Integrating chemical and physical factors into delta vulnerability assessment: the role of erosion and diffuse pollution in the Shkumbin River Delta

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Abstract. Coastal deltas are increasingly exposed to combined marine forcing and land-based pollution. This study analyses the relationship between deltaic vulnerability and diffuse contamination in the Shkumbin River Delta, Albania. It introduces an Integrated Coastal Vulnerability Index (ICVI) framework that couples geomorphological, hydrodynamic, and sediment contamination indicators to quantify both physical and chemical vulnerability using multi-source datasets. The assessment is based on official institutional data on sediment quality (Cr, Ni, Cu), seawater quality near the delta, and geomorphological changes, as well as GIS-based spatial analyses for the 2017–2023 period, complemented by satellite imagery. Results indicate that the delta operates not only as a sink for contaminants but also as a secondary source of pollution. Beyond episodic extreme events, continuous coastal erosion (−32.81 ha) drives the remobilization of heavy metals from sediments into the water column, establishing a feedback mechanism between physical instability and chemical dispersion. Cr and Ni HQ values are consistently above 1 (range 2.6–4.5 and 3.5–4.2 respectively). The ICVI (12.2) indicates high vulnerability. The findings highlight the value of integrated multi-source assessments, support catchment–delta management to reduce upstream pressures, stabilize sediment dynamics, and protect the Karavasta Lagoon, Ramsar site.

1 Introduction

Coastal deltas represent highly dynamic environments shaped by the continuous interaction of fluvial, marine and anthropogenic processes. These systems act as critical transition zones that regulate the transport of water and sediments from continental catchments to the sea. Increasing coastal vulnerability associated with sea-level rise, intensified storm events and sediment imbalance is a global concern, and is often exacerbated by land-based pollution originating from upstream catchments, creating a multidimensional risk for coastal ecosystems [1, 2].

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In the Mediterranean context, shoreline evolution has been increasingly recognized as a key indicator of coastal vulnerability. Applications of the Digital Shoreline Analysis System (DSAS), such as along the Arekmane Coast in Morocco, have demonstrated the value of geospatial approaches in quantifying shoreline retreat and coastal change [3]. Albanian deltas have been studied from separate geomorphological [4, 5] and ecological [6] perspectives, but the coupled interaction between pollution and coastal vulnerability remains insufficiently addressed. In particular, chronic processes such as shoreline erosion are often overlooked, despite their potential to transform deltas from passive pollutant sinks into active sources of contamination [7, 8].

This study aims to bridge this gap by investigating the interaction between diffuse pollution and coastal vulnerability in the Shkumbin River Delta using an integrated Coastal Vulnerability Index (CVI) framework [9, 10]. By analysing how erosion triggers the remobilization of sequestered heavy metals (Cr, Ni, Cu), we propose an integrated management approach at the catchment scale. The work provides evidence that stabilizing the deltaic geomorphology is essential not only for land preservation but also for mitigating the dispersion of legacy pollution into the protected Karavasta Lagoon. In this context, understanding the coupled dynamics between geomorphological change and contaminant redistribution is essential for accurate risk assessment and coastal management.

2 Study area

The Shkumbin River Delta is located along the central Adriatic coast of Albania between approximately 40.95°–41.05° N and 19.40°–19.45° E, extending from the Spille area in the north to the Divjakë–Karavasta region in the south, forming a transition zone between the Shkumbin catchment and the Mediterranean Sea (Figure 1). Morphometric elements of the delta are characteristic of Mediterranean river systems, with dimensions primarily determined by fluvial discharge and solid sediment transport.

Historical geomorphological studies indicate that the Shkumbin River Delta has undergone lateral shoreline migration within a coastal sector of approximately 30 km, extending between the Spille and Divjakë areas, driven by variations in sediment supply and longshore transport processes [1].

Fig. 1. The Shkumbin River delta and its proximity to the Karavasta Lagoon (Ramsar site).

The delta currently maintains the shape of a cone with a deformed apex, exhibiting an asymmetry coefficient of 5–20% (Figure 2). These geomorphological characteristics are increasingly influenced by a sediment imbalance. This imbalance creates the physical conditions necessary for the remobilization of pollutants [1, 11].

Fig. 2. Detail of the Shkumbin delta morphology and erosion sectors.

The catchment is affected by intensive agriculture and historical industrial activities, particularly the Elbasan metallurgical complex. These sources contribute to latent heavy metal contamination of sediments, especially by Cr, Ni, and Cu [6, 12]. The proximity of the delta to the Karavasta Lagoon, a Ramsar-protected site, further increases environmental concern, as deltaic erosion may adversely affect lagoon water quality.

3 Materials and methods

3.1 Shoreline change analysis

Shoreline change analysis for the 2017–2023 period was based on the Albanian Environmental Status Report (2024), produced by the Albanian Geological Survey using GIS-based assessments. The analysis quantified eroded and accreted areas along the delta using a reference shoreline and 200 m segmentation. For illustration purposes, high-resolution satellite images in Google Earth have been used.

3.2 Integrated CVI formulation

The integrated Coastal Vulnerability Index (CVI) for the Shkumbin Delta combines physical, hydrodynamic and environmental stressors. To account for the source-to-sink dynamics and for the feedback loop between erosion and contamination, the index is defined as the geometric mean of eight ranked variables:

$$CVI = [(V_{\text{geom}} \cdot V_{\text{ero}} \cdot V_{\text{slr}} \cdot V_{\text{wave}} \cdot V_{\text{int}} \cdot V_{\text{poll}} \cdot V_{\text{sed}} \cdot V_{\text{flow}})/8]^{1/2} \quad (1)$$

3.3 CVI variables and ranking criteria

Each variable was assigned a vulnerability rank from 1 (very low) to 5 (very high), drawing on national monitoring programs and spatial analyses [1, 13, 14]:

- V_{geom} **(geomorphology):** deltaic shape and asymmetry coefficient, reflecting the inherent physical instability of the Shkumbin mouth (rank 5, critical);
- V_{ero} **(erosion rate):** shoreline retreat rate as the primary trigger of sediment remobilization. Multitemporal Landsat/Sentinel analyses indicate erosion rates of 5–7 m yr^{-1} on the northern sector (rank 5);
- V_{slr} **(sea-level rise):** regional Adriatic trends of 3.2–4.0 mm yr^{-1} (rank 3, medium);
- V_{wave} **(wave height):** mean significant wave height 1.0–1.5 m, peak storm waves >3.5–4 m, sufficient to suspend metal-rich fines (rank 4);
- V_{int} **(intertidal range):** microtidal regime with vertical range <30 cm (rank 1) but with episodic oxidation shocks during wave reworking;
- V_{poll} **(pollution):** concentration of heavy metals (Cr, Ni, Cd, Pb, Cu, Zn) in delta sediments compared with EU Environmental Quality Standards (EQS) and SQGs [6, 12];
- V_{sed} **(sediment balance) :** annual solid-load deficit acting as a driver for deltaic retreat;
- V_{flow} **(hydrological energy):** peak river discharge controlling the capacity to transport pollutants from the catchment to the deltaic sink.

3.4 Chemical hazard assessment

Chemical data were obtained from official reports on environmental status (2023) and from datasets provided by the Albanian Geological Survey project on rivers delta dynamics. These data represent previously measured and validated concentrations of metals in delta sediments. Chemical vulnerability was quantified using the hazard quotient ($HQ_i = C_i / C_{TEC}$), where C_i denotes the reported concentration of metal *i* in delta sediments and C_{TEC} is the corresponding sediment quality guideline (Threshold Effect Concentration, TEC) defined by MacDonald et al. [12]. The Annual Average Environmental Quality Standard (AA-EQS) was used as an additional reference to evaluate long-term toxicological risk. Part of the chemical dataset also includes Cr and Ni data from Divjakë Beach along a 2.5 km coastal segment, particularly at the former Shkumbin River mouth. The results are based on 10 sand samples from the wet zone, collected at 250–300 m intervals. The comparison was made against the British Standard for public environments. Data from the same source include the decline in abundance of European eel (*Anguilla anguilla*) and *Mugil cephalus* in deltaic environments.

3.5 Data integration and uncertainty

The identification of physical-chemical vulnerability hotspots was based on satellite image interpretation, supported by secondary data from official environmental reports and the Albanian Geological Survey project on rivers delta dynamics. These datasets include previously measured geochemical and geomorphological information, with no additional field sampling conducted. This desk-based approach allows assessment of spatial patterns of coastal vulnerability and sediment contamination, but is limited by satellite image resolution, temporal variability, and the lack of in-situ validation. Differences in data sources and methodologies may also introduce uncertainty in the interpretation of results.

4 Results

The ICVI for the Shkumbin Delta is based on the synthesis of multi-source monitoring data. Shoreline retreat values were derived from GIS-based analysis of satellite imagery (2017–2023), while chemical and hydrological parameters were obtained from the National Environmental State Report [14] and from the Geosciences Institute records [13]. Sediment chemistry data were integrated from the AGS national monitoring project on Albanian river deltas [1] and from published surveys of the Karavasta Lagoon and Shkumbin lowland [6] (Table 1).

Table 1. Shoreline change in the Spille–Divjakë–Karavasta sector (2017–2023).

Sector	Accumulation (ha)	Erosion (ha)	Net change (ha)
Spille Beach	2.61	0.69	+1.91
Shkumbin mouth (northern flank)	3.30	1.79	+1.51
Shkumbin mouth (eastern flank)	0.48	31.87	−31.39
Shkumbin delta, mouth (Bështova channel–old Shkumbin mouth)	1.28	2.70	−1.42
Divjaka Beach (north)	19.6	13.5	+6.1
Divjaka Beach	25.9	0.0	+25.9

The data confirm an extreme erosion of −31.39 ha on the eastern flank of the Shkumbin mouth, against limited accumulation on the northern flank, indicating a strong asymmetry of the deltaic dynamics. Peak river discharge of 26.02 $m^3\ s^{-1}$ recorded during high-energy events [12, 13] correlates with the periods of maximum sediment remobilization (Table 2).

Table 2. Heavy-metal concentrations (mg kg^{-1}) in surface sediments near the Shkumbin Delta, threshold and probable effect concentrations and Hazard Quotient HQ = C/TEC.

Parameter	Cr	Ni	Cd	Pb	Cu	Zn
Near delta (range)	289.5–503	171.2–201	0.038–0.085	2.4–5.9	105–199	20.9–56.1
TEC (threshold effect)	43.4	22.7	0.99	35.8	31.6	121
PEC (probable effect)	111	48.6	4.98	128	149	459
HQ_i (= C/TEC)	2.6–4.5	3.5–4.2	0.04–0.09	0.07–0.16	0.7–1.3	0.17–0.46

Cr and Ni HQ values are consistently above 1 (range 2.6–4.5 and 3.5–4.2 respectively), placing the deltaic sediments in the moderate-to-high ecological risk class (HQ between 1 and 5) (Table 3). Cu is at the upper TEC threshold, while Cd, Pb and Zn remain below the TEC. The dominant lithogenic signature of Cr and Ni reflects the contribution of the ultramafic rocks of the Shkumbin upper basin, while Pb and Cu indicate an additional anthropogenic contribution from the Elbasan industrial complex [6].

Table 3. Chemical vulnerability classes based on the Hazard Quotient (HQ).

Class	**HQ value**	**Vulnerability rank**	**Ecological risk**
2	0.1 < HQ < 1	Low	Metals within safety limits.
3	1 < HQ < 5	Moderate	Adverse effects may occur (between TEC and PEC).
4	5 < HQ < 10	High	High probability of biological toxicity.
5	HQ > 10	Critical / very high	Acute and severe toxic effects on the ecosystem.

Applying eq. (1) with $V_{geom} = 5$, $V_{ero} = 5$, $V_{poll} = 3$, $V_{wave} = 4$, $V_{slr} = 3$, $V_{int} = 1$, $V_{sed} = 4$ and $V_{flow} = 3$, the integrated index yields $CVI = [(5 \cdot 5 \cdot 3 \cdot 4 \cdot 3 \cdot 1 \cdot 4 \cdot 3) / 8]^{1/2} \approx 12.2$, classifying the Shkumbin Delta as a very-high-vulnerability zone (CVI > 12) (Table 4).

Table 4. Vulnerability ranking of the eight CVI variables for the Shkumbin Delta.

Factor	**Code**	**Rank (1–5)**	**Scientific reasoning**
Geomorphology	V_{geom}	5	Asymmetric deltaic configuration; high mouth instability.
Erosion rate	V_{ero}	5	Shoreline retreat >5 m yr^{-1} (DSAS analysis), causing massive sediment remobilization.
Pollution hazard	V_{poll}	3	1 < HQ < 5 (moderate). Cr, Ni and Cu above TEC; sediments act as a metal reservoir.
Wave height	V_{wave}	4	High exposure to Adriatic wave energy; driver of erosion.
Sea-level rise	V_{slr}	3	Regional Adriatic trend ~3.5 mm yr^{-1}; raises the flooding baseline of the low-elevation delta.
Intertidal range	V_{int}	1	Microtidal regime (<30 cm); minimal vertical sediment exposure.
Sediment balance	V_{sed}	4	Significant deficit of solid load reaching the delta; driver of retreat.
Hydrological energy	V_{flow}	3	Discharge 26 $m^3 s^{-1}$ capable of triggering remobilization events.

Ecological response: A marked reduction in the abundance of *Anguilla anguilla* (European eel) and *Mugil cephalus* was observed in the deltaic zone. Both species, known for their sensitivity to metal contamination in water and sediments, show a spatial overlap with areas of elevated Cr and Ni concentrations, suggesting a potential link between contaminant hotspots and habitat degradation.

Spatial distribution of contamination: Metal-contaminated waters are predominantly associated with erosion-dominated sectors of the delta, where resuspension processes are active. In contrast, higher concentrations of heavy metals in sediments are observed in depositional zones, where fine-grained material accumulates and acts as a long-term sink for pollutants.

5 Discussion: the erosion–pollution feedback loop

The Shkumbin Delta behaves as a dynamic sedimentary system rather than a stable depositional sink. While historically acting as a receptor of upstream contaminants, it increasingly exhibits a dual function in which sediments can both retain and remobilize pollutants depending on hydrodynamic and geochemical conditions (Figure 3). Similar behavior has been observed in systems such as the Angat River network, where metal concentrations in water and sediments vary spatially and temporally in response to environmental controls [15].

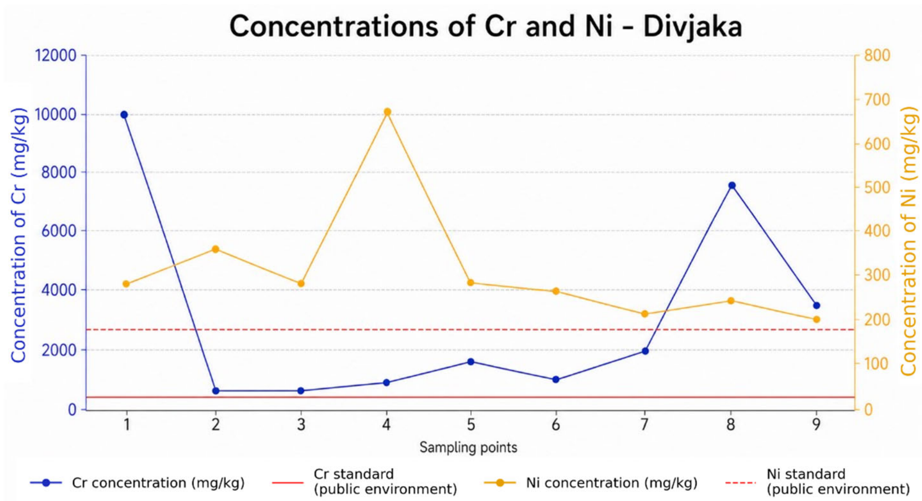

Fig. 3. Graphical presentation of the concentrations of Cr and Ni at Divjakë Beach against the British Standard for public environments.

In the Shkumbin Delta, sediment redistribution is strongly influenced by coastal vulnerability processes captured by the CVI, particularly wave energy and shoreline erosion, which promote the resuspension of previously buried contaminated material. Geochemical factors such as pH, redox conditions and temperature further influence the mobility of heavy metals.

Sediment redistribution occurs through different mechanisms and temporal scales. Chronic shoreline erosion progressively exposes contaminated sediments, while episodic storm events may trigger rapid resuspension and localized contaminant release. River-flood processes provide an additional transport pathway for fine-grained contaminated material from upstream areas toward the coastal zone. These processes contribute to the spatial variability of pollutant distribution observed in the deltaic environment and the coastline.

The proximity of the impacted area to the Karavasta Lagoon, a Ramsar site, highlights the broader ecological implications.

6 Conclusion and recommendations

This study presents an Integrated Coastal Vulnerability Index (CVI) framework applied to the Shkumbin River Delta, identifying the system as highly vulnerable (CVI ≈ 12.2). The results demonstrate that the interaction between shoreline erosion, sediment dynamics, and anthropogenic contamination has altered the traditional sink function of the delta. Erosion-dominated sectors promote the remobilization of legacy pollutants, while depositional areas act as long-term reservoirs for heavy metals such as Cr, Ni, and Cu. At Divjakë Beach, Cr and Ni values are all above the British Standard.

The chemical risk assessment indicates moderate ecological risk, particularly associated with Cr and Ni, reflecting a mixed lithogenic–anthropogenic origin of contamination. Ecologically, a reduction in *Anguilla anguilla* and *Mugil cephalus* abundance was observed.

Methodologically, the study highlights the added value of integrating geomorphological vulnerability with sediment-associated contamination within a unified CVI framework. This approach provides a more comprehensive representation of coastal risk compared to conventional physically based assessments and is transferable to other river-dominated Mediterranean deltas exposed to similar erosion–pollution interactions.

Recommendations for management:

(i) **Integrated catchment–delta management:** the findings support the implementation of an integrated catchment–delta management approach, addressing both geomorphological change and pollution dynamics. The proposed ICVI-based framework can underpin monitoring and early-warning systems that combine shoreline change detection, sediment quality assessment, and ecological indicators (e.g., *Anguilla anguilla* and *Mugil cephalus*).

(ii) **Catchment-scale intervention:** pollution mitigation should prioritize upstream sources (e.g., Elbasan industrial area) to reduce heavy metal inputs into the river system.

(iii) **Nature-based solutions:** soft engineering measures such as dune restoration and salt-marsh conservation are recommended to enhance shoreline stability and reduce sediment remobilization in erosion-prone sectors.

(iv) **Continuous monitoring:** a real-time monitoring network for shoreline change and water quality is essential to protect the neighbouring Karavasta Lagoon, a Ramsar site.

This study builds upon an initial diploma project on the Shkumbin Delta supervised by PhD Monika Hoxhaj, involving former students Entela Dushku and Fation Dedaj, now specialists at the Albanian Geological Survey.

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