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Open source platform for monitoring and preventing illegal mining through geospatial analysis

Plataforma de código abierto para el monitoreo y prevención de la minería ilegal mediante análisis geoespacial

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Abstract
This paper presents the development of an open-source web platform for monitoring and preventing illegal mining using geospatial technologies. The research adopted a quantitative approach with a descriptive, non-experimental design, focused on integrating satellite and georeferenced data for accessible territorial monitoring. The methodology was based on multi-temporal satellite imagery from Sentinel-2 and Landsat, processed in Google Earth Engine (GEE). Spectral indices such as NDVI, NBR, and BSI were applied, along with multi-temporal difference analysis and thresholds, to detect landscape changes and identify areas impacted by informal mining. Spatial data in GeoJSON format were also incorporated and analyzed using geospatial processing and dynamic visualization tools. The results demonstrate that the platform generates thematic maps, identifies affected areas, and facilitates the visualization of patterns relevant to decision-making. Consequently, it strengthens environmental and territorial monitoring. The study concludes that this tool is flexible, scalable, and has high potential for improving environmental governance and preventing illegal mining.

Keywords: geospatial analysis, open source, illegal mining.

Resumen
Este trabajo presenta el desarrollo de una plataforma web de código abierto para el monitoreo y prevención de la minería ilegal mediante tecnologías geoespaciales. La investigación adoptó un enfoque cuantitativo con diseño no experimental descriptivo, centrado en integrar datos satelitales y georreferenciados para una vigilancia territorial accesible. La metodología se basó en imágenes satelitales multitemporales de Sentinel-2 y Landsat, procesadas en Google Earth Engine (GEE). Se aplicaron índices espectrales como NDVI, NBR y BSI, junto con análisis de diferencias multitemporales y umbrales, para detectar cambios en el paisaje e identificar zonas intervenidas por minería informal. Además, se incorporaron datos espaciales en formato GeoJSON, analizados con herramientas de procesamiento geoespacial y visualización dinámica. Los resultados demuestran que la plataforma genera mapas temáticos, identifica áreas afectadas y facilita la visualización de patrones relevantes

para la toma de decisiones. En consecuencia, fortalece la vigilancia ambiental y territorial. Se concluye que esta herramienta es flexible, escalable y con alto potencial para mejorar la gobernanza ambiental y prevenir la minería ilegal.

Palabras clave: análisis geoespacial, código abierto, minería ilegal.

Introduction

Illegal mining represents one of the most persistent and complex threats to environmental sustainability, institutional stability, and economic development in various regions worldwide. This activity, characterized by its informality, systematic evasion of regulations, and indiscriminate exploitation of natural resources, accelerates ecosystem degradation that extends beyond environmental concerns, impacting social, legal, and territorial dimensions (Sonter et al., 2020; Sonter et al., 2017).

It typically manifests with greater intensity in areas of high biodiversity where state presence is limited and institutional control is weak. This not only complicates the timely detection of mining activities but also restricts the capacity for effective intervention (Hallatu et al., 2021; Kayani et al., 2023). Consequently, traditional enforcement tools that rely on physical inspections and sporadic reports are inadequate for addressing a phenomenon that evolves rapidly and often operates clandestinely (Dethier et al., 2019).

In light of this challenging scenario, remote sensing technologies emerge as viable and strategic alternatives for enhancing environmental monitoring. The use of satellite imagery, drones, and geospatial analysis enables the identification of mining activity patterns, mapping of at-risk areas, and generation of critical information that supports informed decision-making (Cabernard & Pfister, 2022; Wang et al., 2020). These tools not only optimize territorial oversight, but also provide essential technical inputs for the design of public policies grounded in solid evidence (Chakuya et al., 2023; Dethier et al., 2023).

Thus, the primary objective of this research is to develop an open-source web platform dedicated to the prevention and monitoring of illegal mining activities through advanced geospatial technologies and predictive modeling. This proposal offers a flexible, replicable, and robust solution, capable of adapting to various territorial contexts and supporting institutions in the strategic planning of their regulatory actions (Asner et al., 2013; Asner & Tupayachi, 2016). Ultimately, this approach—grounded in technological innovation and effective operational application—stands as a fundamental strategy to address challenges in environments highly vulnerable to illegal mining.

Methodology

The research employed a quantitative approach, focusing on integrating geospatial tools to develop an open-source web platform aimed at monitoring and preventing illegal mining activities. Consequently, it adopted an applied character, prioritizing the creation of a functional system that processes and visualizes territorial information in real-time, with immediate practical impact. Furthermore, a non-experimental and descriptive design was utilized, analyzing existing data without intervening in environmental variables, and concentrating on identifying, visualizing, and spatially analyzing patterns associated with informal mining.

Use of satellite imagery for detecting illegal mining

Satellite imagery served as the primary instrument for identifying changes in the territory. These images were obtained through Google Earth Engine (GEE), a platform that facilitated access to time-series data from optical satellites such as Sentinel-2 and Landsat, particularly suited for multitemporal land use analysis and large-scale change detection.

Specifically, satellite data enabled the detection of alterations through two key procedures:

- **Change detection:** Images from different periods were compared to identify transformations in the landscape, such as deforestation, soil removal, road opening, or expansion of disturbed areas. This process was executed using Google Earth Engine's analytical tools, employing specific scripts to calculate spectral indices (NDVI, NBR, BSI), generate multitemporal reflectance differences, and apply automatic thresholds to highlight disturbances directly associated with informal mining activities.
- **Continuous monitoring**: A systematic use of satellite imagery was implemented to periodically surveil the territory. This procedure was conducted through automated scripts in Google Earth Engine (GEE), which continuously updated the time-series data from Sentinel-2 and Landsat. Consequently,

comparative maps were generated between dates, facilitating the detection of risk zones, patterns of mining expansion, and early identification of emerging hotspots in near real-time.

Geospatial data analysis

The system integrated various spatial analysis tools to process the collected information and convert it into useful inputs for decision-making. Among its main functionalities were:

- **Pattern recognition:** Classification algorithms and spatial analysis, implemented in the platform and based on geometric and thematic characteristics of GeoJSON data, accurately detected typical configurations of illegal mining.
- **Multilayer analysis:** The combination of geological, hydrological, and territorial data provided a comprehensive evaluation of affected areas, considering their broader environmental context and the interactions between variables.
- **Thematic visualization:** Maps using percentiles, color gradients, and differentiated iconography clearly represented the types of mining activities, making the information intuitive even for users without specialized knowledge in geospatial analysis.

Predictive modeling for future scenario planning

The tool incorporated predictive modeling capabilities to anticipate future illegal mining behavior and assess the effectiveness of intervention strategies. To achieve this, the following methods were utilized:

- **Trend analysis:** A detailed study of historical records and expansion patterns identified vulnerable zones and recurring territorial dynamics, projecting medium-term risks based on observed trajectories.
- **Scenario simulation:** Models representing different control strategies estimated their potential impact on reducing unauthorized mining activity, thus supporting proactive decision-making and strategic planning.

Results and discussion

Detection and monitoring of illegal mining

The developed system demonstrated its effectiveness in detecting and monitoring unauthorized mining activities. Through the multitemporal analysis of satellite images and geospatial data integrated within the platform, it was possible to accurately identify areas impacted by illegal mining, generating updated georeferenced information on changes occurring in the territory. These capabilities not only enabled continuous surveillance of the landscape but also significantly improved the identification of active hotspots, particularly in remote and inaccessible regions where informal mining tends to expand rapidly and uncontrollably.

Integration and analysis of geospatial data

Moreover, the integration of multiple layers of geospatial data facilitated a comprehensive assessment of the environmental, social, and territorial impacts associated with unregulated mining operations. Consequently, the analytical tools classified zones according to the type of substance extracted, the method of exploitation employed, the level of environmental impact, and the degree of pollution generated. This information was presented through customized filters and interactive thematic maps, allowing for the detection of clear spatial patterns and regional trends, thereby supporting informed decisions in real time.

Figure 1
Total area affected by country

Figure 1 reveals a notable geographical concentration of the impact of illegal mining in Latin America, highlighting spatial patterns that reflect regional structural vulnerabilities. Countries such as Peru, Brazil, and Colombia lead in the area affected, a phenomenon that aligns perfectly with their vast territorial characteristics—extensive Amazonian jungles, mountain ranges rich in gold veins—and the abundance of strategic mineral resources such as gold, coltan, and bauxite. This distribution not only validates documented patterns in previous research but also underscores the urgent need to deploy more robust and sophisticated monitoring tools, along with differentiated intervention strategies that consider each nation's unique geopolitical context, local governance dynamics, and socio-environmental particularities.

Predictive modeling and scenario planning

Furthermore, the predictive modeling capabilities embedded in the platform provided valuable tools for anticipating the expansion of illegal mining. Based on a detailed analysis of historical data and observed spatial patterns, risk scenarios were generated that highlighted areas with a high probability of future intervention, projecting medium-term threat trajectories. Consequently, these results offered a solid foundation for strengthening monitoring and control strategies, enabling authorities to focus resources more efficiently on critical zones. The developed simulations also served as essential technical inputs for designing informed public policies and proactive territorial conservation plans.

Figure 2
Temporal evolution of illegal mining

Figure 2 indicates a sustained upward trend in illegal mining activity during the analyzed period, revealing a pattern of exponential growth that challenges implemented institutional measures. This behavior not only suggests a systematic and uncontrolled expansion of these operations but also correlates directly with critical socioeconomic events—such as rural employment crises, fluctuations in international gold prices, and weaknesses in territorial governance. As a result, these findings urgently highlight the need to implement real-time monitoring and predictive analysis tools that anticipate future trajectories and enable proactive responses.

Frequency analysis of mining variables

As part of processing the data loaded onto the platform, detailed frequency charts were generated to examine the distribution of exploration methods, types of substances extracted, and associated pollutants. The results show an overwhelming predominance of the alluvial exploitation method—typical of rivers and fluvial sediments—followed at a distance by other modalities such as pit or open-cast mining with lower relative incidence.

Regarding mineral substances, gold emerges as the predominant resource in the processed records, reflecting its high economic value and global demand. In terms of pollutants, mercury ranks as the primary agent, widely used in amalgamation processes that cause irreversible damage to aquatic ecosystems and food chains. This detailed characterization not only facilitates precise targeting of control and mitigation strategies but also enables prioritization of interventions in regions of high activity and areas particularly vulnerable due to the type of environmental impact detected.

Figure 3

Frequency of exploration methods

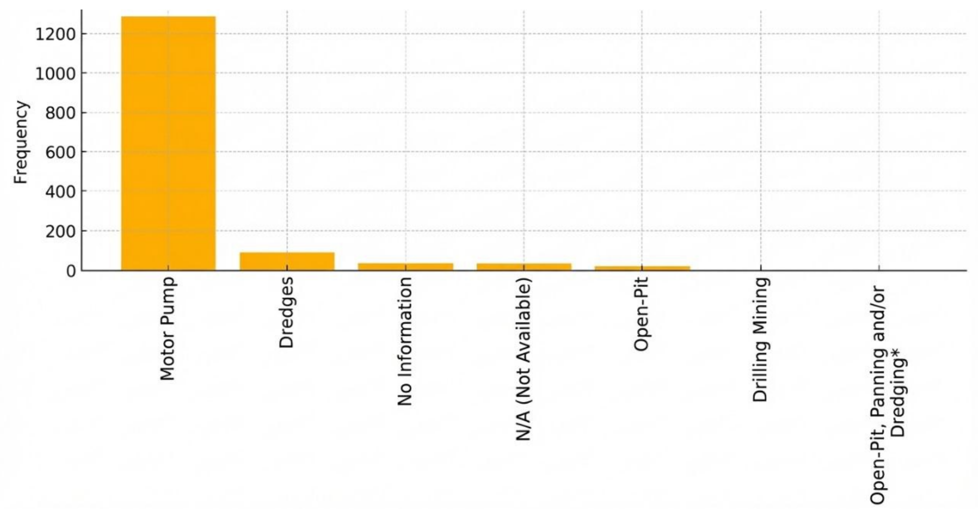


Figure 3 confirms that the alluvial exploitation technique clearly dominates the processed records, ranking as the most frequent method of detected illegal mining. This extraction type, which concentrates primarily in riverbeds, rivers, and alluvial sediments, poses exceptionally high risks to aquatic ecosystems, water resource quality, and dependent riparian communities. Thus, its high incidence not only evidences the structural vulnerability of these environments but also underscores the urgent priority that must be assigned to the intensive monitoring of riparian zones, the implementation of river control barriers, and specific hydrological restoration strategies in critical areas.

Figure 4
Frequency of extracted substances

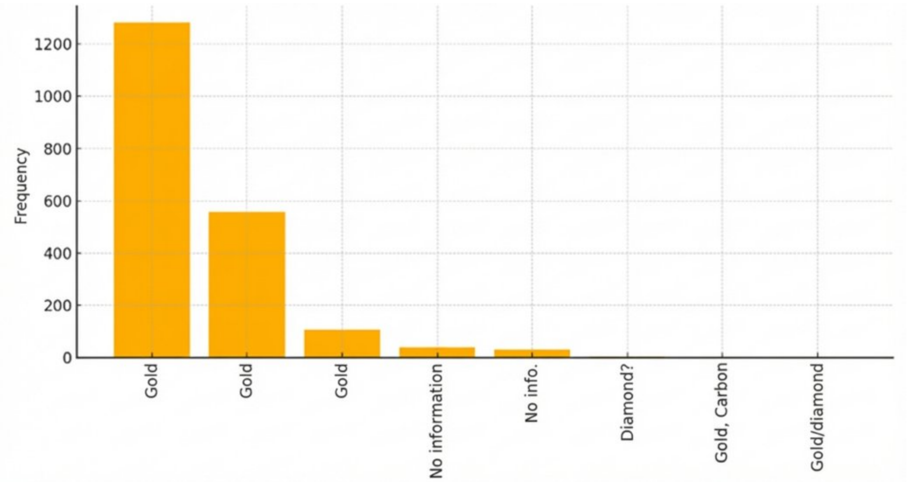
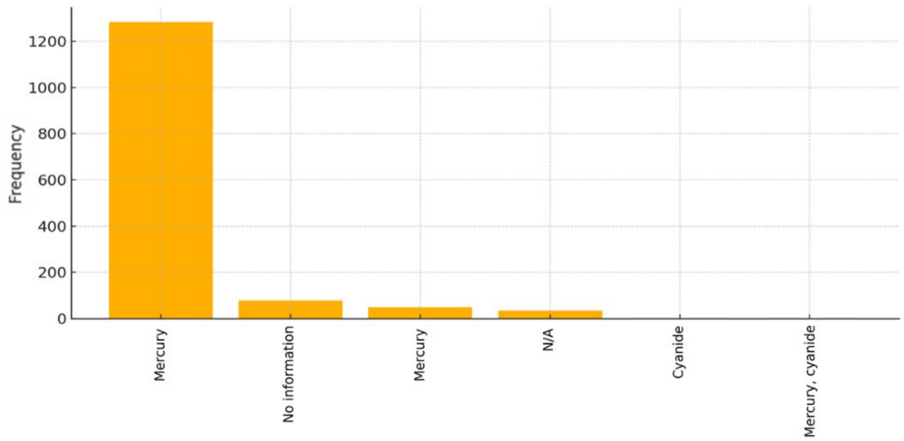


Figure 4 identifies gold as the primary resource extracted in illegal mining operations, with a frequency overwhelmingly higher than other minerals such as coltan or bauxite. This pattern perfectly aligns with the extremely high global demand for this precious metal—driven by the jewelry, technology, and financial industries—and its ease of commercialization in informal markets that evade all forms of traceability. Therefore, this predominance not only confirms irresistible economic incentives for illegal operators but also reinforces their close association with transnational organized crime networks, armed group financing, and illicit flows that perpetuate cycles of violence and corruption in vulnerable regions.

Figure 5
Frequency of associated contaminants



Finally, Figure 5 confirms that mercury dominates as the most commonly linked contaminant to illegal mining, followed at a distance by cyanide and other toxic chemical waste. This finding is particularly alarming, as mercury exhibits extreme environmental persistence—capable of remaining in fluvial sediments for decades—and bioaccumulative toxicity that relentlessly propagates through aquatic food chains. Consequently, its devastating effects transcend ecosystems, severely impacting the health of riparian human communities through chronic poisoning and irreversible neurological damage, while simultaneously threatening the survival of iconic wildlife such as fish, piscivorous birds, and apex felines in critical biodiversity regions.

Conclusions

The integration of geospatial technologies within an interactive web platform proved to be an effective strategy for monitoring and preventing illegal mining, especially in remote and difficult-to-access territories. The use of multitemporal satellite imagery, georeferenced data, and multilayer analysis allowed for precise and contextual representations of the disturbed areas, overcoming the inherent limitations of traditional field inspection methods and facilitating the early detection of spatial patterns associated with unauthorized mining activities.

Moreover, the system's capacity to upload geospatial files in GeoJSON format, apply dynamic filters, and generate thematic visualizations tailored to the content of each file enabled detailed analysis of critical variables such as the type of substance extracted, the level of environmental impact, the methods of exploitation employed, and the contaminants present. This flexibility transformed the platform into a versatile tool, adaptable to diverse institutional, territorial, and community needs, thereby enhancing its real value for territorial management in vulnerable areas.

The frequency analysis and integrated statistical visualizations also facilitated a robust quantitative characterization of illegal mining activity, revealing clear temporal trends and recurring spatial patterns. Consequently, these results provide strategic information for public policy formulation, allowing authorities to prioritize critical intervention zones, optimize the allocation of limited resources, and strengthen control and enforcement strategies more effectively.

The developed platform also generates significant methodological benefits. By centralizing geospatial processing in an accessible, open-source tool, it democratizes access to high-quality satellite data, dramatically reducing reliance on specialized and expensive software. This empowers local institutions, environmental organizations, and even affected communities, enabling them to generate reliable information and make evidence-based decisions grounded in solid geospatial data.

Additionally, the system's modular architecture—implemented with open web technologies—ensures high replicability and scalability. It facilitates integration with existing institutional systems, the seamless incorporation of new territorial layers, and expansion into regions with distinct environmental and social characteristics. Furthermore, this design promotes the technical sustainability of the system by simplifying maintenance and allowing for continuous updates without incurring prohibitive costs.

Complementarily, the study identified relevant limitations that enrich critical analysis. The accuracy of monitoring depends on the spatial and temporal resolution of available satellite images, which may restrict the detection of small-scale or ephemeral mining activities. Likewise, areas with high cloud cover present challenges for multitemporal analyses. However, these limitations can be effectively mitigated through the triangulation of complementary data sources and the integration of denser and more frequent time-series data.

Overall, the results confirm that the developed tool represents a substantial technological and methodological contribution to strengthening environmental governance and optimizing the control of illegal extractive activities. Its practical implementation can enhance effective territorial surveillance, prevent emerging socio-environmental conflicts, and protect sensitive ecosystems, positioning it as a viable and scalable alternative for environmental monitoring efforts in remote or hard-to-access contexts.

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