



## GIS AND REMOTE SENSING-BASED DIGITAL FRAMEWORK FOR ENVIRONMENTAL MONITORING OF DISPERSED HISTORICAL MINING AREAS IN NORTHERN ROMANIA

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**Abstract:** *The historical spatial dispersion of mining activities in the Northern part of Romania generated significant challenges for environmental monitoring, risk assessment, and regulatory compliance. This study proposes an integrated framework based on geographic information systems (GIS), remote sensing, and digital tools to support environmental evaluation in extractive industries. Multi-temporal satellite data, including Sentinel-1 and Sentinel-2 imagery, are combined with in-situ observations and historical mining records to assess land-use changes, surface stability, and environmental pressures.*

*Spatial analysis techniques are applied to identify patterns of land degradation and potential emission sources, enabling the delineation of risk-prone areas. An approach is used to simulate interactions between former mining operations and environmental factors, supporting continuous calibration through time-series analysis. The framework also integrates standardized procedures for performance evaluation and compliance reporting in line with ESG principles and international environmental standards. Results demonstrate improved monitoring accuracy, enhanced spatial decision-support, and increased efficiency in environmental reporting on historical mining activities. The proposed approach provides a scalable solution for managing dispersed mining regions and supports the transition toward sustainable and digitally enabled extractive practices.*

**Keywords:** *digital twin, environmental monitoring, GIS, remote sensing, spatial analysis, Copernicus, Romanian National Exploration Program*

### 1. Introduction

To simulate interactions between former mining operations and environmental factors several literature references were studied [1], [2], [3]. The northern region of Romania, particularly the Maramureș mining district and the Apuseni Mountains, represents one of the most significant historical mining areas in Eastern Europe. Owing to decades of intensive extraction of polymetallic ores, including lead, zinc, copper, gold, and silver, this region has become the subject of numerous environmental and geospatial studies. Scientific investigations have focused on the long-term environmental consequences generated by abandoned mines, waste dumps, tailings ponds, and acid mine drainage. Recent literature increasingly highlights the importance of integrating Geographic Information Systems (GIS), remote sensing technologies, hydrochemical investigations, and environmental risk assessment methods to better understand the interactions between former mining activities and surrounding ecosystems [4], [5], [6], [7], [8].

The Baia Mare–Maramureș metallogenic area is among the most intensively studied mining regions in Romania. Historical mining and ore-processing activities generated extensive tailings impoundments and sterile waste deposits, many of which remain environmentally active even decades after mine closure. Several

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studies have demonstrated that abandoned mining infrastructures continue to release significant quantities of heavy metals and acidic waters into nearby soils, rivers, and groundwater systems. These pollution sources contribute to persistent environmental degradation and affect the ecological stability of adjacent landscapes.

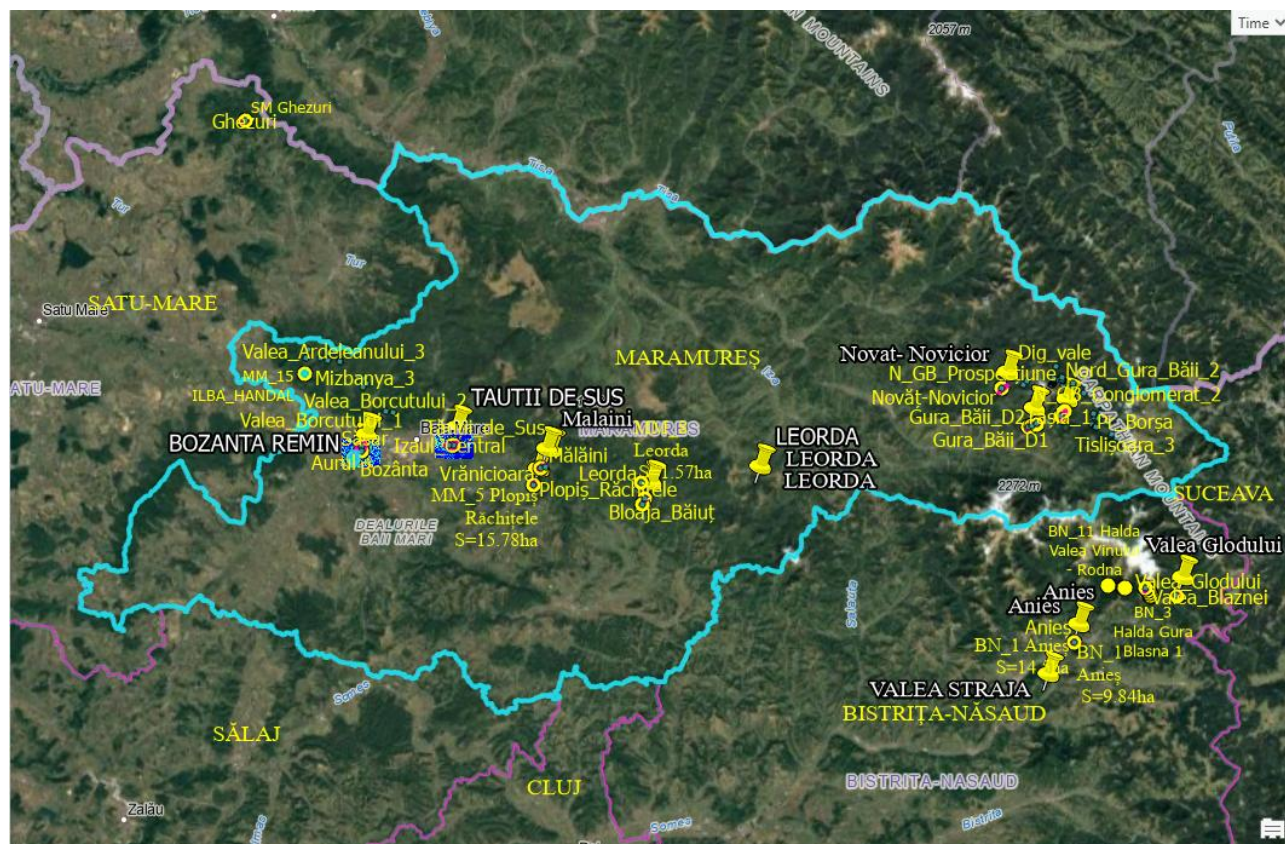


Fig. 1. Some of the existing waste dumps and tailing ponds of the former mining industry in Maramureș and Bistrița Năsăud County

A defining environmental event for northern Romania was represented by the catastrophic tailings dam failures that occurred in January and March 2000 in Maramureș County. These accidents discharged cyanide-contaminated waters and mining tailings into the Tisa and Danube River systems, producing severe transboundary pollution effects in Romania, Hungary, and Serbia.

Long-term environmental monitoring revealed elevated concentrations of heavy metals such as lead, zinc, copper, cadmium, and iron within river sediments, floodplains, and aquatic ecosystems. The accidents also highlighted the vulnerability of mining infrastructures and the need for improved environmental monitoring and risk management systems.

Research conducted within the Someș–Tisa hydrographic basin further demonstrated that mine closure does not eliminate environmental hazards. Abandoned underground galleries, waste dumps, and poorly rehabilitated tailings facilities continue to generate acid mine drainage enriched in iron, manganese, zinc, copper, lead, cadmium, and nickel. Consequently, many authors recommend continuous environmental monitoring supported by GIS-based spatial analysis and hydrochemical modelling in order to evaluate contamination pathways and long-term ecological risks [9].

### Site investigation

Additional investigations in mining areas such as Ilba and Băiuț (two out of 75 existing in the CLOUDUT data base <https://cloudut.utcluj.ro/en/>) analyzed tailings deposits and sterile dumps using field measurements, laboratory analyses, and GIS spatial assessment techniques. These studies identified high concentrations of toxic metals in soils and waste materials, instability processes affecting dump slopes, and the potential generation of acid drainage under changing climatic conditions [10].

Similar environmental impacts were documented in the Lăpuș River basin, where contaminated sediments transported from historical mining sites contributed to soil degradation and ecological disturbances in riparian environments [11], [12].



Fig. 2. Ilba – Handal waste dump with a length over 200m

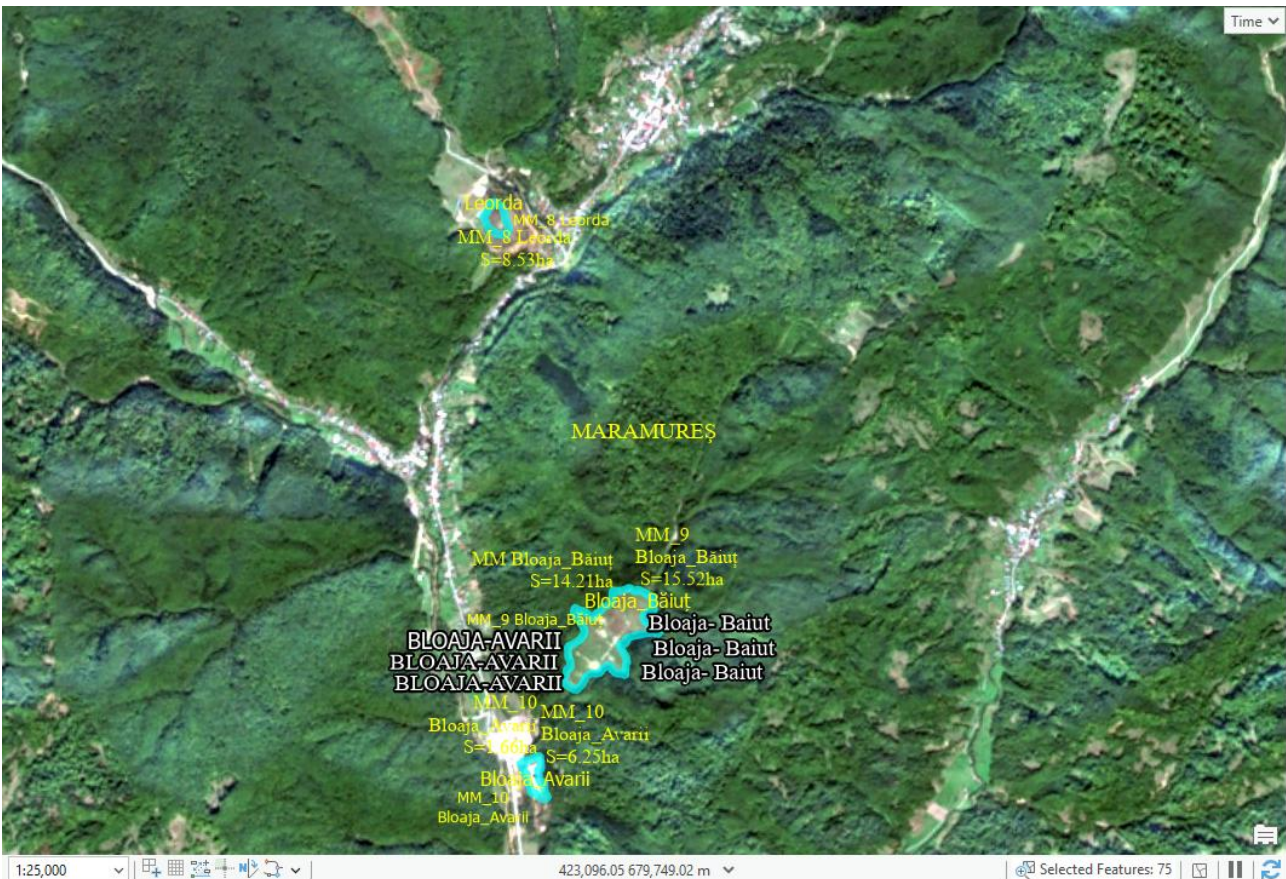


Fig. 3. Tailing ponds based on Baiut mining perimeter near population

Modern research increasingly relies on advanced remote sensing and GIS technologies for monitoring post-mining landscapes. Sentinel-1 and Sentinel-2 satellite imagery are widely used for land use and land cover change detection, vegetation stress analysis through NDVI, moisture assessment using NDWI, subsidence monitoring, and identification of unstable tailings structures. These integrated approaches provide valuable tools for simulating the interactions between former mining operations and environmental factors, including erosion, hydrological connectivity, geomorphological instability, and ecosystem degradation.

## 2. Methods and workflow

After the site investigation and baseline GIS inventory for a GIS and remote sensing-based digital framework for environmental monitoring of dispersed historical mining areas in Northern Romania, the next steps proposed by the authors will follow a structured workflow that integrates spatial analysis, environmental diagnostics, predictive modelling, and decision-support tools. A logical framework can be organized into the following stages:

### 2.1 Spatial Database Consolidation and Geodatabase Development

Step 1. Following field investigation, all collected spatial and environmental data will be integrated into a centralized GIS geodatabase. This includes digitized mining perimeters, tailings ponds, waste dumps, hydrographic networks, geological maps, DEMs, historical maps, and field sampling locations. Remote sensing datasets such as Copernicus Programme **Sentinel-1** and **Sentinel-2** imagery, UAV data (if available), and ancillary datasets such as **LUCAS 2018 soil data** and national environmental monitoring records should also be incorporated. Attribute harmonization and metadata standardization are essential for ensuring interoperability and future updates.



Fig. 4. Example of DEM for Bloaja Baiut – Copyright of MDT\_directia topografica militara (2021)

### 2.2 Multi-Temporal Remote Sensing Analysis

Step 2. The next step involves temporal analysis of satellite imagery to detect environmental changes associated with abandoned mining sites. Key analyses include:

- **Land Use/Land Cover (LULC) Change Detection** to identify expansion or stabilization of disturbed areas;
- **NDVI (Normalized Difference Vegetation Index)** for vegetation stress and ecological recovery assessment;
- **NDWI (Normalized Difference Water Index)** for moisture anomalies and tailings pond water dynamics;
- **Surface deformation and subsidence monitoring** using **Sentinel-1 InSAR** techniques;
- **Thermal anomaly detection** (if using NASA **Landsat** or thermal sensors) or UAV with thermal cameras.

Obs. These analyses help quantify environmental trends and identify high-risk zones.

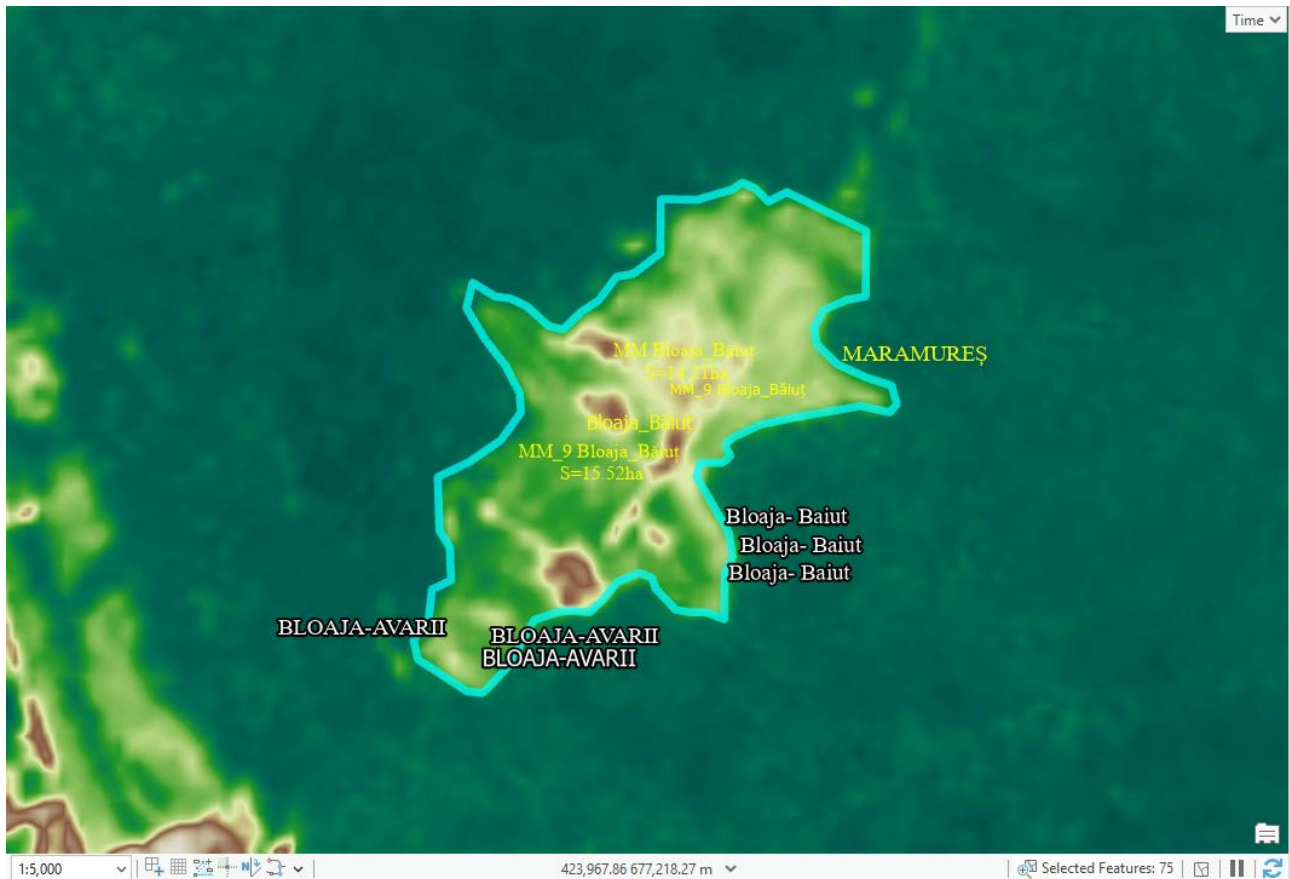


Fig. 5. NDVI base map using Copernicus images

### 2.3 Environmental Risk Mapping and Spatial Modeling

Step 3. Using GIS-based spatial analysis, environmental vulnerability and hazard maps will be developed. Recommended models will include:

- **Heavy metal dispersion models** for soils and water bodies;
- **Hydrological connectivity modeling** to simulate contaminant transport through drainage systems;
- **Slope stability and erosion susceptibility assessment** using DEM-derived parameters;
- **Multi-Criteria Decision Analysis (MCDA)** to rank mining sites according to environmental risk.

This phase supports prioritization of intervention areas and provides a regional overview of cumulative impacts.

### 2.4 Geochemical and Field Data Integration

Step 4. Laboratory results (e.g., pH, EC, metal concentrations, XRF data, soil moisture measurements) will be spatially interpolated and integrated into GIS layers. Geostatistical tools such as **Kriging** or **IDW interpolation** can be used to generate contamination surfaces and compare field observations with remote sensing indicators.

Using this type of image is it possible to delineate accurately the limits and exposure of the former tailing ponds and waste dumps.

### 2.5 Predictive Simulation and Scenario Analysis

Step 5. A digital framework should include predictive capabilities to simulate future environmental behavior under different scenarios, such as:

- Increased precipitation and AMD generation;
- Tailings dam failure or erosion events;
- Vegetation recovery under natural succession;
- Land-use changes affecting contaminant mobility.

Machine learning algorithms or spatial statistical models can improve prediction accuracy and identify early-warning indicators.

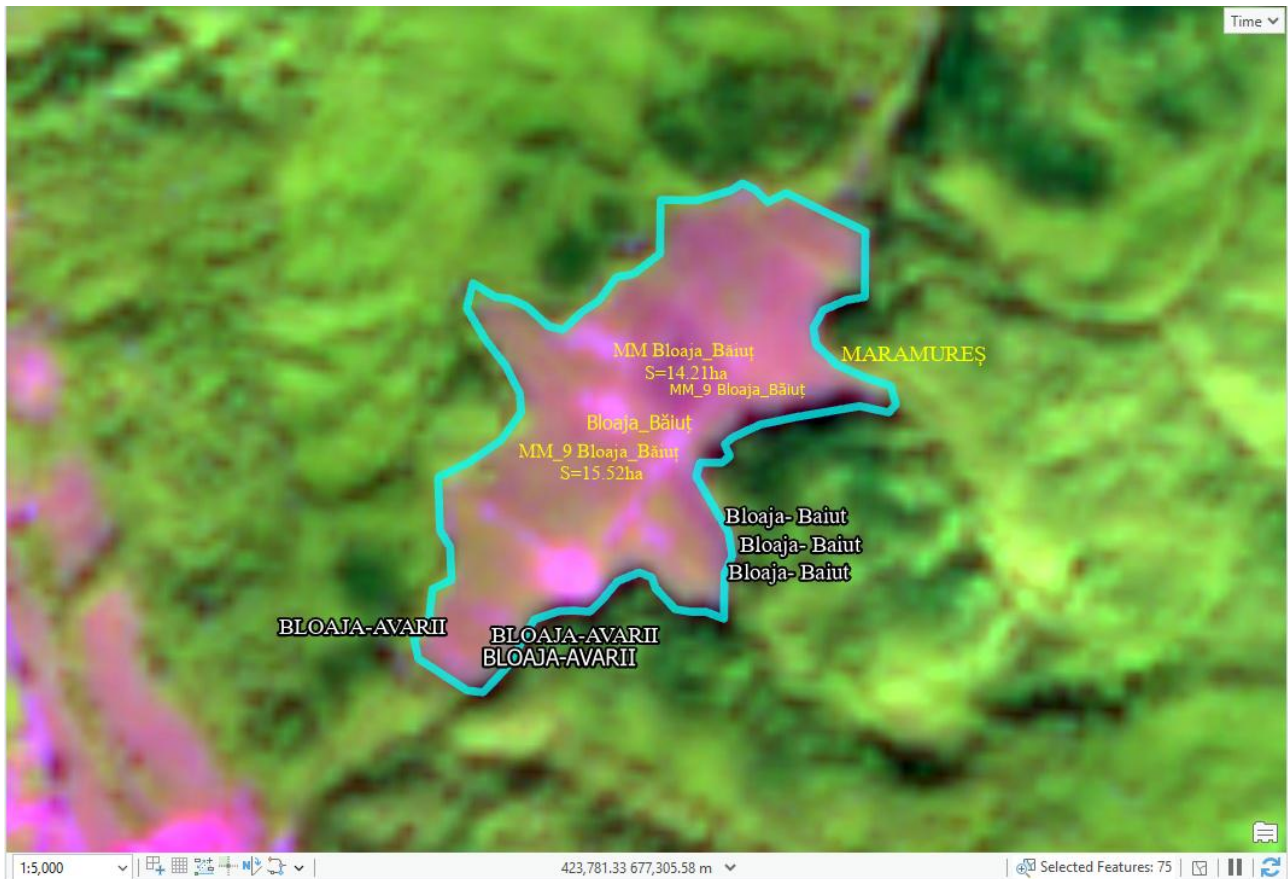


Fig. 6. Bands shortwave infrared-2, shortwave infrared-1, red (12, 8, 4) with dynamic range adjustment applied.

## 2.6 Development of a Digital Monitoring Dashboard

Step 6. To support long-term monitoring, a GIS dashboard will be developed using platforms such as ArcGIS Pro, **ArcGIS Online**, or **QGIS WebGIS**. The dashboard will display:

- Active risk hotspots;
- Satellite-derived environmental indicators;
- Historical change timelines;
- Field monitoring data;
- Alert thresholds for critical changes.

## 2.7 Decision Support and Management Recommendations

Step 7. The final step is translating analytical outputs into practical environmental management strategies. This includes:

- Prioritizing remediation or stabilization measures;
- Designing continuous monitoring protocols;
- Supporting authorities with risk communication tools;
- Establishing adaptive management plans for former mining sites.

## 3. Conclusions and suggestions

The proposed framework incorporates several complementary components designed to improve the efficiency and reliability of environmental monitoring. These include a centralized cloud GIS geodatabase for storing spatial and laboratory data, numerical simulations (2D & 3D), multi-temporal Sentinel-1 and Sentinel-2 satellite analysis, UAV-based terrain inspection, DEM-derived hydrological and geomorphological modelling, and automated environmental risk mapping. Additional components involve machine learning algorithms for anomaly detection and predictive simulations, real-time environmental dashboards, geostatistical analysis modules, and integration of field sensor networks for monitoring water quality, slope stability, and soil moisture conditions.

The framework also supports land use and land cover change analysis, vegetation stress monitoring through NDVI, moisture assessment using NDWI, and identification of potential subsidence or erosion

processes affecting tailings facilities and abandoned mining structures. Furthermore, the integration of hydrochemical modelling, contamination pathway simulations, and spatial multicriteria analysis enhances the understanding of interactions between former mining operations and environmental factors.

The authors propose to integrate following steps in to the Romanian National Exploration Program (RNEP):

### 3.1 Site Investigation

Identification and delineation **of all historical mining perimeters** using historical maps, satellite imagery, and field reconnaissance; Inventory of abandoned mining infrastructure, including tailings ponds, waste dumps, galleries, and processing facilities GPS/GNSS surveying of critical environmental features and contaminated zones; Collection of soil, sediment, surface water, and mine water samples for laboratory analysis: In-situ measurements of pH, electrical conductivity (EC), temperature, dissolved oxygen, and redox potential; Field assessment of acid mine drainage occurrences and visible contamination pathways; Visual inspection of slope instability, erosion processes, and tailings dam conditions; Documentation of vegetation stress, barren surfaces, and land degradation indicators UAV/drone reconnaissance for high-resolution orthophoto generation and terrain inspection; Mapping of drainage channels, seepage zones, and hydrological connectivity around mining sites; Identification of potential heavy metal dispersion routes toward rivers and settlements; **Geological and geomorphological characterization of mining-affected areas**; Collection of geotagged photographs and field observations for GIS integration; Verification of land use and land cover classes identified from remote sensing analysis; Identification of environmentally sensitive receptors, including agricultural land, forests, and water bodies; Assessment of anthropogenic pressures and ongoing informal mining-related activities; Integration of field observations into a GIS geodatabase for subsequent spatial analysis; Establishment of baseline environmental conditions for long-term monitoring; Selection of representative control points and monitoring stations for temporal analysis, and Preliminary evaluation of environmental risk associated with abandoned mining structures

### 3.2 GIS Database

The proposed GIS database will be tailored as follows:

Table 1. Components and description of the proposed data base

| Component                       | Description                                                    |
|---------------------------------|----------------------------------------------------------------|
| Coordinate Reference System     | Standard projection system for all datasets EPSG3844           |
| Administrative Boundaries       | Country, county, municipality, concession limits               |
| Topographic Maps                | Elevation contours, terrain features                           |
| Digital Elevation Model (DEM)   | Terrain elevation for slope and drainage analysis              |
| Orthophotos / Satellite Imagery | Current and historical imagery                                 |
| Land Use / Land Cover           | Forests, agriculture, urban areas                              |
| Geological Maps                 | Lithology, faults, structural geology                          |
| Soil Maps                       | Soil type, permeability, erosion susceptibility                |
| Hydrography                     | Rivers, streams, lakes, groundwater features                   |
| Transportation Network          | Roads, railways, access routes                                 |
| Climate Data                    | Rainfall, temperature, wind, evaporation of the monitored site |

The tailing ponds and waste dumps components will be spitted as follows:

Table 2. Tailing pond components in the GIS data base

| Layer                      | Geometry Type | Key Attributes                        |
|----------------------------|---------------|---------------------------------------|
| Tailings Pond Boundary     | Polygon       | ID, name, operator, status            |
| Embankments / Dams         | Line/Polygon  | height, material, construction method |
| Decant Structures          | Point         | type, capacity, condition             |
| Spillways                  | Line          | discharge capacity                    |
| Pipelines                  | Line          | diameter, material, flow              |
| Pump Stations              | Point         | capacity, operational status          |
| Monitoring Stations        | Point         | sensor type, installation date        |
| Seepage Collection Systems | Line/Point    | flow rate, maintenance                |

Also, the operational information will be included in the monitoring assessment of the tailing ponds in the Romanian National Exploration Program (RNEP) starting the Northwestern part of Romania:

*Table 3. Tailing pond characteristics used / proposed for the RNEP*

| <b>Dataset</b>            | <b>Example Fields</b>              |
|---------------------------|------------------------------------|
| Tailings Characteristics  | grain size, density, moisture      |
| Deposition Records        | deposition date, volume            |
| Water Balance             | inflow, evaporation, discharge     |
| Freeboard Measurements    | design vs actual freeboard         |
| Storage Capacity          | current volume, remaining capacity |
| Dam Construction Method   | upstream/downstream/centerline     |
| Stability Classification  | risk category                      |
| Distance to Nature 2000   | Distance in km                     |
| Mineralogical composition | Symbols of the minerals            |

In relation to the Environmental Monitoring the authors propose the following table 4:

*Table 4. Tailing pond environmental monitoring characteristics*

| <b>Layer/Table</b>       | <b>Parameters</b>                                                     |
|--------------------------|-----------------------------------------------------------------------|
| Surface Water Monitoring | pH, TSS- Total Suspended Solids, heavy metals                         |
| Groundwater Wells        | water table, contaminants                                             |
| Air Quality Stations     | PM10, PM2,5 dust concentration, mineralogical composition of the dust |
| Soil Sampling Points     | contamination levels                                                  |
| Vegetation Monitoring    | NDVI, rehabilitation progress                                         |
| Seepage Monitoring       | seepage rate, chemistry                                               |

The waste dump components could be separated in the GIS data base as follows:

*Table 5. Waste dumps GIS components - Physical Structure Layers*

| <b>Layer</b>         | <b>Geometry</b> | <b>Attributes</b>        |
|----------------------|-----------------|--------------------------|
| Waste Dump Footprint | Polygon         | ID, area, volume, height |
| Benches / Terraces   | Line/Polygon    | width, slope angle       |
| Drainage Channels    | Line            | condition, capacity      |
| Toe Berms            | Line            | dimensions               |
| Retaining Structures | Polygon         | material, stability      |
| Access Roads         | Line            | condition                |

The parameter of the geotechnical information are critical for the waste dumps aswell as for the tailing ponds, here are highlighted in a common approach:

*Table 6. Geotechnical Data for waste dumps/tailing ponds*

| <b>Dataset</b>         | <b>Parameters</b>                                                                      |
|------------------------|----------------------------------------------------------------------------------------|
| Slope Stability Zones  | factor of safety – Numerical simulations results out of FLAC2D, FLAC3D, UDEC2D, 3DEC   |
| Failure History        | landslides, erosion events                                                             |
| Material Properties    | cohesion, friction angle, density, needed for the numerical assesment                  |
| Settlement Monitoring  | displacement rates, displacements out of numerical simulations, on ground measurements |
| InSAR Deformation      | subsidence, movement                                                                   |
| Geotechnical Boreholes | stratigraphy, groundwater                                                              |

Do the fact that the Hydrology & Drainage Components are critical for both type of mining storages, the data table will include:

*Table 7. Hydrology & Drainage Components for waste dumps and tailing ponds*

| <b>Component</b>          | <b>Purpose</b>                  |
|---------------------------|---------------------------------|
| Catchment Boundaries      | runoff modeling                 |
| Flow Direction            | drainage analysis               |
| Flow Accumulation         | erosion risk                    |
| Flood Zones               | inundation assessment           |
| Stormwater Infrastructure | culverts, channels              |
| Sedimentation Ponds       | sediment control                |
| Groundwater Flow Model    | seepage pathways                |
| Inundability results      | Based on ArcGIS Pro simulations |

For the Risk & Hazard Assessment Layers it is important to mention that the results will flow in as open data information to the Municipalities and Territorial Administrative Offices, and Environment Agency based on the Table 8:

*Table 8. Risk & Hazard Assessment Layers and maps*

| <b>Layer</b>                | <b>Description</b>                |
|-----------------------------|-----------------------------------|
| Dam Breach Inundation Zones | downstream impact areas           |
| Erosion Susceptibility      | high-risk slopes                  |
| Seismic Hazard Zones        | earthquake risk                   |
| Flood Hazard Areas          | extreme rainfall impacts          |
| Contamination Plumes        | groundwater/surface contamination |
| Human Exposure Zones        | nearby settlements/infrastructure |
| Emergency Response Routes   | evacuation planning               |
| <b>Natura 2000 Zones</b>    | <b>Biodiversity protection</b>    |

To prepare the involved costs for the monitoring of the former mining perimeters, the authors propose to use the so called amount saved by the former mining companies as “general budget” to populate the data base as highlighted for the future assessment of the next waste dumps and tailing ponds created.

A strong GIS for mining waste facilities will include temporal monitoring using the new technologies like remote sensing data, hyperspectral data, thermal data.

*Table 9. Monitoring & Time-Series Database*

| <b>Dataset</b>         | <b>Frequency</b>  |
|------------------------|-------------------|
| Drone Surveys          | monthly/quarterly |
| LiDAR Surveys          | annual            |
| Satellite Monitoring   | weekly/monthly    |
| Piezometer Readings    | daily/hourly      |
| Weather Stations       | real-time         |
| Water Quality Sampling | monthly           |
| Deformation Sensors    | real-time         |

The Remote Sensing Components would include inspections as follows:

*Table 10. Remote Sensing Components proposed for RNEP*

| <b>Data Type</b>      | <b>Use</b>                 |
|-----------------------|----------------------------|
| UAV/Drone Imagery     | high-resolution inspection |
| LiDAR                 | precise topography         |
| Multispectral Imagery | vegetation stress          |
| Thermal Imagery       | seepage detection          |
| SAR/InSAR             | deformation monitoring     |

The Attribute Database Structure with typical core tables will be needed to be developed under a Romanian National Consortia (National Authorities, National Institutes, Universities, Research Institutes, Local Authorities, SMEs with legal base in Romania).

*Table 11. Attributes of the database structure for a Romanian National Consortia*

| <b>Table Name</b>   | <b>Purpose</b>       |
|---------------------|----------------------|
| Facilities          | master inventory     |
| Inspections         | inspection records   |
| Monitoring_Results  | environmental data   |
| Geotechnical_Data   | borehole/lab results |
| Maintenance_Records | repairs              |
| Incidents           | spills/failures      |
| Compliance          | permits/audits       |
| Rehabilitation      | closure progress     |

Of course, the Metadata & Data Governance it is essential for regulatory compliance, therefor the authors propose the Table 12 as example of metada exchanges between national and international other data bases.

Table 12. Metadata & Data Governance

| Component             | Description            |
|-----------------------|------------------------|
| Metadata Records      | source, accuracy, date |
| QA/QC Logs            | validation procedures  |
| Version Control       | edit tracking          |
| User Permissions      | access management      |
| Data Standards        | naming conventions     |
| Regulatory References | compliance linkage     |

This framework aligns well with the monitoring works on **Ilba**, **Bozânta Mare**, **Baia Mare**, and other perimeters in the Northwestern part of Romania, and can serve as a robust methodological backbone for GIS based decisions.

For Advanced Components (Recommended) and for modern mine waste assessment, the authors propose:

Table 13. Advanced Feature and benefits for the environment, population and mining perimeters

| Advanced Feature           | Benefit               |
|----------------------------|-----------------------|
| Real-time IoT Sensors      | live monitoring       |
| Digital Twin Models        | predictive analysis   |
| AI-based Failure Detection | early warning         |
| WebGIS Dashboards          | operational awareness |
| Mobile Field Apps          | inspection collection |
| 3D GIS                     | volumetric analysis   |
| Machine Learning           | risk prediction       |

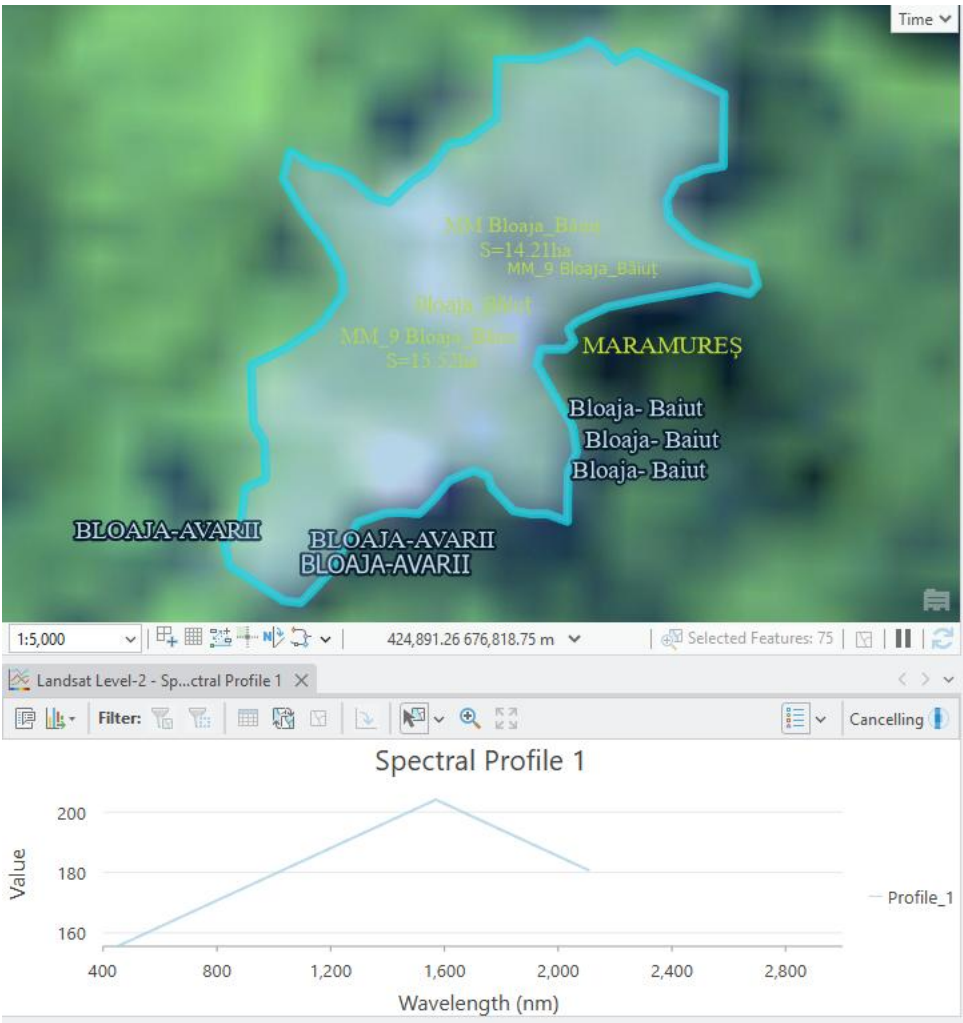


Fig. 7. Landsat-Level 2 B7, B6 and B2 with the spectral profile of Bloaja between 400 and 2100nm

Using the created database, the economical assessment of those waste dumps and tailing ponds (around 300 in the database of UTCN) will be possible by combining the existing information with the metal price listet on the stock exchange (e.g. definitive closing or recovering of the useful metal).

Another important advancement is represented by the development of centralized cloud databases and interactive digital dashboards that provide real-time access to environmental indicators, monitoring results, and spatial analyses. This improves communication between researchers/universities, national institutes, authorities, environmental agencies, and mining stakeholders while supporting transparent and data-driven decision-making processes.

The proposed framework additionally supports long-term environmental rehabilitation planning by integrating historical mining data, remote sensing time series, climate-related variables, and field validation measurements into a unified spatial platform. Such integration enhances the capacity to simulate future environmental scenarios, prioritize remediation measures, and optimize monitoring activities across complex post-mining landscapes.

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