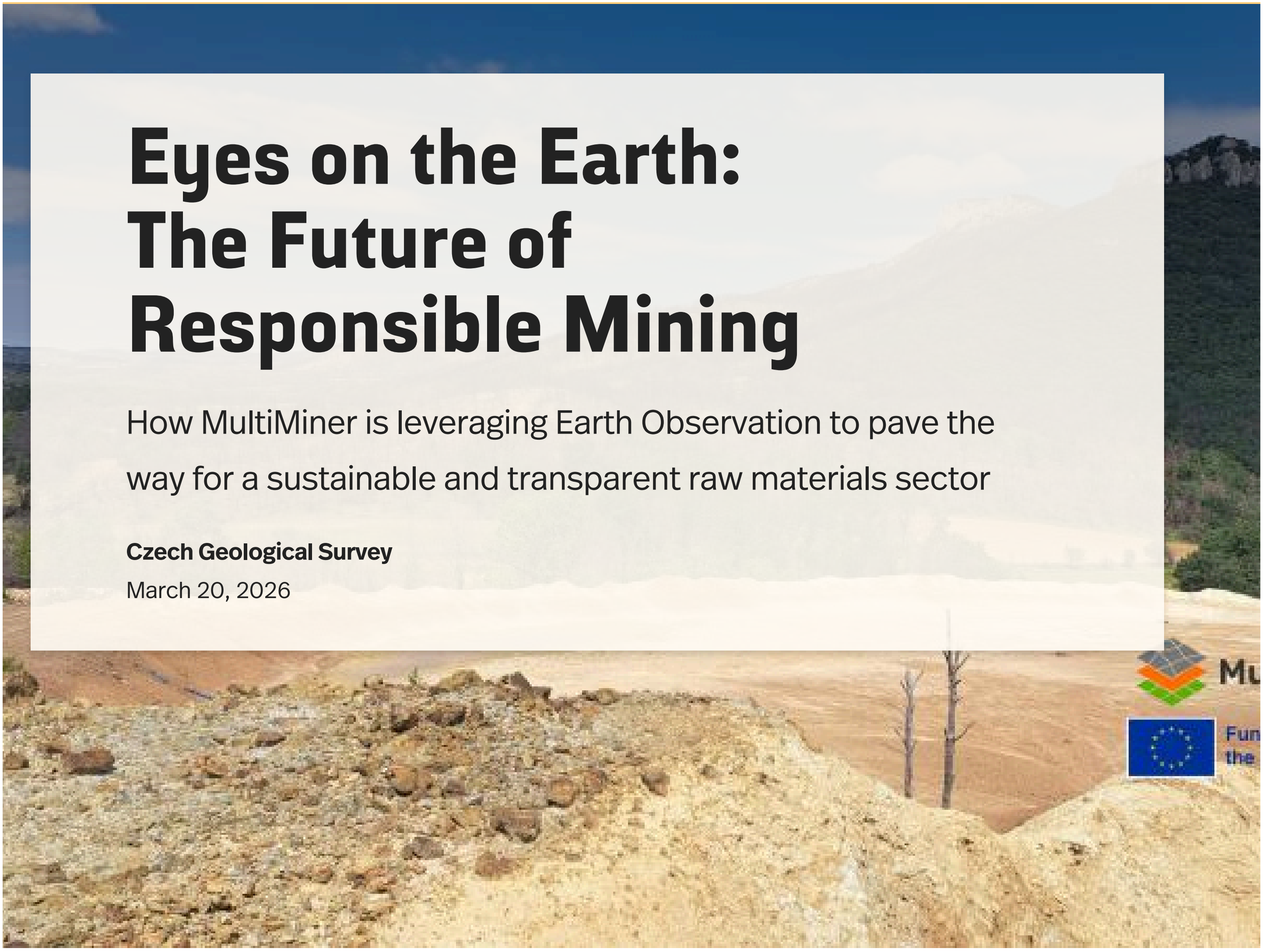

Eyes on the Earth: The Future of Responsible Mining

How MultiMiner is leveraging Earth Observation to pave the way for a sustainable and transparent raw materials sector

Czech Geological Survey

March 20, 2026

Introducing MultiMiner

The **MultiMiner** project is a pan-European initiative funded by the **European Union’s Horizon Europe** programme (2023–2026). It brings together a consortium of 12 partners—including geological surveys, research institutes, and industry leaders like Hellas Gold and Nordkalk—to revolutionize how we find and monitor the minerals that power our modern world.

The project’s mission is twofold: to strengthen Europe’s strategic autonomy by discovering new sources of Critical Raw Materials (CRM) and to ensure that mining operations are as transparent and environmentally sound as possible. By "unlocking" the vast potential of EO data—ranging from Copernicus Sentinel satellites to high-altitude aircraft and low-flying drones—MultiMiner provides a digital shield for the environment throughout the entire mining life cycle.

What sets MultiMiner apart is its commitment to low-impact exploration. By utilizing advanced, non-invasive sensors and innovative machine learning, the project reduces the need for disruptive ground-based drilling during the early stages of exploration. From the subarctic quarries of Finland to the ancient mineral veins of Greece, MultiMiner is paving the way for a sustainable, carbon-neutral economy that respects the land it harvests.

MultiMiner: Breakthrough Tools for Smarter Mineral Exploration

MultiMiner_EU

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MultiMiner: Breakthrough Tools for Smarter Mineral Exploration

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The MultiMiner Framework

Multi-Source & Multi-Scale Monitoring

The modern challenge of raw material extraction lies in balancing the global demand for minerals with the necessity of environmental preservation. The **MultiMiner project** meets this challenge by redefining how we observe the Earth. Traditionally, environmental monitoring and mineral exploration relied on sporadic ground measurements or low-resolution satellite imagery. MultiMiner breaks these barriers by implementing a **Multi Source and Multi Scale Earth Observation** framework that synchronizes data from the edge of space to the microscopic level of a mineral grain.

Bridging the Scales: From In-Situ to Space

Our methodology functions as a data hierarchy, where each level informs the next:

In-situ Ground Truth: At the base of our hierarchy are physical samples and field sensors. By collecting water chemistry, mineral geochemistry, and real-time particulate matter data, we provide the ground truth that validates every pixel captured from above.

Airborne & UAV Platforms: To bridge the gap between space and ground, we employ drones equipped with hyperspectral sensors. These platforms provide the close range sensing—capturing centimeter-scale details that satellites miss, such as specific mineral precipitates in a stream or localized dust plumes from a haul road.

Satellite Constellations: We leverage the high-revisit capabilities of Copernicus Sentinel missions and high-resolution commercial satellites. These provide the "Big Picture," allowing for regional surveillance of dust patterns, vegetation health, and large-scale geological patterns.

The Power of Novel Machine Learning

The true innovation of MultiMiner is not just in collecting data, but in how we interpret it. The project develops novel Machine Learning (ML) solutions specifically designed to handle the "Big Data" of the mining life cycle.

A primary barrier in traditional remote sensing is the need for massive "ground truth" datasets—which are expensive and time-consuming to collect. MultiMiner overcomes this by focusing on **unsupervised and weakly-supervised learning algorithms**. These AI tools are trained to recognize complex patterns with minimal human labeling. Whether it is identifying the subtle spectral signature of a Critical Raw Material (CRM) or forecasting a spike in PM10 dust levels, our ML architecture transforms raw data into actionable environmental intelligence.

A Transparent Mine Life Cycle

By integrating these technologies, MultiMiner supports every stage of the mining journey:

1. **Exploration:** Low-impact, satellite-based detection of new mineral sources to strengthen EU resource autonomy.
2. **Operational Monitoring:** Real-time tracking of water quality and air dust to ensure immediate response to environmental shifts.
3. **Closure & Rehabilitation:** Long-term satellite surveillance to ensure that once a mine closes, the land successfully returns to a stable, healthy ecosystem.

> *Through this integrated approach, we are increasing the transparency of the mining industry, ensuring that operations are not only economically efficient but also socially acceptable and environmentally sound.*

Multiminer project partners involved in activities.

The MultiMiner project is funded by the European Union's Horizon Europe research and innovation actions programme under Grant Agreement No. 10109137474

Research Locations


Haskovo
Kardzhali
Smolyan
Kırklareli
Rhodope Mountain Range National Park
Luleburgaz
Kirki (Agios Philippos Mine)
Drama
Xanthi
Komotini
East Macedonia
Tekirdag
Kavala
Edirne
Gelibolu
Biga
Gönen
Çan
Esri | TomTom | Garmin | FAO | NOAA | USGS
20 mi
Powered by Esri

1 Kirki (Agios Philippos Mine)

Located in the hilly terrain of the Thrace region in Northeastern Greece, the Kirki site is a complex polymetallic vein- and breccia-type deposit hosted within Tertiary volcanic and sedimentary rocks. Geologically, the area is defined by a high concentration of sulfides–specifically pyrite, galena, and sphalerite–which makes it a significant source of environmental concern. From a mining perspective, Kirki is a legacy site where historical extraction of Lead and Zinc has left behind open pits and waste rock piles that now generate severe acid mine drainage (AMD). The interaction between these sulfide-rich rocks and the local stream network creates a highly acidic environment, characterized by low pH levels and high dissolved metal content, serving as a critical study area for mineral-water chemical interactions.

2 Kassandra Mining District (Chalkidiki)

Situated on the Chalkidiki Peninsula of Northern Greece, the Chalkidiki district is set within a topographically diverse landscape of steep slopes and coastal valleys. It is geologically part of the Serbo-Macedonian Massif, featuring world-class "Kassandra-type" deposits that include gold-copper porphyries and carbonate-replacement skarns rich in gold, silver, lead, and zinc. As a major active mining hub, the area hosts several large-scale underground and open-pit operations, such as the Olympias and Stratoni mines. Mining here is technically demanding, requiring a sophisticated balance between high-volume mineral production and the environmental protection of sensitive Mediterranean ecosystems, with a specific focus on monitoring both the local watershed and air quality for industrial dust.

3 Ihalainen (Lappeenranta)

The Ihalainen site is located in Southeast Finland, uniquely integrated into the urban and industrial landscape of the city of Lappeenranta near Lake Saimaa. Ihalainen is hosted within the Svecofennian domain and is characterized by massive Proterozoic calcite and dolomite marble deposits embedded in high-grade metamorphic rocks. The site operates as a large-scale, active open-pit quarry dedicated to the extraction of high-quality limestone for the paper and construction industries. Because of its proximity to residential areas, the mining operations are at the center of atmospheric research, specifically focusing on the management of "spring dust" (PM10) and the use of satellite data to ensure air quality standards in a northern, subarctic climate.

The Technology Behind the Data

From autonomous aerial surveys to specialized ground-based sensors, this gallery showcases the full technical arsenal utilized for high-resolution data acquisition and field validation.

When Mines Meet Water

Water quality monitoring is a critical responsibility for the mining sector. Mining operations of all kinds can significantly impact local water resources through **sediment loading, metal leaching, and changes to hydrological regimes**. Regular, reliable monitoring is essential for ensuring compliance with environmental regulations, enabling early detection of contamination, and supporting informed management decisions. Yet traditional approaches – **point-based field sampling followed by laboratory analysis** – are labor-intensive, costly, and spatially limited, providing only a fragmentary picture of water quality dynamics across complex catchments.

The Multiminer project addresses this challenge across two contrasting mining districts in Greece. At **Kirki in the northeast**, an abandoned polymetallic sulfide mine – active from as early as 1880 until the late 1990s – has left behind an **acidic open-pit lake (pH as low as 1–2)**, extensive sulfide-rich tailings, and no post-closure remediation, making it a textbook AMD environment. At **Chalkidiki in northern Greece**, three active mines operate within a sensitive coastal setting where **continuous surface water quality surveillance** is required to protect downstream ecosystems and meet regulatory standards, even in the absence of severe acid drainage. Together, these two sites represent the full spectrum of water quality monitoring challenges faced by the mining industry –

from **legacy contamination to present-day operational oversight** – and provide the testing ground for a new generation of UAV-based spectroscopic monitoring tools developed within the project.

The Acid Chain: How Mining Releases Metals

The chemistry of AMD begins with a deceptively simple reaction: **pyrite reacts with oxygen and water to release ferrous iron and sulfuric acid**. From that starting point, a cascade of secondary processes unfolds. Bacteria accelerate iron oxidation, driving pH down further and enabling the dissolution of metals that would otherwise remain locked in rock. The result is a chemical mixture that can include **iron, arsenic, zinc, copper, lead, cadmium, and manganese** at concentrations exceeding safe limits for aquatic life and human health.

What makes AMD particularly difficult to manage is its **persistence and spatial complexity**. The contamination does not stay where it originates. Acidic waters migrate through the landscape, following surface drainage networks and groundwater pathways, depositing secondary minerals along the way. At Kirki, field measurements confirm **pH values between 1 and 4 in source zones**, with strong acidity and elevated sulfate concentrations persisting along stream corridors for significant distances. Total iron and total sulfur concentrations both **spike below pH 4.5**, reflecting the formation of ferric hydroxides and oxyhydroxysulfates from the oxidizing mine waste. Above pH 5, sulfur drops and iron shifts toward more stable hydroxide forms – a geochemical transition that is visible not just in water chemistry, but in the **yellow, orange, and rust-red mineral deposits** coating streambeds and rock surfaces throughout the affected catchment.

Why Spectroscopy? Decoding Contaminants Through Reflected Light

Conventional water quality monitoring relies on field sampling followed by laboratory analysis – an approach that is accurate but **slow, expensive, and spatially limited**. A sample collected at a single point on a single day captures a snapshot of one location; understanding how contamination varies across an entire catchment, or how it changes through seasons and storm events, requires either an impractically large sampling program or a different kind of tool entirely.

Spectroscopy offers that alternative. **Every mineral, dissolved compound, and suspended particle interacts with light in a characteristic way** – absorbing certain wavelengths, scattering others – producing a spectral fingerprint that encodes chemical information without requiring physical contact with the material. Iron in its various oxidation states absorbs strongly in the blue and ultraviolet regions; sulfate minerals have diagnostic absorption features in the shortwave infrared; silicate frameworks reveal themselves through fundamental molecular vibrations in the thermal infrared.

By measuring the spectrum of reflected or emitted light **across a broad range of wavelengths – from the visible spectrum (350 nm) out to the longwave infrared (15,000+ nm)** – it becomes possible to identify and quantify key AMD-related compounds across continuous spatial transects. Applied from **drones, aircraft, or satellites**, spectroscopy transforms water quality assessment from a labor-intensive point-sampling into a **scalable, repeatable observation** capable of covering entire mining catchments in a single survey – while maintaining the geochemical specificity needed for meaningful environmental assessment.

Secondary Minerals: The Footprints of AMD

The transformation of pyrite under AMD conditions follows a predictable but chemically rich sequence. As iron sulfide oxidizes and acid is generated, **a succession of secondary iron-bearing minerals precipitates out of solution**, each stable within a particular window of pH and redox chemistry. This mineral zonation creates a visible spatial pattern across AMD-affected landscapes – one that spectroscopy is particularly well-suited to detect.

Below pH 4.5, the dominant secondary phases are **jarosite** – a bright yellow crystalline sulfate – and **schwertmannite**, an orange-ochre amorphous iron oxyhydroxysulfate. Together, these minerals form the characteristic staining of AMD source zones: **vivid yellows and oranges coating streambeds and rock surfaces** near acidic pit lakes and tailings piles. As pH rises above approximately 5, these unstable phases transform into **ferrihydrite and goethite**, shifting the color palette toward rust-red and deep brown. Under locally reducing conditions, bacterial sulfate reduction can even produce **secondary sulfides**, partially reversing the oxidation cycle.

This pH-controlled mineral gradient was directly confirmed in Kirki field data: **total sulfur and Fe_2O_3 concentrations both increase sharply below pH 4.5**, while above pH 5, sulfur concentrations drop rapidly and iron shifts to more stable hydroxide forms. Each mineral in this sequence carries its own spectral signature – making the **spatial pattern of AMD severity readable from spectral data** across the visible, shortwave infrared, and thermal infrared.

Beyond Pure Minerals: Spectral Libraries from Real AMD Mixtures

Spectral libraries built from **pure, finely ground mineral powders** are the foundation of remote sensing and geochemical spectroscopy. They provide controlled reference spectra that allow scientists to identify diagnostic absorption features, calibrate algorithms, and build spectral unmixing models. Yet **real-world AMD environments present a different challenge**.

In nature, minerals never occur in isolation. Mine waste surfaces are **intimate mixtures of jarosite, quartz, kaolinite, partially oxidized sulfides, and iron hydroxides**. Grain size, surface coatings, hydration state, and oxidation all distort the spectral signal – shifting absorption band positions, suppressing diagnostic features, and introducing **nonlinear scattering effects** that libraries built from pure minerals cannot predict. The result is **systematic mismatches between field spectra and reference libraries**, degrading the reliability of spectral mapping and quantitative retrievals.

The Multiminer dataset directly addresses this gap. Rather than grinding individual minerals, the team collected and characterized **26 natural AMD surface samples from Kirki** – composite assemblages reflecting the real chemical and physical complexity of mine waste surfaces. Spectral measurements were acquired across the full electromagnetic range: in the field, a Spectral Evolution SR-2500 spectroradiometer with pistol grip captured VNIR–SWIR reflectance spectra from 350–2,500 nm under natural illumination conditions; in the laboratory, the same samples – homogenized and sieved to below 74 μm – were measured by the same instrument using a benchtop probe, followed by the measurement with the MWIR–LWIR range from 2,500 to 15,375 nm using an Agilent 4300 Handheld FTIR spectrometer in diffuse reflectance mode. The two datasets were subsequently merged into a **harmonized spectral library spanning 350–15,375 nm.**

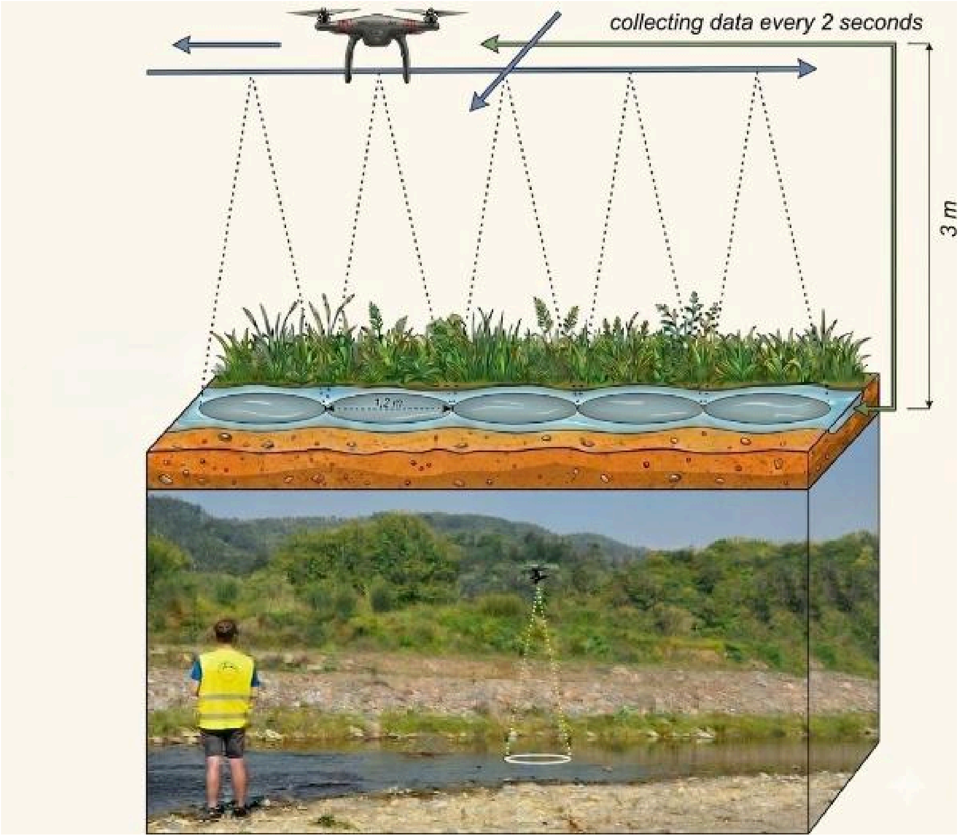
Each sample was analyzed in aboratory testing for mineral and chemical composition to create a comprehensive reference data. Validated through PLSR modeling against these independent chemical measurements, the dataset provides **an open-access spectral library** specifically designed for AMD environments – one that bridges the gap between the idealized world of pure minerals and the chemical complexity of actual mine sites.

Taking Spectroscopy Airborne: UAV-Based Water Monitoring

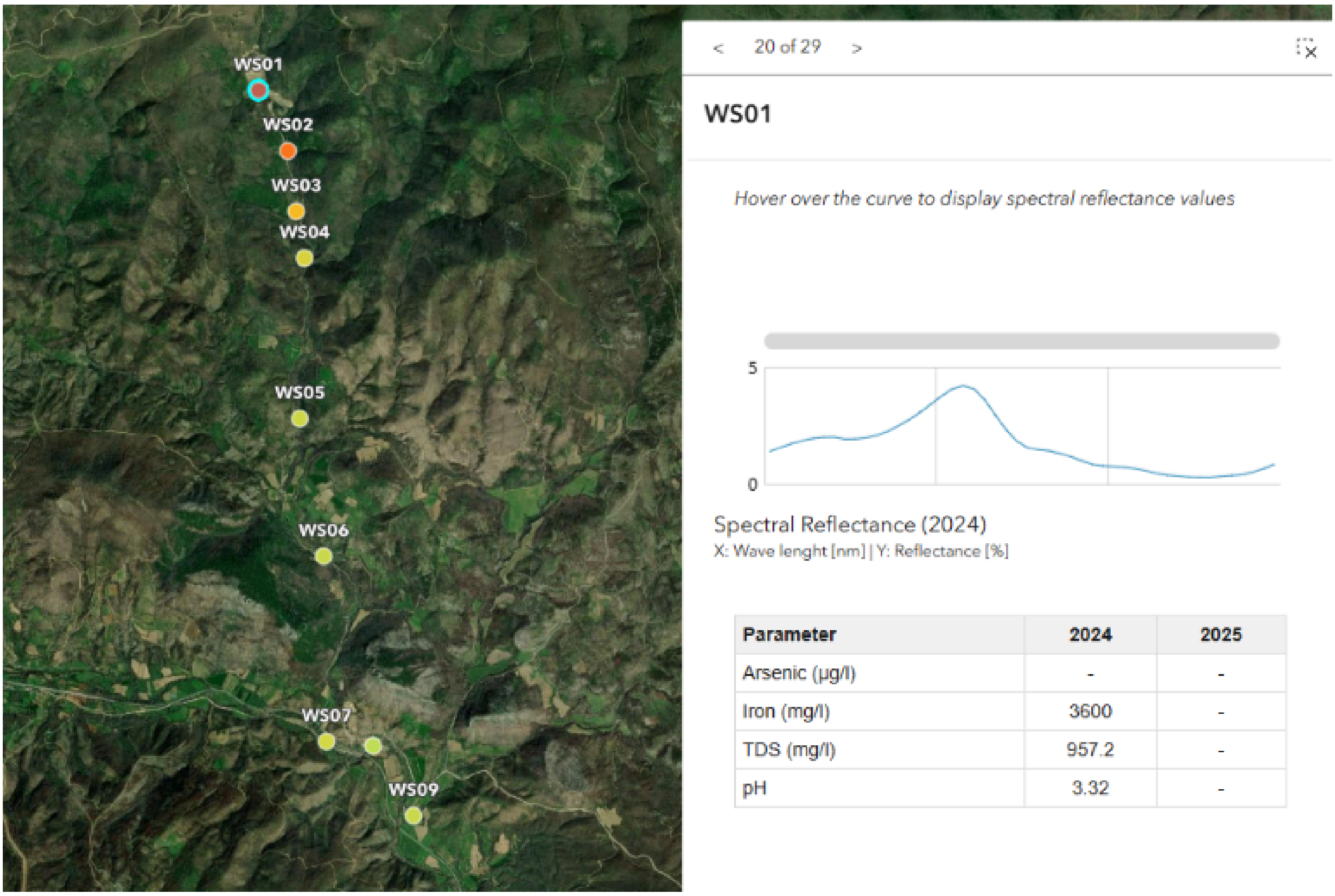
Measuring water quality from a drone offers a practical solution to one of AMD monitoring's most persistent challenges: **safe, repeatable access to contaminated sites**. Highly acidic streams and steep-walled pit lakes are hazardous or physically inaccessible to conventional sampling. A drone-mounted spectrometer **flies above the hazard**, collecting spatially distributed spectral measurements without disturbing the water surface, without exposing personnel to chemical risk, and without the logistical constraints of traditional field campaigns.

The Multiminer team developed and validated a **compact VNIR hyperspectral system covering 337–823 nm** with 1.2 nm spectral resolution, mounted on a commercial drone platform. Flights were conducted at **3 meters altitude**, producing a spatial footprint of approximately 1.2 meters per measurement – fine enough to resolve variability across the narrow streams typical of mining catchments in Kirki and Chalkidiki. Data were collected in **three**

systematic passes at each site: upstream, downstream, and diagonally across the water body.



UAV-based water monitoring scheme



Parameter	2024	2025
Arsenic (µg/l)	-	-
Iron (mg/l)	3600	-
TDS (mg/l)	957.2	-
pH	3.32	-

Mining-Impacted Waters: Geochemistry, Optical Properties, and Field Sampling

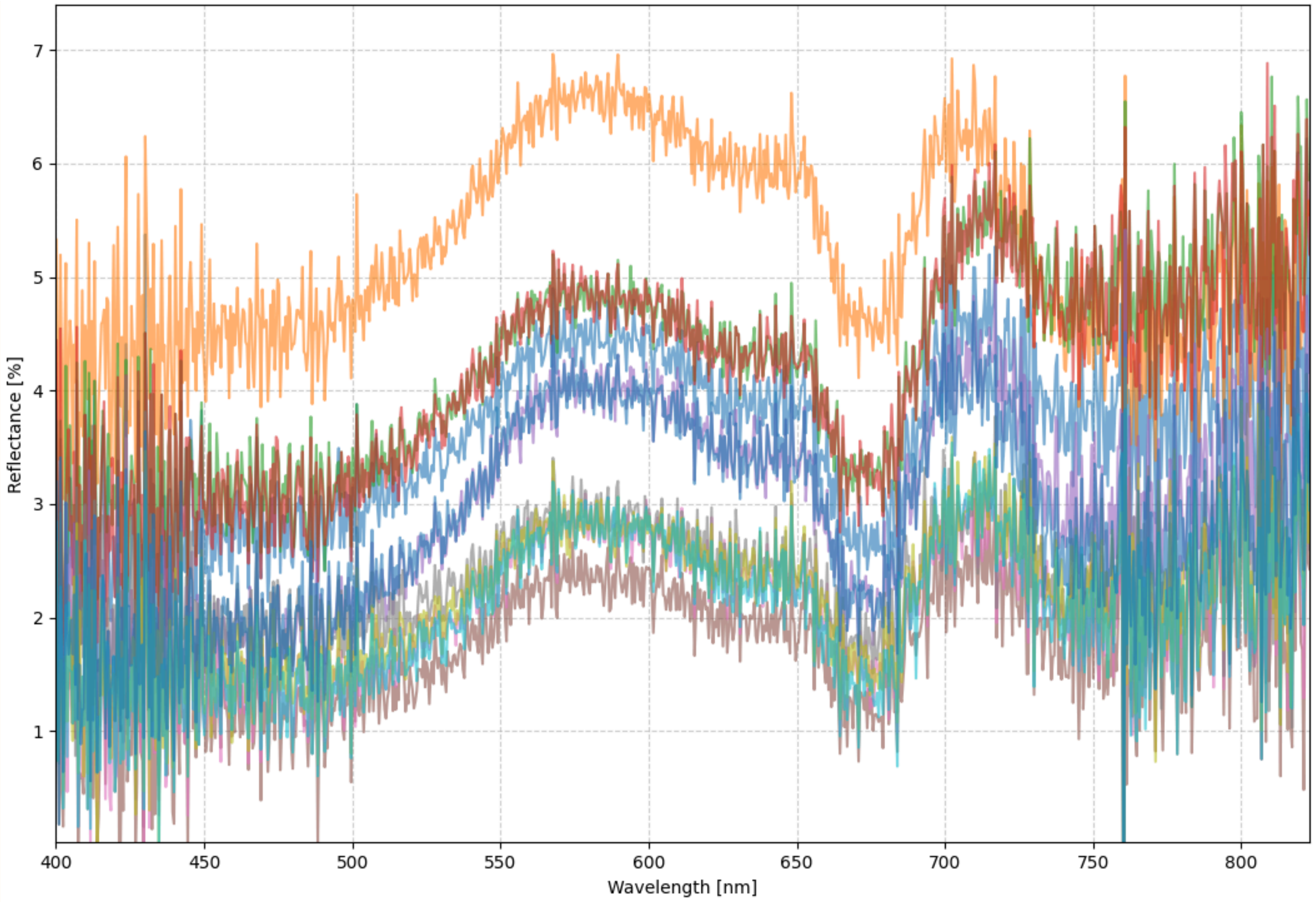
Mining operations affect surrounding water bodies in diverse ways – through **sediment mobilization, metal leaching, changes in pH, and altered hydrological connectivity**. The nature and severity of these impacts varies significantly between sites: while some environments are dominated by **strongly acidic drainage with elevated heavy metal loads**, others are characterized by more subtle changes in **suspended sediment concentrations, turbidity, or trace element budgets** that nonetheless require careful monitoring to meet regulatory standards and protect aquatic ecosystems.

Once contaminants enter the water column, several **optically active constituents** – dissolved iron, suspended particulates, and colloidal precipitates – alter how light is absorbed and scattered, creating spectral signatures detectable from airborne sensors. Key constituents like **dissolved ferric iron** and **total suspended solids (TSS)** create distinct spectral signatures detectable via remote sensing. Iron absorbs strongly in the blue region (400–440 nm), while TSS elevates reflectance in the green and red-edge regions (535–680 nm). While arsenic is spectrally invisible at environmental concentrations, its strong geochemical affinity for iron precipitates and particulate matter allows it to be tracked indirectly. By utilizing iron and TSS as **geochemical proxies**, arsenic distribution can be mapped through established co-transport relationships.

Field Sampling and Data Acquisition

To characterize these relationships, **surface water samples were systematically collected** across both Kirki and Chalkidiki during field campaigns in 2024 and 2025. Samples were collected by hand from accessible stream sites; at hazardous or inaccessible locations a **UAV-borne DROSENS water sampler** was deployed. At each site, **in-situ water quality parameters** were simultaneously recorded. Samples were subsequently analyzed in certified laboratories for **total and dissolved** iron, sulfate, and trace elements (As, Cd, Zn, Pb, Cu). **Simultaneously, surface water reflectance spectra were acquired** using a miniature VNIR spectrometer, producing **co-located spectral and chemical**

datasets at each sampling site – the paired acquisition that makes quantitative spectral-chemical modeling possible.



Signal-to-Noise Optimization in UAV Water Spectroscopy

Water surfaces are **notoriously difficult targets for spectroscopy**. Water-leaving radiance is inherently weak – often contributing less than 10% of the total signal received at the sensor – while the remainder arises from atmospheric scattering and surface reflections such as sun glint. Variable wave geometry and transient illumination further complicate measurements. To address this, all spectra were preprocessed using the **Savitzky-Golay filter (SGF)** – a smoothing technique that fits successive subsets of adjacent data points with a low-degree polynomial, suppressing high-frequency electronic noise and sensor artefacts while **preserving the subtle absorption and scattering features** needed for chemical retrieval. The optimization process involved systematically testing multiple filter window sizes and acquisition geometries to maximize data quality for various target parameters.

RAW

SFG 66

SFG 99

SFG 132

Translating Spectra into Chemistry: PLSR Modeling

Quantifying chemical concentrations from the high-dimensional, noisy spectral data inherent in environmental sensing requires a robust statistical framework. **Partial Least Squares Regression** (PLSR) was employed as a multivariate calibration technique to extract latent factors capturing the maximum covariance between spectral predictors and measured concentrations. This approach is particularly suited to reflectance data, as it efficiently manages highly correlated wavelength variables and predicts composition from limited sample sets. The convergence between PLSR-identified diagnostic wavelengths and the established physical properties of the target constituents serves to validate that the models are capturing authentic chemical signals rather than spurious statistical correlations.

Fe2O3

Path to Satellite Upscaling

Bridging UAV-based measurements with satellite monitoring is an explicit ambition of the project. Spectral consistency between the drone-mounted sensor and **PlanetScope satellite imagery** was assessed using the Spectral Angle Mapper (SAM).

Fe2O3 development at Kassandra mines

Arsenic development at Chalkidiki rivers

TSS development at Chalkidiki rivers

Science advances fastest when its data are shared. One of the core outputs of the Multiminer project is a **fully open-access, harmonized dataset** published via open repositories: laboratory mineral reflectance spectra spanning **350–15,375 nm**, in-situ water spectra from **337–823 nm**, co-registered mineralogical analyses (XRD, XRF, ICP-MS), and complete water geochemistry for both Kirki and Chalkidiki. This **multi-scale, multi-domain dataset** is rare in AMD research and is designed to serve a broad community: spectral algorithm developers, sensor calibration teams, machine learning researchers, and planetary scientists studying sulfate-iron mineral assemblages analogous to those found on Mars.

AMD Spectral Dataset

Looking further ahead, the validated spectral-chemical relationships and **reproducible field protocols** developed within Multiminer provide a transferable toolkit. Drone surveys can be repeated seasonally to **track how contamination plumes evolve through time**, while PLSR models calibrated on Kirki and Chalkidiki data can be adapted to new AMD sites sharing similar mineralogy. The combination of **open spectral libraries, documented acquisition methods, and peer-reviewed validation** lays the groundwork for a new generation of cost-effective, spatially continuous environmental surveillance across **mining-impacted landscapes in Europe and beyond**.

When Mines Meet Air

Mining environmental impact does not end at the water edge. Every stage of open-pit mining – **blasting, crushing, hauling, and wind erosion of exposed waste surfaces** – releases large quantities of coarse particulate matter into the atmosphere. This airborne dust carries not just mineral particles but also **heavy metals**, which settle on surrounding soils, watercourses, and vegetation, and penetrate the respiratory tracts of workers and nearby residents.

The European Union's Directive 2008/50/EC sets a **daily PM10 limit of 50 µg/m³**, not to be exceeded more than 35 times per year. Mining areas regularly push against these thresholds, particularly during dry seasons or periods of intense operational activity. Yet conventional monitoring – networks of fixed ground stations – captures only isolated points in space, missing the full spatial extent of dust plumes, their origin zones, and their seasonal dynamics.

The Multiminer project developed a **combined atmospheric and surface dust monitoring framework** that integrates in-situ air quality measurements, passive dust traps, spectral analysis of vegetation, UAV surveys, and satellite data across contrasting mining environments in Greece and Finland. The ambition is the same as in water monitoring: to move **from sparse point observations toward spatially continuous, temporally resolved surveillance** capable of supporting both regulatory compliance and environmental management decisions.

The Dust Cycle: From Source to Deposition

Mine dust does not behave as a single, uniform problem. It follows a **three-stage environmental pathway** – generation at the source, transport through the atmosphere, and deposition on surrounding surfaces – and each stage presents a distinct monitoring challenge that requires different tools and data.

Source

Exposed mine surfaces, waste rock piles, tailings, unpaved haul roads, and crushing facilities generate dust through mechanical disturbance and wind erosion. The mineral composition of this dust reflects the underlying geology – at Chalkidiki, particles carry **iron oxides, sulfides, and heavy metal-bearing phases** characteristic of polymetallic mining; at the Finnish limestone quarry in Ihalainen, dust is dominated by **carbonate-rich particles**.

Transport

During **atmospheric transport**, dust is dispersed by wind, mixed with background aerosols including regional pollution and Saharan dust intrusions, and gradually deposited. The concentration of PM10 at any given receptor location depends on emission rate, meteorological conditions, topography, and distance from source – a complex interaction that no single ground station can fully characterize.

Deposition

Dust accumulates on vegetation, suppressing photosynthesis, altering leaf optical properties, and introducing heavy metals into plant tissues. This biological signal is persistent and spatially integrative – making **dust-loaded vegetation a valuable indirect indicator** of chronic dust exposure that complements instantaneous atmospheric measurements.

In-Situ Monitoring: Ground Truth from Dust Traps and Air Stations

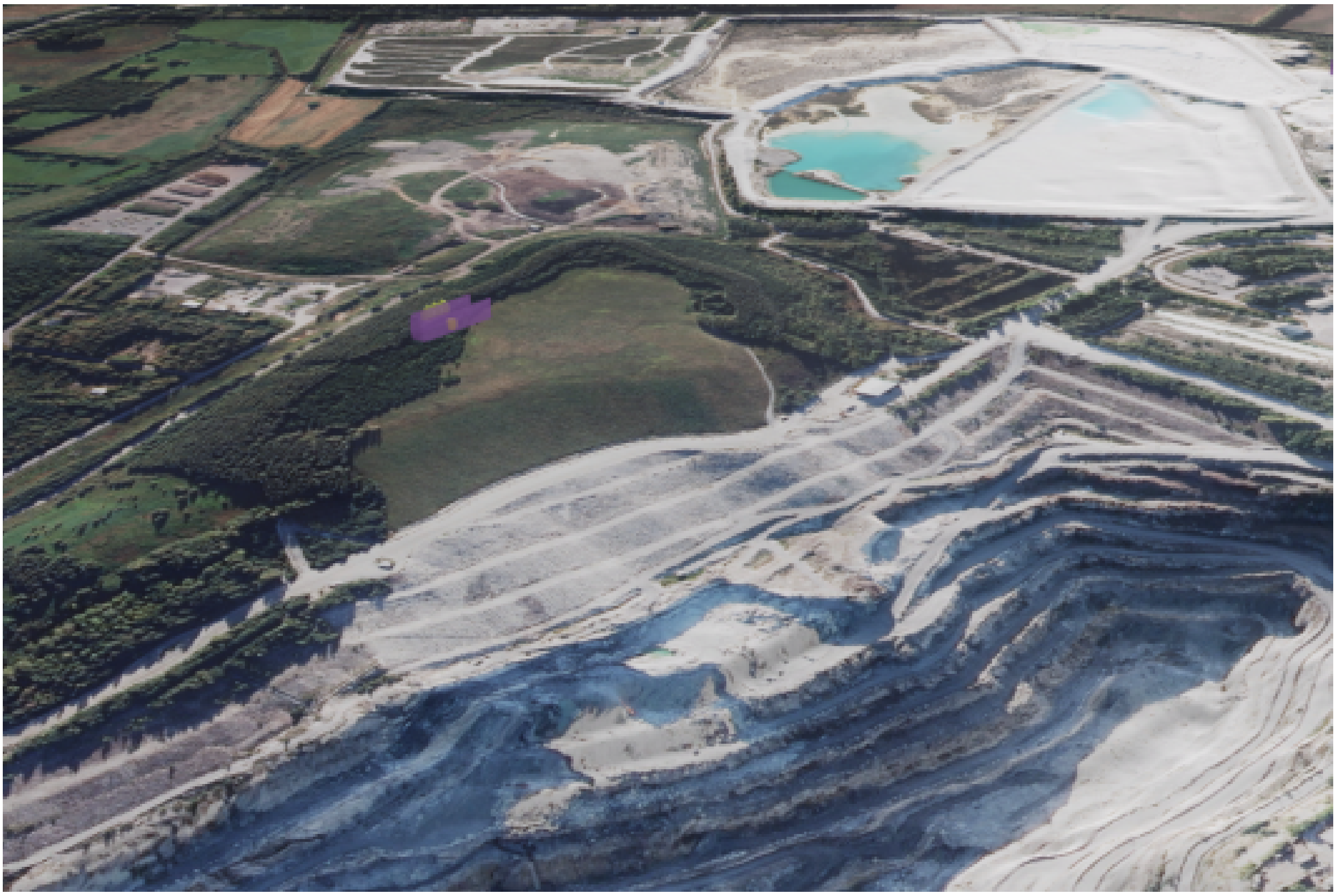
Reliable remote sensing begins with reliable ground truth. Before satellite data can be used to monitor dust, it must be validated against independent measurements that directly quantify what is happening at the surface and in the lower atmosphere.

The project utilizes extensive long-term air quality data from both Greece and Finland. At **Chalkidiki**, the Hellas Gold platform operates 12 stations recording hourly PM10 concentrations (2015–2024), with data publicly accessible via the IEMS platform. Similarly, seven stations managed by the Finnish Meteorological Institute around **Lappeenranta** provide a decade of continuous records dating back to 2013.

Complementing the fixed station network, **passive TE-200-PAS dust traps** were installed around each mine site. These devices house polyurethane foam disks that passively capture airborne particles without requiring electricity or active maintenance, making them ideal for deployment in remote or difficult terrain. Disks were retrieved seasonally and transported to the laboratory for chemical and gravimetric analysis.

Additionally, **broad-leaved vegetation samples** were collected at both sites to estimate surface dust accumulation. Dust was mechanically removed from leaves with wet tissue of known weight, air-dried under controlled conditions, and weighed – providing an independent, ground-level measure of dust deposition load that bridges atmospheric measurements and vegetation spectral responses.

Passive dust sampler installed at the Ihalainen mining site.

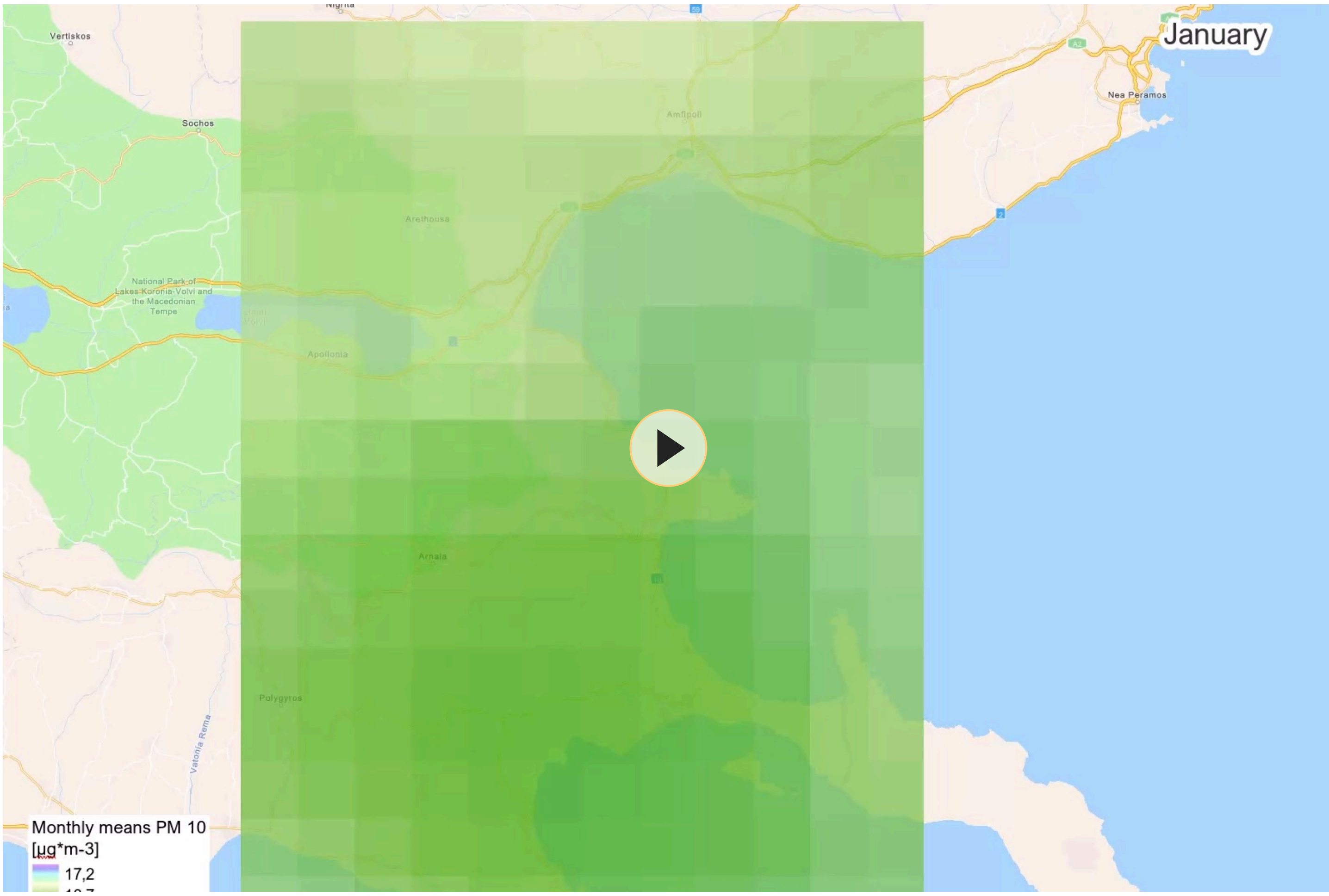


Spectral Signatures of Dust on Vegetation

When dust settles on vegetation, it leaves a measurable spectral imprint. **Dust particles coating leaf surfaces suppress chlorophyll absorption features, increase overall reflectance, and alter the spectral shape** across the visible and near-infrared in ways that vary with dust load, mineralogy, and particle size. This optical response creates an opportunity: by measuring the reflectance spectra of dust-laden leaves, it becomes possible to quantify dust accumulation and, eventually, to map deposition patterns from the air.

The Multiminer team collected **VNIR–SWIR reflectance spectra (350–2,500 nm)** from broad-leaved samples at Chalkidiki and Ihalainen spanning the full range of dust conditions – from completely clean leaves to heavily loaded surfaces. Measurements were acquired using an **SR-2500 spectroradiometer with a contact probe**. Each spectral measurement was paired with gravimetrically determined dust weight, establishing a quantitative link between spectral response and actual dust load.

Scaling this signal from individual leaves to the landscape requires airborne observation. A Resonon **PikaL pushbroom camera** mounted on a drone and flown at 60 meters altitude produced 150 spectral bands in resulting hyperspectral mosaics (380–1225 nm) at aproximatelly 8 cm pixel resolution. These high-resolution mosaics capture the spatial pattern of vegetation dust loading at a detail far exceeding what any satellite can provide – and serve as the critical bridge between leaf-level spectral measurements and the coarser but spatially extensive view from orbit.



Satellite Data for Atmospheric Dust: CAMS and MODIS

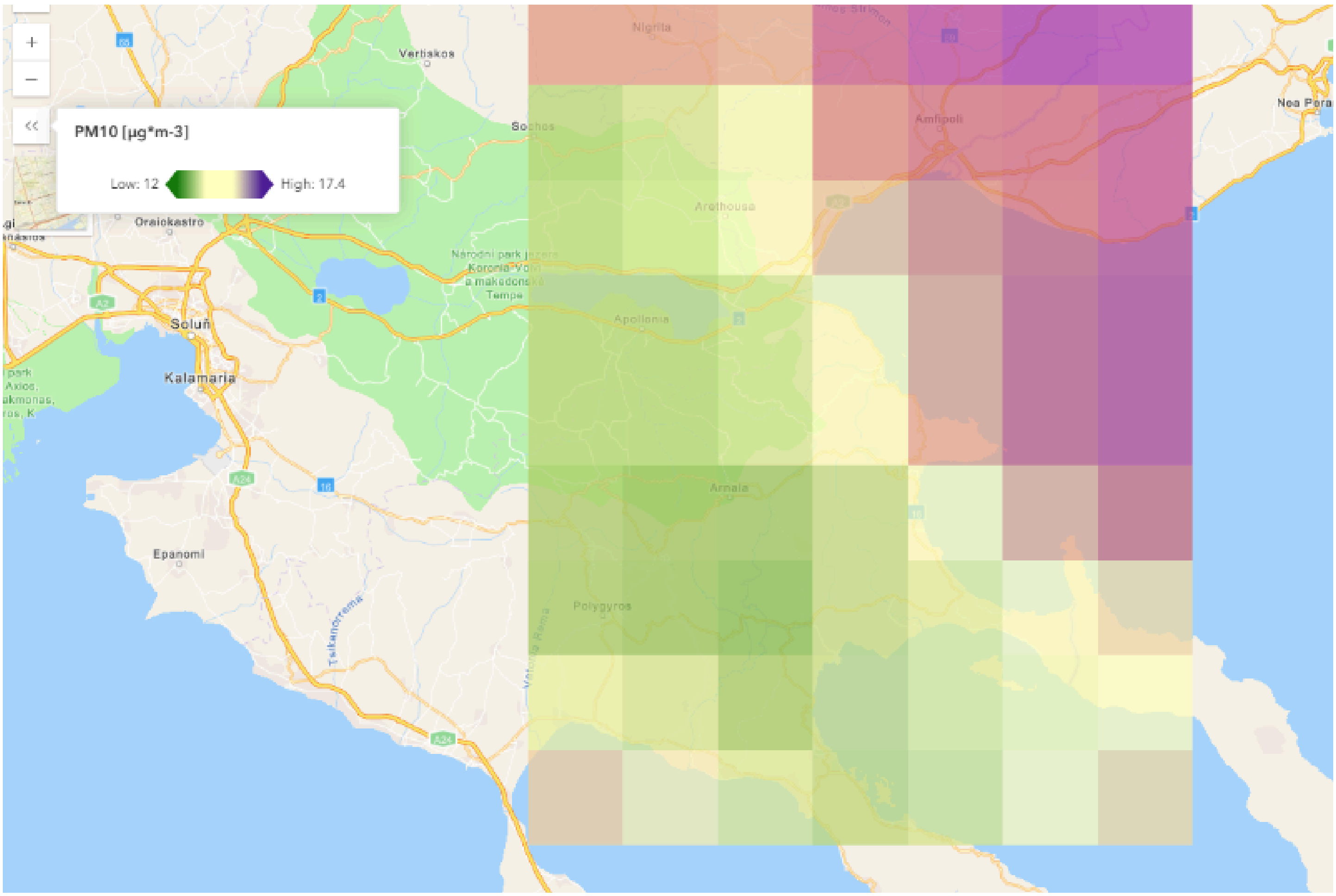
Fixed ground stations offer precision at specific points, but satellites provide the necessary coverage everywhere else. Within the Multiminer framework, two complementary satellite products are used to characterize atmospheric dust dynamics in mining regions:

MODIS Aerosol Optical Depth (AOD): This product measures how atmospheric particles extinguish solar radiation across a vertical column. While it offers near-daily global coverage and a multi-decade archive, it faces significant challenges. Retrievals are restricted to cloud-free conditions and struggle over bright or heterogeneous surfaces, often resulting in substantial data gaps. Additionally, because AOD represents the entire atmospheric column, there is inherent uncertainty when translating these values to ground-level PM10 concentrations.

CAMS (Copernicus Atmosphere Monitoring Service): CAMS generates gridded PM10 fields using numerical models that assimilate satellite data, surface measurements, and meteorological analyses. This modeling approach ensures temporal continuity even during cloudy periods. Its primary limitation is spatial resolution; the grid spacing means local emission hotspots near individual mines are often smoothed out, leading to an underestimation of peak concentrations.

Chalkidiki CAMS monthly means

Ihalainen CAMS monthly means



Long-Term Trends and Seasonal Patterns in PM10

Analysis of PM10 records spanning 2013–2024 at both Chalkidiki and Ihalainen reveals how profoundly **local geography, climate, and industrial context shape the character of mining dust pollution** – even when the underlying monitoring challenge is superficially similar.

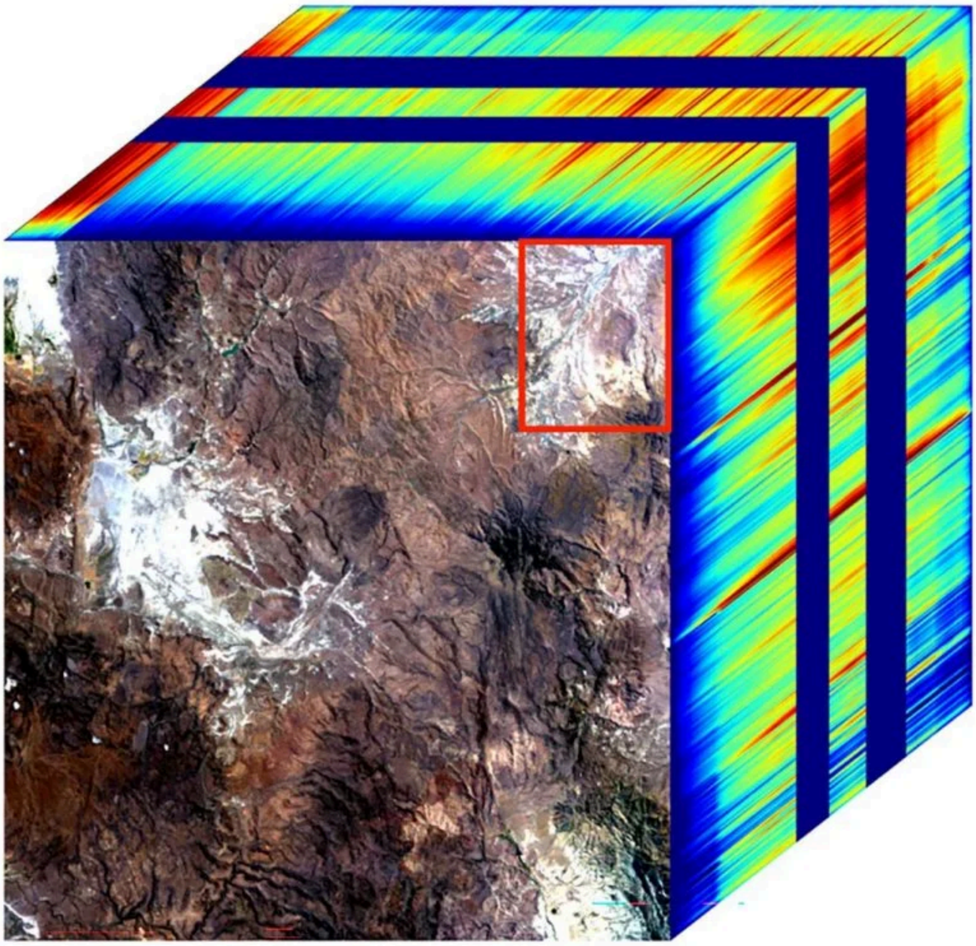
Chalkidiki: The seasonal cycle here is complex. Concentrations typically rise in late spring and summer due to dry conditions, strong winds, and regional Saharan dust intrusions. Coastal areas are influenced by sea-breeze recirculation, while residential zones see increases in winter from domestic heating and traffic. This spatial heterogeneity makes attributing PM10 to specific sources particularly difficult in such a mixed environment

Chalkidiki PM 10 long-term trends

Ihalainen: The atmospheric profile is more streamlined. A well-defined spring peak occurs during snowmelt and road dust resuspension, followed by lower summer values as precipitation suppresses local emissions. The high regional coherence suggests a more uniform signal across monitoring stations compared to more complex climates.

Ihalainen PM 10 long-term trends

Across both sites, time series decomposition identifies a **broadly downward long-term trend** in PM10 over the monitoring period – suggesting gradual improvements in air quality.



Identifying Dust Source Zones: Hyperspectral Satellite Mapping

Knowing that dust is present in the atmosphere is only half the problem. **Identifying which specific surface zones are generating it** – and what their mineral composition is – requires a different class of observation entirely: hyperspectral imaging from space.

The **EMIT imaging spectrometer** was utilized to map surface - a NASA imaging spectrometer mounted on the International Space Station - mineralogy by capturing continuous reflectance spectra across the VNIR–SWIR range. By employing vegetation masking and automated absorption feature extraction followed by unsupervised classification, the analysis successfully identified diverse mineral surface classes, including iron oxides, clays, and serpentinite. These classes represent the mineralogical diversity of potential dust source surfaces, and provide a basis for understanding which mine zones are likely contributing iron-bearing or clay-rich particles to the atmosphere.

Complementary hyperspectral coverage from satellites like **PRISMA**, alongside thermal data from ECOSTRESS, further reveals spatial patterns of vegetation stress and suppressed evapotranspiration across the landscape. These observations are consistent with the physiological impacts of chronic dust deposition on plant health, effectively closing the loop between atmospheric dust transport and its measurable consequences on the surrounding ecosystem

Forecasting PM10: Machine Learning for Operational Dust Surveillance

Monitoring tells you what has happened; forecasting helps you prepare for what is coming. The Multiminer project evaluated various statistical and machine learning models to predict PM10 concentrations using CAMS data, aiming to establish a framework for operational dust surveillance. For long-term trend analysis, the **Prophet model** was utilized due to its additive time series framework and ability to handle seasonal data and missing values. For short-term daily predictions, the study compared the performance of **XGBoost and Random Forest**, while also testing an iterative multi-step XGBoost configuration for extended horizons. This reproducible workflow—encompassing data acquisition, preprocessing, STL decomposition, and model fitting–is designed for transferability. It provides a cost-effective air quality surveillance layer for regions where establishing dense in-situ monitoring networks is logistically or financially impractical.

A Blueprint for Sustainable Mining

The MultiMiner project has successfully redefined environmental monitoring in the mining sector by implementing a "Multi-Source and Multi-Scale" Earth Observation framework. By synchronizing data from ground-based sensors, drone-mounted hyperspectral systems, and satellite constellations, the project has bridged the gap between microscopic mineral analysis and regional surveillance. Significant contributions include the creation of a unique, open-access spectral library for acid mine drainage (AMD) and the development of compact UAV-based systems for safe, repeatable water and dust monitoring across diverse environments in Greece and Finland.

Beyond technical data acquisition, MultiMiner has pioneered the use of novel machine learning models to transform raw environmental data into actionable intelligence for forecasting PM10 concentrations. These workflows are designed to be openly reproducible and transferable, offering a cost-effective surveillance layer for mining sites worldwide, particularly where ground-based infrastructure is limited.

Ultimately, the project ensures a more transparent and environmentally sound mining lifecycle–from low-impact exploration to long-term rehabilitation–paving the way for a sustainable, carbon-neutral economy that respects the land it harvests.

Published Works

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MultiMiner
Earth Observation for Smart Mining

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Hellas Gold	Zabokas G., Agali A., Gounaris K., Gazea E.
Hellenic Survey of Geology and Mineral Exploration	Anastasatou M., Liakopoulos, A., Mavrogonatos, C.
Nordkalk	Salmela U., Kukkula H.
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