



INTEGRATED MODEL FOR THE ASSESSMENT AND PRIORITISATION OF ENVIRONMENTAL RISKS ASSOCIATED WITH INACTIVE TAILINGS DUMPS IN THE JIU VALLEY

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Abstract: Tailings dumps in post-mining coalfield regions may represent persistent sources of pressure on soils, surface waters, the landscape and local communities. In the Jiu Valley, the regional inventory comprises 49 tailings dumps, of which 26 are rehabilitated, 9 are active and 14 are inactive. This study develops and applies a Synthetic Risk Index (ISR) to all 14 inactive dumps by integrating three components: the integrated geochemical index (IG), the morphometric index (IM – area and volume) and the site vulnerability index (IV – proximity to water bodies and settlements, wind exposure and sensitive land uses). The geochemical component was calculated using the common set of metals Cr(total), Cu and Ni, available for all sites, based on values determined at sampling points P1–P17 in 2023. The model uses min–max normalisation and a weighted scheme in which geochemical pressure is the main component, while physical size and spatial vulnerability act as risk-amplifying factors. The results indicate that the Ramura 1–4 Petrila, Defor, Balomir, Funicular Vechi, Bloc 0 and Ramura 1–2 dumps fall within the high-risk class, whereas the remaining sites are distributed between the moderate- and low-risk classes. The proposed model provides a regional screening tool that is useful for prioritising the monitoring, stabilisation and ecological rehabilitation of inactive dumps, with potential for subsequent integration into a GIS-based decision-support framework.

Keywords: inactive tailings dumps; Jiu Valley; environmental risk; synthetic risk index; multicriteria assessment; heavy metals; post-mining regeneration.

1. Introduction

Long-term mining activities cause persistent landscape transformations through excavation, the deposition of waste material, changes in the hydrological regime and the development of degraded surfaces that are difficult to reintegrate into economic and ecological circuits. Tailings dumps resulting from coal extraction and preparation are heterogeneous deposits consisting of sterile rocks, coal-bearing fragments, clayey and sandy materials and secondary mineral alteration products. Even after mining has ceased, these structures may remain geochemically active through oxidation, leaching, erosion, surface transport and wind dispersion processes [1, 2, 3, 4].

The assessment of soil and mine-waste contamination is frequently based on geochemical indices such as the geoaccumulation index (I_{geo}), the contamination factor (FC), the total contamination factor (FCT) or the potential ecological risk index (PERI). These tools are useful for quantifying contaminant pressure relative to reference values, but they do not fully describe operational and territorial risk. A dump with a moderate contamination level, but with a large volume and an unfavourable location in relation to watercourses or inhabited areas, may generate a higher management priority than a locally contaminated site that is isolated and small in size [5, 6, 7, 8].

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The Jiu Valley is one of Romania's most important coalfield regions, with a long mining history and a large number of waste deposits. At regional level, 49 tailings dumps have been inventoried and are found in different functional stages: active, rehabilitated or inactive. This study focuses on the 14 inactive dumps as the relevant group for post-mining risk assessment and for establishing priorities for monitoring, stabilisation and rehabilitation [9, 10, 11, 12].

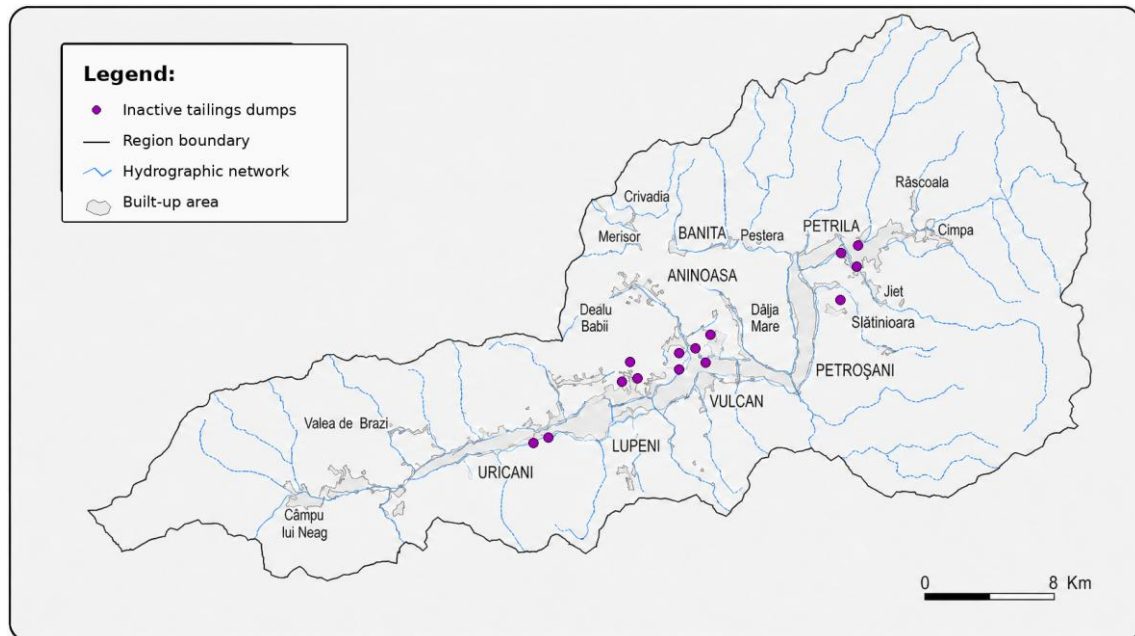


Fig. 1. Spatial distribution of inactive tailings dumps in the Jiu Valley in relation to the regional boundary, hydrographic network and built-up areas

The main objective of this study is to develop and apply a Synthetic Risk Index (ISR) for the 14 inactive tailings dumps in the Jiu Valley, using geochemical, morphometric and spatial vulnerability data. The specific objectives are to integrate geochemical indices into a comparable sub-index; to include area and volume as expressions of source magnitude; to introduce site vulnerability as an exposure factor; to classify the dumps into risk classes; and to formulate prioritisation directions for monitoring and post-mining regeneration.

2. Materials and methods

2.1 Study area and data used

The study area is the Jiu Valley, a mountainous region located in south-western Romania, characterised by fragmented relief, a dense hydrographic network and a historical concentration of coal-mining operations. Following coal extraction and preparation activities, 49 tailings dumps have been inventoried. Of these, 26 are rehabilitated, 9 are active and 14 are inactive. The 14 inactive dumps constitute the population analysed in this study, being relevant for post-mining risk assessment and for prioritising monitoring, stabilisation and rehabilitation works [9, 13].

Table 1. Structure of the regional inventory of tailings dumps in the Jiu Valley.

Tailings dump category	Number of dumps	Relevance in the context of the study
Rehabilitated	26	Dumps included in the regional inventory, found in different stages of rehabilitation or stabilisation.
Active	9	Dumps still in operational regime or associated with the deposition of waste material.
Inactive	14	Dumps analysed in this study for post-mining risk assessment.

The geochemical data derive from determinations carried out in 2023 at sampling points P1–P17 for Cr(total), Cu and Ni, the metals common to all the analysed dumps. For certain sites, values were also available for Zn, Co and Pb; these elements were used as supplementary information for the local interpretation of the respective sites. The regional geochemical component of the ISR model was calculated on the basis of the common Cr(total)–Cu–Ni set, in order to ensure a uniform assessment basis across all 14 inactive dumps [13, 14, 15].

The primary geochemical dataset consisted of measured concentrations and corresponding point-level Igeo and FC calculations for P1–P17. In the regional ISR model, only Cr(total), Cu and Ni were retained because these metals were available for the complete set of 14 inactive dumps; Zn, Co and Pb were considered only as supplementary elements for local interpretation where available.

The morphometric data included dump area and the estimated volume of deposited material, while the vulnerability data included proximity to water bodies and human settlements, potential exposure to wind dispersion and the presence of agricultural or sensitive land uses in the vicinity. For each dump, the values determined at sampling points P1–P17 were summarised at site level in order to calculate the geochemical indices used in the multicriteria assessment [16].

Table 2. Inactive dumps included in the analysis, morphometric characteristics and the normalised morphometric index

Locality	Tailings dump name	Area (m ²)	Volume (thousand m ³)	IM
Uricani	Funicular Vechi	51,700	31.169	0.016
Uricani	Balomir	13,000	39,000.000	0.540
Lupeni	Bloc 0	18,400	9.200	0.005
Lupeni	Noua Victoria	31,800	2,875.000	0.046
Lupeni	Ramura 1–2	11,420	7,756.442	0.102
Vulcan	Coroiești Ramura 1	126,000	3.150	0.039
Vulcan	Tericon cota 360	13,700	220.000	0.006
Vulcan	Hypolit	2,500	5.000	0.000
Vulcan	Puț 7 Vest – tericoane	100,000	1,056.000	0.044
Vulcan	Puț 7 Vest – halda veche	35,000	588.000	0.018
Livezeni	Puț Auxiliar Est	10,900	144.000	0.004
Petrila	Ramura 1–4 Petrila	1,600,860	10,210.000	0.631
Petrila	Defor	127,500	2,149.970	0.067
Petrila	Valea lui Ciort	7,190	21.570	0.002

2.2. Construction of the Synthetic Risk Index

The proposed model starts from the general relationship $R = f(H, S, V)$, where H represents geochemical hazard, S source magnitude and V site vulnerability. For operationalisation, the three components were translated into three sub-indices: IG – integrated geochemical index, IM – morphometric index and IV – vulnerability index. This structure is compatible with the general principles of risk management, in which hazard must be interpreted together with exposure and receptor vulnerability [17].

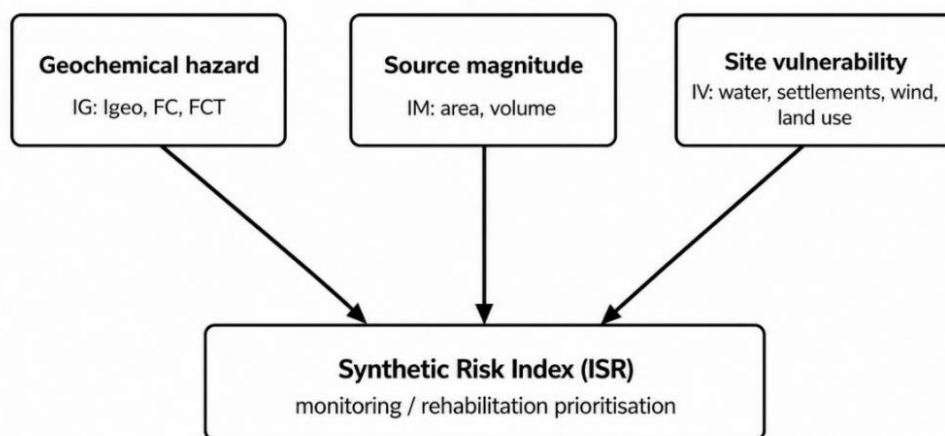


Fig. 2. Conceptual structure of the multicriteria ISR model for the integrated risk assessment of inactive tailings dumps

The quantitative indicators were normalised using the min–max method, according to the following relationship [18]:

$$N(x_i) = \frac{x_i - x_{\min}}{x_{\max} - x_{\min}} \quad (1)$$

where $N(x)$ is the normalised value of the indicator x , while $x_{\min}$ and $x_{\max}$ represent the minimum and maximum values recorded for that indicator across the analysed dataset. For indicators in which high values indicate higher pressure or risk, normalisation preserves the direct meaning of the variable.

For distance-related vulnerability variables, the reversed score was calculated as

$$N_{\text{rev}}(x_i) = \frac{x_{\max} - x_i}{x_{\max} - x_{\min}} \quad (2)$$

so that shorter distances to sensitive receptors correspond to higher vulnerability values.

The geochemical component was calculated using the common set of metals Cr(total), Cu and Ni, available for all 14 inactive dumps. For the contamination factor, the reference/background values used in the 2023 calculation sheet were Cr(total) = 30 mg/kg, Cu = 20 mg/kg and Ni = 20 mg/kg. The same values were applied consistently to all 14 inactive dumps to ensure comparability within the regional dataset [19, 20].

The contamination factor was calculated as:

$$FC_i = \frac{C_i}{B_i} \quad (3)$$

where C_i is the measured concentration of metal i and B_i is the corresponding reference/background value.

For each dump, the total contamination factor was calculated as the sum of the mean FC values for Cr(total), Cu and Ni:

$$FCT = \overline{FC_{\text{Cr(total)}}} + \overline{FC_{\text{Cu}}} + \overline{FC_{\text{Ni}}} \quad (4)$$

Before integration, mean I_{geo} , mean FC and FCT were min–max normalised across the 14 inactive dumps. The integrated geochemical index was then calculated as [5, 6, 18]:

$$IG_i = \frac{N(I_{\text{geo}_i}) + N(FC_i) + N(FCT_i)}{3} \quad (5)$$

where IG_i is the integrated geochemical index for dump i , N represents min–max normalisation, I_{geo_i} is the mean geoaccumulation index, FC_i is the mean contamination factor, and FCT_i is the total contamination factor calculated for the same dump. The common Cr(total)–Cu–Ni set ensures a uniform basis for calculating the integrated geochemical index for all 14 inactive dumps, while the values available for Zn, Co and Pb complement the local interpretation where these elements were determined.

The morphometric index was calculated as the arithmetic mean of the normalised area and normalised volume of each dump:

$$IM_i = \frac{N(A_i) + N(V_i)}{2} \quad (6)$$

where IM_i is the morphometric index for dump i , A_i is the area of the dump, and V_i is the estimated volume of deposited material.

Site vulnerability was assessed through four semi-quantitative variables, scored on an ordinal 0–1 scale, where 0 represents the least vulnerable condition within the investigated set and 1 the most vulnerable condition. For distance-related variables, the score followed reversed min–max normalisation; therefore, shorter distances to water bodies or settlements generated higher vulnerability scores. For wind exposure and nearby agricultural or sensitive land use, scores were assigned according to field observations, map interpretation and the presence/absence or intensity of exposure conditions. The same scoring logic was applied consistently to all 14 dumps to support relative comparison rather than absolute exposure quantification. The operational criteria used for vulnerability scoring are shown in Table 3.

Table 3. Operational criteria for scoring site vulnerability.

Variable	Scoring direction	Low value	High value
Proximity to water	Score inversely proportional to distance	Dump located far from watercourses/torrents	Dump located close to watercourses/torrents
Proximity to settlements	Score inversely proportional to distance	Isolated site	Site located close to dwellings/infrastructure
Wind exposure	Score directly proportional to exposure	Stabilised or protected surface	Surface exposed to wind dispersion
Agricultural use nearby	Score directly proportional to land use	No relevant agricultural uses	Agricultural land / gardens nearby

Intermediate values between 0 and 1 were used when the local condition was neither clearly low nor clearly high. For example, partially stabilised surfaces, intermediate distances to receptors or discontinuous sensitive land uses were assigned intermediate scores. This approach preserves the screening-level character of the assessment and reduces overinterpretation of categorical field information.

The vulnerability index was calculated as the arithmetic mean of the four scored vulnerability variables:

$$IV = \frac{V_{water_i} + V_{settlements_i} + V_{wind_i} + V_{agriculture_i}}{4} \quad (7)$$

where IV_i is the vulnerability index for dump i , V_{water_i} is the vulnerability score related to proximity to water bodies, $V_{settlements_i}$ is the vulnerability score related to proximity to settlements, V_{wind_i} is the score assigned to wind exposure, and $V_{agriculture_i}$ is the score assigned to nearby agricultural or sensitive land use.

The final synthetic risk index was calculated using the following formula:

$$ISR_i = 0.50 \times IG_i + 0.20 \times IM_i + 0.30 \times IV_i \quad (8)$$

The weighting scheme used in Eq. (8) was defined as an expert-based screening scenario: 0.50 for IG , 0.20 for IM and 0.30 for IV . The largest weight was assigned to IG because geochemical pressure represents the primary hazard term, while IV represents receptor/exposure susceptibility and IM represents the physical magnitude of the contaminant source. A higher weight was therefore retained for contamination pressure than for source size, but vulnerability was kept above morphometry because proximity to receptors can increase management priority even for smaller dumps. The weights are not regulatory coefficients and were not calibrated as toxicological probabilities; they were selected to support transparent regional prioritisation and remain adjustable in future applications [7, 18, 21].

The ISR values were classified into three operational risk classes, as shown in Table 4. The 0.40 and 0.60 breakpoints were defined as operational interpretation intervals on the normalised 0–1 scale, separating lower, intermediate and upper relative-priority groups within the 14-dump dataset. They are intended to facilitate management communication and prioritisation, not to define legally binding thresholds, regulatory limit values or quantitative toxicological risk levels. In this study, ISR therefore expresses a relative ranking of inactive dumps under a common methodological framework.

Table 4. Operational classification of ISR values.

ISR range	Risk class	Operational interpretation
$ISR < 0.40$	Low risk	Lower relative priority for monitoring or intervention
$0.40 \leq ISR < 0.60$	Moderate risk	Intermediate priority; periodic monitoring recommended
$ISR \geq 0.60$	High risk	Higher priority for monitoring, detailed assessment or intervention

Note: The ISR thresholds are used for comparative ranking within the analysed dataset and do not represent regulatory limit values, toxicological thresholds or absolute risk values.

3. Results

3.1. Geochemical synthesis and model components

The mean concentrations determined at sampling points P1–P17 show a relatively heterogeneous distribution of $Cr(\text{total})$, Cu and Ni among the inactive dumps. For the common set of metals, the highest values of the integrated geochemical index (IG) were obtained for Defor, Funicular Vechi, Ramura 1–4 Petrila and Bloc 0. This result indicates that the geochemical pressure associated with the common metals is not limited to a single mining sector, but has a regional expression, with differences in intensity between sites. The values reported in Table 5 represent site-level averages derived from the complete P1–P17 calculation sheets, not single-point measurements [22, 23].

Table 5. Geochemical synthesis for the common $Cr(\text{total})$, Cu and Ni set, 2023.

Dump	Mean Cr	Mean Cu	Mean Ni	Mean I_{geo}	Mean FC	FCT	IG
Funicular Vechi	36.40	58.92	85.70	0.563	2.815	8.445	0.939
Balomir	34.62	58.03	84.72	0.553	2.764	8.291	0.792
Bloc 0	35.62	57.23	86.28	0.558	2.788	8.363	0.860
Noua Victoria	34.03	56.73	82.26	0.539	2.695	8.084	0.594

Dump	Mean Cr	Mean Cu	Mean Ni	Mean I _{geo}	Mean FC	FCT	IG
Ramura 1–2	35.90	58.62	83.23	0.553	2.763	8.289	0.790
Coroiești Ramura 1	33.49	55.73	76.70	0.516	2.579	7.738	0.264
Tericon cota 360	36.55	56.26	78.28	0.530	2.648	7.945	0.462
Hypolit	37.42	55.11	74.02	0.514	2.568	7.704	0.232
Puț 7 Vest – tericoane	37.79	57.05	78.58	0.536	2.680	8.041	0.553
Puț 7 Vest – halda veche	38.43	57.48	81.19	0.548	2.738	8.215	0.719
Puț Auxiliar Est	34.15	54.19	72.28	0.497	2.487	7.462	0.000
Ramura 1–4 Petrila	38.37	55.17	87.44	0.561	2.803	8.409	0.905
Defor	37.34	58.32	86.96	0.567	2.836	8.509	1.000
Valea lui Ciort	33.48	56.61	82.38	0.538	2.689	8.066	0.577

The morphometric component strongly differentiates the dumps according to area and volume. Ramura 1–4 Petrila has the largest area, while Balomir stands out through the largest reported volume in the inventory of inactive dumps. Therefore, these two sites have high IM values and may act as important sources of potentially mobilisable material, even where a strictly geochemical interpretation is insufficient to explain management priority. The IV component highlights the amplifying role of site location, especially for dumps located close to watercourses, torrents, dwellings or agricultural land [16].

3.2. Classification of dumps based on ISR

The integration of IG, IM and IV into ISR enables the 14 inactive dumps to be ranked according to relative risk. Ramura 1–4 Petrila has the highest score as a result of the combination of high geochemical pressure, very large morphometric magnitude and site vulnerability. Defor and Balomir are also located in the upper part of the classification, but through different mechanisms: Defor through the geochemical component and vulnerability, and Balomir through the important contribution of volume and vulnerability [13, 14, 15].

Table 6. ISR values and risk classification for the 14 inactive dumps analysed, 2023.

Dump	IG	IM	IV	ISR	Risk class
Ramura 1–4 Petrila	0.905	0.631	0.775	0.811	High
Balomir	0.792	0.540	0.850	0.759	High
Defor	1.000	0.067	0.800	0.753	High
Funicular Vechi	0.939	0.016	0.725	0.690	High
Bloc 0	0.860	0.005	0.725	0.649	High
Ramura 1–2	0.790	0.102	0.775	0.648	High
Puț 7 Vest – halda veche	0.719	0.018	0.625	0.550	Moderate
Noua Victoria	0.594	0.046	0.775	0.539	Moderate
Valea lui Ciort	0.577	0.002	0.750	0.514	Moderate
Puț 7 Vest – tericoane	0.553	0.044	0.625	0.473	Moderate
Tericon cota 360	0.462	0.006	0.650	0.427	Moderate
Coroiești Ramura 1	0.264	0.039	0.700	0.350	Low
Hypolit	0.232	0.000	0.600	0.296	Low
Puț Auxiliar Est	0.000	0.004	0.900	0.271	Low

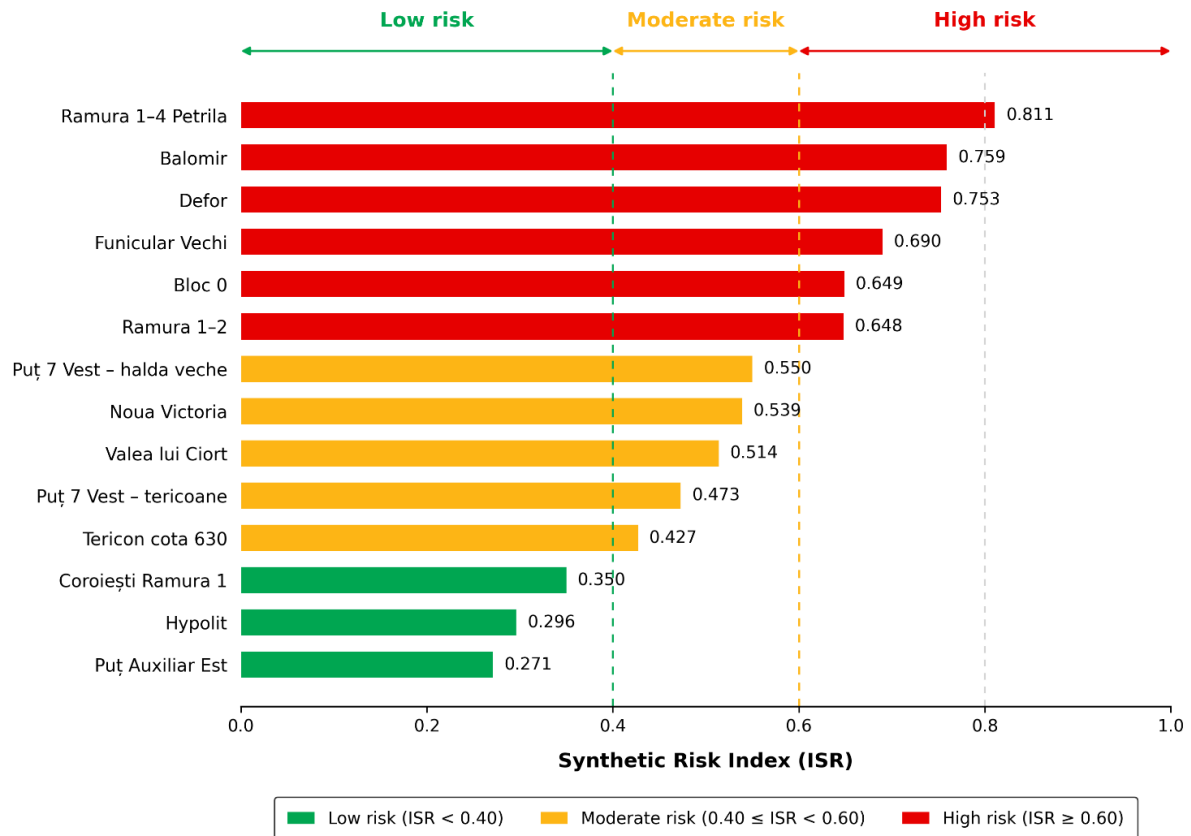


Fig. 3. Comparative classification of the 14 inactive tailings dumps based on the Synthetic Risk Index (ISR), 2023

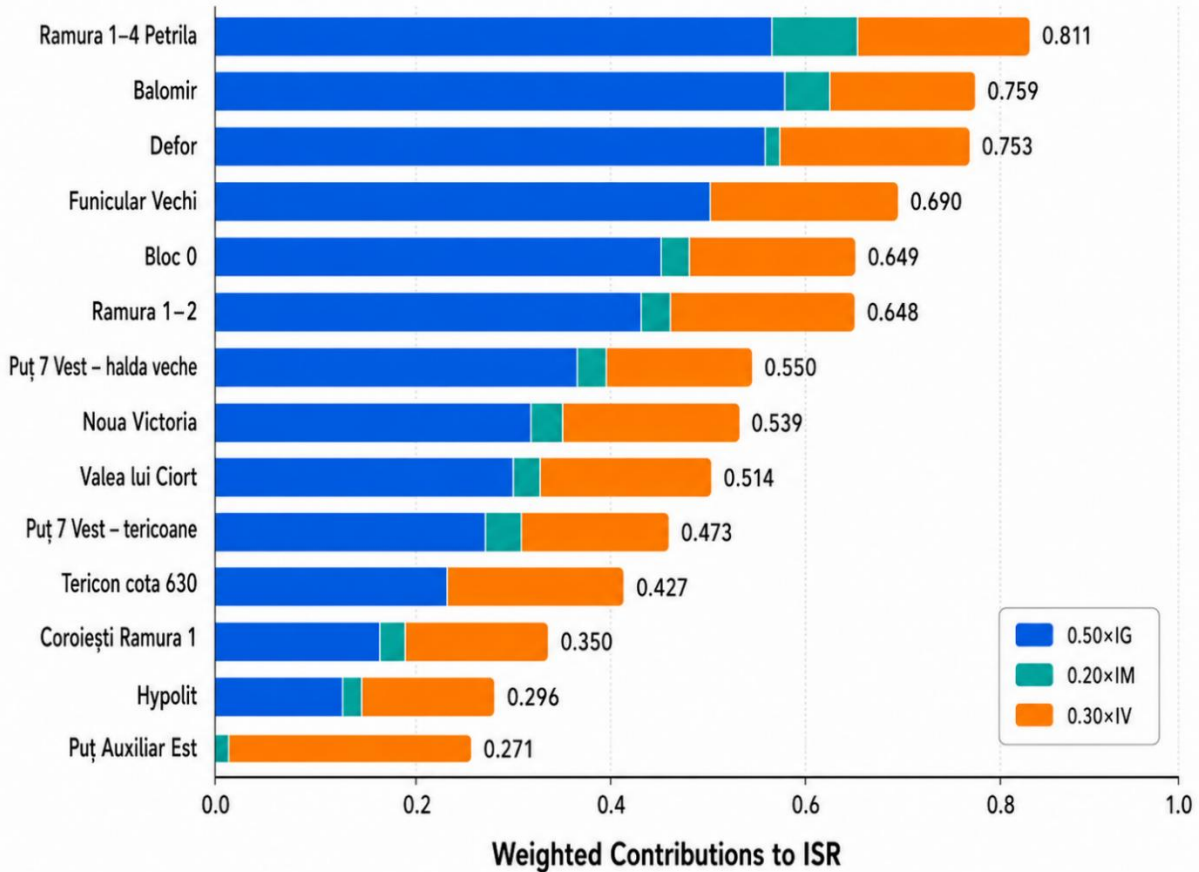


Fig. 4. Contribution of the weighted components ($0.50 \times IG$, $0.20 \times IM$ and $0.30 \times IV$) to the differentiation of ISR scores

4. Discussion

4.1. Integrated interpretation of risk

The results confirm that the risk hierarchy cannot be inferred solely from a single geochemical index. In the case of tailings dumps, risk is conditioned by at least three dimensions: contaminant pressure, the mass and area of deposited material, and the location of the dump in relation to vulnerable receptors. The ISR model addresses this complexity through a synthetic score in which the contribution of each component can be analysed separately [8, 18].

Ramura 1–4 Petrila represents the clearest example of component convergence. The dump simultaneously shows high geochemical pressure, important morphometric magnitude and considerable spatial vulnerability, which explains its first position in the ISR hierarchy. Defor is also classified as high risk, mainly due to the geochemical component and site vulnerability. Balomir demonstrates the role of the morphometric component: although it is not always the highest site from a geochemical point of view, its very large volume and site vulnerability place it within the group of priority sites [16].

The inclusion of all 14 inactive dumps provides a more complete regional picture of monitoring priorities. Funicular Vechi, Bloc 0 and Ramura 1–2 reach the high-risk class through relevant geochemical values for the common Cr(total)–Cu–Ni set and through spatial vulnerability. By contrast, Coroiești Ramura 1, Hypolit and Puț Auxiliar Est have lower ISR scores, although certain local components, especially vulnerability in the case of Puț Auxiliar Est, support their continued inclusion in surveillance programmes [14].

Accordingly, ISR should be interpreted as a comparative prioritisation tool for the analysed inactive dumps, rather than as an absolute regulatory risk threshold [18, 21].

4.2. Implications for monitoring and post-mining regeneration

The ISR model can function as a screening tool for the management of post-mining sites. By converting heterogeneous data into a common score, it enables clearer communication of priorities among researchers, local authorities, operators and decision-makers. Each sub-index can subsequently be associated with GIS layers: geochemical indices, area and volume, distances to water bodies and settlements, prevailing wind directions and land uses. The model can therefore be updated as new data become available and can support the periodic monitoring of dumps [10, 11, 12].

The resulting classification suggests three levels of action. For high-risk sites, interventions should focus on detailed geochemical monitoring, the control of surface runoff, the reduction of particle dispersion and vegetative or technical stabilisation. For moderate-risk sites, periodic monitoring, verification of surface stability, vegetation control and assessment of functional reconversion options are recommended. For low-risk sites, management may include surveillance at longer intervals and the maintenance of existing stability conditions [1, 4, 16, 24].

The model provides a preliminary ranking of inactive dumps based on the available geochemical, morphometric and spatial data. A brief uncertainty and sensitivity consideration is necessary because the final ISR is influenced by min–max normalisation, the selected weighting scenario and the semi-quantitative vulnerability scores. The ranking is expected to be more robust for sites clearly separated from the class boundaries, such as Ramura 1–4 Petrila, Balomir, Defor and Funicular Vechi in the high-priority group, while sites located closer to threshold values should be interpreted with greater caution. Dumps situated near the 0.60 high-risk breakpoint or the 0.40 low/moderate breakpoint may change class if additional metals, multiyear data, alternative weights or refined receptor-distance datasets are introduced. Consequently, ISR should be used as a first-tier screening and prioritisation tool, followed by site-specific investigations for dumps selected as priorities. Future developments may include the testing of several weighting scenarios, the inclusion of metal mobility and bioavailability parameters, validation through biological or ecotoxicological indicators, and implementation of the model in a GIS platform [18, 23, 24].

5. Conclusions

This study developed and applied an integrated model for the assessment and prioritisation of environmental risks associated with inactive tailings dumps in the Jiu Valley, through the construction of the Synthetic Risk Index (ISR). Unlike approaches based exclusively on contamination indices, the model combines geochemical pressure, source size and site vulnerability, providing a more complete picture of monitoring and rehabilitation priorities.

The application of the model to all 14 inventoried inactive dumps revealed a differentiated risk hierarchy. Ramura 1–4 Petrila, Defor and Balomir emerge as priority sites through the combination of the geochemical component, source magnitude and spatial vulnerability. Funicular Vechi, Bloc 0 and Ramura 1–2 are also classified as high risk by the comparative model, indicating the need to extend monitoring across the entire category of inactive dumps, rather than only the sites previously considered most problematic.

The main contribution of the study consists in proposing a transparent, extensible multicriteria framework that is compatible with GIS integration and useful for regional screening and for directing resources towards sites with greater environmental risk relevance. The proposed ISR must therefore be interpreted as a comparative screening and prioritisation tool, not as a regulatory risk value, toxicological threshold or substitute for a detailed site-specific quantitative risk assessment. Its role is to indicate where monitoring, stabilisation and post-mining regeneration resources should be directed first, while final intervention design should rely on detailed field, geochemical, hydrological and ecological investigations.

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