



Policy Brief

Multi-Scale and Multi-Source Innovations for Sustainable Mineral Exploration, Mining Safety and Environmental Monitoring in Europe

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Introduction

Ensuring secure, sustainable, and resilient access to raw materials remains a strategic priority for the European Union. The Critical Raw Materials Act (CRMA) provides a policy framework to reduce dependencies, strengthen domestic capacities, and improve sustainability, monitoring, and innovation across the raw materials value chain. Achieving these objectives requires operational, data-driven solutions that support mineral exploration and extraction, and safety and environmental monitoring of mining operations.

Earth Observation (EO) and Machine Learning (ML) feature among the most promising technological enablers in this context. EO provides continuous information on geology, land use, environmental conditions and ground stability, while ML supports the extraction of practical insights from large and heterogeneous datasets. Combined EO and ML approaches can reduce uncertainty and cost in mineral exploration, improve environmental performance, strengthen operational safety and support better informed decision-making.

The MultiMiner project developed and demonstrated EO and ML solutions to support the detection of currently underexplored critical raw material (CRM) resources in Europe, enhance monitoring of mining operations, safety risks and environmental impacts, and ensure that data and knowledge generated remain accessible for future use. Tested across five demonstration sites in Finland, Austria and Greece, these technological building blocks can help public and private actors move from fragmented, site-specific practices towards more systematic, interoperable, multi-source and multi-scale approaches. This is particularly relevant for implementation of the Critical Raw Materials Act, but also for broader EU priorities related to strategic autonomy, environmental protection, digitalisation and responsible resource development.

This policy brief presents the main MultiMiner results, outlines the project's exploitation roadmap, and highlights policy recommendations to support the wider uptake of these innovations by mining companies, geological surveys, public authorities, EO service providers and other stakeholders across Europe.



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MultiMiner results at a glance

The MultiMiner results form a modular ecosystem of EO and ML solutions that can be deployed as standalone tools or integrated into larger operational platforms and digital mining environments.

Mineral exploration

MultiMiner developed several tools and datasets to support critical raw materials exploration from regional screening to site-specific interpretation:



Mineral Mapper: AI and ML based mineral mapping algorithms for automated identification of minerals from satellite and airborne data, improving accuracy, versatility and repeatability of mineral mapping workflows, increasing efficiency of critical raw material exploration efforts.



Dedicated CRM Spectral Library: a specialised spectral database built from field and laboratory measurements, complemented by AI-generated synthetic spectra and associated mineralogical and chemical metadata supporting more precise detection and identification of critical minerals.



Mineral Prospectivity Wizard: a user-oriented decision support tool translating complex EO-derived outputs into prospectivity maps for exploration geologists, helping prioritise areas with high potential for CRM deposits, streamlining exploration planning and reducing fieldwork.



Multiscale interpretation workflows: semi-automated workflows combining EO data, geological information and expert knowledge to improve transparency, reproducibility and added value of prospectivity assessments.

Environmental and safety monitoring

MultiMiner developed methods for continuous environmental and safety monitoring across mining sites, to support early warning, better risk assessment, and more systematic observation of environmental impacts:



Generic Mine Site Monitoring (GMSM): a novel and flexible framework capable of ingesting multi-sensor data across varying spatial, spectral and temporal resolutions for continuous mine site monitoring and supporting environmentally sustainable mining practices.



Plant diversity estimation: EO time-series based methods for estimating plant diversity and supporting baseline assessment and post-rehabilitation monitoring.



Ground moisture monitoring: SAR-based modelling workflows to retrieve near-surface ground moisture and support seepage detection around tailings storage facilities and dams.



Water quality and Acid Mine Drainage monitoring: Sentinel-2 based algorithms supporting early warning of pollution and larger-scale assessment than traditional airborne methods.



Atmospheric and surface dust monitoring: scalable methods combining air quality products with multispectral EO data to map and differentiate dust sources.



Tailings Storage Facility mapping: workflows combining UAV, hyperspectral, photogrammetric and in-situ data to assess mineral composition, spatial distribution and rehabilitation needs.



Open pit and dam stability monitoring: algorithms and derived maps to support stability assessment and early detection of hazardous deformations.

Cross-cutting outputs

In addition to these technical outputs, MultiMiner produced harmonised fieldwork instructions, a metadata database, accuracy assessment protocols, open-access publications and training materials. One commercial application was also developed in the context of the project, a drone-borne multi-frequency electromagnetic GEM-2 measurement service for seepage detection in difficult-to-access environments.

The MultiMiner exploitation roadmap

The MultiMiner Roadmap on Exploitation Opportunities outlines how the project results can be sustained and further developed after the end of the funded period. It presents exploitation as a combination of open-source software and algorithms, open-access datasets and derived maps, demonstrations and validation at test sites, follow-up research and innovation activities, synergies with sister projects, integration into existing European platforms and initiatives, contribution to EU standardisation and harmonisation efforts, service-oriented commercial applications, and training and capacity-building resources.

Short term priorities (0 to 1 year)

Immediate exploitation efforts will focus on reducing barriers to adoption and increase the visibility, accessibility, and credibility of MultiMiner results. The priority will be to integrate the project outputs into widely used platforms, supporting EO-based approaches with additional in-situ measurements and sensor networks, and carrying out additional demonstrations and validation activities. The dissemination of open-source and open-access resources will support transparency, maintainability, community-driven improvement and the integration of MultiMiner outputs into academic training and capacity-building activities. Collaboration with existing partners, EO value-adding companies, and related projects will be pursued to increase potential for further development.

Mid-term priorities (1 to 3 years)

After the initial uptake, the emphasis shifts to consolidation, scalability and transition to more systematic operational deployment and towards predictive monitoring assessments. This includes maintaining compatibility of open-source components with evolving EO platforms and data ecosystems, supporting EU-level harmonisation and standardisation efforts, and supporting the integration of super-resolution approaches, shared training datasets and multi-sensor workflows. The roadmap also highlights the growing importance of training, professional courses and engagement with other European-level initiatives to enable a wider adoption of EO- and ML-based innovations.

Long term priorities (beyond 3 years)

Eventually, the multi-source and multi-scale approaches developed by MultiMiner should be integrated into European geoinformation, monitoring and digital mining ecosystems. The project outputs would feed into European interoperable digital infrastructures, supported by the development of digital twins of mining environments integrating surface and subsurface information and upcoming hyperspectral and dual-use satellite constellations for continuous monitoring. In this context, EO-based environmental and safety monitoring should be promoted as standard practice to increase transparency and accountability of mining operations across Europe.

Main barriers to adoption

The adoption of MultiMiner results depends not only on technical maturity and additional developments, but also on the policy, regulatory and operational conditions that enable adoption across the European critical raw materials sector. Indeed, the project identified a range of institutional, regulatory and operational constraints that continue to limit adoption of EO and ML solutions in the critical raw material sector, through targeted consultations with other EU-funded projects and representative from various end-user and stakeholder groups.

Such challenges have been described in a joint policy brief with the European Sustainable Mining and Innovation Network (ESMIN), including the limited awareness of EO capabilities, insufficient knowledge transfer, dependence on in-situ reference data for calibration and validation, high cost and uneven accessibility of high-resolution EO data, fragmented regulation for UAV-based operations, and the absence of harmonised standards for data quality, validation and interpretability. Without clear regulatory frameworks, end-users, mining operators and authorities have fewer incentives to invest in these EO- and ML-based approaches.

Policy recommendations

MultiMiner has demonstrated that EO- and ML-based approaches can improve mineral exploration, mine safety and environmental monitoring, but their wider deployment will require stronger support for interoperable data infrastructures, validation environments, regulatory recognition, skills development and trusted governance mechanisms. In that respect, MultiMiner identified five policy priorities emerge for the increased uptake of its results and other related EO- and ML-based innovations in Europe.

Strengthen access to interoperable digital infrastructures for EO- and ML-based mining applications

European and national actors should support the integration of EO- and ML-based project outputs into widely used cloud-based EO, geospatial and digital mining platforms in order to reduce entry barriers and facilitate operational testing by end-users. This includes algorithms, workflows, datasets, derived maps and decision-support tools developed through EU-funded research and innovation actions.

Such support should also extend to trusted repositories, open-access infrastructures, FAIR data practices and persistent identifiers, so that project results remain accessible, reusable and interoperable beyond the lifetime of individual projects. In the longer term, these efforts should contribute to broader European geoinformation and digital mining infrastructures capable of hosting and connecting exploration, environmental and safety monitoring outputs at scale.

Improve data availability, interoperability and reference data for validation

The deployment of EO- and ML-based methods in the raw materials sector depends on access to robust, well-structured and interoperable data. Policy support should therefore strengthen storage, querying and processing capacities for exploration and monitoring datasets, while also facilitating access to representative in-situ reference data needed for calibration, validation and uncertainty assessment.

This is particularly important for applications such as prospectivity mapping, ground moisture retrieval, water quality monitoring, dust analysis and stability assessment, where the quality and comparability of outputs depend on well-documented data inputs and validation practices. Improving data interoperability across EO, geophysical and operational datasets would also support smoother integration of project results into existing industrial and public-sector workflows.

Establish validation environments, common standards and progressive regulatory recognition

A central barrier to adoption is the gap between technical readiness and institutional acceptance. To address this, policy frameworks should support representative testbeds, living labs and pilot sites where mining operators, SMEs, geological surveys, regulators and research organisations can validate EO- and drone-enabled workflows under realistic operational conditions.

In parallel, a common European validation and quality assurance framework should be developed on EO product requirements, model validation, uncertainty reporting, auditability and minimum quality standards for applications in mineral exploration, mine safety and environmental monitoring in order to build trust and reduce fragmentation across Member States. Over time, these efforts should support the gradual recognition of validated EO- and ML-derived evidence in permitting, environmental reporting, mine closure assessment and post-mining governance.

Invest in skills, training and knowledge transfer across the critical raw materials sector

The wider use of MultiMiner results will require stronger capabilities among regulators, industry actors, EO service providers and technical experts. Policy action should therefore support targeted training and knowledge exchange activities that demonstrate the operational relevance of EO and ML methods in concrete mining and exploration contexts.

This should include shared case studies, reference datasets, professional courses, academic modules and capacity-building materials that help users understand both the potential and the limitations of EO- and ML-based approaches. Strengthening these capabilities is essential not only to improve uptake, but also to increase trust in digital tools, enhance internal expertise and reduce dependence on fragmented external support.

Promote secure, transparent and predictive digital mine monitoring

European policy should support the transition from fragmented and largely reactive mining site monitoring practices towards integrated, predictive and transparent digital mine monitoring systems. This includes the combination of EO, in-situ and subsurface information in digital mine representations and, where relevant, future digital twins capable of supporting better environmental and safety management over time.

To enable this transition, secure and interoperable data governance frameworks will be needed, especially where sensitive industrial or environmental information is concerned. At the same time, better access to relevant environmental information for public authorities, civil society and local stakeholders would strengthen transparency, accountability and trust in mining activities. These conditions are important for the responsible deployment of digital monitoring solutions across the European critical raw materials sector.

Conclusion

MultiMiner shows that EO- and ML-based innovations can provide practical support for critical raw materials exploration, environmental monitoring and mine safety across Europe. The project has developed innovative tools, workflows, datasets and methods that are already relevant for geological surveys, mining companies, public authorities, EO service providers and research actors. It has also demonstrated that open science, validation at demonstration sites and collaboration with related European initiatives can create strong foundations for long-term uptake.

At the same time, wider adoption will depend on more than scientific research and technical developments alone. Stronger digital infrastructures, improved access to interoperable and validated data, clearer quality standards, targeted skills development and a more enabling regulatory environment are all necessary to translate research outputs into operational products and services. Without these enabling conditions, EO- and ML-based innovations are likely to remain underused despite their demonstrated potential.

Supporting the uptake of MultiMiner results would therefore contribute not only to the legacy of one Horizon Europe projects, but also to broader European objectives under the Critical Raw Materials Act and related policy agendas. By enabling more efficient exploration, safer mining operations, stronger environmental oversight and better-informed decision-making, MultiMiner provides concrete building blocks for a more resilient, sustainable and transparent critical raw materials sector in Europe.

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The Policy Brief was prepared by the MultiMiner project.

More information

MultiMiner: www.multiminer.eu

Citation

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- [ESMIN Policy Brief: Leveraging Earth Observation and Machine Learning to Address Critical Raw Material Challenges in the EU](#)
- [European Critical Raw Material Act](#)

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