End Term Report

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Abstract

Effective regulatory oversight of open-cast mining requires continuous, objective monitoring of excavation footprints and adherence to geo-fenced boundaries. Traditional remote sensing approaches often rely on fixed spectral thresholds, rendering them brittle across diverse geological landscapes and seasonal variations. In this work, we present an operational, end-to-end Decision Support System (DSS) that utilizes multi-sensor satellite fusion (Sentinel-2 and Sentinel-1) and adaptive Change Vector Analysis (CVA) to autonomously track mining progression. Unlike static models, our system dynamically calculates extraction thresholds based on statistical percentiles (85th percentile), ensuring mine-agnostic scalability without manual calibration. The system features a decoupled architecture, processing large-scale multi-temporal satellite archives on the cloud and serializing results into a lightweight, interactive client-side dashboard for monthly compliance auditing. Experimental results on the target mine demonstrate the system's ability to automatically detect encroachment into No-Go zones with high temporal consistency.

1 Introduction

Open-pit mining activities involve rapid terrain modification, vegetation removal, and potential encroachment into ecologically sensitive areas. Regulatory bodies require frequent, accurate audits to ensure that excavation remains within licensed boundaries. However, manual ground surveys are infrequent, and traditional satellite monitoring is often hindered by cloud cover, seasonal phenological changes, and the spectral heterogeneity of different mineral types (e.g., Coal vs. Bauxite).

We address these challenges by deploying a fully automated, unsupervised monitoring pipeline. Our contribution is twofold:

1. A **Robust Backend Algorithm** that utilizes adaptive statistical thresholding and temporal filtering to generate consistent excavation masks.
2. An **Operational Dashboard** that translates complex geospatial data into actionable "Audit Logs" and compliance alerts.

This report details the operational execution of the system, shifting from the proposed framework to a deployed full-stack solution.

2 Methodology: Adaptive Geospatial Backend

The proposed system is implemented in Python using the Google Earth Engine (GEE) API. It is a fully unsupervised and mine-agnostic pipeline that monitors excavation activity through temporal persistence of surface change rather than fixed spectral thresholds or supervised learning models.

2.1 Data Acquisition and Pre-processing

The system utilizes multi-temporal satellite data from two complementary sensors:

- **Sentinel-2 Level-2A (Optical):** Multispectral surface reflectance used to detect vegetation loss and soil exposure.
- **Sentinel-1 GRD (SAR):** C-band radar backscatter used to detect surface roughness changes independent of cloud cover.

Cloud-contaminated Sentinel-2 pixels are removed using the `QA60` quality band by masking opaque cloud and cirrus flags. For both sensors, monthly median composites are generated to suppress random noise, atmospheric artefacts, and short-term fluctuations.

2.2 Adaptive Change Vector Analysis (CVA)

Mining excavation causes abrupt and persistent changes in surface reflectance and backscatter. To capture these changes, Change Vector Analysis (CVA) is applied between consecutive monthly composites ($t-1$, t).

2.2.1 Optical CVA

From Sentinel-2 imagery, indices sensitive to vegetation loss and surface disturbance are computed. The optical change magnitude is defined as:

$$M_{optical} = \sqrt{(\Delta NDVI)^2 + (\Delta NBR)^2 + (\Delta SWIR)^2} \tag{1}$$

where Δ denotes the difference between consecutive monthly composites. This formulation captures combined changes due to vegetation removal, exposed soil, and material excavation.

An adaptive threshold is computed from the statistical distribution of change magnitudes:

$$T_{optical} = P_{85}(M_{optical}) \tag{2}$$

2.2.2 SAR CVA

To ensure robustness during cloudy periods, SAR-based change detection is also performed using Sentinel-1 VV and VH polarizations and their ratio:

$$M_{SAR} = |VV_t - VV_{t-1}| + |VH_t - VH_{t-1}| + |RATIO_t - RATIO_{t-1}| \tag{3}$$

A dynamic SAR threshold is computed as:

$$T_{SAR} = P_{80}(M_{SAR}) \tag{4}$$

2.3 Multi-Sensor Fusion

Optical and SAR detections are fused using a logical OR operation to improve robustness:

$$Mask_{candidate} = Mask_{optical} \vee Mask_{SAR} \tag{5}$$

This fusion enables reliable excavation detection even under persistent cloud cover.

2.4 Temporal Consistency and Stabilization

Mining is a physically irreversible process; excavated areas persist once formed. To eliminate transient noise and enforce physical consistency, a temporal stabilization rule is applied:

$$Mask^t_{stable} = Mask^t_{candidate} \cap Mask^{t-1}_{candidate} \tag{6}$$

Stable detections are accumulated over time to generate a cumulative excavation mask, which forms the basis for area quantification, time-series analysis, and alert generation.

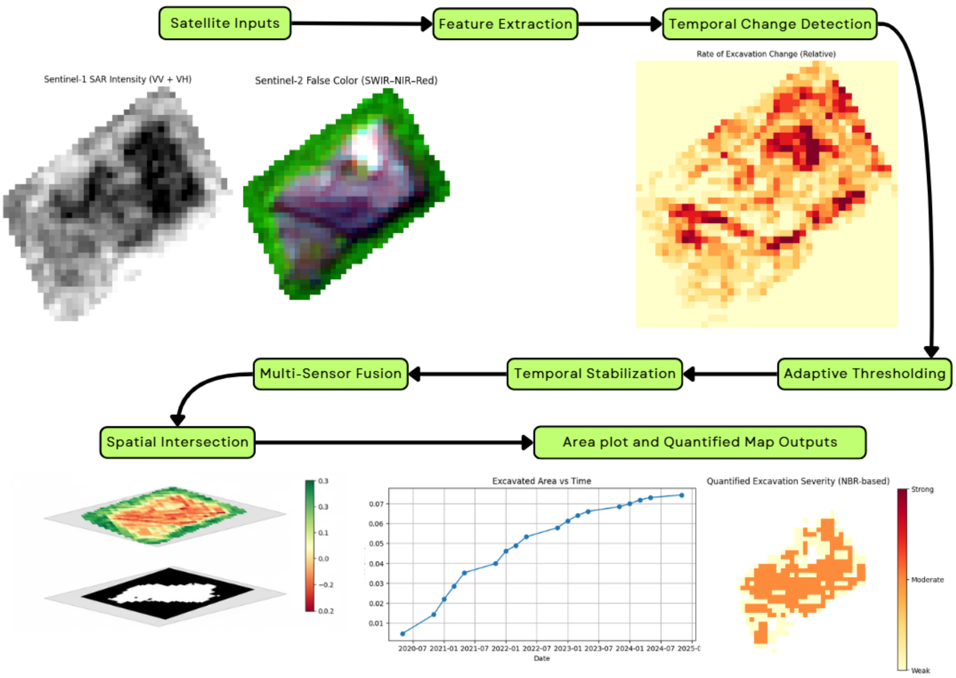

Figure 1: End-to-end adaptive mining detection pipeline using multi-sensor CVA, percentile-based thresholding, and temporal stabilization.

3 System Architecture and Dashboard-Driven Decision Support

The proposed system follows a decoupled, production-oriented architecture in which all geospatial intelligence is computed in the backend prior to visualization, while the frontend dashboard serves as a lightweight decision-support layer. This separation ensures scalability, reproducibility, and usability for regulatory authorities.

3.1 Overall System Architecture

The backend is implemented in Python using the Google Earth Engine (GEE) API for large-scale satellite processing, while the frontend is a client-side dynamic web application that allows users to upload serialized analytical outputs and interactively visualize backend-derived metrics without requiring live backend connectivity.

- **Backend:** Python, Google Earth Engine, Geemap, NumPy, Pandas
- **Frontend:** HTML5, CSS3, JavaScript (Chart.js, Leaflet.js)
- **Data Interface:** Pre-computed `output.json` (no live backend calls)

This design allows the system to operate efficiently even in low-bandwidth or offline field environments.

3.2 Operational Dashboard and Metric Interpretation

The operational dashboard provides an interactive interface for visualizing backend-derived excavation metrics and compliance indicators. The dashboard components are numbered to directly map visual elements to their corresponding analytical outputs discussed in this section.

Figure 2 shows the dashboard in the *Legal Zone* context, presenting cumulative excavation statistics and temporal trends for the permitted mining area.

Figure 2: Dashboard view for Legal Zone monitoring.

Figure 3 presents the *No-Go Zone* monitoring context, where zone-specific excavation metrics and violation status indicators are displayed for compliance assessment.

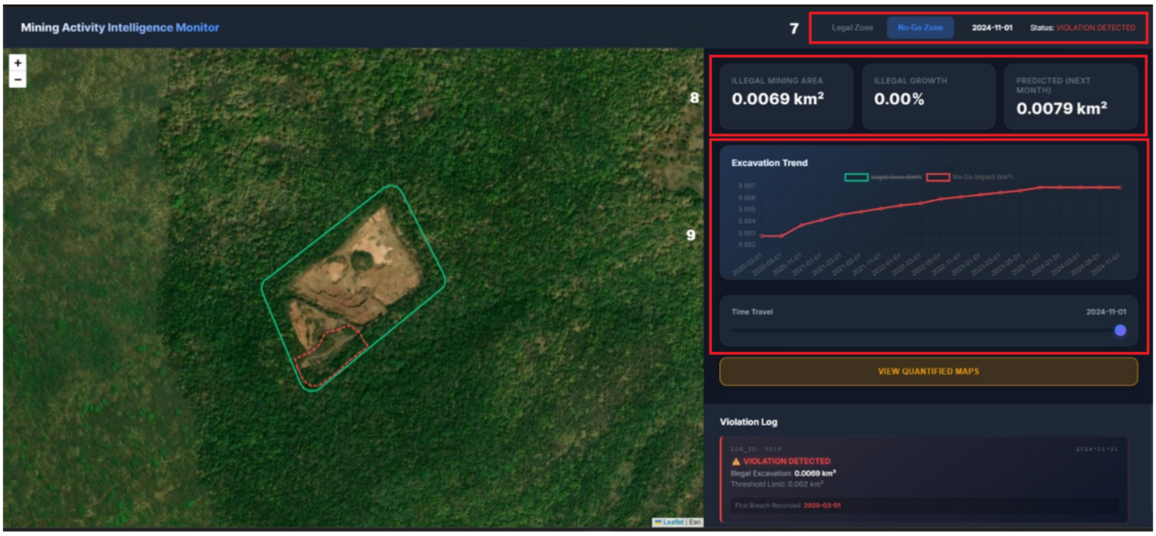

Figure 3: Dashboard view for No-Go Zone monitoring.

3.3 Key Dashboard Components

1. **Current Legal Excavation Area:**
   Displays the latest cumulative excavated area (km^2) within the legally permitted mine boundary, computed from temporally stabilized CVA-derived excavation masks.

2. **Monthly Growth Rate:**
   Represents the month-to-month percentage increase in excavated area, derived directly from the excavation time-series and used as an indicator of excavation acceleration or slowdown.

3. **Predicted Excavation (Next Month):**
   A short-term forecast obtained via linear regression on historical excavation trends, enabling early-warning assessment of potential boundary stress.

4. **Excavation Time-Series Trend with Temporal Slider:**
   A cumulative excavation time-series plot equipped with an interactive temporal slider, allowing smooth inspection of excavation extent and growth dynamics for any historical month.

5. **Quantified Map Viewer:**
   Enables overlay of backend-generated excavation masks on true-color satellite imagery, supporting visual verification of detected changes and reducing black-box ambiguity.

6. **Violation Log:**
   A chronological, immutable audit trail documenting detected No-Go zone violations, including first breach date, quantified illegal area, and compliance status.

7. **Zone Context Selector and Compliance Status Indicator:**
   Allows switching between the Legal Zone and individual No-Go Zones while simultaneously displaying real-time compliance status (Compliant / Violation Detected). All metrics, plots, and alerts are dynamically updated based on the selected zone context.

8. **No-Go Zone Summary Metrics:**
   Displays zone-specific illegal excavation area, growth rate, and predicted near-term expansion, enabling localized risk assessment for each restricted boundary.

9. **No-Go Zone Excavation Trend:**
   Time-series visualization of cumulative excavation progression within restricted zones, supporting forensic analysis of violation onset and escalation patterns.

3.4 Backend Processing and Data Serialization

The backend (`pipeline.py`) operates as a batch-processing geospatial analytics engine. Multi-temporal Sentinel-1 and Sentinel-2 imagery are processed to generate stabilized excavation masks using adaptive Change Vector Analysis (CVA) and temporal consistency constraints.

From the finalized excavation masks, the following metrics are computed:

- **Cumulative Excavation Area:** Calculated as the total pixel area classified as excavation within a zone, converted to km^2.
- **Monthly Growth Rate:** Derived as the percentage change in cumulative excavation area between consecutive observation dates.
- **No-Go Zone Impact:** Computed via spatial intersection between excavation masks and restricted zone polygons.
- **Violation Status:** Triggered when detected excavation area exceeds predefined soft or hard thresholds within any No-Go zone.
- **Short-Term Forecasting:** Next-month excavation area estimated using linear regression on the verified excavation time-series.

All computed outputs are serialized into a structured JSON payload (`output.json`), which serves as the single source of truth for the dashboard. This design eliminates real-time computation on the client side, ensuring deterministic performance, low-latency interaction, and reliable deployment in low-bandwidth field environments.

4 Results and Analysis

The proposed adaptive monitoring system was evaluated on a target mining site over a multi-year period from March 2020 to November 2024. All results presented in this section are derived directly from the system-generated `output.json` payload.

4.1 Excavation Time-Series Analysis

The excavation dynamics of the target mine were quantified using a temporal analysis of cumulative excavated area and month-to-month growth rates derived from the backend-generated time-series data.

Figure 4 illustrates the temporal evolution of mining activity, where the cumulative percentage of land mined is plotted alongside the monthly growth rate. The results indicate a steady and physically consistent expansion of the mining footprint, with the total excavated area increasing from **0.0306 km**^{2} (May 2020) to **0.077 km**^{2} (November 2024).

By the end of the observation period, approximately **47.26%** of the licensed mining area had been excavated, providing a direct and interpretable compliance metric for regulatory monitoring. The monotonic increase in cumulative excavation confirms the effectiveness of the temporal stabilization logic, ensuring that transient changes are excluded.

Monthly growth rate analysis reveals higher excavation intensity during early operational phases, followed by a gradual decline in growth rates in later years. This trend is consistent with expected mine development behavior and indicates a transition toward operational stabilization rather than abrupt expansion.

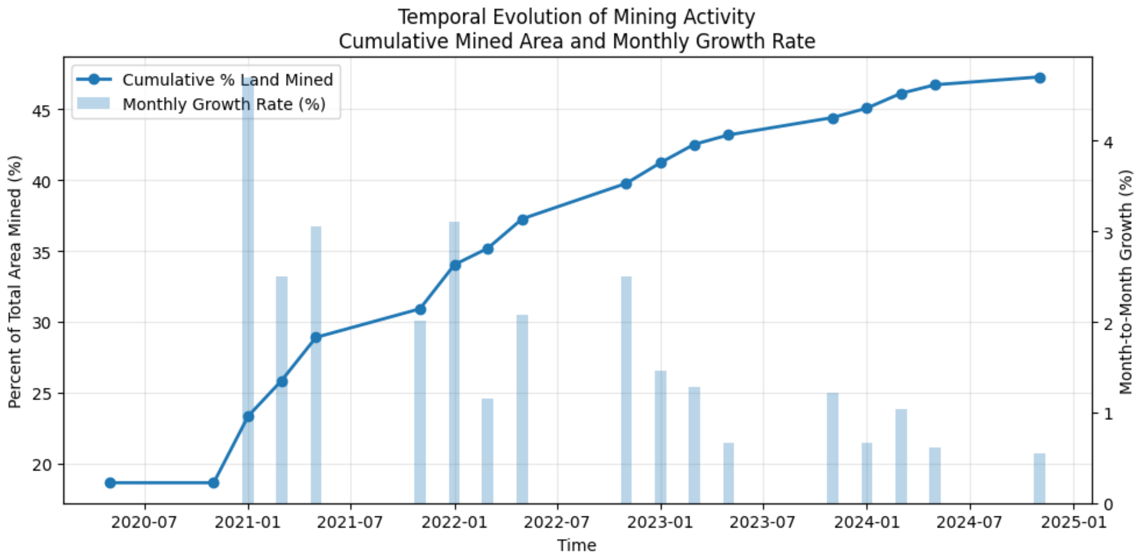

Figure 4: Temporal evolution of mining activity showing cumulative percentage of excavated area (line) and month-to-month growth rate (bars).

4.2 No-Go Zone Violation Detection

The system autonomously monitored spatial intersections between the detected excavation masks and geo-fenced no-go zones to identify regulatory violations. Any non-zero intersection triggered a compliance alert, enabling immediate flagging of illegal encroachment.

For all monitored zones (green, yellow, and red), the system detected the first violation on **2020-05-01**, immediately classifying the events as **Hard Alerts**. This demonstrates the system's sensitivity to even minimal illegal excavation activity.

Quantitative analysis of the red zone reveals an average violation growth rate of **0.0001 km^2/month**, with a peak encroachment of **0.0004 km^2** recorded in **March 2021**, indicating a brief period of intensified illegal activity.

By the end of the analysis period, the total excavated area within each no-go zone was measured as:

- **Green Zone:** 0.0026 km^2
- **Yellow Zone:** 0.0104 km^2
- **Red Zone:** 0.0022 km^2

These results confirm the system's ability to generate an auditable, time-stamped record of illegal mining activity, supporting regulatory enforcement and long-term compliance monitoring.

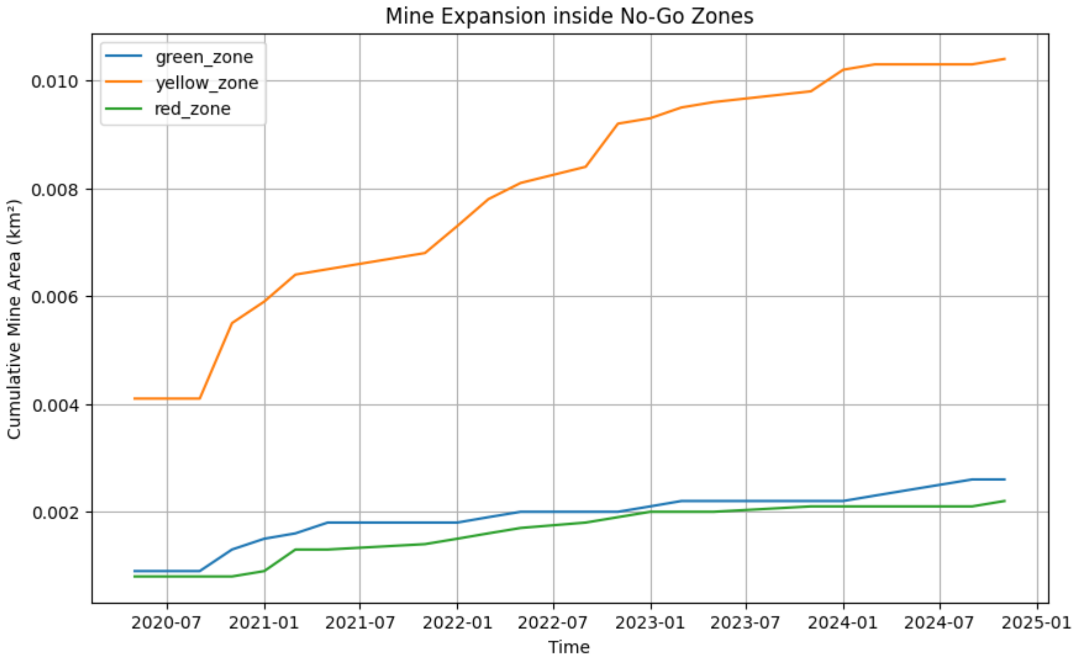

Figure 5: Cumulative mine expansion within designated no-go zones over time. Persistent growth trends confirm sustained regulatory violations, with zone-wise separation highlighting differential encroachment intensity.

4.3 Spatial Validation

To validate quantitative outputs, the system generated monthly excavation maps for both the main mine and all no-go zones. These maps overlay stable excavation masks on corresponding satellite imagery, visually confirming progressive pit expansion and boundary violations.

The strong spatial correspondence between detected masks and visible excavation features demonstrates that the system reliably distinguishes true mining activity from seasonal vegetation loss, cloud artefacts, or sensor noise.

5 Discussion

5.1 Adaptiveness: Mine-Agnostic Change Detection

A central requirement of the problem statement was robustness across diverse mine types (e.g., coal, bauxite, limestone) without manual parameter tuning. This is achieved through **percentile-based adaptive thresholding** applied to Change Vector Analysis (CVA).

Rather than relying on fixed spectral thresholds (e.g., $NDVI < 0.2$), which are sensitive to soil color, illumination, and seasonal variability, the system dynamically derives change thresholds from the statistical distribution of observed changes within each region of interest (85th percentile for optical and 80th percentile for SAR). As a result, the pipeline self-calibrates to local contrast conditions, enabling consistent performance across heterogeneous geological and environmental settings.

5.2 Scalability and Operational Feasibility

The system architecture is designed for scalable and operational deployment by decoupling backend geospatial computation from frontend visualization.

- **Backend Scalability:** All computationally intensive processing is executed within the Google Earth Engine environment, leveraging its distributed infrastructure for large-scale, multi-temporal satellite analysis.

- **Deployment Efficiency:** Analytical outputs are serialized into a compact JSON payload, which is consumed by a lightweight web dashboard without requiring live backend computation or specialized hardware.

This design enables responsive interaction, reproducible analysis, and practical deployment in bandwidth-constrained or field-based regulatory environments.

6 Conclusion

This work demonstrates a fully implemented, end-to-end geospatial decision support system for automated mining activity monitoring and No-Go zone compliance assessment. By combining adaptive multi-sensor change detection with temporal stabilization and structured analytics delivery, the system converts raw satellite imagery into interpretable compliance intelligence.

The proposed approach eliminates manual threshold tuning, supports mine-agnostic deployment, and provides transparent audit trails through quantified maps and time-series analytics. These capabilities position the system as a practical tool for regulatory monitoring, environmental oversight, and early-warning assessment of illegal excavation.

References

[1] Lorena, R. B., et al. (2002). "A change vector analysis technique to monitor land use/land cover." *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences.*

[2] Drusch, M., et al. (2012). "Sentinel-2: ESA's Optical High-Resolution Mission for GMES Operational Services." *Remote Sensing of Environment.*