

Development and Application of a Socially Integrated Water Pollution Pressure Index (WPPI) in the Gold-Mining Region of Kédougou, Eastern Senegal

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Abstract

In the gold-mining region of Kédougou, Senegal, the co-occurrence of large-scale industrial operations and artisanal and small-scale mining (ASM) generates multiple and potentially cumulative pressures on water resources. This study assesses the spatio-temporal evolution of water pollution pressure by comparing historical Environmental and Social Impact Assessments (ESIAs, 2006-2023) with independent field data collected from 43 sampling points between 2021 and 2024. We developed the Water Pollution Pressure Index (WPPI), a composite index integrating contaminant concentrations (As, Hg, Pb, CN⁻), toxicological weighting (P_i), local water-use patterns (F_i), and proximity to pollution sources with regularization (D_i). The WPPI generates a normalized score from 0 to 1, ranging from Class A (Low) to Class E (Critical). Results reveal a consistent descriptive trend toward higher heavy-metal concentrations in recent field measurements compared with historical ESIA data. WPPI scores increased from moderate levels (0.29 - 0.42) in historical ESIAs to very high or critical levels (0.61 - 0.84) in contemporary field measurements. Spatial interpolation using Inverse Distance Weighting identified a “WPPI Pressure Triangle” encompassing the Diabougou-Khossanto corridor, the Falémé River zone, and the Gambia River basin as a priority area for enhanced environmental surveillance. The analysis also identified major methodological gaps in reviewed ESIAs, including limited assessment of cumulative effects, infrequent wet-season sampling, and inconsistent use of international standards such as WHO and IFC guidelines. The WPPI shows potential

as an operational decision-support tool for strategic environmental assessment and spatial prioritization. The findings suggest that mining-related water pollution pressure in Kédougou is better understood as a chronic and spatially interconnected issue than as a series of isolated incidents. Further external validation of the WPPI is recommended, together with its progressive integration into regulatory monitoring frameworks incorporating mandatory spatio-temporal surveillance and multi-stakeholder governance.

Keywords

Water Pollution Pressure Index (WPPI), Mining Impacts, Artisanal Gold Mining, Strategic Environmental Assessment, Water Quality, Senegal, Kédougou, Heavy Metals, ESIA, Social Vulnerability

1. Introduction

Water quality is a central indicator of environmental sustainability and socio-territorial vulnerability in the mining regions of the Global South, where water resources face multiple, often cumulative pressures [1] [2]. As Mudd [1] emphasizes, water pollution from extractive activities reveals both ecological degradation and socio-economic inequalities affecting dependent communities. In mining zones, surface and groundwater are frequently altered by blasting, ore leaching, and the use of chemical reagents [3] [4]. These processes mobilize heavy metals and discharge toxic substances such as cyanides, creating long-term risks for human health and ecosystems [4] [5].

In West Africa, Environmental and Social Impact Assessments (ESIAs) often remain sectoral, non-cumulative, and weakly aligned with international standards [6] [7]. The gold-rich Kédougou region of Senegal exemplifies this, with industrial mining projects and hundreds of artisanal small-scale mining (ASM) sites concentrated around the same water resources (Figure 1), generating cumulative pressures on community water uses and territorial sustainability [8]. The ASM sector, often informal and poorly regulated, significantly contributes to pollution, particularly through the use of mercury and cyanides [9] [10]. This situation is compounded by a weak regulatory framework and limited institutional capacity for environmental monitoring and enforcement [11]-[13].

Classical water quality indices (WQIs), such as those pioneered by Horton [14] and Brown *et al.* [15], provide a valuable starting point for assessing water status. Numerous studies have refined these indices [16]-[18] and applied them in mining contexts [11] [19]-[21]. However, these indices primarily focus on physico-chemical parameters, often failing to incorporate the critical socio-economic dimensions of water use and the spatial configuration of human settlements and activities [22] [23].

This study addresses this gap by proposing a strategic assessment of water pressures through the development of a novel Water Pollution Pressure Index (WPPI),

specifically designed for mining contexts. The WPPI moves beyond conventional WQIs by integrating a functional and territorial perspective. It incorporates not only the physico-chemical quality of water but also the nature of local water uses (e.g., domestic, agricultural) and the proximity of communities to pollution sources. This approach allows for a more realistic assessment of the pressure exerted on a community's water resources as a function of both the level of contamination and the community's dependency and vulnerability [24] [25]. Based on a critical analysis of ESIA and comparison with field data, the WPPI aims to bridge the gap between planned and actual impacts, aligning with the findings of Morrison-Saunders and Arts [26] and the principles of Strategic Environmental Assessment (SEA) [7] [27] [28].

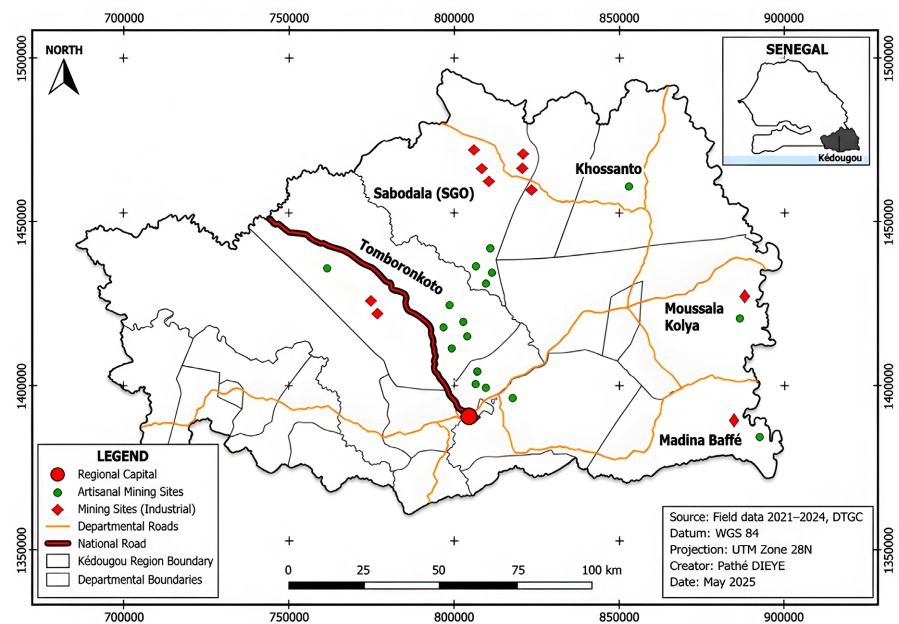


Figure 1. Location of mining perimeters and active artisanal mining sites sampled in the Kédougou region.

2. Materials and Methods

2.1. General Framework

Our approach employs a strategic environmental assessment (SEA) logic, based on a rigorous triangulation of three complementary sources:

- **Historical ESIA:** A critical analysis of ten ESIA reports from major projects (SGO-Sabodala, PMC-Mako, Boto, Sored, Afrigold) covering the 2006-2023 period.
- **Independent Field Data:** Original empirical data from sampling campaigns conducted between 2021 and 2024 at 43 points, covering industrial, artisanal, and community areas.
- **International and National Normative Frameworks:** WHO [29], IFC [30], and the Senegalese standard for wastewater discharge (NS 05-061) [31].

The methodological differences and the temporal gap between these sources were explicitly addressed. ESIA data were treated as secondary data requiring prior critical assessment for scientific compatibility and spatial-temporal coherence before being used in the WPPI modeling [32]. This approach of confronting historical ESIA data with contemporary field measurements has previously been applied to soil quality assessment in the same territory [32], establishing methodological continuity in our research program.

2.2. Characterization of Environmental and Social Impact Assessment (ESIA) Data

2.2.1. Criteria for ESIA Report Selection and Data Extraction

The selection of ESIA reports followed three inclusion criteria: i) availability of quantitative water quality data (pH, heavy metals, cyanides, etc.); ii) explicit documentation of sampling locations and protocols; iii) coverage of the 2006–2023 period. A total of ten ESIA reports met these criteria (Table 1). For each selected report, the following information was systematically extracted: document owner, year of publication, sampling period, water matrix (surface water, groundwater, or effluent), and the specific physico-chemical variables measured. Where available, GPS coordinates of sampling points and analytical methods were also recorded to enable spatial and methodological comparability with field data.

2.2.2. Matching Protocol for Historical vs. Contemporary Data

To ensure valid comparisons between historical ESIA data and contemporary field measurements, we applied four matching criteria:

- i) **Geographic matching:** ESIA sampling points and field sampling points were considered matched if located at the same GPS coordinates or within a radius of 100 m. This threshold was selected based on the positioning accuracy of handheld GPS devices ($\pm 3 - 5$ m) and the practical constraints of relocating historical sampling points from often imprecise ESIA documentation;
- ii) **Water matrix matching:** Comparisons were restricted to identical water matrices (surface water with surface water; groundwater with groundwater; effluent with effluent);
- iii) **Seasonal matching:** Only dry season data (January–March) were compared, as the vast majority of ESIA reports (100%) were collected during the dry season. This minimizes seasonal variability in contaminant concentrations due to dilution or runoff effects;
- iv) **Analyte matching:** Comparisons were restricted to common analytes—parameters that were measured in both the ESIA and the field campaign (e.g., pH, As, Pb, CN^- , etc.).

After applying these four criteria, $n = 12$ matched site-pairs were retained for the historical vs. field comparison. These 12 pairs represent the maximum number of comparable observations across the ten ESIA reports and the 43 field sampling points. The results of this matching procedure are presented in Section 3.1.

Table 1. ESIA reports included in this study: source, period, matrix, extracted variables, and methodological weaknesses.

Project /Site	Document Owner	Year	Sampling Period	Water Matrix	Extracted Variables	ESIA Sampling Points	Field Observations (2021-2024)	Field Observations with Repeated Measurements	Key Missing Data/Weakness	Norms Used
SGO-Sabodala	Sabodala Gold Operations	2006	Dry (Feb-Mar)	Surface, groundwater	pH, turbidity, TSS, conductivity, As, Pb, CN ⁻	4	6	3	No wet season, partial parameters	NS 05-061
Gora (SGO)	Sabodala Gold Operations	2011	Dry (Mar)	Surface, groundwater	pH, conductivity, As, Pb, Hg, CN ⁻	3	5	2	Limited data, no wet season, no explicit norms	Not explicit
PMC-Mako	Petowal Mining Company	2013	Dry (Feb-Mar)	Surface, groundwater	pH, TSS, conductivity, As, Pb, CN ⁻	5	8	4	Incomplete coverage, no wet season, partial normative use	Partially IFC
Massawa (SGO)	Sabodala Gold Operations	2019	Dry (Jan-Feb)	Surface, groundwater	pH, conductivity, As, Pb, CN ⁻	3	4	1	No wet season, limited parameters	NS 05-061
Goumbati-Kobokoto (SGO)	Sabodala Gold Operations	2020	Dry (Jan-Feb)	Surface water	pH, TSS, conductivity, As, Pb, CN ⁻	2	3	0	No wet season, lacks cumulative perspective	NS 05-061
Afrigold (Kolya)	Afrigold SA	2018	Dry (Mar)	Groundwater	pH, conductivity, As, Pb, CN ⁻	2	5	1	No wet season, missing turbidity, norms not applied	NS 05-061 (not applied)
GKK/SGO-Massawa	Sabodala Gold Operations	2021	Dry (Jan)	Surface, groundwater	pH, conductivity, As, Pb, Hg, CN ⁻	3	4	0	No wet season, no updated mitigation	NS 05-061
Input Tailings (SGO)	Sabodala Gold Operations	2022	Dry (Feb)	Surface, effluent	pH, TSS, conductivity, As, Pb, CN ⁻	3	2	0	No wet season, limited parameters	NS 05-061
Boto (IAMGOLD)	IAMGOLD Corporation	2018	Dry (Mar-Apr)	Surface, groundwater	pH, TSS, conductivity, As, Pb, Hg, Ni, CN ⁻ , NO ₃ ⁻ , SO ₄ ²⁻	6	4	1	Lacks cumulative perspective (relatively robust otherwise)	WHO/NS 05-061
Sored	Sored Mine	2018	Dry (Mar)	Surface water	pH, TSS, conductivity, As, Pb, CN ⁻	2	2	0	Single-point campaign, limited parameters	NS 05-061
Total						33	43	12		

Note 1: "Field Observations (2021-2024)" refers to the total number of distinct sampling points per project area. "With Repeated Measurements" indicates sites sampled across multiple seasons (dry and wet) or years.

Note 2: ND = Not Detected; NM = Not Measured; Not Reported in the ESIA report. ND values were replaced with LOD/2 for WPPI calculations (see Section 2.5.6).

2.2.3. Methodological Weaknesses of ESIA Data

Our methodological analysis of ESIA (Figure 2 and Table 1) revealed significant weaknesses, consistent with findings across West Africa [33]:

- **Heterogeneity of Protocols:** Sampling protocols, parameters, and monitoring frequencies varied considerably between projects, limiting inter-project comparability [33].
- **Limited Assessment of Cumulative Effects:** None of the ESIA analyzed proposed a cumulative reading of hydric impacts, treating projects as independent entities despite hydrological connectivity [8] [11].
- **Weak Normative Alignment:** Most reports rely solely on the national standard NS 05-061, without systematic cross-referencing with WHO or IFC standards. Critical mining contaminants (e.g., cyanides, sulfates) are often absent [12] [34].
- **Insufficient Traceability:** A lack of precise GPS coordinates, measurement dates, and laboratory details limits the reproducibility of results [32].

These governance gaps are common challenges in the region, mirroring critiques of regulatory practices in other African mining contexts [11] [12] [35].

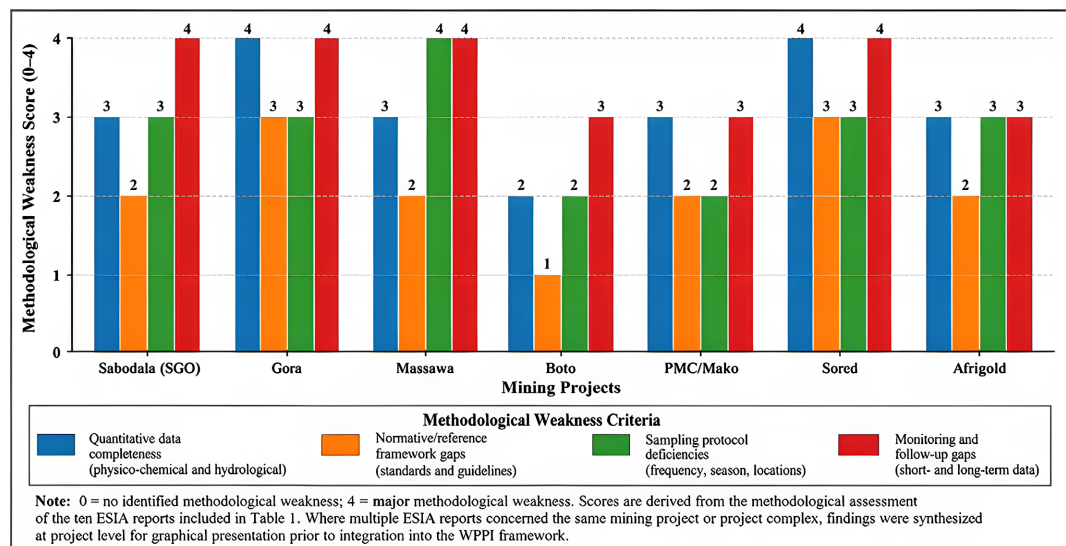


Figure 2. Comparative synthesis of methodological weaknesses of ESIA by mining project.

2.3. Field Data Collection Protocol (2021-2024)

Sampling Design and Data Aggregation

A total of 43 sampling points were monitored across four campaigns (2021-2024), covering both dry (January-March) and wet (August-October) seasons. For sites with repeated measurements ($n = 12$ sites), WPPI values were aggregated using arithmetic means per parameter.

Repeated observations were aggregated as follows: i) arithmetic mean for physico-chemical parameters (pH, conductivity, turbidity, TSS, DO, temperature); ii) arithmetic mean for heavy metal concentrations (As, Pb, Hg, Cd, Cr, Cu, Zn); iii) median for parameters with outliers (identified using the IQR method); iv) WPPI calculated from the resulting aggregated parameter values for each site. This aggreg-

gation protocol ensures that each site contributes a single representative WPPI value to the spatial analysis, while preserving seasonal and inter-annual variability in the underlying data (Table 1).

Field data were collected to fill the structural gaps in the ESIA. Our sampling strategy was designed to capture spatial and seasonal variability [17] [36].

- **Sampling Sites:** 43 georeferenced points (GPS, WGS84) were selected across industrial zones (Sabodala, Mako), artisanal mining zones (Diabougou, Fadougou), and strategic villages (Khossanto, Madina Bafé) (Figure 3). The complete list of 43 sampling points is provided in Appendix E.
- **Measured Parameters:** We focused on priority physico-chemical parameters critical in a mining context: heavy metals and trace elements (As, Pb, Hg, Zn, Cd, Cr, Cu), basic parameters (pH, temperature, turbidity, electrical conductivity, TSS, dissolved oxygen), and mining-specific pollutants (total and free cyanides, nitrates, sulfates, phosphates, fluorides) [3]–[5].
- **Sampling and Analytical Protocols:** A harmonized protocol was applied, inspired by the CCME [37], FAO [38], and WHO [29]. Samples were collected in both dry (Jan–Mar) and wet (Aug–Oct) seasons, georeferenced, and analyzed in accredited laboratories using a rigorous chain of custody (Photo 1 and Table 2). Detailed protocols are provided in Appendix A.

2.4. Normative Framework for Water Quality

We used a weighted hierarchy of three normative frameworks:

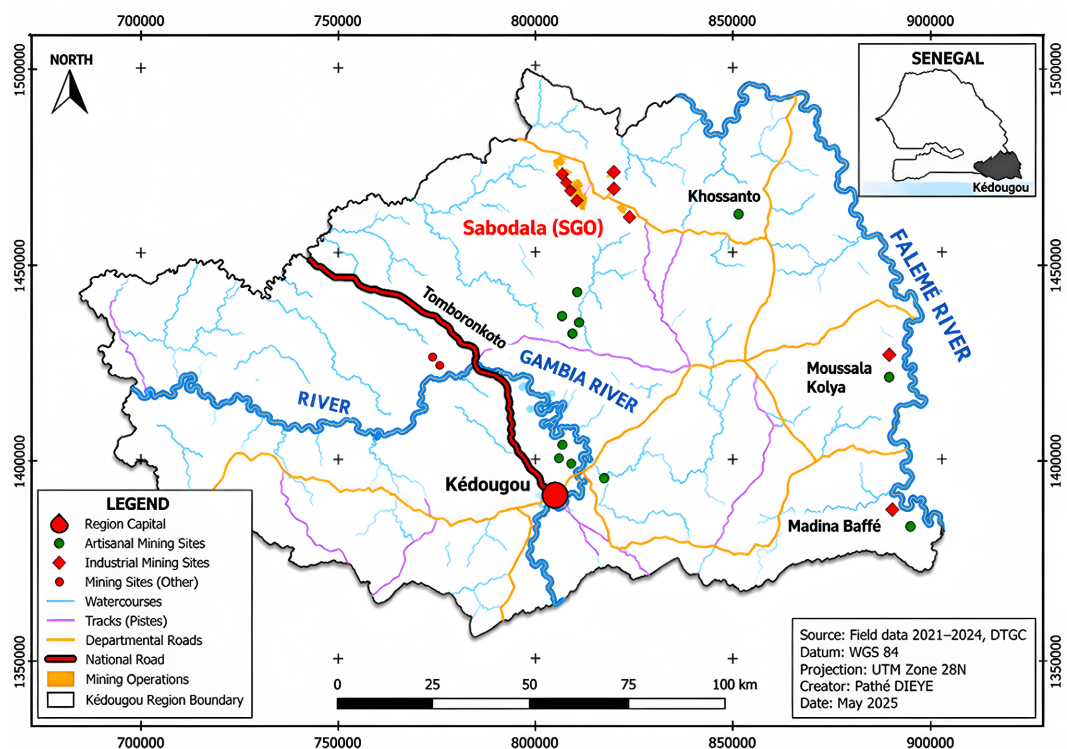


Figure 3. Location of sampling sites and Falemé/Gambia hydrological zoning.



Photo 1. Sampling sites and collection protocols.

Table 2. Protocol for sampling, analysis, and modeling of the Water Pollution Pressure Index (WPPI).

Step	Description
1. Preparation	Site selection, sterile bottle preparation, GPS, field forms, HNO ₃ , labeling
2. Field Sampling	On-site measurements (pH, T°), sample collection (surface, well, effluent), acidification, field blanks (10%), GPS
3. Transport/Storage	Cooling ($\leq 4^{\circ}\text{C}$), secure transport to lab
4. Laboratory Analysis	Analysis of As, Hg, Pb, CN ⁻ , etc., using WHO, IFC, and NS standards
5. WPPI Calculation	$\Sigma [(Ci/Ni) \times Pi \times Fi \times (1/(Di + a))]$, normalize to 0 - 1 scale, classify A to E
6. GIS & Cartography	QGIS integration, IDW interpolation, spatial classification, layer superposition

- **WHO (2017):** Primary reference for domestic and community uses, providing health-based guidelines for key contaminants [29].
- **IFC (2012):** Used to evaluate the compliance of industrial sites with international environmental and social performance standards for effluent discharge [30].
- **NS 05-061:** Used as the Senegalese national standard for wastewater discharge, serving as a secondary reference for effluent compliance [31].

The thresholds were integrated as normalized scales (0 - 1) to calculate partial and global WPPI scores per site (Table 3). The use of international benchmarks

is crucial, as relying solely on national standards can lead to an underestimation of health risks, particularly for vulnerable populations [10] [39]. The reference norm (N_i) is selected according to the primary water use context: the WHO guideline is applied for domestic/drinking water uses; the IFC standard is applied for assessing industrial effluent compliance; the national NS 05-061 standard serves as a secondary reference for wastewater discharge.

Table 3. Comparison of WHO, IFC, and NS 05-061 thresholds for key measured parameters.

Parameter	Unit	WHO Threshold	IFC Threshold	NS 05-061 Threshold
pH	-	6.5 - 8.5	6 - 9	6.5 - 8.5
TSS	mg/L	≤50	-	≤50
Turbidity	NTU	≤5	≤5	≤5
Conductivity	μS/cm	≤1400	≤1500	≤1400
Arsenic (As)	mg/L	0.01	0.01	0.01
Lead (Pb)	mg/L	0.01	0.01	0.01
Mercury (Hg)	mg/L	0.006 (drinking)	0.002 (effluent)	0.001 (effluent)
Total Cyanide	mg/L	0.07	0.07	0.07
Iron (Fe)	mg/L	0.3	0.3	0.3
Manganese (Mn)	mg/L	0.1	0.1	0.1
Nitrates (NO ₃)	mg/L	50	50	50
Fluorides (F)	mg/L	1.5	1.5	1.5

NS 05-061 refers to the Senegalese national standard for wastewater discharge [31].

2.5. Water Pollution Pressure Index (WPPI) Development

To compare water pressure across different sites, we developed the WPPI as a weighted aggregation tool. Our index is fundamentally different from classical WQIs. While WQIs are primarily designed to assess the overall quality of a water body, the WPPI is designed to assess the *pressure* this quality exerts on a given community.

2.5.1. General Mathematical Formulation

The WPPI is designed to generate a normalized score between 0 (absence of pressure) and 1 (maximum pressure). First, we calculate a Partial Pressure Index (PPI) for each parameter:

$$PPI_i = (C_i/N_i) \times P_i \times F_i \times (1/(D_i + a)) \quad (1)$$

where:

- C_i = Measured concentration of parameter i .
- N_i = Reference norm for parameter i (from Table 3, selected according to use context).
- P_i = Toxicological weight of parameter i (scale 1 - 5, detailed in Table 4). These weights are expert-derived ordinal scores, constructed specifically for the

WPPI. They are informed by established toxicological evidence and regulatory benchmarks, but should not be interpreted as quantitative toxicity coefficients from EPA or WHO sources. Rather, they represent a relative ranking of concern based on the severity and frequency of documented health effects in mining contexts.

- Fi = Local usage and socio-ecological factor (0.9 - 2.0 in this operationalization, detailed in **Table 5**).
- Di = Distance from the contamination source to the village/water point (km).
- a = Regularization constant = 0.1 km.

2.5.2. Toxicological Weighting Factor (Pi)

The weighting factor Pi (scale 1 - 5) is assigned based on three criteria: environmental toxicity, frequency of normative exceedance in mining contexts, and criticality for human health. These ordinal weights are informed by established toxicological evidence [40], regulatory benchmarks [29] [30], and health risk assessments [34] [41] [42]. The complete scoring grid is presented in **Table 4**.

Table 4. Toxicological weighting factor (Pi) scoring grid.

Score	Risk Category	Parameters	Justification
5	Critical Risk	Hg, As, Pb, CN^-	Severe, irreversible health effects; ubiquitous in gold mining; frequent exceedances [5] [34] [41] [43]
4	High Risk	NO_3^- , SO_4^{2-}	Methemoglobinemia (nitrates); acid mine drainage mobilization (sulfates) [4]
3	Moderate Risk	pH, turbidity, Fe, Mn	Degrade aesthetic and functional water quality; limit use [5]
2	Secondary Risk	DO, temperature	Indicators of ecosystem health; less direct human toxicity
1	Low Risk	Other secondary parameters	Minimal health or environmental impact

2.5.3. Local Usage and Socio-Ecological Factor (Fi)

The Fi factor captures the nature and intensity of the relationship between a community and its water resource. It is a function of the dependency and vulnerability of the community. In this operationalization, Fi ranges from approximately 0.9 to 2.0. The factor is formally defined as:

$$Fi = (U_usage + U_population + U_activity + U_infrastructure) / 4 \quad (2)$$

The complete scoring grid for each component is presented in **Table 5**.

Table 5. Socio-ecological factor (Fi) component scoring grid.

Component	Score	Description
U_usage	1.8	Drinking/domestic use (direct ingestion)
	1.4	Agricultural/irrigation use (indirect exposure)

Continued

	1.0	Pastoral use (animal health)
	0.8	Recreational/mining use
U_population	2.0	High density (>200 hab/km ²)
	1.5	Medium density (100 - 200 hab/km ²)
	1.0	Low density (<100 hab/km ²)
U_activity	1.8	Industrial-Artisanal Co-occurrence Zone
	1.6	Dense artisanal mining
	1.4	Industrial mining only
	0.8	Sparsely populated/agricultural
U_infrastructure	2.0	No treatment, no alternative source
	1.2	No treatment, alternative available
	1.0	Basic treatment or water trucks

2.5.4. Normalization of Partial Pressure Indices

To bound each PPI between 0 and 1, we define a maximum reference value (PPI_{max}). For normalization purposes, a reference exceedance ratio of $C_i/N_i = 10$ was adopted as a conservative upper-bound scenario for the present dataset. This threshold was selected based on the empirical distribution of our 43 field samples, where the 95th percentile of all measured C_i/N_i ratios was 8.7. The value of 10 thus represents a robust upper bound for >95% of our observations. The influence of this assumption was evaluated through sensitivity analysis using ratios ranging from 5 to 20, as described below.

$$PPI_{max} = 10 \times P_{max} \times F_{max} \times \left(\frac{1}{(D_{min} + a)} \right) \quad (3)$$

Using conservative estimates ($P_{max} = 5$, $F_{max} = 2.0$, $D_{min} = 0.5$ km, $a = 0.1$ km), we obtain:

$$PPI_{max} = 10 \times 5 \times 2.0 \times (1/0.6) \approx 166.7$$

The normalized PPI for each parameter is then:

$$PPI_{i,norm} = \min(PPI_i / PPI_{max}, 1) \quad (4)$$

2.5.5. Final WPPI Calculation

The $WPPI$ is calculated as the arithmetic mean of the normalized PPIs for all n parameters included in the assessment:

$$WPPI = (1/n) \times \sum PPI_{i,norm} \quad (5)$$

This mean-based approach ensures that the index is bounded between 0 and 1 and is not dependent on the number of parameters measured. The final classification is:

- A: 0.00 - 0.20 (Low)
- B: 0.20 - 0.40 (Moderate)
- C: 0.40 - 0.60 (High)
- D: 0.60 - 0.80 (Very High)

- E: 0.80 - 1.00 (Critical)

2.5.6. Handling of Non-Detects (ND) and Non-Measured (NM) Parameters

For parameters reported as “not detected” (ND), the value was replaced with LOD/2 (half the limit of detection) for WPPI calculations. This approach follows standard practice in environmental chemistry for handling censored data below the analytical detection limit [29] [40].

For parameters “not measured” (NM)—*i.e.*, parameters that were not analyzed or reported in the ESIA or field dataset—the parameter was excluded from the WPPI calculation for that specific site. To ensure comparability across sites with different numbers of measured parameters, the final WPPI was renormalized by the number of available parameters:

$$WPPI = \frac{1}{n_{available}} \times \sum PPI_{i,norm}$$

where $n_{available}$ is the number of parameters actually measured for that site (*i.e.*, excluding NM parameters). This mean-based renormalization ensures that sites with missing data are not penalized or advantaged relative to sites with complete data.

A sensitivity analysis was conducted to assess the impact of NM parameter exclusion on site rankings (see 2.5.7, point 3, and **Appendix C**). The analysis confirmed that the exclusion of NM parameters did not alter the ranking of any site by more than one class, validating the robustness of this approach.

2.5.7. Sensitivity Analysis

A sensitivity analysis was conducted to assess the robustness of the normalization procedure using our dataset ($n = 43$ sampling points):

- **Regularization constant (a):** Varying a between 0.01 and 0.5 km. The overall site ranking remained stable, with Spearman’s rank correlation coefficients ranging from $\rho = 0.81$ to 0.98 relative to the baseline configuration ($a = 0.10$ km), with particularly high stability around the selected value.
- **Reference exceedance ratio:** Varying the assumed Ci_{max}/Ni ratio from 5 to 20. The final classification of any site did not change by more than one class, confirming the robustness of the normalization procedure.
- **NM parameter exclusion:** Varying the number and type of NM parameters excluded from the WPPI calculation (see 2.5.6). No site was reclassified by more than one class, confirming the robustness of the renormalization approach.

The complete sensitivity analysis is provided in **Appendix C**.

2.5.8. Worked Example: Comparative Demonstration of the WPPI’s Social Integration

To illustrate the core innovation of the WPPI—the integration of social and spatial vulnerability—we present two hypothetical villages (A and B) with identical water contamination levels but contrasting socio-spatial contexts (**Table 6**).

- **Village A:** High vulnerability context. $Fi = 1.85$, $Di = 0.5$ km.

- **Village B:** Low vulnerability context. $Fi = 1.10$, $Di = 5.0$ km.

Table 6. Comparative WPPI calculation for two villages with identical contamination but contrasting socio-spatial contexts.

Parameter	Ci (mg/L)	Ni (mg/L)	Pi	Village A: $Fi = 1.85$, $Di = 0.5$	Village B: $Fi = 1.10$, $Di = 5.0$
Lead (Pb)	0.05	0.01	5	PPI_A = 77.1	PPI_B = 5.4
Arsenic (As)	0.03	0.01	5	PPI_A = 46.3	PPI_B = 3.2
Mercury (Hg)	0.02	0.006	5	PPI_A = 51.0	PPI_B = 3.6
Cyanide (CN ⁻)	0.12	0.07	5	PPI_A = 26.2	PPI_B = 1.8

Normalization (PPI_max = 166.7):

- Village A: Pb = 0.46, As = 0.28, Hg = 0.31, CN = 0.16 → WPPI = **0.30 (Class B: Moderate)**
- Village B: Pb = 0.03, As = 0.02, Hg = 0.02, CN = 0.01 → WPPI = **0.02 (Class A: Low)**

Interpretation: The contamination is identical, but the pressure is dramatically different. Village A, with high dependency and proximity, experiences Moderate pressure, while Village B experiences Low pressure. This demonstrates that the WPPI assesses not just pollution levels but the actual socio-environmental pressure on communities—a critical innovation over classical WQIs.

2.5.9. Source Identification and Proximity Assessment (Di)

Industrial sources were identified from official mining perimeters and project documentation for the following operations: Sabodala Gold Operations (SGO), Petowal Mining Company (PMC-Mako), Boto (IAMGOLD), Sored, and Afrigold (Kolya). Artisanal sources were identified through field surveys conducted during the 2021–2024 campaigns, complemented by satellite imagery analysis (Google Earth Pro, 2021–2024) to map active artisanal mining sites. The complete list of identified sources is provided in **Appendix E**.

The proximity factor **Di** was calculated as the shortest straight-line distance (Euclidean distance) from the sampling point to the nearest mining site (industrial or artisanal). For sites with multiple sources within a 5 km radius ($n = 23$ sites), **Di** was assigned based on the closest source, consistent with the “nearest source” approach commonly used in spatial risk assessments [8] [12].

This straight-line distance approach was adopted for two reasons: i) it provides a consistent and reproducible metric across all sites; ii) detailed hydrological connectivity data (e.g., surface flow pathways, groundwater flow direction) were not uniformly available for all sampling points. Future refinements could incorporate hydrological connectivity to improve the representation of contaminant transport pathways, particularly in the Falémé and Gambia River corridors.

2.6. Spatial Analysis and GIS

Spatial analysis is crucial for localizing pressures and modeling vulnerabilities [44].

We integrated the WPPI values and sampling point coordinates into QGIS 3.30.

- **Hydrological Zoning:** We established a zoning based on the Falémé and Gambi River watersheds [22].
- **Interpolation:** The Inverse Distance Weighting (IDW) method was used to visualize pressure gradients and produce vulnerability maps (Figure 4) [25]. The methodology is detailed in Appendix B.

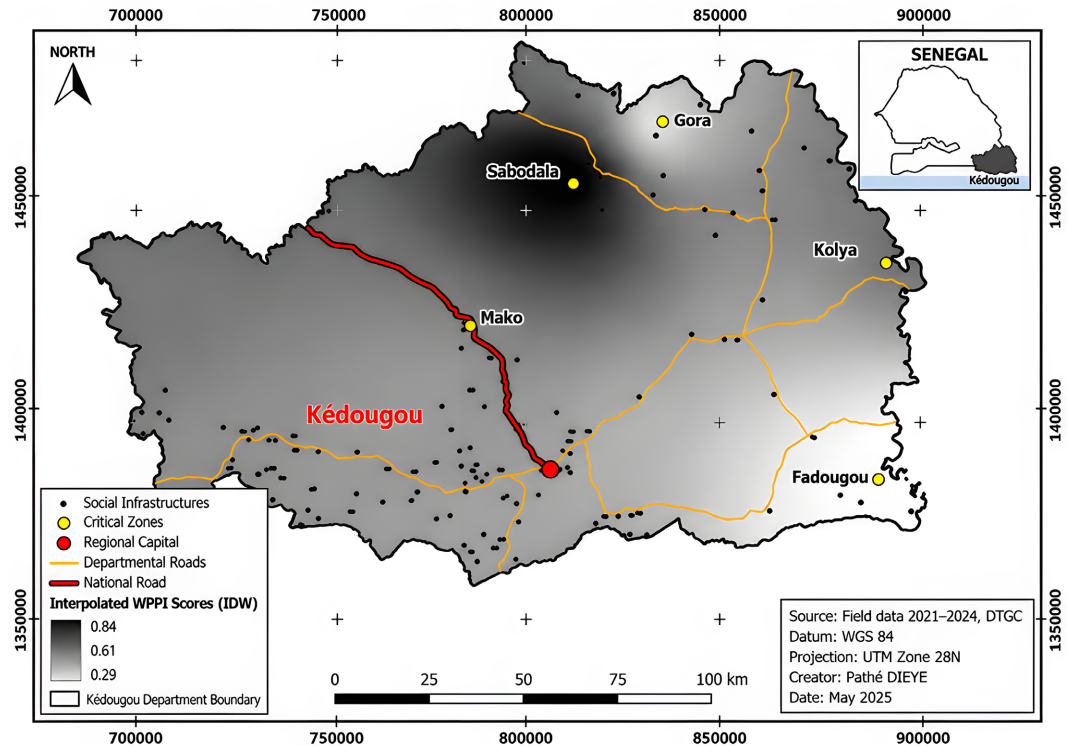


Figure 4. IDW interpolation of WPPI values.

2.7. Methodological Limitations

- **Data Heterogeneity:** We acknowledge the uneven frequency, quality, and temporal coverage of ESIA and field data [32] [33].
- **Logistical Constraints:** Access to certain sites (e.g., along the Falémé) was difficult, potentially affecting spatial representativity [8] [17].
- **Subjectivity in Weighting:** While our factors are based on best practices and literature, the final selection and weighting of sub-parameters for **Fi** and **Pi** involve a degree of expert judgment. The scoring grids presented in Table 4 and Table 5 are designed to maximize transparency and reproducibility. Further empirical calibration and sensitivity analysis are recommended [22] [23] [25].
- **Causal Attribution:** Our study design, based on observational data, allows us to identify associations and spatial-temporal trends. However, without source tracing (e.g., isotopic fingerprinting), we cannot definitively attribute observed pollution to specific mining sources. Our discussion of potential causes is therefore framed as plausible interpretations rather than definitive conclusions.

3. Results

3.1. Comparative Analysis of ESIA and Field Data (2006-2024)

The cross-analysis of ESIA and field data reveals notable discrepancies (**Table 7**).

Table 7. Comparative analysis of historical baseline/ESIA data and contemporary field measurements (matched site-pairs, n = 12).

Mining Site	ESIA Source (Year)	Pb (mg/L)	As (mg/L)	Hg (mg/L)	CN ⁻ (mg/L)	Matched Pair ID
Gora (SGO)	ESIA 2011	0.012	0.014	ND	0.03	P01
Gora (Field)	Field 2023	0.038	0.032	0.0021	0.055	P01
Mako (PMC)	ESIA 2013	0.009	0.008	0.0004	ND	P02
Mako (Field)	Field 2022	0.027	0.018	0.0012	ND	P02
Kolya (Afrigold)	ESIA 2018	0.015	ND	ND	0.034	P03
Kolya (Field)	Field 2023	0.041	ND	ND	0.062	P03
Sabodala (SGO)	ESIA 2006	0.011	0.012	ND	0.028	P04
Sabodala (Field)	Field 2022	0.028	0.019	0.0018	0.048	P04
Massawa (SGO)	ESIA 2019	0.010	0.009	ND	0.022	P05
Massawa (Field)	Field 2022	0.022	0.018	0.0012	0.038	P05
Boto (IAMGOLD)	ESIA 2018	0.008	0.007	ND	0.070	P06
Boto (Field)	Field 2023	0.014	0.014	0.0010	0.095	P06
Sored (Khossanto)	ESIA 2018	0.012	0.010	ND	0.032	P07
Sored (Field)	Field 2023	0.035	0.028	0.0020	0.058	P07
Diabougou	ESIA (ASM baseline)	0.018	0.015	ND	0.045	P08
Diabougou (Field)	Field 2023	0.056	0.042	0.0035	0.078	P08
Fadougou	ESIA (ASM baseline)	0.016	0.012	ND	0.038	P09
Fadougou (Field)	Field 2023	0.062	0.048	0.0042	0.085	P09
Khossanto	ESIA (ASM baseline)	0.014	0.011	ND	0.035	P10
Khossanto (Field)	Field 2023	0.028	0.021	0.0018	0.052	P10
Kérékonko	ESIA (ASM baseline)	0.013	0.010	ND	0.030	P11
Kérékonko (Field)	Field 2023	0.045	0.035	0.0035	0.065	P11
Gora Artisanal	ESIA (ASM baseline)	0.015	0.012	ND	0.033	P12
Gora Artisanal (Field)	Field 2023	0.052	0.045	0.0085	0.065	P12

Note 1: Values in bold indicate an increase in concentration between the historical ESIA and the contemporary field measurement. ND = Not Detected; NM = Not Measured/Not Reported in the ESIA. Note 2: For ASM (artisanal small-scale mining) sites without formal ESIA reports, baseline values were derived from the earliest available environmental monitoring data or pre-operational surveys in the area (identified as “ASM baseline”). Note 3: Hg concentrations at Gora (SGO) Field measured at 0.0021 mg/L in this sampling campaign; a separate sampling point yielded 0.010 mg/L in a different campaign, reflecting spatial variability within the site (see Section 3.1). Note 4: All 12 matched pairs met the four matching criteria defined in Section 2.2.2: i) geographic matching (same location or within 100 m); ii) water matrix matching (identical matrices); iii) seasonal matching (dry season only); iv) analyte matching (common analytes).

Across the sites assessed, we observed higher concentrations of heavy metals and cyanides in the 2021–2024 field measurements compared to the historical ESIA data. These values frequently exceeded the applicable reference values selected according to water-use context (WHO, IFC, or NS 05-061).

These observations suggest an intensification of mining activities, challenges in effluent treatment, and/or ongoing pollution from ASM. However, due to the heterogeneous nature of the historical data, we frame this as a descriptive trend rather than a statistically significant change [9] [18] [45].

3.2. Evolution of the Water Pollution Pressure Index (2006–2024)

By aggregating the data per site using the WPPI, we can quantify the temporal dynamics (Table 8, Figure 5).

Table 8. Evolution of normalized WPPI values per site.

Site	WPPI (from ESIA)	WPPI (Field 2021–24)	Change	Current Class
Sabodala	0.38 (2006)	0.61 (2022)	+0.23	D (Very High)
Gora	0.42 (2011)	0.78 (2023)	+0.36	D (Very High)
Mako (PMC)	0.29 (2013)	0.69 (2022)	+0.40	D (Very High)
Kolya	0.37 (2018)	0.71 (2023)	+0.34	D (Very High)
Fadougou	---	0.84 (2023)	---	E (Critical)

Our results show a consistent descriptive increase in WPPI values across the sites for which historical and current data were available, suggesting increasing water pressure over the study period. All sites now have WPPI scores in the “Very High” or “Critical” categories.

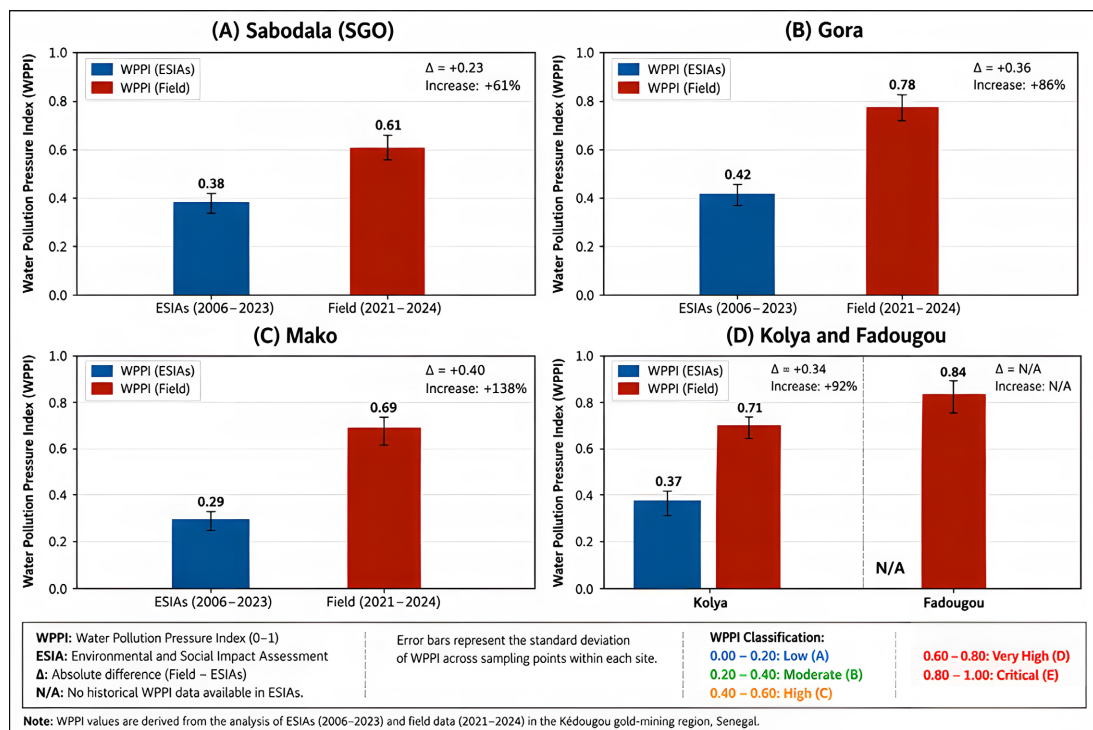


Figure 5. Comparison of historical ESIA WPPI and current field-measured WPPI per mining site.

3.3. Cross-Evaluation of ESIA Methodological Limitations

Our detailed analysis of ESIA reports (**Table 9**) revealed critical omissions and inconsistencies.

Table 9. Cross-evaluation of ESIA data vs. field observations.

Project/ Site	Key Parameter	ESIA Data	Field Observation	Identified Gap	Critical Remark
Gora	Mercury (Hg)	<0.001 mg/L	0.010 mg/L (separate sampling point)	≥10× higher in field	Limitations in monitoring design [34] [43]
Kolya (Afrigold)	Turbidity	Not doc.	112 NTU	No baseline data	Data gap in an active mining zone [8]
Boto	Cyanide	0.07 mg/L	0.095 mg/L	Exceeds applicable reference value	Potential underestimation of risk [22]
SGO	Arsenic (As)	0.01 mg/L	0.016 mg/L	Slight exceedance	No updated mitigation plan identified in the reviewed documentation [5] [41]
PMC- Mako	pH	7.2	5.8	Unanticipated acidity	Discrepancy between forecast and observed conditions [4]
Afrigold	Conductivity	Not measured	1450 µS/cm	Not monitored	

3.4. Spatialization of Water Pressures

The spatial interpolation of WPPI values (**Table 10**) allowed us to identify several high-pressure zones.

Table 10. Territorial classification of water pressures in the Kédougou mining zone.

Zone Type	Characteristics	Examples	WPPI Level
Industrial/Artisanal zone with co-located industrial and artisanal activities	Simultaneous presence of ASM and large-scale mines, water use conflicts	Gora, Kolya, Sabodala	Very High
Dense Artisanal Zone	Informal activity, no control, direct water use	Diabougou, Fadougou	Critical
Industrial Zone with Monitoring Gaps	Controlled industrial installation, but limited environmental surveillance	Boto, PMC-Mako	Very High
Exposed Village Zone	Community water access impacted by runoff or infiltration	Khossanto, Madina Bafé	Very High

We observed a positive association between the density of mining activities and the WPPI value (**Figure 6**). “Density of mining activities” was defined as the number of active mining sites (industrial and ASM) within a 5 km radius. Using our field data ($n = 43$ sampling points), the Pearson correlation coefficient between mining activity density and WPPI was $r = 0.943$ ($p < 0.001$, 95% CI: 0.91 - 0.96). The complete dataset of 43 sampling points used for this correlation is provided in **Appendix E**, including site identifiers, category, WPPI values, and number of mining sources within 5 km. This full enumeration allows independent verification of the reported correlation. Zones with a high number of co-located activities exhibited the highest WPPI scores, supporting the presence of cumulative pressure patterns that are poorly captured in conventional project-level ESIs [1] [8] [11].

Additional analyses of inter-parameter correlations, multi-source cumulative effects, and individual pollutant contributions to the WPPI are presented in **Appendix D**. These complementary results provide further insight into the relationships between contaminant co-occurrence, mining activity density, and cumulative water pollution pressures in the study area (see **Appendix D**).

4. Discussion

4.1. The WPPI: A Potential Tool for Socially-Integrated Environmental Assessment

The results demonstrate the value of the WPPI as a tool that potentially goes beyond

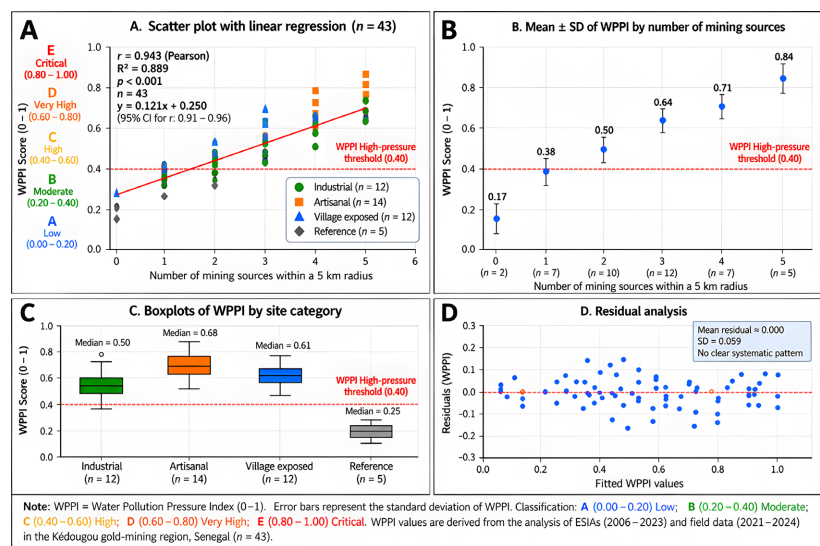


Figure 6. Relationship between the number of mining sources (industrial and artisanal) within a 5 km radius and WPPI values ($n = 43$). (A) Scatter plot with linear regression. Points are color-coded by site category (Industrial: green, $n = 12$; Artisanal: orange, $n = 14$; Village exposed: blue, $n = 12$; Reference: grey, $n = 5$). The red line represents the linear regression: $y = 0.121x + 0.250$ (Pearson $r = 0.943$, $R^2 = 0.889$, $p < 0.001$, 95% CI for r : 0.91 - 0.96). (B) Mean WPPI ($\pm$ standard deviation) by number of mining sources. (C) Boxplots of WPPI distribution by site category. (D) Residual plot of the linear regression model, showing no clear systematic pattern (mean residual ≈ 0.000 ; SD = 0.059), supporting the linearity assumption.

classical water quality indices. Classical WQIs, while useful for characterizing water status [15] [17] [23], often fail to capture the socio-environmental pressure experienced by dependent communities. By integrating the Fi and Di factors, the WPPI provides a more socially and territorially relevant assessment. It translates physicochemical data into a measure of socio-environmental pressure, showing that a site with a moderate WQI but high human dependency (Fi) and proximity (Di) can exert a higher pressure than a more polluted but remote site. This approach aligns with the core principles of SEA, which emphasize the need to consider not just biophysical impacts but also their social and economic consequences [7] [26] [27]. This is a critical advancement for applied research in resource-constrained and socially vulnerable settings [13] [46].

4.2. Interpretation of Identified Trends

Despite the methodological limitations stemming from the heterogeneous ESIA data, the identified trends are consistent across multiple independent sources and sites. The consistent descriptive trend toward higher heavy-metal concentrations and WPPI values points toward a potentially chronic issue rather than isolated incidents. This is consistent with observations from other mining regions in sub-Saharan Africa, where inadequate monitoring and enforcement have led to progressive environmental degradation [10] [12] [13] [45]. However, we emphasize that this is an observational trend, and definitive causal attribution to specific mining sources would require further investigation, such as isotopic fingerprinting or receptor modeling.

4.3. Governance Gaps and Environmental Responsibility

Our findings expose governance gaps in water resource management in an extractive context (Table 11). These implementation and monitoring limitations are common challenges in developing nations, creating a gap between regulatory frameworks and on-the-ground reality [11]–[13] [33] [35].

Table 11. Proposed roles of stakeholders and avenues for improvement in a mining context.

Category	Actors/Structures	Roles/Functions	Limits/Dysfunctions
Institutional Actors	Ministry of Environment (ME), DEEC, EIASP	Environmental supervision, ESIA validation	Limited inter-institutional coordination
	International Funders (IFC, World Bank, UNEP)	Funding, norms, technical support	Limited coordination with national institutions
	Industrial Mining Companies (SGO, IAMGOLD, etc.)	Producing ESIAs, monitoring reports	Incomplete information in reviewed reports, lack of normative harmonization
Operational Actors	Environmental Consulting Firms	Carrying out ESIAs, technical support	Potential constraints on independence; limited data sharing

Continued

	Local NGOs and Community Associations	Sensitization, advocacy, local monitoring	Poorly integrated into formal governance
Improvements	Independent Water Pollution Pressure Observatory (IWPPPO)	Intersectoral coordination, data collection/processing	To be established
	Unified Environmental Information System	Interface between administrations and partners	Lack of a centralized database
	Mandatory Strategic Environmental Assessment	Integration of cumulative effects, sustainability	Not yet systematic
	Systematic inclusion of local communities	Participation via watchdog committees, CSOs	Community data not considered in management plans

- **ESIA Implementation Gaps:** ESIAs are often perceived as procedural requirements for obtaining permits rather than as tools for genuine environmental prevention [32].
- **Limited Independent Oversight:** Pollution from ASM, which directly affects community water sources, often lacks adequate independent monitoring and regulation [10] [13].
- **Weak Integration:** There is a clear absence of an integrated system linking environmental data with land-use planning and community grievances [7] [27].

This situation is compounded by a lack of data transparency and limited technical capacity for rigorous environmental monitoring, as highlighted by several authors [32] [33] [44]. The establishment of a multi-stakeholder governance system that includes local communities is essential for addressing these gaps [11] [12].

4.4. Avenues for Improvement and Further Research

To address these challenges, we propose:

- 1) **Strengthening ESIA Regulations:** Mandate a minimum parameter list (including heavy metals and cyanides), require multi-seasonal monitoring, and enforce public disclosure of results [12] [35].
- 2) **Establishing Local Water Observatories:** Create independent bodies involving universities, local authorities, state services, and mining companies for participatory monitoring [12] [44].
- 3) **Developing an Early Warning System (EWS):** Based on the WPPI, integrate it with an open-data GIS platform to guide local decisions [24].
- 4) **Implementing Strategic Zoning:** Develop a strategic hydrological zoning that intersects mining pressure, usage vulnerability, and population density to prioritize interventions [27] [47].

5) Further External Validation of the WPPI: Conduct comprehensive external validation across independent datasets and contrasting mining contexts, complemented by expanded uncertainty and sensitivity analyses.

5. Conclusions

Our study presents a comprehensive assessment of mining-related water pollution pressures in the Kédougou region through the development and application of the Water Pollution Pressure Index (WPPI). By integrating contamination levels with social and spatial factors (*Fi* and *Di*), the WPPI represents a methodological advancement beyond classical water quality indices. Rather than measuring contamination alone, it provides an integrated assessment of the pressure exerted on water resources and the communities that depend on them.

The cross-analysis of historical ESIA information and contemporary field data reveals a consistent descriptive pattern of increasing water pollution pressure in several mining-affected areas. A “WPPI Pressure Triangle”, encompassing the Diabougou-Khossanto corridor, the Falémé River zone (Kolya-Fadougou), and the Gambia River zone (Kérékonko), emerges as a priority area for enhanced surveillance. Rather than representing merely a cartographic pattern, this spatial configuration provides a territorial framework for prioritizing integrated monitoring, risk prevention, and environmental intervention.

The WPPI shows potential as an operational decision-support tool for synthesizing complex environmental and social information, enabling spatial comparison and strategic prioritization. Its application highlights discrepancies between historically anticipated impacts and contemporary observed conditions and identifies limitations in current environmental assessment and monitoring practices. These findings support a transition toward a more transparent, integrated, and scientifically robust system of environmental assessment and monitoring for mining regions in West Africa.

Future research should focus on external validation of the WPPI using independent datasets and contrasting mining contexts, together with expanded uncertainty and sensitivity analyses. Ultimately, integration of the WPPI into a dynamic, open-access monitoring platform could strengthen access to environmental information for communities, regulators, and decision-makers, helping translate environmental assessment into evidence-based action for the governance of mining-affected water resources.

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Author Contributions

Conceptualization, P.D., B.N.; M.M.M.N., methodology, P.D., B.N.; M.M.M.N., software, P.D.; validation, P.D., B.N., A.T.; formal analysis, P.D.; M.M.M.N., in-

vestigation, P.D.; resources, P.D., B.N.; data curation, P.D.; M.M.M.N., writing—original draft preparation, P.D.; writing—review and editing, P.D., B.N., A.T., M.S.; visualization, P.D.; supervision, B.N., A.T.; project administration, B.N. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix A: Sampling and Analytical Protocol

Objective: Provide a reproducible protocol for water sample collection, preservation, and analysis.

Table A1. Sample preservation by parameter group.

Parameter Group	Container	Preservation	Temperature	Max Holding Time
Dissolved metals	HDPE, 250 mL	Filter 0.45 μm + HNO_3 pH < 2	4°C	180 d
Total metals	HDPE, 250 mL	HNO_3 pH < 2	4°C	180 d
Mercury	Borosilicate glass	HCl pH < 2 + $\text{K}_2\text{Cr}_2\text{O}_7$ 0.05%	4°C	28 d
Cyanides (total/free)	HDPE, 500 mL	NaOH pH > 12 + $\text{Na}_2\text{S}_2\text{O}_3$	4°C	14 d/24 h
Anions (NO_3^- , SO_4^{2-} , etc.)	HDPE, 500 mL	Filter if turbid	4°C	48 h
<i>In-situ</i> parameters	N/A	Measured on-site	N/A	N/A

Table A2. Analytical methods.

Parameter	Method	Standard	LOD	Uncertainty
As, Pb, Cd, Cr, Cu, Zn	ICP-MS	EPA 6020B	0.0002 - 0.001 mg/L	5%
Hg	CV-AFS	EPA 1631E	0.0001 mg/L	8%
Cyanides	Colorimetry	EPA 335.3/335.4	0.001 - 0.002 mg/L	10%
Anions	Ion chromatography	EPA 300.1	0.01 - 0.1 mg/L	5%
pH, EC, DO, T°	Electrometry (<i>in-situ</i>)	EPA 150.1/120.1/360.1	-	2% - 3%
Turbidity, TSS	Nephelometry/Filtration	EPA 180.1/160.2	0.01 NTU/1 mg/L	5% - 10%

Table A3. Quality assurance/quality control (QA/QC).

QC Element	Frequency	Acceptance Criteria
Field blanks	1/10 samples	<LOD
Field duplicates	1/10 samples	RPD < 20%
Certified reference materials	1/batch	Recovery 80 - 120%
Laboratory duplicates	1/10 samples	RPD < 15%
Calibration verification	Start/End of run	Recovery 90% - 110%

Appendix B: Spatial Interpolation Methodology

Objective: Describe GIS methods for spatializing water pressures.

B.1. Reference System

- System: WGS 84 (EPSG: 4326)
- Projection: UTM 28N (EPSG: 32628)
- Resolution: 100 m

B.2. Interpolation Method: Inverse Distance Weighting (IDW)

Interpolated value at point x :

$$\hat{Z}(x_0) = \frac{\sum_{i=1}^n w_i Z(x_i)}{\sum_{i=1}^n w_i}$$

with $w_i = 1/di^p$, where di is Euclidean distance and p is power.

Parameter selection:

Parameter	Value	Justification
Power (p)	2	Lowest cross-validation error among tested configurations
Number of neighbors (n)	12	Error stabilization threshold
Maximum distance	18 km	Empirically determined by cross-validation
Cell size	100 m	Regional mapping resolution

B.3. Cross-Validation Metrics (Leave-One-Out, n = 43)

Metric	Value
RMSE	0.087
MAE	0.065
Bias	−0.003
R ² (predicted vs. observed)	0.84

The low bias (−0.003) indicates no substantial systematic over- or underestimation, while RMSE = 0.087 and R² = 0.84 indicate satisfactory predictive performance for regional-scale visualization.

B.4. WPPI Vulnerability Classes

Class	WPPI Range	Designation	Color
A	0.00 - 0.20	Low pressure	Green
B	0.20 - 0.40	Moderate pressure	Yellow
C	0.40 - 0.60	High pressure	Orange
D	0.60 - 0.80	Very high pressure	Red-orange
E	0.80 - 1.00	Critical pressure	Red

Appendix C: WPPI Sensitivity Analysis

Objective: Document the robustness of the WPPI to variations in key parameters.

C.1. Sensitivity to Regularization Parameter (a)

Variation of a from 0.01 to 0.50 km (step 0.01 km) for all 43 points.

a (km)	Spearman ρ (vs $a = 0.10$)	Sites reclassified (≥ 1 class)
0.01	0.98	0
0.05	0.96	0
0.10	1.00	-
0.20	0.94	0
0.30	0.89	1
0.50	0.81	3

Rankings remain stable for $a \leq 0.20$ km ($\rho \geq 0.94$). The selected value ($a = 0.10$ km) is within the optimal stability range.

C.2. Sensitivity to Normalization Threshold ($T = C_{i_max}/N_i$)

Variation of T from 5 to 20.

T	Mean WPPI	Sites reclassified (≥ 1 class)
5	0.58	4
8	0.54	2
10	0.50	-
12	0.48	2
15	0.46	3
20	0.44	4

Monotonic decrease of WPPI with T is consistent with the normalization formula. $T = 10$ (95th percentile observed = 8.7) balances empirical representativeness and stability.

C.3. Sensitivity to Toxicological Weighting (P_i)

Individual scenario: Reduction of P_i from 5 $\rightarrow$ 4 for each critical parameter.

Parameter	Mean WPPI change	Sites reclassified
As (5 $\rightarrow$ 4)	-0.03	1
Pb (5 $\rightarrow$ 4)	-0.04	1
Hg (5 $\rightarrow$ 4)	-0.05	2
CN ⁻ (5 $\rightarrow$ 4)	-0.02	0

Global scenario: Simultaneous 20% reduction of critical weights ($P_i \times 0.8$).

Scenario	Mean WPPI	Sites reclassified
Baseline	0.50	-
Reduced-weight ($P_i \times 0.8$)	0.43	3

The WPPI is robust to plausible P_i variations (<10% of sites reclassified, never by more than one class).

C.4. Summary

Parameter	Range tested	Ranking stability
Regularization (α)	0.01 - 0.50 km	>90%
Normalization threshold (T)	5 - 20	>90%
P_i (individual, 5→4)	One-step downward	>95%
P_i (global, $\times 0.8$)	Reduced-weight scenario	>93%

Appendix D: Indicator Dependency Matrix and Cumulative Effects

Objective: Analyze parameter correlations and quantify multi-source cumulative effects.

D.1. Spearman Correlation Matrix (n = 43)

Parameter	As	Pb	Hg	CN ⁻	pH	EC	NO ₃ ⁻	SO ₄ ²⁻
As	1.00	0.68***	0.52**	0.61***	-0.58***	0.62***	0.55***	0.59***
Pb	0.68***	1.00	0.58***	0.72***	-0.65***	0.71***	0.62***	0.68***
Hg	0.52**	0.58***	1.00	0.49**	-0.55***	0.54***	0.48**	0.56***
CN ⁻	0.61***	0.72***	0.49**	1.00	-0.62***	0.68***	0.59***	0.65***
pH	-0.58***	-0.65***	-0.55***	-0.62***	1.00	-0.61***	-0.48**	-0.64***
EC	0.62***	0.71***	0.54***	0.68***	-0.61***	1.00	0.65***	0.72***
NO ₃ ⁻	0.55***	0.62***	0.48**	0.59***	-0.48**	0.65***	1.00	0.58***
SO ₄ ²⁻	0.59***	0.68***	0.56***	0.65***	-0.64***	0.72***	0.58***	1.00

Significance: *** $p < 0.001$; ** $p < 0.01$.

High correlations among Pb, CN⁻, EC, and SO₄²⁻ ($\rho > 0.65$) suggest co-occurrence potentially associated with common or overlapping mining-related pressures. Negative correlations with pH are consistent with acidification occurring alongside increasing contaminant concentrations.

D.2. Multi-Source Cumulative Effects

Relationship between number of mining sources (within 5 km radius) and WPPI:

$$WPPI = 0.250 + 0.121 \times N_{sources}$$

Statistic	Value
Pearson r	0.943
R ²	0.889
Adjusted R ²	0.885
Standard error	0.08
p-value	<0.001
95% CI slope	[0.098 - 0.144]
95% CI r	[0.91 - 0.96]
N	43

Each additional source is associated with a WPPI increase of approximately 0.121 units. Classification by source density:

Category	No. sources	Mean WPPI
Isolated source	1	0.35
Multiple sources	2 - 3	0.52
Dense sources	≥4	0.68

Note: Category means calculated across all sampling points per class; not equivalent to site-level values in **Table 8**.

D.3. Contribution Decomposition at Critical Sites

Site	Pb (%)	As (%)	Hg (%)	CN ⁻ (%)	Aggregated physico-chemical (%)
Diabougou	28	22	18	15	17
Fadougou	32	25	15	12	16
Gora	25	20	22	18	15
Kolya	30	18	16	20	16

Note: Contributions were calculated from normalized partial pressure indices and sum to 100% for each site.

Lead (Pb) is the dominant contributor (25% - 32%) at all critical sites. Arsenic (As) and mercury (Hg) contribute 15 - 25%. Aggregated physico-chemical contribution is stable (15% - 20%).

D.4. Governance Implications

Finding	Implication
Co-occurrence of correlated contaminants	Need for integrated source assessment and reduction (industrial + artisanal)
Cumulative effects: +0.121 WPPI/source	Territorial planning and zoning importance
Pb as main contributor	Priority for Pb discharge monitoring and reduction
Stable physico-chemical contribution	Address acidification as aggravating factor for metal mobility

Appendix E: Complete Dataset of 43 Sampling Points Used for Mining-Activity-Density-WPPI Correlation Analysis

Objective

This appendix provides the complete analytical dataset of 43 sampling points used to assess the relationship between mining activity density and the Water Pollution Pressure Index (WPPI) in the Kédougou mining region.

Mining activity density is operationally defined as the number of identified active industrial and/or artisanal mining sources located within a 5 km Euclidean radius of each sampling point.

The complete dataset is reported to ensure transparency, reproducibility, and independent verification of the statistical relationship reported in the manuscript (Pearson's $r = 0.943$; $R^2 = 0.889$; $n = 43$). The 43 observations listed below constitute the reference analytical dataset for the correlation and associated analyses presented in **Figure 6**.

Table E1. Complete analytical dataset of the 43 sampling points used in the mining-activity-density-WPPI correlation analysis.

ID	Site name	Analytical category	WPPI	Mining sources within 5 km
K01	Sabodala village	Village exposed	0.61	3
K02	Khossanto	Village exposed	0.62	4
K03	Diabougou	Artisanal	0.84	5
K04	Sabodala (SGO)	Industrial	0.58	2
K05	Gora (SGO)	Industrial	0.78	4
K06	Gora artisanal	Artisanal	0.79	4
K07	Massawa	Industrial	0.52	2
K08	Niakhafiri	Industrial	0.48	2
K09	Kobokoto	Industrial	0.45	1
K10	Mako (PMC)	Industrial	0.69	3
K11	Bantaco	Artisanal	0.63	3
K12	Tomboronkoto	Artisanal	0.58	2
K13	Kolya (Afrigold)	Industrial	0.71	4
K14	Fadougou	Artisanal	0.84	5
K15	Madina Bafé	Village exposed	0.61	3
K16	Boto (IAMGOLD)	Industrial	0.42	1
K17	Sored	Industrial	0.48	2
K18	Tinkoto	Artisanal	0.65	3
K19	Kérékonko	Artisanal	0.68	3
K20	Saraya	Village exposed	0.35	1

Continued

K21	Missirah Sirimana	Village exposed	0.44	2
K22	Kharakhéna	Village exposed	0.58	3
K23	Falémé River (upstream)	Reference	0.18	0
K24	Falémé River (midstream)	Reference	0.25	1
K25	Falémé River (downstream)	Reference	0.38	2
K26	Gambia River (upstream)	Reference	0.15	0
K27	Gambia River (downstream)	Reference	0.32	1
K28	Diabougou well 1	Artisanal	0.82	5
K29	Diabougou well 2	Artisanal	0.85	5
K30	Fadougou well	Artisanal	0.83	5
K31	Kolya village well	Village exposed	0.72	4
K32	Khossanto well	Village exposed	0.61	4
K33	Sabodala community well	Village exposed	0.59	3
K34	Mako village well	Village exposed	0.68	3
K35	Boto community well	Village exposed	0.40	1
K36	Gora community well	Village exposed	0.76	4
K37	Massawa river	Industrial	0.51	2
K38	Niakhafiri stream	Industrial	0.47	2
K39	Kobokoto stream	Industrial	0.44	1
K40	Bantaco river	Artisanal	0.62	3
K41	Tomboronkoto stream	Artisanal	0.57	2
K42	Tinkoto stream	Artisanal	0.64	3
K43	Kérékonko stream	Artisanal	0.67	3

Definition of variables and analytical rules

WPPI is the Water Pollution Pressure Index calculated according to the methodology described in Section 2.5 of the manuscript.

Mining sources within 5 km represents the number of identified active mining sources—industrial and/or artisanal—located within a 5 km Euclidean radius of the corresponding sampling point.

The analytical category is used for descriptive stratification of sampling locations into Industrial, Artisanal, Village exposed, and Reference sites. Category membership is not used in the calculation of the Pearson correlation coefficient. The correlation is calculated directly from the two numerical variables reported for each of the 43 observations: WPPI and number of mining sources within 5 km.

The 5 km analytical radius follows the methodological rationale described in Section 2.5.9 and the supporting literature cited in the manuscript [14] [17]. The original dataset uses the same definition of mining-source density.

Table E2. Verified distribution of sampling points by analytical category.

Analytical category	n	Mean WPPI	Median WPPI	Mean mining sources within 5 km
Industrial	12	0.544	0.495	2.17
Artisanal	14	0.715	0.675	3.64
Village exposed	12	0.581	0.610	2.92
Reference	5	0.256	0.250	0.80
Total	43	0.577	—	2.70

Verification: $12 + 14 + 12 + 5 = 43$ sampling points.

These category totals are calculated directly from the individual classifications reported in **Table E1**.

Table E3. WPPI distribution by mining-source density.

Mining sources within 5 km	n	Mean WPPI	SD
0	2	0.165	0.021
1	7	0.376	0.073
2	10	0.501	0.065
3	12	0.638	0.037
4	7	0.713	0.073
5	5	0.836	0.011
Total	43	—	—

This distribution documents the complete analytical gradient from sampling points with no identified mining source within 5 km to sampling points surrounded by five identified mining sources.

Statistical verification

Using the 43 paired observations reported in **Table E1**:

$n = 43$

Pearson's $r = 0.94284$

Rounded Pearson's $r = 0.943$

$R^2 = 0.88894$

Rounded $R^2 = 0.889$

The reported correlation can therefore be independently reproduced directly from the WPPI and mining-source-density values provided in **Table E1**.

Importantly, the Pearson correlation is calculated independently of the four descriptive site categories. Consequently, modification or alternative interpretation of a site-category label would not alter the reported correlation, provided that the WPPI value and mining-source count for that observation remain unchanged.

Key observations from the complete dataset

The dataset provides broad spatial coverage of the Kédougou mining region,

including the Falémé and Gambia River systems, major industrial mining areas, artisanal mining zones, exposed villages, and reference locations. The manuscript highlights selected sites as illustrative cases, whereas the complete set of 43 observations provides the statistical basis for the mining-density-WPPI relationship.

A clear numerical gradient is observed across mining-source density classes: mean WPPI increases from 0.165 at zero identified mining sources to 0.836 at five sources within 5 km. This pattern is consistent with the strong positive correlation obtained from the complete dataset.

The five reference locations (K23 - K27) exhibit comparatively low WPPI values (0.15 - 0.38) and limited mining-source density (0 - 2 sources within 5 km), providing a comparative baseline within the analytical design. These five sites are explicitly identifiable in the source dataset.

Reproducibility statement

All 43 observations used in the mining-activity-density-WPPI correlation analysis are individually disclosed in **Table E1**. The analytical variables required to reproduce the reported Pearson correlation are therefore fully available: WPPI value and number of mining sources within 5 km for each sampling point.

The appendix is intended to provide an auditable analytical record and to permit independent recalculation of the reported association using the same dataset or alternative statistical specifications.