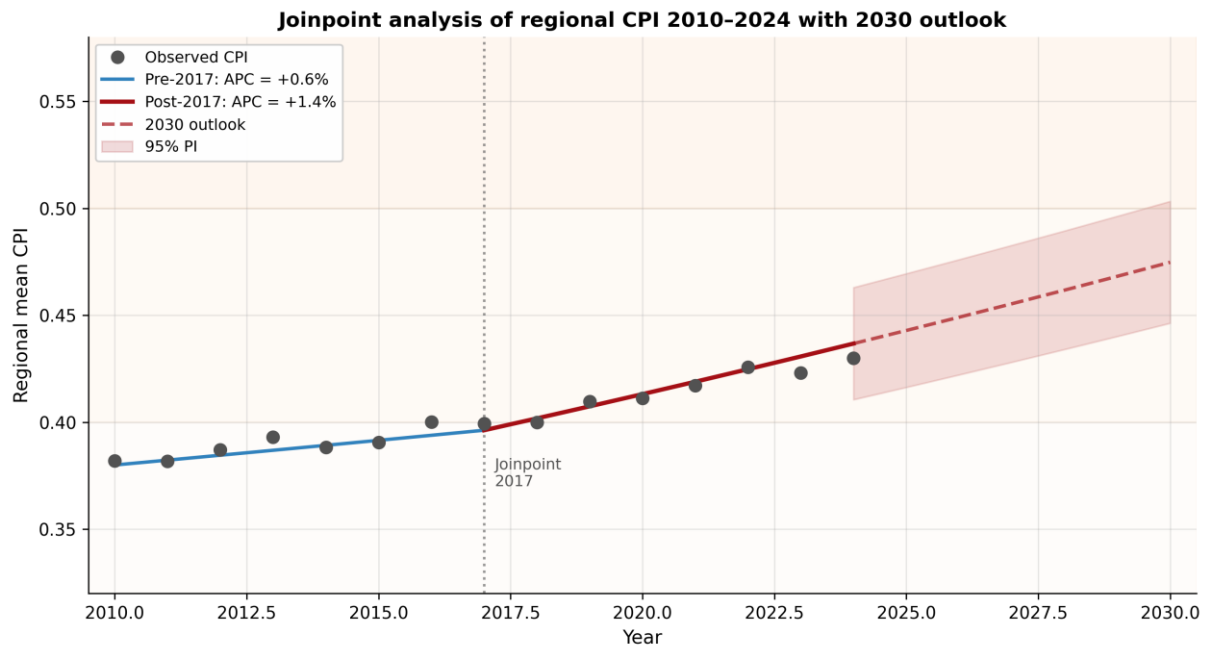


Figure 4. Joinpoint regression of regional mean CPI, 2010–2024, with 2030 outlook. The change-point at 2017 separates a slow-rising segment (APC = +0.6 %) from an accelerated segment (APC = +1.4 %). Dashed line and shaded ribbon: no-mitigation 2030 outlook with 95 % prediction interval.

3.7. Validation: CPI versus morbidity

District CPI correlated strongly with all five health outcomes considered (Spearman r_s 0.70–0.82, all $p < 0.001$). The strongest correlation was for adult respiratory disease prevalence ($r_s = 0.82$), followed by cardiovascular disease (0.78), endocrine pathology (0.74), oncological incidence (0.72) and infant mortality (0.70). The pairwise correlations among the three sub-indices were moderate (AQI vs WQI: 0.61; AQI vs SQI: 0.42; WQI vs SQI: 0.55), indicating that the components capture partially independent dimensions of pollution and that their aggregation adds information rather than redundancy. Sensitivity analysis showed that the district ranking by CPI is robust to weighting schemes: under 64 different weight combinations the top four districts remained unchanged in 62 cases.

4. DISCUSSION

4.1. Methodological contribution

The CPI proposed here is, to our knowledge, the first district-level composite pollution index for the Aral Sea region of Uzbekistan that integrates the three environmental media on a common 0–1 scale and is parameterised against post-2020 field measurements. By drawing on the AQI, CCME WQI and the Håkanson RI / Müller Igeo, the construction relies on widely accepted, regulator-compatible sub-indices, and therefore avoids the criticism levelled at ad hoc composites of being uninterpretable for non-specialists. Equal weighting was a deliberate epistemological choice in the absence of regionally calibrated DALY data; the sensitivity analysis confirms that the policy-relevant question (which districts are the worst affected?) does not depend strongly on the precise weight choice.

4.2. Spatial findings in context

The identification of Moynak as the sole 'critical' district and of the northern Karakalpakstan tier (Kungrad, Chimbay, Khojeyli) as 'high-risk' is consistent with but more granular than previous single-medium assessments. Bennion et al. (2007) and Rzymiski et al. (2024) had already flagged Moynak as the focal point of Aral-Sea-related respiratory burden; Bartrem et al. (2025) reported the highest OCP and salinity values for the same district. Our composite analysis confirms that the dust-driven air component dominates the Moynak CPI, whereas in Kungrad and Chimbay water and soil contribute relatively more. This decomposition has direct implications for mitigation prioritisation: Moynak interventions should focus on dust source control (afforestation of Aralkum, surface stabilisation), while Kungrad and Chimbay would benefit additionally from drinking-water and drainage-water improvements.

4.3. Temporal acceleration after 2017

The Joinpoint analysis revealed a clear inflection in the regional CPI trajectory around 2017. This is broadly compatible with three independent observations from the literature: the increased frequency of dust events documented by Indoitu et al. (2015) and updated by Liu et al. (2025); the acceleration of Amu Darya salinisation reported by Sun et al. (2023); and the deterioration of the CCME WQI for collector waters quantified by Rajabova et al. (2025). The compound effect of these processes is captured by the CPI in a way that single-medium analyses cannot. The 2030 outlook — a regional mean CPI of 0.51 — should be interpreted with caution, as it assumes continuation of recent trends and does not incorporate the potential effects of the announced Uzbekistan Aral Sea National Trust Fund afforestation programme or planned upgrades to the Tuyamuyun reservoir water-treatment infrastructure (UNECE, 2025).

4.4. Construct validity through morbidity

The CPI correlated with all five major disease categories at $r_s \geq 0.70$, exceeding the corresponding correlations of any single component index (best single-medium correlation: AQI vs respiratory disease, $r_s = 0.74$). This finding supports the epistemological proposition that combined ecological burdens are more strongly associated with population-level morbidity than any single medium taken in isolation. The correlation is not, by itself, causal: CPI is a spatially aggregated indicator of long-term exposure and the morbidity data reflect cumulative outcomes across decades. Causal attribution requires individual-level exposure assessment, which is beyond the scope of this paper. However, the consistency of the rank correlation across five mechanistically distinct disease groups (respiratory, cardiovascular, oncological, endocrine and infant) suggests that CPI is capturing a meaningful environmental signal.

4.5. Limitations

Four limitations should be noted. First, monitoring coverage is unequal across districts; in particular, only two Uzhydromet stations operate in Karakalpakstan, and air-quality fields rely heavily on CAMS reanalysis. The Yusupov et al. (2024) ground-CAMS comparison reports an RMSE of approximately $12 \mu\text{g m}^{-3}$ for PM₁₀ in Nukus, which translates to an AQI uncertainty of approximately ± 15 units. Second, OCP and heavy-metal data are based on a single comprehensive campaign (Bartrem et al., 2025); temporal variability of soil contamination cannot therefore be characterised. Third, the equal-weighting scheme can be revisited as regionally calibrated DALY weights become available — for example through the Global Burden of Disease subnational estimates. Fourth, the CPI does not currently incorporate biological indicators (e.g., body burdens of OCPs in blood or urine), which would be required for individual-level health risk assessment.

4.6. Transferability and policy implications

The methodology developed here is transferable to other arid degraded basins facing combined multi-medium pollution — for example, the Lake Urmia basin in Iran, the Lop Nur basin in China, or the Salton Sea basin in the United States. From a policy perspective, the CPI offers three concrete advantages: it produces a single, communicable number per district that can underpin budget allocation; it decomposes that number into its constituent media, supporting targeted interventions; and it admits a simple temporal extension so progress can be monitored. We recommend that the Uzbekistan Ministry of Ecology, Environmental Protection and Climate Change consider adopting the CPI as a standing reporting metric within its annual environmental performance review, complementing rather than replacing the existing single-medium indices.

5. CONCLUSIONS

This study has developed and validated a district-level Composite Pollution Index (CPI) for the Aral Sea region of Uzbekistan, drawing on US EPA AQI, CCME WQI and Håkanson/Müller soil indices to produce a single normalised metric on the 0–1 scale. Applied to 27 administrative units of Karakalpakstan and Khorezm with monitoring data for 2010–2025, the CPI ranged from 0.31 to 0.64. Moynak emerged as the sole 'critical' district, with a CPI of 0.64 dominated by air pollution from the desiccated Aral seabed. The regional mean CPI rose by 15.8 % between 2010 and 2025, with an accelerating trend after 2017 that places the 2030 outlook at 0.51 under unchanged policies. CPI correlated with five major disease categories at r_s 0.70–0.82, supporting its construct validity as an integrated ecological-health indicator. The CPI is parsimonious, transparent, easily reproducible, and suitable for standing environmental reporting. Its routine adoption could materially improve the prioritisation of mitigation investment in one of the world's most severely impacted arid basins.

ACKNOWLEDGEMENTS

The authors thank the Karakalpakstan Republican Hydrometeorological Service (Uzhydromet) and the Karakalpakstan Republican Health Department for providing access to monitoring data. The constructive comments of [Reviewers] greatly improved the manuscript.

REFERENCES

1. Banks, J.R., Toon, O.B., Giles, D.M., Heavens, N.G., Mathers, J. (2022). Impacts of the desiccation of the Aral Sea on the Central Asian dust life-cycle. *Journal of Geophysical Research: Atmospheres*, 127(15), e2022JD036618.
2. Bao, A., Yu, T., Xu, W., Lei, J., Jiapaer, G., Chen, X., Tojibaev, K., Shomurodov, X. (2024). Ecological problems and ecological restoration zoning of the Aral Sea. *Acta Geographica Sinica*, 79(5), 1234–1248.
3. Bartrem, C., Kurbanov, M.I., Keller, B.D., Fiori, A., von Lindern, I., Khajiev, P.Z., Rustamov, D., Lee, J., Steiner, M., Paluaniyazova, G. (2025). Organochlorine pesticides and salinity in Karakalpakstan, Uzbekistan: a multimedia assessment. *International Journal of Environmental Research and Public Health*, 22(11), 1751.
4. Bazarbayev, S., et al. (2022). Physical and chemical properties of dust in the Pre-Aral region of Uzbekistan. *Environmental Science and Pollution Research*, 29, 75123–75139.
5. Bennion, P., Hubbard, R., O'Hara, S., Wiggs, G., Wegerdt, J., Lewis, S., Stocks, J. (2007). The impact of airborne dust on respiratory health in children living in the Aral Sea region. *International Journal of Epidemiology*, 36(5), 1103–1110.
6. CCME (2017). Canadian Water Quality Guidelines for the Protection of Aquatic Life: CCME Water Quality Index — User's Manual. Canadian Council of Ministers of the Environment, Winnipeg.

7. Danielsson, R., Surkan, A.J. (1996). Integrated environmental indices: an approach to combining and displaying environmental data. *Environmental Monitoring and Assessment*, 40(2), 105–118.
8. Erkudov, V.O., Rozumbetov, K.U., Gonzalez-Fernandez, F.T., Shashkova, I.S., Ovsyannikova, A.G. (2024). The effect of environmental disaster on body composition of children in Karakalpakstan. *Environmental Research*, 246, 118015.
9. Ge, Y., Wu, N., Abuduwaili, J., Kulmatov, R., Issanova, G., Saparov, G. (2022). Identifying seasonal and diurnal variations and the most frequently impacted zones of dust over Central Asia using CALIPSO observations. *Atmospheric Research*, 275, 106255.
10. Håkanson, L. (1980). An ecological risk index for aquatic pollution control: a sedimentological approach. *Water Research*, 14(8), 975–1001.
11. Indoitu, R., Kozhoridze, G., Batyrbaeva, M., Vitkovskaya, I., Orlovsky, N., Blumberg, D., Orlovsky, L. (2015). Dust emission and environmental changes in the dried bottom of the Aral Sea. *Aeolian Research*, 17, 101–115.
12. IQAir (2024). World Air Quality Report 2024. IQAir AG, Goldach, Switzerland.
13. Iskandarova, Sh., et al. (2023). River water quality of the Amu Darya in the territory of Karakalpakstan. *E3S Web of Conferences (ConMechHydro 2023)*.
14. Jin, M., Wu, J., Zhang, H., et al. (2023). Study on the Aral Sea crisis from the risk assessment of PAHs and OCPs in surface water. *Frontiers in Earth Science*, 11, 1295485.
15. Kawabata, Y., et al. (2011). Uranium pollution of ground water in Karakalpakstan. In: *The New Uranium Mining Boom*. Springer Geology, 161–166.
16. Liu, J., Ding, J., Liu, B., et al. (2025). Characteristics of salt dust aerosols and their transport implications in the Aral Sea region. *Atmospheric Chemistry and Physics*, 25(5), 2891–2912.
17. Liu, W., Ma, L., Abuduwaili, J. (2020). Historical change and ecological risk of potentially toxic elements in the lake sediments from North Aral Sea. *Applied Sciences*, 10(15), 5267.
18. Müller, G. (1969). Index of geoaccumulation in sediments of the Rhine River. *GeoJournal*, 2(3), 108–118.
19. NCI (2022). Joinpoint Regression Program, version 4.9.0.0. National Cancer Institute, Statistical Methodology and Applications Branch.
20. Rajabova, N., Sherimbetov, V., Sadiq, R., Aboukila, A.F. (2025). An assessment of collector-drainage water and groundwater quality using the CCME WQI model. *Water*, 17(15), 2191.
21. Rzymiski, P., Marszelewski, W., Rybak, M., Klimaszuk, P. (2024). Health impacts of the Aral Sea disaster: current state, research gaps, and policy recommendations. *Environmental Health Perspectives*, 132(7), 075001.
22. Saidmamatov, O., Sobirov, Yu., Matyakubov, U., Rajabov, N., Manakov, Yu. (2024). Dynamics of human fertility, environmental pollution, and health in Aral Sea basin. *Environmental Pollution*, 357, 124398.
23. Sun, Y., et al. (2023). Historical salinity trends along the Amu Darya River (50-year analysis). *Journal of Hydrology: Regional Studies*, S2214581823000629.
24. Takao, Y., et al. (2024). Increasing uranium pollution in groundwater in Karakalpakstan over 15 years. *Journal of Arid Land Studies*, 34(2), 47–58.
25. Tomlinson, D.L., Wilson, J.G., Harris, C.R., Jeffrey, D.W. (1980). Problems in the assessment of heavy-metal levels in estuaries and the formation of a pollution index. *Helgoländer Meeresuntersuchungen*, 33, 566–575.
26. Turdimuratova, J., Sadullaeva, S., Karimova, N., et al. (2024). Health impact assessment of the surface water pollution in Nukus. *International Journal of Geosciences and Environmental Management*, 18(3), 211–228.
27. Turekian, K.K., Wedepohl, K.H. (1961). Distribution of the elements in some major units of the Earth's crust. *Geological Society of America Bulletin*, 72, 175–192.
28. Tussupova, K., Zhupankhan, A., Khaibullina, Zh., Kabiyeu, Ye., Persson, K.M. (2020). Health impact of drying Aral Sea: one health and socio-economic approach. *Water*, 12(11), 3261.
29. UNECE (2025). Environmental Performance Reviews: Uzbekistan, 4th Cycle (ECE.CEP.204). United Nations Economic Commission for Europe, Geneva.
30. US EPA (2024). Technical Assistance Document for the Reporting of Daily Air Quality — the Air Quality Index (AQI). EPA-454/B-24-001, Research Triangle Park, NC.
31. WHO (2021). WHO Global Air Quality Guidelines: Particulate Matter (PM_{2.5} and PM₁₀), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide. World Health Organization, Geneva.
32. Yusupov, A.R., et al. (2024). Comparative analysis of PM₁₀ concentrations in Nukus and Tashkent, Uzbekistan: ground observation versus satellite reanalysis. *E3S Web of Conferences (CADUC 2024)*.