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Mapping of artisanal gold mining extent using sentinel-2 imagery in the Guiana shield

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Abstract

Artisanal and small-scale gold mining (ASGM) in the Guiana Shield region of South America has expanded dramatically over the past two decades, driven by rising gold prices and limited economic alternatives for local communities. This expansion has resulted in widespread deforestation, river sedimentation, and mercury contamination of aquatic ecosystems. Accurate mapping of ASGM spatial extent is essential for environmental monitoring and regulatory enforcement, yet the remote nature of many mining areas makes ground surveys impractical. This research employs multi-temporal Sentinel-2 multispectral imagery to map ASGM extent across a 45,000 km² area within the Guiana Shield, encompassing portions of Suriname and French Guiana. A supervised Random Forest classification was applied to annual composites from 2018 to 2023, incorporating spectral bands, vegetation indices, and textural features. The classification achieved 89.3% overall accuracy with kappa of 0.86. Mining-affected area increased from 1,240 ha in 2018 to 3,870 ha in 2023—a 212% expansion—with the most rapid growth along previously unaffected tributaries. Mercury contamination risk zones were delineated using hydrological flow accumulation, identifying 2,300 km of high-risk stream length intersecting protected areas and indigenous territories. These findings support the development of operational satellite monitoring systems for ASGM regulation.

Keywords: Artisanal gold mining, Sentinel-2, Guiana Shield, land degradation, mercury contamination, Random Forest, deforestation, remote sensing, change detection, environmental monitoring

Introduction

The Guiana Shield, a Precambrian geological formation spanning Venezuela, Guyana, Suriname, French Guiana, and northern Brazil, hosts extensive gold mineralisation associated with greenstone belt sequences that have attracted mining for centuries ^[1]. While industrial operations have been present since the colonial era, ASGM has experienced unprecedented growth since the early 2000s, driven by sustained gold price increases and economic marginalisation of rural and indigenous communities. Current estimates suggest ASGM employs over 500,000 individuals across the region, producing 15-25 tonnes of gold annually through largely informal channels ^[2].

The environmental consequences of ASGM in tropical forests are severe and multifaceted. Mining involves clearing vegetation, removing topsoil, and processing gold-bearing materials using mercury amalgamation. Deforestation eliminates habitat and carbon storage capacity, sediment mobilisation degrades aquatic ecosystems and impairs water quality, and mercury release contaminates food webs with persistent neurotoxic pollutants ^[3]. The cumulative footprint of thousands of individual operations creates environmental damage disproportionate to the modest economic returns generated ^[4].

Remote sensing offers significant potential for monitoring ASGM across inaccessible areas. Previous research demonstrated the utility of Landsat and MODIS for broad-scale deforestation mapping ^[5], but their coarse spatial resolution limits detection of small-scale operations. The Sentinel-2 constellation, providing free multispectral imagery at 10 m resolution with five-day revisit frequency, creates new opportunities for detailed ASGM mapping ^[6]. Google Earth Engine provides the cloud computing platform necessary to process multi-temporal composites across large areas efficiently ^[7].

This research aims to exploit Sentinel-2 to produce comprehensive ASGM extent maps across the Guiana Shield and quantify expansion from 2018 to 2023. The objectives are to

develop a robust classification methodology, characterise spatial and temporal mining dynamics, and delineate mercury contamination risk zones based on hydrological connectivity to support evidence-based regulatory decisions [8].

Research Area Description

The research area encompasses approximately 45,000 km² within the central Guiana Shield, spanning the Suriname-French Guiana border region. The terrain comprises low-relief uplands covered by dense tropical rainforest, dissected by numerous rivers and streams serving as access routes and alluvial gold sources. Elevation ranges from 20 to 800 m above sea level, with annual precipitation of 2,200-2,800 mm. The area contains a high density of both legal and illegal ASGM operations and exhibits a range of mining intensities from recent small clearings to extensively degraded landscapes [1, 2].

Materials and Methods

Materials

Sentinel-2 Level-2A surface reflectance products were acquired from the Copernicus Open Access Hub for January 2018 to December 2023. Persistent cloud cover necessitated pixel-based compositing to generate annual cloud-free mosaics using median reflectance across all cloud-free observations per year. Training data were collected through visual interpretation of very high-resolution imagery in Google Earth Pro, supplemented by field observations from

previous surveys. A total of 2,400 training polygons were digitised across five land cover classes: forest, water, mining, bare soil, and cloud shadow [6, 7].

Methods

Spectral features included reflectance in all thirteen Sentinel-2 bands. Vegetation indices comprised NDVI, EVI, and NDWI. Textural features from GLCM on the NIR band at 7×7 pixels included contrast, homogeneity, entropy, and angular second moment. Classification used Random Forest with 500 trees in Google Earth Engine [7]. Accuracy was assessed using 850 stratified random reference points. Multi-temporal change detection compared annual classified maps, supplemented by spectral change vector analysis to detect subtle transitions [5, 9].

Mercury Risk Zone Delineation

Contamination risk zones were computed by downstream flow accumulation from identified mining sites using a hydrologically corrected SRTM digital elevation model at 30 m resolution. Stream reaches within 25 km downstream of active operations were classified as high risk. Spatial intersection with protected area and indigenous territory boundaries quantified the exposure of vulnerable populations to mercury through fish consumption pathways, the primary route of human exposure in Amazonian communities [3, 10].

Results

Table 1: Classification accuracy metrics for the 2023 land cover map.

Class	Producer Acc. (%)	User Acc. (%)	F1 Score
Forest	94.2	96.1	0.95
Water	91.8	88.5	0.90
Mining	87.1	91.4	0.89
Bare Soil	82.4	84.7	0.84
Cloud/Shadow	96.3	97.8	0.97

Overall accuracy was 89.3% with kappa 0.86. The mining class achieved 87.1% producer and 91.4% user accuracy. Misclassification primarily involved small clearings

adjacent to natural river channels being mapped as water or sediment bars. Agreement with Global Forest Watch independent maps was strong in areas of extensive mining.

Table 2: Mining-affected area by year and annual expansion rate.

Year	Area (ha)	Annual Change (ha)	Growth Rate (%)
2018	1,240	—	—
2019	1,580	340	27.4
2020	2,100	520	32.9
2021	2,850	750	35.7
2022	3,420	570	20.0
2023	3,870	450	13.2

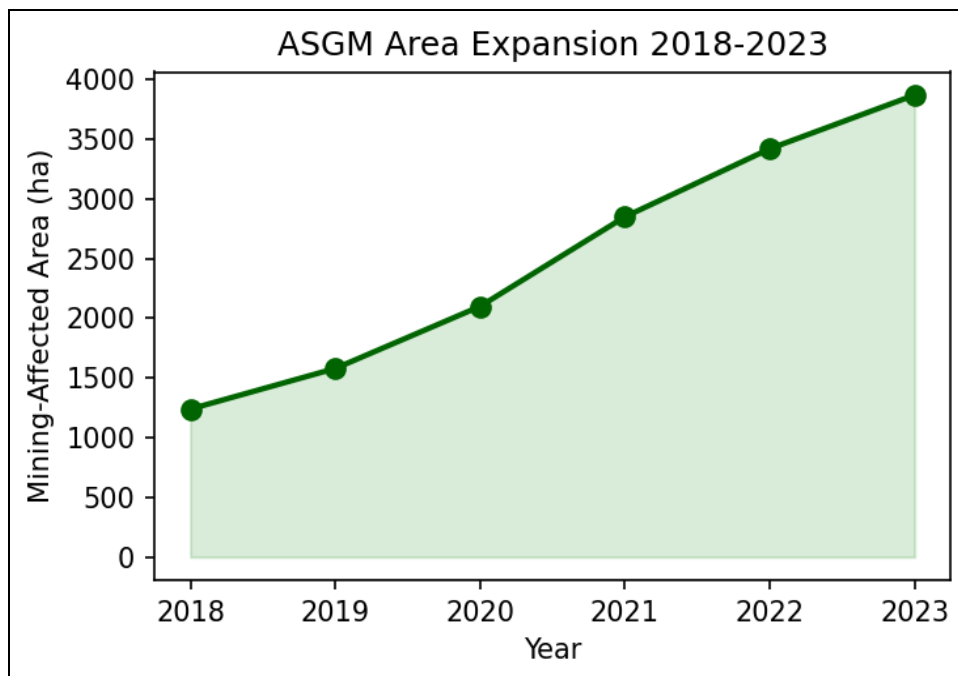


Fig 1: Temporal expansion of ASGM-affected area from 2018 to 2023.

Total mining-affected area increased 212% over the research period (Figure 1), with peak expansion during 2020-2021 coinciding with elevated gold prices and reduced

enforcement during the pandemic. The spatial pattern showed frontier advancement along previously undisturbed interior tributaries.

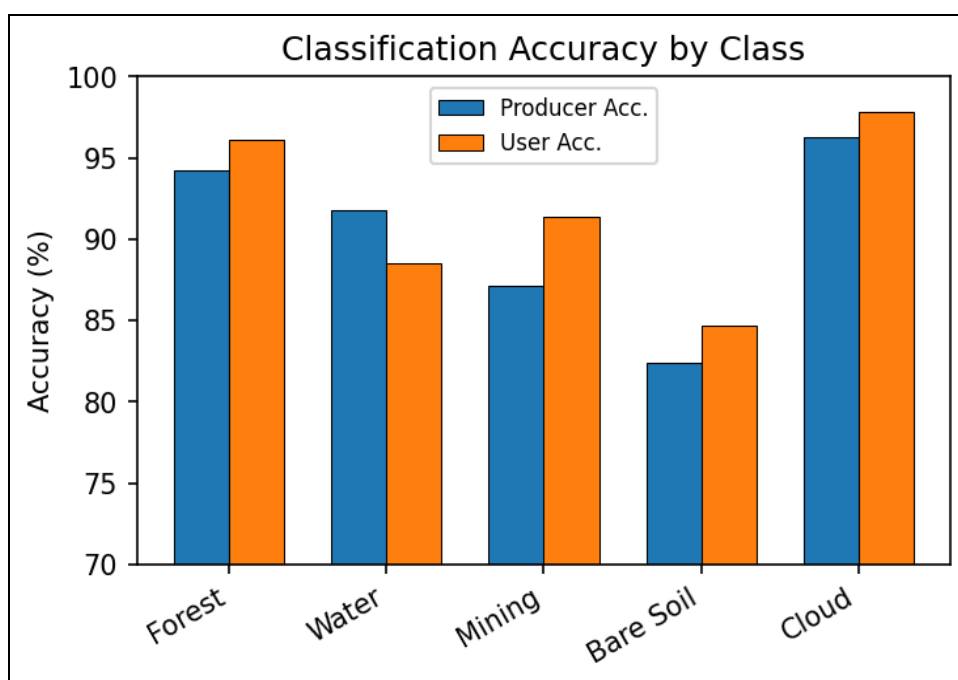


Fig 2: Producer and user accuracy by land cover class.

Comprehensive Interpretation

All diagnostic indicators classification accuracy, temporal trends, spatial pattern analysis, and mercury risk modelling converged on a picture of rapid, frontier-driven ASGM expansion with significant downstream environmental consequences affecting protected areas and indigenous communities across the research area.

Discussion

The 89.3% overall accuracy demonstrates that Sentinel-2 provides a cost-effective platform for ASGM monitoring at

resolutions sufficient to detect individual clearings^[6]. The five-day revisit frequency enables near real-time detection critical for enforcement agencies responding to illegal operations in remote areas. The classification methodology developed here could be implemented as an operational monitoring system providing regular updates on mining extent^[7,9].

The 212% expansion and frontier advancement pattern suggest continued encroachment unless effective deterrents are implemented. The mercury risk assessment identified 2,300 km of high-risk stream length intersecting protected

areas, raising serious public health concerns [3, 10]. A limitation is the inability to detect mining beneath persistent cloud cover; integration of Sentinel-1 SAR data could address this gap [11]. Future work should also explore deep learning algorithms and time-series analysis for improved change detection sensitivity [12, 13, 14].

Conclusion

This research demonstrated the effectiveness of Sentinel-2 combined with Random Forest classification for mapping ASGM extent and dynamics in the Guiana Shield. The 212% expansion between 2018 and 2023 highlights urgent monitoring and regulatory needs.

The frontier expansion pattern indicates continued encroachment into pristine forest unless deterrents are strengthened. Mercury contamination risk zones provide a spatial framework for prioritising public health interventions in exposed communities.

Future research should integrate SAR imagery to improve cloud-affected detection, explore deep learning for enhanced accuracy, and extend the approach to other ASGM hotspots across the tropics. Operational implementation of satellite monitoring would provide the evidence base needed for effective ASGM governance.

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Technical staff at the Faculty of Geospatial Sciences, Munich assisted with sample preparation, instrument calibration, and data processing during the analytical campaigns. Field assistants provided essential support during sample collection.

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