Automated Mining Excavation Monitoring System

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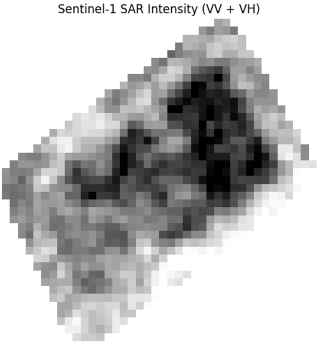
Satellite Data Sources: Optical Imagery

1. **Automated Acquisition**
   - Source: **Google Earth Engine (GEE) API**.
   - Process: Auto-fetching monthly composites.
   - Constraint: Max **10%** cloud cover.
2. **Feature Selection:** $\{$**B4, B8, B11, B12**$\}$
   - **Vegetation Loss:** Sharp decrease in **NBR** (B8, B11) and **NDVI** (B4, B8).
   - **Material Exposure:** Pronounced response in **SWIR (B11, B12)** and **Red (B4)**.
   - **Fresh Disturbance: B12** captures moisture variations in freshly turned earth.
   - **Stability:** Normalized indices suppress illumination and seasonal noise.
   - **Design:** Smallest representative set with minimal redundancy.

Sentinel-2 optical false-color composite of the mine area

Satellite Data Sources: SAR Imagery

1. **All-Weather Radar Sensing**
   - Source: **Sentinel-1 C-band SAR**.
   - Capability: Cloud- and illumination-independent monitoring.
2. **Backscatter Feature Selection**
   - **VV Polarization:** Sensitive to surface roughness and structural changes.
   - **VH Polarization:** Captures volume scattering from vegetation and loose material.
   - **VV/VH Ratio:** Enhances discrimination of excavation-induced disruption.
3. **All-weather acquisition:** Sentinel-1 microwave SAR operates independent of sunlight and penetrates clouds and atmospheric haze.
4. **Physical surface sensitivity:** Backscatter directly encodes surface roughness, geometry, and dielectric changes caused by excavation.



Sentinel-1 SAR backscatter image (VV/VH) of the same mine area

Detection Algorithm: Change Vector Analysis

- Mining activity is inferred from **spectral–temporal change**, not absolute reflectance.
- Relative change improves robustness across land-cover, illumination, and seasonality.

Per-pixel Temporal Differencing

For each pixel, spectral features are differenced between consecutive observations:

$$\Delta I_t = I_t - I_{t-1} \tag{1}$$

where $I \in \{\mathrm{NDVI}, \mathrm{NBR}, \mathrm{SWIR}, \mathrm{VV}, \mathrm{VH}, \mathrm{VV}/\mathrm{VH}\ \mathrm{Ratio}\}$.

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Multi-Index Change Vector Analysis (CVA)

To jointly capture complementary excavation signatures, Change Vector Analysis is defined as:

$$\mathrm{CVA}_{optical} = \sqrt{(\Delta\mathrm{NDVI})^2 + (\Delta\mathrm{NBR})^2 + (\Delta\mathrm{SWIR})^2} \quad (1)$$

$$CVA_{SAR} = |\Delta VV| + |\Delta VH| + |\Delta RATIO| \quad (2)$$

- Excavation manifests as vegetation loss and exposed soil/rock.
- CVA captures **change magnitude independent of direction**.
- Eliminates index-specific hard thresholds.

Detection Algorithm: Adaptive Statistical Thresholding

- Fixed spectral thresholds are brittle under varying geology, illumination, and seasonal conditions.
- Thresholds are therefore derived from the **statistical distribution of per-pixel change**.

Percentile-Based Change Selection

For each temporal interval, thresholds are computed from the distribution of Change Vector Analysis (CVA) magnitudes within the region of interest:

$$T_{\text{optical}} = P_{85}\left(\{\text{CVA}^{(i)}_{\text{optical}}\}\right), \quad T_{\text{SAR}} = P_{80}\left(\{\text{CVA}^{(i)}_{\text{SAR}}\}\right) \tag{3}$$

Pixels exceeding the threshold are treated as **candidate disturbances**, not final excavation.

- Percentiles isolate statistically extreme change rather than assuming a fixed mined fraction.
- Threshold values adapt automatically to local contrast and sensor noise characteristics.
- Final excavation is confirmed through **temporal persistence**, not a single decision step.

Detection Algorithm: Temporal Stabilization

- True excavation produces **persistent, spatially coherent** change.
- Transient effects (seasonality, illumination, atmosphere) are non-persistent.

Persistence-Based Stabilization

A pixel is confirmed as excavation only if the change persists across consecutive observations:

$$M^{t}_{\text{stable}} = M^{t}_{\text{candidate}} \cap M^{t-1}_{\text{candidate}} \tag{4}$$

- Enforces physical consistency and **suppresses false positives**.
- Stable detections are accumulated over time to form a cumulative excavation mask.
- Ensures **monotonic spatial growth** of detected mining extent.

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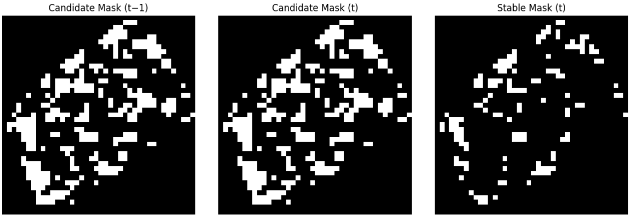

Persistence-based temporal stabilization of excavation masks

Detection Algorithm: Multi-Sensor Fusion

- Optical and SAR sensors capture **complementary excavation signatures**.
- Optical data is sensitive to vegetation loss and surface exposure.
- SAR data responds to structural and roughness changes, independent of clouds.

Logical Fusion Strategy

To ensure robust detection under varying acquisition conditions, the two detection streams are fused using a relaxed logical OR:

$$M_{\text{candidate}} = M_{\text{optical}} \lor M_{\text{SAR}} \tag{5}$$

- Preserves detections when either modality is reliable.
- Ensures continuity during cloud cover or optical data gaps.
- Fusion occurs **before temporal stabilization**.

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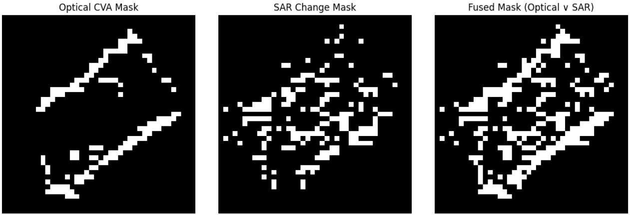
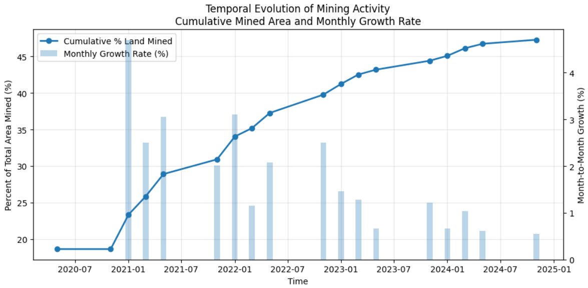


Optical CVA, SAR-based change detection, and fused excavation mask

Results: Cumulative Excavation Area vs Time



- Mining activity is quantified through temporal analysis of stabilized excavation masks.
- Cumulative excavated area captures long-term, physically consistent mine expansion.
- Month-to-month growth rates reveal short-term excavation intensity and operational phases.

System Robustness and Generalization

- **Mine-agnostic detection:** Excavation is inferred from relative spectral–temporal change rather than absolute reflectance values.
- **Adaptive self-calibration:** Percentile-based thresholds are derived from local change statistics, avoiding fixed, site-specific tuning.
- **Cross-sensor robustness:** Optical and SAR signals capture complementary excavation signatures under clouds and low-light conditions.
- **Deterministic, non-ML inference:** Physics-informed change metrics and statistical rules produce reproducible results with clear pixel-level reasoning.
- **Operational efficiency:** The absence of model training and inference overhead enables fast, scalable deployment for continuous monitoring.