GEOSPATIAL APPROACHES FOR ECOLOGICALLY SUSTAINABLE MINING MANAGEMENT IN LINE WITH SDGS AND ESG FRAMEWORKS

Elia Stoyanova, Viktor Vitov

Elia Stoyanova, M.Eng.
University of Architecture, Civil Engineering and Geodesy (UACEG), Faculty of Geodesy,
Dept. of Photogrammetry and Cartography
1, Hristo Smirnenski Blvd, Sofia 1164, Bulgaria
E-mail: stoyanova.elia@gmail.com

Viktor Vitov, M.Eng.
University of Mining and Geology "St. Ivan Rilski", Faculty of Geology and Exploration,
Department of Engineering Geoecology, Sofia, Bulgaria
1, Prof. Boyan Kamenov Street, Studentski Grad, Sofia 1700, Bulgaria
E-mail: vvitov@abv.bg

Abstract
This study examines the application of remote sensing and Geographic Information Systems (GIS) for sustainable mining, specifically in environmental monitoring aligned with the Sustainable Development Goals (SDGs) and the principles of Environment, Social, and Governance (ESG). SDGs and ESG are essential in mining because they guide companies to minimize environmental impacts, promote social responsibility, and ensure sustainable resource management. The report reviews successful global examples that demonstrate the potential of remote sensing and GIS tools for rapid and cost-effective environmental monitoring. These technologies offer a valuable pathway for the mining industry to balance economic growth with environmental stewardship and social responsibility.

Keywords: *SDGs, GIS, ESG, remote sensing, ecology, environmental monitoring, mining activities, sustainable development*

INTRODUCTION

The Sustainable Development Goals (SDGs), adopted by the United Nations (UN) in 2015, represent a global framework of 17 goals aimed at addressing urgent challenges such as poverty, inequality, environmental degradation, and climate change by 2030. In recent years, the SDGs have had a significant influence on government policies, corporate strategies, and investment decisions worldwide. Many companies, including those in the mining sector, have incorporated the SDGs into their corporate social responsibility and sustainability initiatives, aligning their operations with broader global efforts toward sustainable development. Policymakers have also integrated the SDGs into national development plans and environmental regulations, further reinforcing their relevance.

Similarly, the Environment, Social, and Governance (ESG) criteria have emerged as an important set of standards for evaluating a company's ethical impact and overall sustainability. ESG considerations encompass environmental responsibility, social equity, and sound governance practices. Their influence is growing rapidly, as institutional investors and financial organizations increasingly prioritize companies that demonstrate strong ESG performance, recognizing that such companies tend to be more resilient to risks and often achieve better long-term financial outcomes. Regulatory developments, particularly within the European Union, are also driving stricter ESG reporting and transparency requirements.

In recent years, Geographic Information Systems (GIS) and remote sensing technologies have advanced rapidly, driven by improvements in satellite imagery, unmanned aerial systems (UAS), and artificial intelligence. These technologies are essential for monitoring environmental change, managing natural resources, and supporting sustainable development. In the mining industry, GIS and remote sensing enable more effective land-use planning, biodiversity monitoring, and compliance with environmental standards in accordance with SDGs and ESG principles. As a result, these technologies have become critical for achieving sustainability objectives and improving decision-making processes at a global scale.

MAIN SECTION

This section presents an overview of successful global examples in which remote sensing and GIS technologies have been applied in support of sustainable mining. The focus is on environmental monitoring practices aligned with the Sustainable Development Goals (SDGs) and the principles of Environment, Social, and Governance (ESG).

SDG-Based Monitoring of Environmental Restoration - Taiyuan, China

Yuan et al. (2023) present a study assessing environmental restoration in Taiyuan, a historically industrial and mining-intensive city in China, using remote sensing techniques in support of the Sustainable Development Goals (SDGs). The authors identify industrial development, and coal mining in particular, as major contributors to environmental degradation in the region. To address this, they developed a Vegetation Growth Condition Index (VGCI) designed to capture changes in vegetation recovery over time. The index integrates multiple indicators related to water protection (SDG 6.3.2), air quality (SDG 11.6.2), and ecosystem conservation (SDGs 6.6.1, 15.1.1, 15.3.1, and 15.4.2), resulting in a multidimensional assessment framework.

Using satellite data, the study applies the VGCI to various environmental restoration initiatives. The analysis demonstrates significant improvements in water quality, air conditions, forest cover, and particularly vegetation recovery on reclaimed mining sites. These positive trends correspond closely with the implementation of ecological restoration projects in Taiyuan (Fig. 1). The authors conclude that combining VGCI with SDG-aligned indicators provides a robust framework for evaluating environmental restoration, which can be applied to cities with legacy mining and heavy industrial activities.

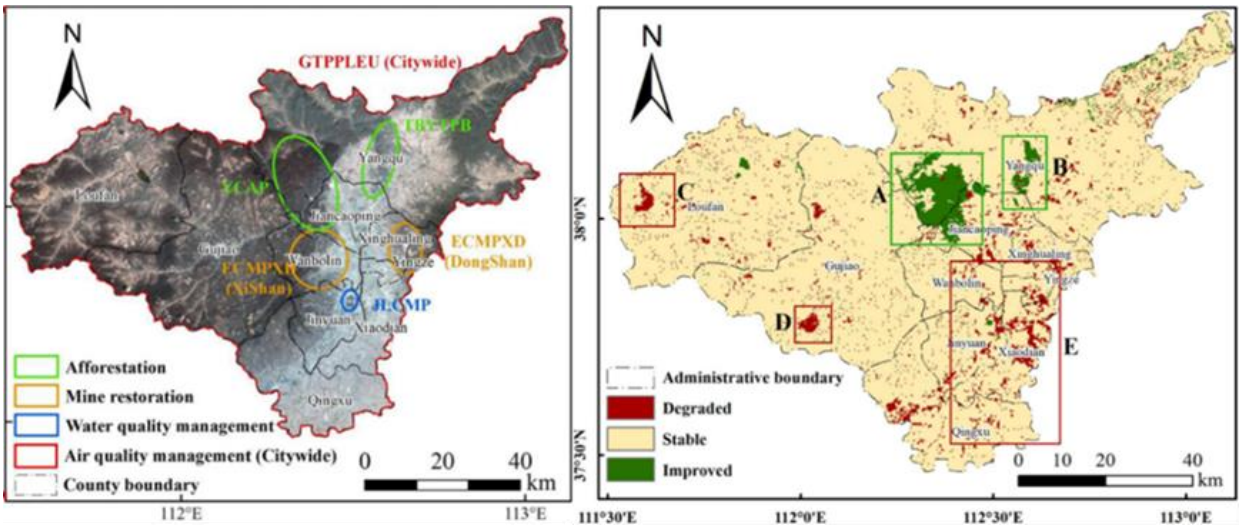


Figure 1. Map of implemented ecological projects in Taiyuan and map of land degradation and restoration in Taiyuan from 2010 to 2020 (Yuan et al., 2023)

The study by Yuan et al. (2023) offers a compelling, data-driven model for assessing environmental recovery. By demonstrating successful reclamation of former mining areas and employing SDG aligned indicators, the article provides a practical methodology for monitoring restoration using GIS and remote sensing technologies. Mining companies can adapt this approach to improve their ESG performance and to report progress in sustainable environmental management in a transparent and standardized manner.

Near-Real-Time Alerts for Illegal Gold Mining in the Amazon

The study by Becerra et al. (2024) presents a novel methodology for generating near-real-time alerts of deforestation caused by illegal gold mining. The study was conducted in the Madre de Dios region of southeastern Amazonia, where small, unlicensed mining operations are the primary drivers of deforestation in forests, national parks, and Indigenous territories. The method uses a time series of Sentinel-1 synthetic aperture radar (SAR) data from February to December 2022, processed using Google Earth Engine and analyzed with the intelligent Omnibus Q-test change detection algorithm developed by Morton Canty. The results were validated using high-resolution optical imagery from Planet NICFI and PlanetScope, achieving an overall accuracy of 99.98% in detecting forest cover loss. The system successfully identifies both the location and timing of deforestation events, including areas smaller than 1 ha.

A public web-based platform, RAMI (Radar Mining Monitoring), was developed to visualize alerts (Fig. 2) and to support law enforcement agencies in allocating resources and personnel for rapid response operations against illegal gold mining. The platform has been integrated into Operation Mercury, Peru's national initiative to combat illegal mining, and also generates monthly reports highlighting deforestation hotspots.

This methodology demonstrates the effectiveness of deforestation monitoring and highlights the value of open-access SAR data for environmental surveillance in regions with persistent cloud cover, where optical imagery is often limited. SAR sensors penetrate cloud cover and provide information on surface texture and moisture, making them particularly suitable for dynamic monitoring. Sentinel-1 delivers this capability at a spatial resolution of 10 m using dual polarization (VV + VH).

The application of this approach demonstrates how remote sensing and GIS can serve as powerful tools in combating illegal activities in the mining industry, particularly in remote and protected areas. RAMI enables spatial analysis of mining activities, tracking their spatial expansion and temporal dynamics based on SAR and GIS data. The presented methodology not only identifies illegal activities but also supports strategic planning in compliance with environmental standards and global sustainable development goals.

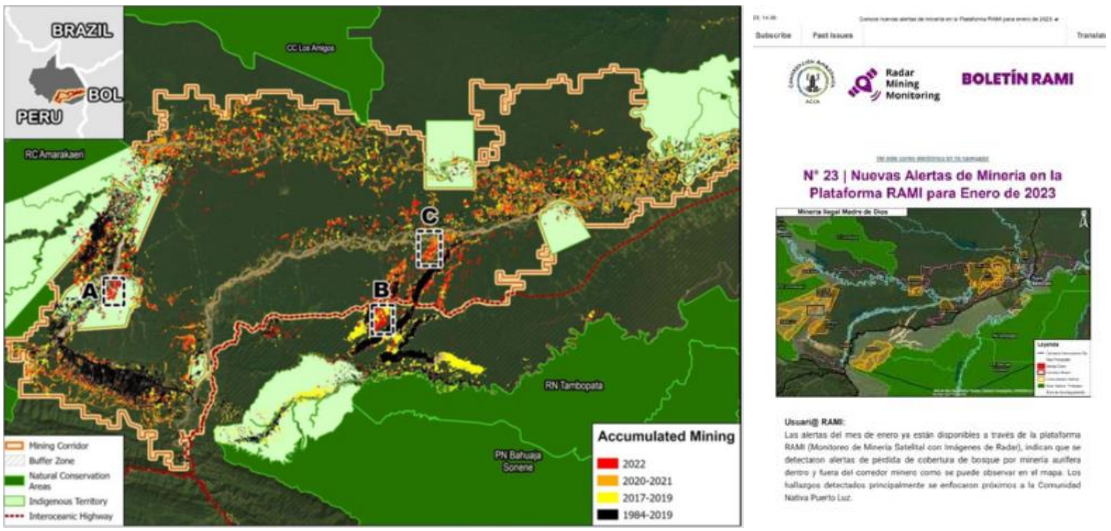


Figure 2. ***Left:*** *Mining alerts in Indigenous territories within national reserves,* ***Right:*** *Example of the January 2023 bulletin. (Becerra et al., 2024)*

Ecosystem Restoration – Noamundi and West Bokaro, India

The study by Husain et al. (2024) analyzes ecosystem services restoration through the implementation of biodiversity management plans at two mining sites in India: the Noamundi iron ore mine and the West Bokaro coal mine. The authors evaluate (Fig. 3) how effectively these plans contribute to the achievement of SDG 15. They apply an assessment method that measures the number and potential of implemented "preventive measures" in relation to specific ecosystem services, including carbon sequestration, erosion control, habitat improvement, and others.

The targeted restoration areas exceed 1,019 ha in Noamundi, where 91.9% of the land is converted into forests, wetlands, water bodies, small public spaces, and agricultural plots, and 1,740 ha in West Bokaro using a similar approach. The results indicate that afforestation and the establishment of new forest areas provide the greatest contribution, enhancing carbon sequestration, stabilizing erosion, supporting habitats, and conserving biodiversity. Wetlands, although covering smaller areas, play a critical role in regulating water flows, supplying and purifying freshwater, and further preventing erosion. The allocation of agricultural and public lands has a more moderate yet meaningful impact on soil fertility and air quality, while cultural services (such as recreation and spiritual value) are considered significant, albeit of lower priority compared to other ecosystem functions.

This study is particularly important because it focuses directly on the rehabilitation of mining-impacted lands and provides a toolkit for evaluating environmental outcomes. The methodology includes territorial mapping, land-use identification, and ecosystem services assessment. It is closely linked to GIS and remote sensing, as these technologies enable spatial visualization and monitoring of restoration dynamics. The authors further recommend integrating satellite imagery and GIS layers and analyzing time series data to achieve more accurate assessment and validation of restoration measures.

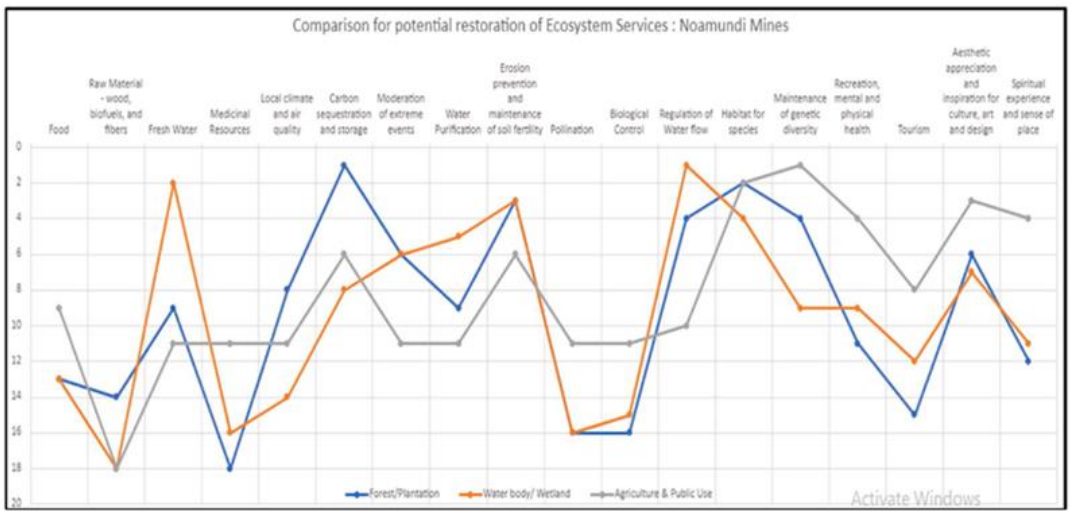


Figure 3. Comparison of the potential restoration of ecosystem services based on the type of land use in which degraded land was restored (Husain et al., 2024)

Monitoring of Reclaimed Lands: A Case Study in Inner Mongolia, China

The study by Wang et al. (2021) uses remote sensing to assess vegetation recovery in a mining region in China. The authors focus on how vegetation cover changes during the reclamation of lands affected by mining activities. They utilize satellite data from Sentinel-2 and Landsat, applying the Green Red Normalized Difference Vegetation Index (GRNDVI) to classify vegetation conditions in 2016 and 2018, achieving classification accuracies between 91% and 94%.

Through time-series analysis, the authors observe trends in vegetation growth and recovery, finding that despite the environmental measures implemented for land reclamation, there is a noticeable improvement in green cover. The use of GRNDVI enables clear differentiation between areas with good, moderate, and poor vegetation conditions and allows tracking of their evolution over time. The results (Fig. 4) show an increase in areas with dense vegetation and a decrease in bare land, indicating successful restoration measures. These findings are validated through field data and additional monitoring.

The study demonstrates how GIS and remote sensing are integrated into the analysis to track the impacts of reclamation projects in the mining industry. These methods allow spatial and temporal mapping of changes in vegetation cover, facilitating the planning of restoration activities and the evaluation of their effectiveness. This is achieved through the generation of GRNDVI maps, which are visualized, analyzed, and compared within a GIS environment across different time periods. The proposed method is scientifically sound and effective, and it can be applied in various mining regions due to the flexibility of remote sensing and GIS-based analysis.

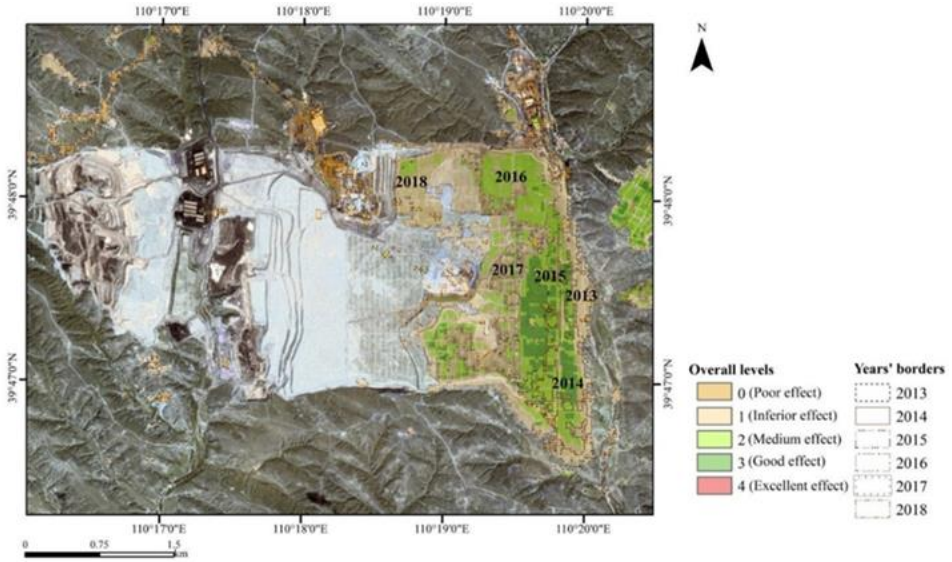


Figure 4. Overall effects of vegetation recovery from 2013 to 2018 (Wang et al., 2021)

Mining and Restoration Monitoring of Rare Earth Element – Southern Jiangxi, China

The study by Xie et al. (2020) presents an innovative method for monitoring both mining activities and restoration efforts in open-pit rare earth element deposits in southern Jiangxi. The authors propose a new set of Mining and Restoration Assessment Indicators (MRAIs), which combine traditional vegetation indices such as NDVI, SAVI, and GDVI with additional biophysical parameters - albedo, tasseled cap brightness, and land surface temperature (LST) - derived from multi-temporal Landsat imagery spanning 1988 to 2019. They show that these MRAIs are more sensitive than NDVI and other indices, especially in areas with low vegetation cover, allowing the detection of finer changes in the ecological status of the territories. The use of these indicators revealed the trajectory of mining area expansion up to 2010, followed by vegetation recovery due to restoration measures implemented after 2010 (Fig. 5). Seven counties in the region were covered, analyzing over 1,158 mines spanning approximately 66.3 km².

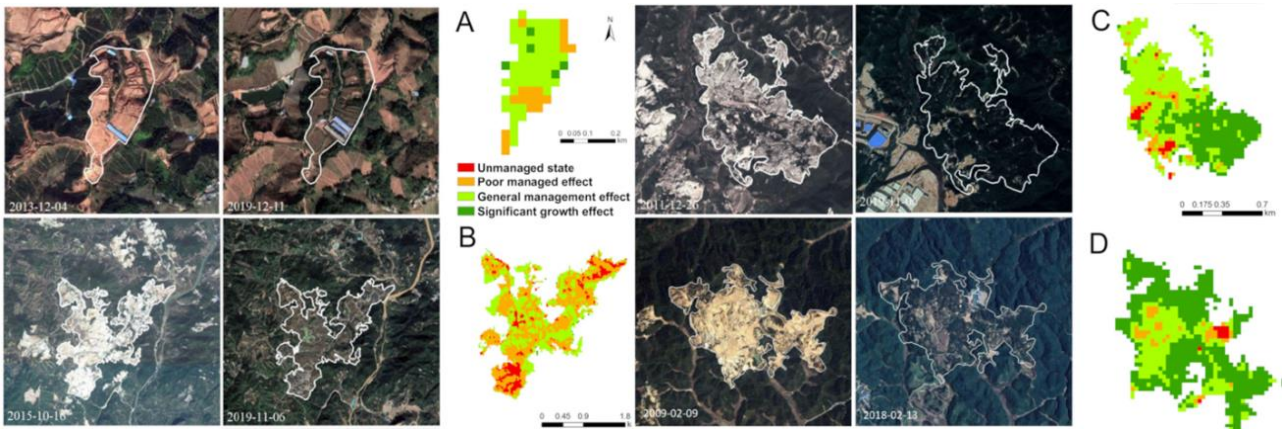


Figure 5. Comparison of the results from the mining to restoration stages (Xie et al., 2020)

In conclusion, the authors demonstrate that by integrating vegetation indices and surface biophysical parameters into unified indicators, it is possible to achieve precise monitoring of mining impacts and the effectiveness of restoration measures. This provides significant benefits for spatial and temporal analysis of the mining environment.

Their study develops methods for monitoring open-pit rare earth element mining using GIS and remote sensing. Landsat data are processed and used for mapping to visualize mining areas, land use changes, and vegetation conditions over time. The MRAI indicators used in the article provide a series of maps of the territory for different time periods, thereby integrating information on vegetation, albedo, and temperature. This allows mining operators and regulators to assess restoration processes clearly and quantitatively.

Remote monitoring of ecological and economic impacts - Chinese mining projects outside China

The study by Jiang et al. (2022) presents a systematic monitoring of ecological and socio-economic effects from Chinese mining projects outside China - specifically, Sino Iron in Australia and Taldybulak Levoberezhny in Kyrgyzstan. They use multispectral Landsat satellite imagery and nighttime light (NTL) data from DMSP-OLS and NPP-VIIRS for the period 2000-2020. The integrated approach allows the extraction and mapping of different surface types - open pits, waste dumps, roads, water bodies, and vegetation - through visual interpretation and automated algorithms. Landsat datasets are used for quantitative tracking of changes in vegetation cover, bare land, and mining areas, while nighttime light datasets track economic activity and the impact on the socio-economic environment (Fig. 6). Increases in nighttime lights correlate with regional economic development, and the mapping accuracy reaches over 95% for Sino Iron and approximately 90% for Taldybulak. The analysis shows that despite mining activity, ecological damage to vegetation and soil is limited, and effective protection and restoration measures have been implemented without disrupting the ecological balance.

This study analyzes open-pit mines at an international scale and assesses the ecological and economic consequences caused by mining industry operations. Satellite and nighttime light data provide quantitative temporal analyses for mapping land use changes, high-resolution imagery allows visual verification of restoration measures, and GIS integrates all these data into series of maps. The methodology enables monitoring of mining impacts and evaluation of the effectiveness of environmental measures. In this way, a spatio-temporal monitoring model is established, supporting planning, tracking, and optimization of mining impacts relative to ecological and economic objectives. The report demonstrates how these modern approaches can support sustainable and responsible management of mining areas, combining environmental, economic, and technological aspects.

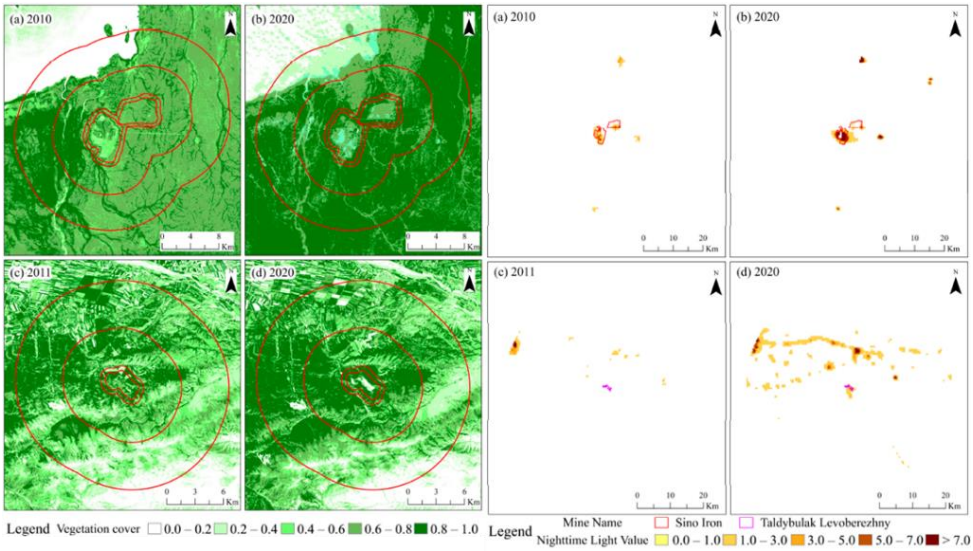


Figure 6. Distribution of vegetation cover and nighttime lighting in mining areas over different time periods: a,b - Sino Iron (Australia) and c,d - Taldybulak Levoberezhny (Kyrgyzstan) (Jiang et al., 2022)

Application of GIS and remote sensing in "Ellatzite-Med" AD

Reclamation Using Unmanned Aerial Systems (UAS)

In 2023, successful grass seeding of 25 ha of the eastern dump was carried out using a UAS, marking the first such operation in Bulgaria. The area includes two sections with slope inclinations of 37° and heights of up to 100 m, which limit access and make the terrain difficult for traditional reclamation methods. The approach is innovative, as UAS are typically used for agricultural purposes such as spraying and fertilizing crops; in this case, they were used to distribute seeds over a humus base applied on uneven terrain. The specially selected grass mixture is adapted to high altitudes, ensuring successful vegetative coverage. This method aims for effective biological reclamation of areas affected by mining activities. The project is part of the long-term environmental program of "Ellatzite-Med" AD for restoration and environmental improvement, in line with sustainability commitments.

Development of a Geographic Information System (GIS) and Web Portal

At "Ellatzite-Med" AD, a GIS is being actively developed in response to the need for a standardized approach to collecting spatial data and storing it securely in an appropriate format. This system integrates spatial data from various sources, including satellite imagery, UAS surveys, field measurements, digitized archival data, and others, to support real-time decision-making. The system is built entirely using open-source software. An important component is the interactive web portal, which provides easy access to spatial information across all departments (Fig. 7). The purpose of the GIS being developed is to provide management and technical staff with accurate and up-to-date information on the precise location and characteristics of cadastral objects, management plans, protected areas, engineering infrastructure, production facilities, and other available data related to the operations of "Ellatzite-Med" AD.

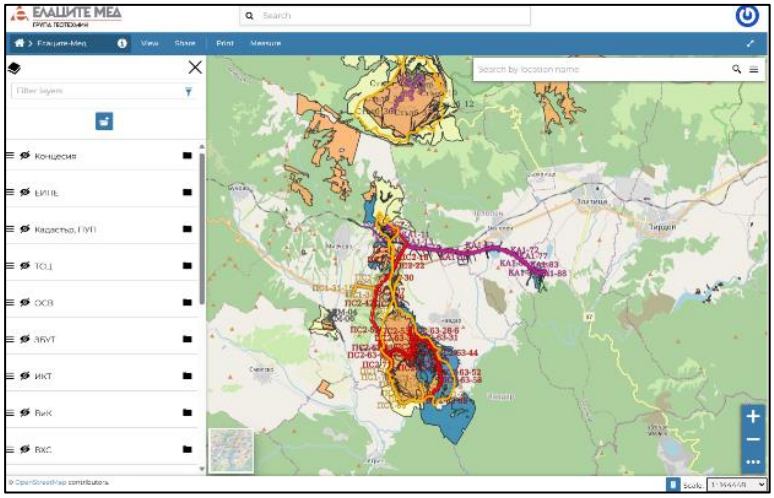


Figure 7. Web GIS Portal

Remote Sensing for Monitoring the "Benkovski-2" Tailings Storage Facility

An experimental study was conducted in 2023, presenting an innovative approach for monitoring the "Benkovski-2" tailings storage facility using multispectral satellite analysis. For the purposes of the study, only freely available data from the Sentinel-2 mission and open-source software (QGIS, SNAP) were used. The goal was to track the boundaries between the settling ponds and the wet sand within the facility (Fig. 8) by applying spectral indices (NDWI and WRI).

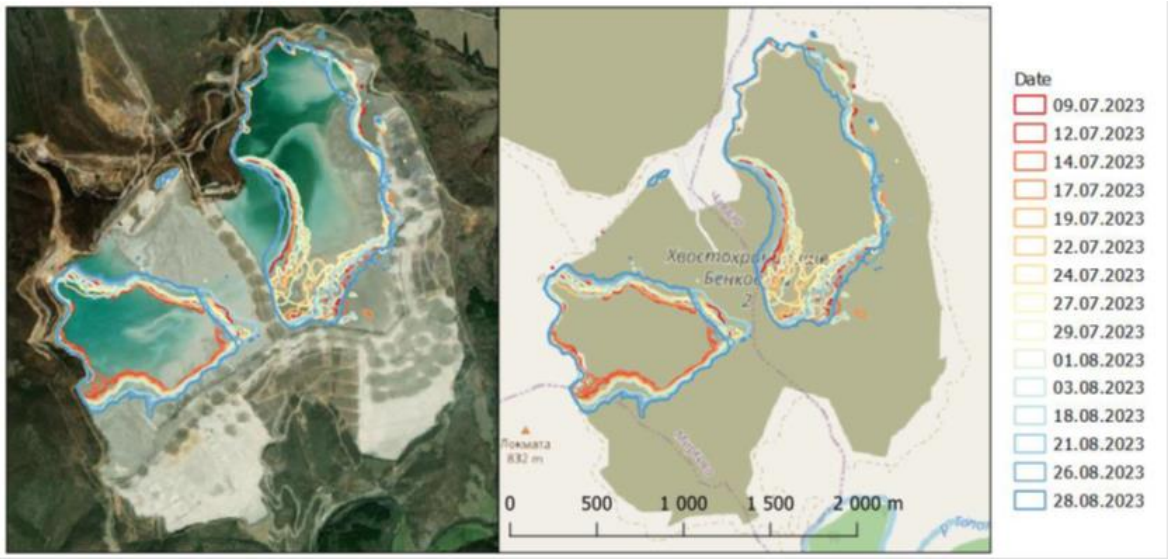


Figure 8. Boundaries between settling ponds and beaches

As a result, these boundaries were clearly delineated, and quantitative data on changes in the area of the settling ponds in different sections of the tailings facility were obtained. This method facilitates early risk detection, efficient water management, and maintenance of the structural safety of the facility. The approach is cost-effective and supports sustainable management of mining waste.

CONCLUSION

In the context of increasing public and institutional pressure for sustainable development, combined with the requirements of the UN Sustainable Development Goals (SDGs) and ESG principles, the application of remote sensing and GIS technologies in the mining industry emerges as a particularly effective approach for environmental monitoring and impact management. An analysis of international case studies from China, India, Peru, Australia, and Kyrgyzstan shows that modern satellite and geospatial technologies enable not only precise mapping of environmental damage but also the assessment of restoration measures over time. They support the monitoring of vegetation cover, erosion, water resources, and biodiversity through vegetation indices, biophysical parameters, and automated change detection algorithms.

Furthermore, the integration of open data, artificial intelligence, and cloud platforms such as Google Earth Engine enables rapid detection of illegal activities, as in the case of the Amazon, and enhances the capacity of regulatory authorities for timely response. The diversity of applied methodologies- from vegetation and ecosystem service assessment to spatial analysis of economic activity using nighttime lights - demonstrates that GIS and remote sensing are no longer merely scientific tools but have become key components of corporate sustainability strategies and responsible natural resource management.

Therefore, sustainable mining cannot be achieved without high-tech solutions for monitoring and analysis. For the successful transformation of the sector, it is essential that mining companies, institutions, and the scientific community work collaboratively to implement and improve geospatial systems that not only monitor environmental impacts but also promote restoration, transparency, and accountability to society and future generations.

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BIOGRAPHY



Elia Stoyanova graduated from the University of Architecture, Civil Engineering and Geodesy with a Master's degree in Geodesy. She is currently a PhD student at the Department of Photogrammetry and Cartography at the same university. Her research and professional interests include geodesy, remote sensing, satellite imagery, natural disasters, spatial analysis, GIS, and cartography. She is a member of the Union of Surveyors and Land Managers in Bulgaria, the Chamber of Engineers in Geodesy, the Bulgarian Cartographic Association, the Scientific and Technical Union of Mining, Geology and Metallurgy, and the ISPRS Student Consortium.



Viktor Vitov graduated from the University of Mining and Geology "St. Ivan Rilski" with a Master's degree in Ecology and Environmental Protection in 2021. He is currently enrolled in a PhD programme in Systems and Devices for Environmental Protection. His research and professional interests include water purification, acid mine drainage (AMD) and acid rock drainage (ARD), as well as the application of biotechnologies for remediation and waste management. He has over six years of experience in environmental protection and management in both the public and private sectors. He is a member of the Scientific and Technical Union of Mining, Geology and Metallurgy.