



Spatial expansion of artisanal and small-scale gold mining nearby the Nile River, Sudan and its potential environmental impacts: Insights from Planetscope data and machine learning

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ABSTRACT

Artisanal and small-scale gold mining (ASGM) has dramatically expanded along the Nile River, North Sudan; however, the rates and environmental impacts were not sufficiently assessed. We aimed to use PlanetScope data to detect and map ASGM and highlight its environmental impacts around the Nile River, North Sudan, using the random forest (RF) classifier in three steps. First, a visual inspection and analysis were performed to evaluate how distinguishable ASGM sites are from rock units/geological features in color composites; then, reference data were collected from processed images for training and testing, and supervised classification was conducted using binary and multiclass RF classifiers. RF and PlanetScope data were efficient in discriminating ASGM sites with high overall accuracy (0.84–0.92). The binary approach ensured higher accuracy over the multiclass approach, but the latter helped to understand the spatial distribution of illegal mining. Our findings showed that ASGM areas significantly expanded from 50 ha (2016) to 90 ha (2021) and 125 ha (2024). Additionally, we highlighted the environmental risks associated with the development of ASGM in the region. The results can help decision makers and stakeholders to obtain better information on the environment, and the methodology helps to monitor ASGM activities.

1. Introduction

The mining sector (whether on a small or large scale) is vital for human development, as it supplies the necessary raw materials for infrastructure, technology, and energy, propelling economic growth and contemporary life (Mvile and Bishoge, 2024). However, it has considerable effects on the environment, leading to habitat destruction, pollution, loss of biodiversity, and contributes to climate change through resource extraction and waste production (Ganesan et al., 2024). Artisanal and Small-Scale Gold Mining (ASGM) is a local phenomenon that is rapidly growing in developing countries and has become a global issue (Hentschel, 2002; Veiga and Delgado-Jimenez, 2024). ASGM usually refers to mining by individuals, groups, families, or cooperatives with minimal or no mechanization, often in the informal (illegal) sector of the market (World Bank, 2024). Miners engaged in these activities usually extract gold and other metals such as silver, tin, tungsten, tantalum, chromite, copper, or minerals such as gemstones, depending on local geology and markets (Fritz et al., 2018). ASGM

comprises approximately 16% of the global mineral production and sustains more than 40 million individuals globally (Carman, 1985; Schwartz, Lee and Darrah, 2021). However, ASGM has huge environmental impacts on water (Zelenáková et al., 2021), soil (Ali et al., 2017), landscape and vegetation (Mhangara, Tsoeleng and Mapurisa, 2020), and ecosystems (Goji and Bala, 2024), increases erosion, and causes loss of viability for agricultural purposes (Mensah, 2015). ASGM is common in developing countries in South America (Tarras-Wahlberg et al., 2000; Nunan, Barnes and Krishnamurthy, 2023), Asia (Soe et al., 2022), and Africa (Yakovleva and Vazquez-Brust, 2014; Hilson and Maconachie, 2020). In addition, ASGM provides job prospects for considerable individuals and families, yet simultaneously presents relevant ecological difficulties. ASGM has been present in Sudan since ancient civilizations, especially concerning precious metals such as gold, which were mined by various groups including the ancient Egyptians, Nubians, Turks, British, and Sudanese (Zeinelabdein and Nadi, 2014); however, ASGM has been distributed across Sudan since 2011 (Darfour, Kordofan, Blue Nile, Rive Nile State, and Red Sea state). This expansion is attributed to

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rising gold prices (gold was valued at 14,000 USD/kg in 2006, increased to 38,000 USD/kg from 2010 onwards, and exceeded 62,000 USD/kg post-2020)(Price, 2024), as well as the economic shock resulting from South Sudan's independence, which caused Sudan to lose 80% of its oil resources. The economic recession that resulted from this loss led to widespread unemployment across other sectors, which depended on oil revenue. ASGM was promoted in Darfur, Kordofan, the Blue Nile, River Nile, and the Red Sea because of the promise of high financial returns and minimal government regulation. ASGM areas are usually located remotely or are characterized by poor infrastructure (roads, clean water, and electricity). Therefore, the ASGM expansion and its impact are usually poorly investigated or remain unexplored.

The ASGM sector in Sudan is estimated to directly employ over 1 million miners, with broader ASGM communities, including miners' families and associated workers, comprising over 2 million individuals (Ahmed El Tohami, 2018; Elwaleed et al., 2024; "Minamata Convention" 2015). However, the actual number may be greater and on the rise, given that a large portion of this activity is informal and poorly documented (Seccatore et al., 2014). These figures, however, highlight ASGM's considerable socioeconomic importance in Sudan, especially in rural regions where other sources of income are limited. Despite this increasing economic influence, there is a significant deficiency in systematic and spatially explicit environmental monitoring in Sudan. Several field-based studies have provided compelling evidence of the pollution risks associated with ASGM.

Numerous studies have utilized remote sensing technology to investigate the ASGM; although most of them achieved promising results, they used data with a lower spatial resolution, such as Landsat or Sentinel-2 (Gallwey et al., 2020a; Simionato et al., 2021; Ngom et al., 2023; Nursamsi et al., 2024). PlanetScope data have also been used in mining-related and geological feature mapping (Chalkley et al., 2022; Dozzo et al., 2024). These studies used PlanetScope data to monitor acid mine drainage through same-day observations and determine the area covered by tephra following an explosive event. However, none of the previous studies have assessed the potential of PlanetScope data in mapping and monitoring ASGM.

Previous evaluations of the PlanetScope have primarily concentrated on limited timeframes (a few days) and mapping wetlands and/or floats, in contrast to this study. We broaden the scope of our investigation to encompass a 9-year period and incorporate a detailed spatial analysis of ASGM activities and their relationships with rock units and other land cover types in the region, enabling us to pinpoint potential sources of

gold in Sudan along the River Nile. Our aims were to (i) determine the applicability of PlanetScope data to identify ASGM areas, and (ii) test the efficacy of binary and multiclass classification approaches.

2. Materials and methods

2.1. Geology of study area

The study area is located in the eastern part of the Nile River, western part of the Arabian Nubian Shield (ANS) in North Sudan (Fig. 1), 15 km from Albawga, 40 km from Berber, and 60 km to the north of Atbara, in an area with a high population density. Geologically, the area is covered mostly by low-grade volcano-sedimentary island-arc/back-arc ophiolite assemblages (Schandelmeyer, Richter and Harms, 1987; Zeinelabdein and Nadi, 2014). The lithological units in the eastern part of the Bayouda Desert, where our study area is located, are typical low-grade green schists that vary from meta-basaltic andesite to Meta-andesite to Meta-dacite (Almond and Ahmed, 1987; Abdelsalam and Stern, 1993; Küster and Jean-Paul, 2001). The rock units are highly deformed and subjected to varying degrees of metamorphism. Based on our field observations, the ASGM activities were mainly in the meta-andesite and meta-basalt, in some cases.

2.2. Remote sensing data

We applied PlanetScope data in the analysis, and the dates of acquisition were selected from dry seasons to minimize atmospheric and vegetation-related interference to ensure optimal conditions for geological mapping. In arid and semi-arid regions, dry seasons are characterized by minimal cloud cover and occurrence of vegetation, which eliminates the obscuration of key geological and anthropogenic features (e.g., ASGM sites and lithological contacts) that are crucial for accurate classification (Lillesand and Kiefer, 2015; Fonseca et al., 2024). The chosen dates were May 10, 2016; May 27, 2021; and May 16, 2024. The dataset comprises VNIR spectral bands with a high spatial resolution (3 m), enabling the detection and analysis of ASGM, vegetation, water bodies, and urban areas, which was the reason for choosing PlanetScope over Landsat, Sentinel-2, and ASTER. High spatial resolution and consistent data availability throughout the study period emerged as the optimal choice for achieving the study objectives. The spectral and spatial characteristics of the sensors are listed in the (Table 1).

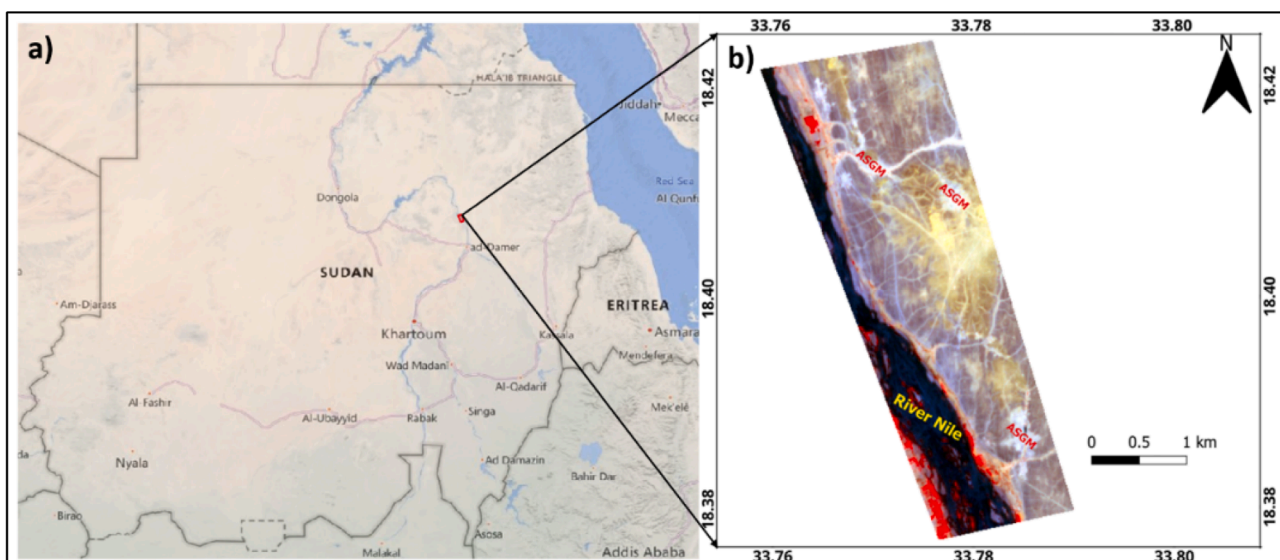


Fig. 1. Location of the study area.

Table 1
Spectral of PlanetScope data.

Band	wavelength (nm)
Band 1 (Coastal Blue)	431 - 452
Band 2 (Blue)	465 - 515
Band 3 (Green 1)	513 - 549
Band 4 (Green 2)	547 - 583
Band 5 (Yellow)	600 - 620
Band 6 (Red)	650 - 680
Band 7 (Red-Edge)	697 - 713
Band 8 (Near Infra-red)	845- 885

2.3. Image preparation, processing and reference data collection

Level-2A bottom-of-atmosphere surface reflectance data, pre-processed with atmospheric and geometric corrections, were utilized in this study. Color composites were used for visual inspection, and the b4-b3-b1 and b8-b6-b2 combinations were the most informative (Fig. 2). Several authors have recommended the application of composites for mapping lithology, ASGM sites, and land cover classifications (Zeinelabdein and Nadi, 2014; Mwaniki et al., 2015; Mhangara et al., 2020; Shebl et al., 2023; Elrasheed and Szabó, 2024). Visual inspection and interpretation were important in collecting reference data, where color composites helped to enhance geological features with other ancillary data, such as previous geological maps and high-resolution Google Earth images.

This method has been recommended by several authors (Hansen et al., 2008; Rabiei-Dastjerdi et al., 2022) (Fig. 2). The spectral profiles of the land cover and geological features of the PlanetScope data are shown in (Fig. 3).

2.4. Image classification

Recently, machine learning classifiers have been widely used in lithological or land-use land cover mapping (Georganos et al., 2021; Farmonov et al., 2024; Hebri et al., 2024; Shanthi et al., 2024; Wang et al., 2024). In this study, we applied the Random Forest (RF) classifier because of its flexibility and ability to model complex nonlinear relationships in data without assuming a predefined functional form (Belgiu and Drăguț, 2016). RF was developed by Breiman.(2001) as a combination of decision trees (DT). Instead of a single DT, RF considers hundreds of DTs, where all trees have their own randomly selected

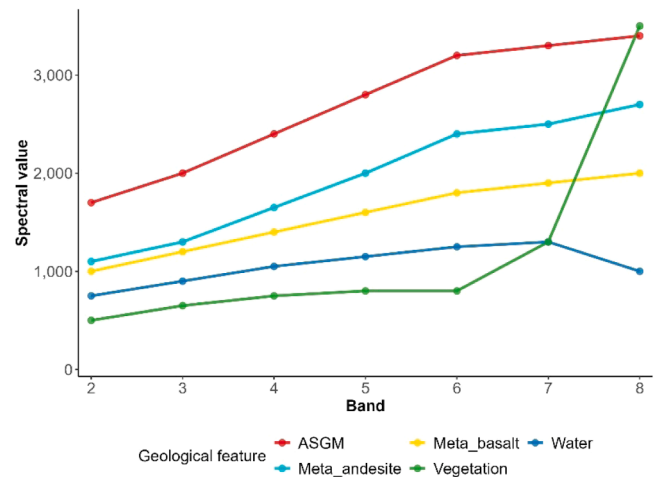


Fig. 3. Spectral profiles of land cover and geological features of the PlanetScope data.

dataset with bootstrapping, and the number of predictor variables is randomly selected. The final classification is determined by the number of votes of the DTs (as a proportion of the total number of DTs and the number of results for a given class). RF classifiers are widely used to process remote sensing data for lithological and mining mapping (Mohamed Taha et al., 2022; Shebl et al., 2023; Xi et al., 2023).

We implemented a systematic workflow to develop and evaluate the classification model. Initially, we split the reference dataset into training (70%) and testing (30%) subsets using random sampling to ensure a representative distribution of the data points. We then utilized the training data to build the RF model, whereas the test data were retained for an independent accuracy assessment. To build the RF model, we used a 10-fold cross-validation approach that minimizes overfitting by iteratively training and validating the model on different subsets of the training data. We applied 500 DTs and incorporated a hyperparameter tuning process with a grid of the mtry parameter (the number of variables considered at each split) across a range of values (1–8).

Finally, we assessed the predictive performance of the RF model using the testing dataset. We determined the confusion matrix and accuracy metrics. The overall accuracy (OA), user's accuracy (UA), producer's accuracy (PA), and F1-score, as the harmonic mean of UA and

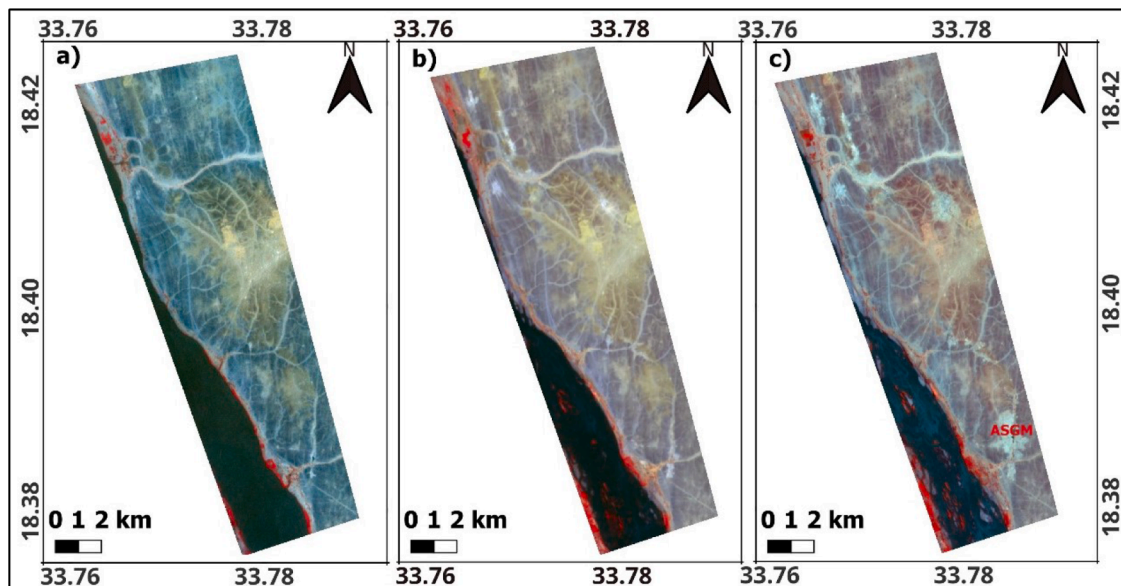


Fig. 2. Color composites of the study area (PlanetScope images; a: b4-b3-b1 in 2016, b: b8-b6-b2 in 2021, and c: b8-b6-b2 in 2024).

PA, were calculated. Both RF model building and prediction and accuracy assessment were computed using R 4.4.3 (R Core Team, 2024) with the caret package (Kuhn, 2008). The workflow used in this study for ASGM identification is shown in Fig. 4.

3. Results

3.1. Binary and multi-class classification

We obtained six classified maps utilizing the binary and multiclass RF for the PlanetScope data input in 2016, 2021, and 2024. The results of the binary image classification showed that, in 2016, the distribution of ASGM was restricted and was mainly located in the northern part of the study area (Fig. 5/a), covering an area of 50 ha. In 2021 and 2024, the ASGM area grew to 90 ha and 125 ha, respectively, encompassing the central-eastern and southern regions of the study area (Fig. 5/b and /c). The multiclass approach yielded similar results (Fig. 6/a, /b, and /c). Multi-class RF. The multiclass RF classification result confirmed what we obtained using the binary RF (ASGM is growing steadily from 2016 to 2021 and 2024). The results also indicated that the ASGM began in the central eastern and northern parts of the study area in 2016 and then extended in the following years (2021 and 2024) to the eastern and western sectors (Fig. 6/a, b, and c). Furthermore, multi-class RF classification results clearly showed that the main lithology targeted by the miners was meta-andesite and, to some degree, meta-basalt. For example, in 2016, miners targeted meta-andesite and adjacent streams (Fig. a 6/a); in 2021 and 2024, the ASGM continued sprawling mainly over meta-andesite (Fig. 6/b).

Maps had high classification performance: the binary approach had the highest OA, 92 % (2021), the lowest OA was 87% (Table 2), and the multiclass approach ensured 87 % OA, with notable variations in the class-level metrics (Table 3). These results are supported by well-defined F1-scores, UAs, and PAs, affirming the reliability of the classification outcomes. Moreover, qualitative validation was carried out during field visits and through Google Earth imagery, which confirmed a high degree of spatial correspondence (>85%) between PlanetScope-derived ASM footprints and observed mining sites. It should be noted that increased spatial extent of ASGM does not necessarily equate to ongoing mining activity, as some sites may have been abandoned during the study period. However, in arid regions like Sudan, abandoned sites remain

clearly visible due to long-lasting surface disturbances. While this can introduce potential misclassification, we interpret such cases as indicators of cumulative landscape impacts and potential early warning signals of environmental vulnerability.

3.2. ASGM change analysis

Both binary and multiclass classification maps revealed an increasing trend in the ASGM areas between 2016 and 2024. In 2016, the ASGM area was only 50 ha, which increased to 90 ha by 2021 and 125 ha by 2024 (Fig. 7), whereas the non-ASGM area was 780 ha in 2016, 740 ha in 2021, and 705 ha in 2024 (Fig. 7). Concerning the multiclass methodology, we observed inter-class changes between the ASGM and other classes (vegetation, water, meta-andesite, and meta-basalt), suggesting that miners primarily targeted meta-andesite and less frequently targeted meta-basalt (Figs. 8 and 9). 75 ha hectares of meta-andesite area was transferred to ASGM from 2016 to 2024, whereas 21 ha of meta-basalt was transferred to ASGM between 2016-2024. We detected an almost zero transfer rate between the ASGM, water, and vegetation.

3.3. Field observations and environmental impact of ASGM

ASGM operations in the area relevantly affected the landscape, geology, soil, drainage system, and water. Field observations across the study area revealed extensive environmental degradation resulting from ASGM activity. Evidence collected from field observations demonstrates relevant impacts on land stability, natural drainage systems, and geological integrity. Mining activities utilize basic wooden support structures within excavated pits, reflecting inadequate safety protocols that endanger workers while simultaneously causing severe landscape deformations (Fig. 10). Systematic removal of surface materials fundamentally alters the original topography, leading to areas of increased instability and accelerated erosion. According to our observations near the Nile, adjacent to mining sites, there are extensive debris fields and topographic disruptions with significant soil stripping and sediment displacement patterns. These alterations substantially compromise land-use sustainability and ecosystem functions in the affected regions. Examination of the collapsed mining pits revealed exposed subsurface geological layers, demonstrating the destruction of current exploitation practices. ASGM systematically weakened the structural integrity of the

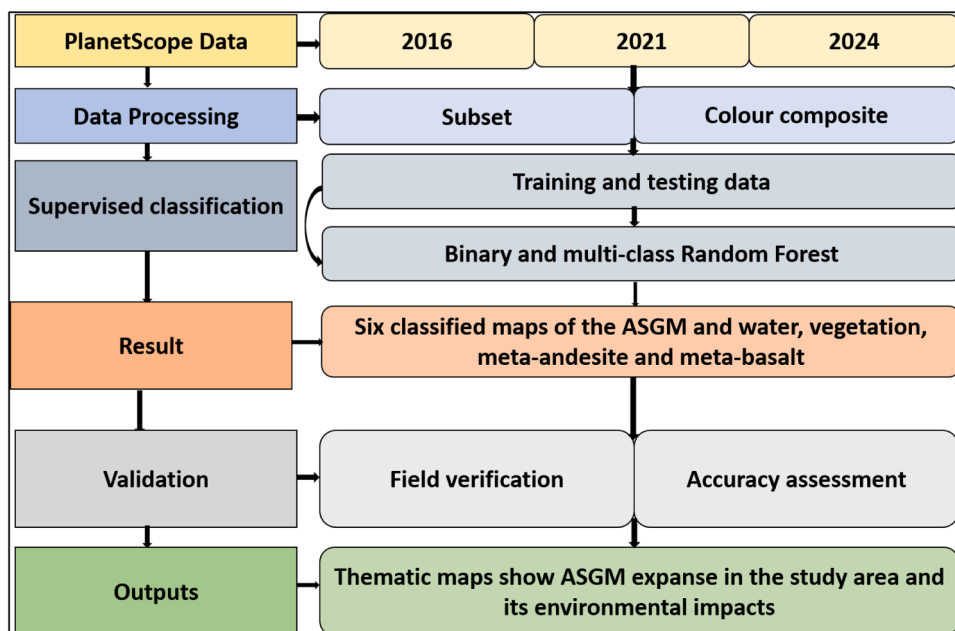


Fig. 4. Workflow of the artisanal and small-scale gold mine (ASGM) identification.

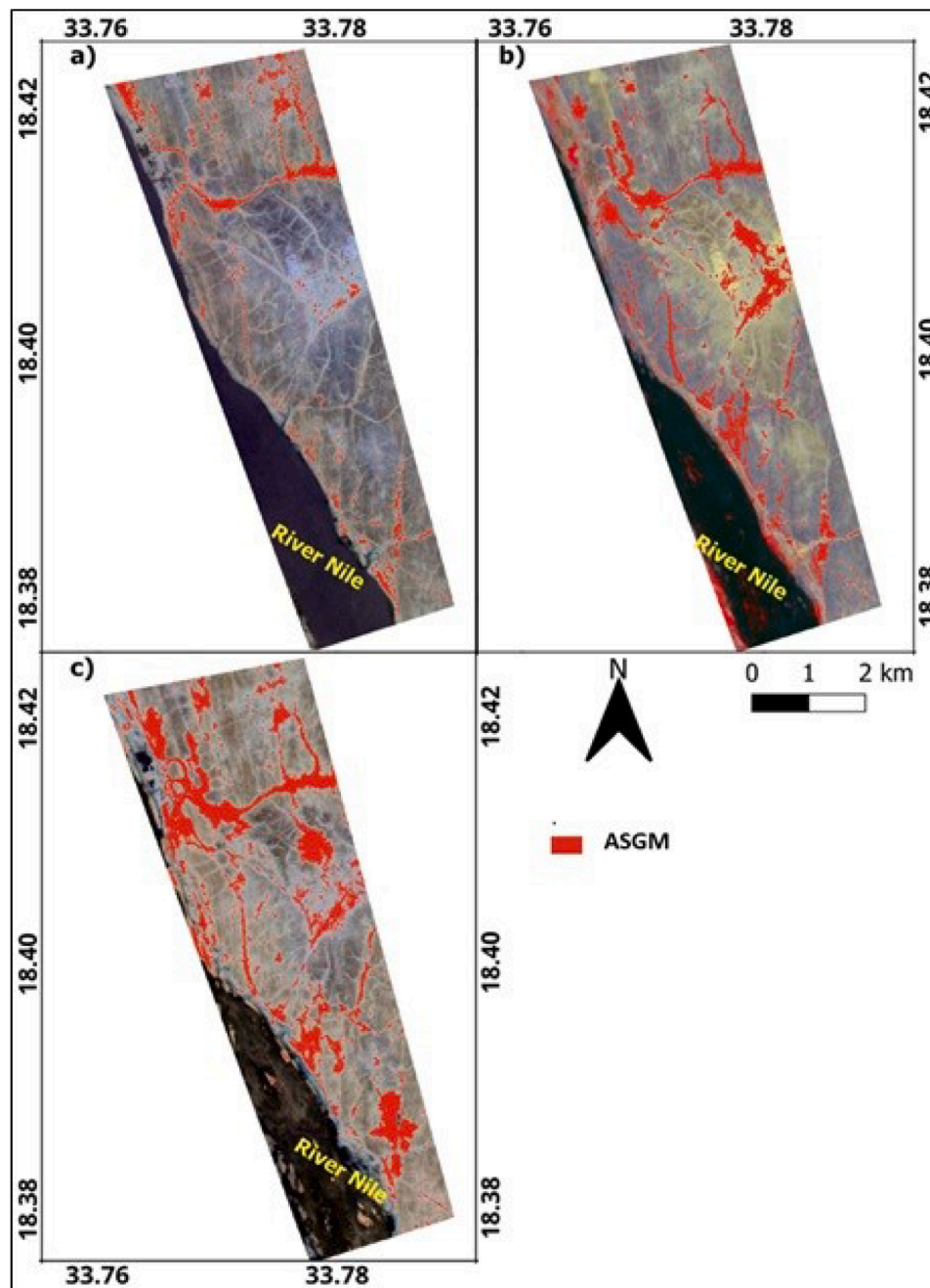


Fig. 5. ASGM expansion over time using binary classification (a: 2016, b: 2021, c: 2024).

soil and increased the land subsidence risk, thereby forming environmental vulnerability zones. Abandoned mining locations exhibited advanced stages of erosion and structural instability, providing clear evidence of the long-term geomorphological consequences associated with ASGM activities. These degraded sites represented persistent sources of sediment runoff that directly influence the quality and ecological balance of adjacent water bodies and terrestrial ecosystems.

Ore washing and panning relied on constructed artificial pools where miners concentrated sediment-laden materials, leading to localized pollution that adversely affected both terrestrial and aquatic ecosystems. Mechanical ore processing involving crushing operations generated substantial particulate matter emissions, and the resulting dust clouds contain respirable mineral particles that pose health risks, particularly respiratory complications and pulmonary disorders, for exposed workers. Airborne dust contaminants contributed to both

immediate health hazards and long-term chronic exposure. Waste management at ASGM sites was also insufficient: illegal activities did not require standards; consequently, mining facilitated the direct infiltration of toxic materials into subsoil layers and groundwater as persistent contamination sources and generated long-term ecological degradation. Hg amalgamation processes represented the most hazardous aspect of gold extraction, involving the direct manual manipulation of elemental Hg in aqueous slurries without appropriate protective equipment. This exposure posed neurological health risks to workers while also introducing Hg contamination into the local environment, raising both acute toxicity concerns and chronic bioaccumulation potential (Fig. 11).

Hydrological changes in the study area showed systematic alterations in natural drainage due to the ASGM. The observed modifications in the drainage patterns and sediment transport indicated that these interventions disrupted the flow regimes and sediment deposition

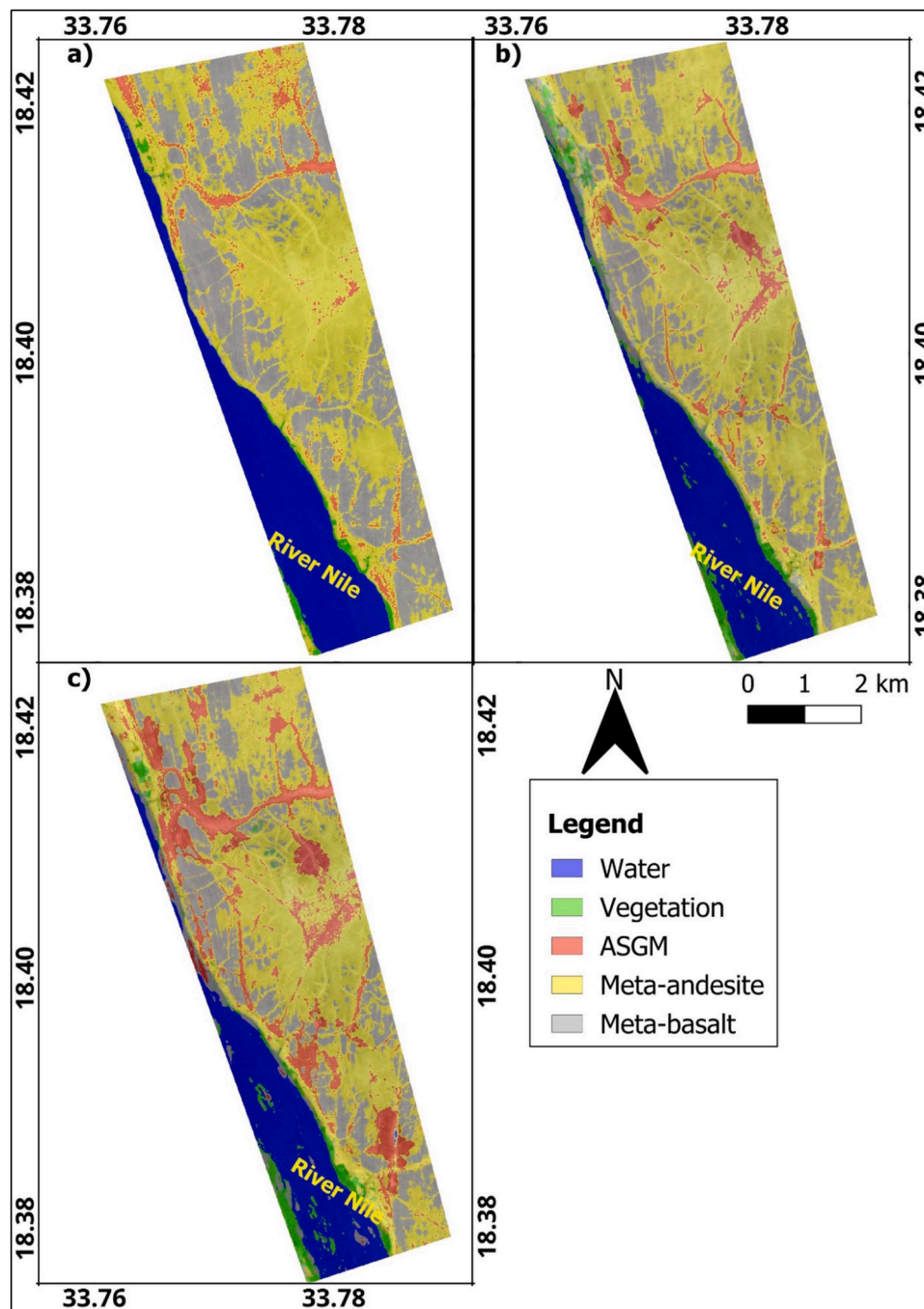


Fig. 6. ASGM expansion over time using multiclass classification (a: 2016, b: 2021, c: 2024).

processes. The ASGM and associated waste accumulations were located near existing drainage networks, leading to hydraulic interference that increased the sediment loading and flow-obstruction mechanisms. The spatial relationship between extraction sites and natural watercourses has resulted in conditions that accelerate sedimentation rates and reduce the channel capacity. These anthropogenic changes fundamentally influenced watershed functionality by disrupting established flow pathways and introducing artificial barriers to surface water movement (Fig. 12).

4. Discussions

ASGM operations have recently gained global attention as an essential source of income and a critical driver of environmental

disruption, especially in mineral-rich and geographically diverse regions, where regulatory oversight is often limited. Our analysis revealed a notable expansion of ASGM activity over the study period, a trend that aligns with the findings of previous studies. Barenblitt et al. (2021), Gallwey et al. (2020b), and Simionato et al. (2021) documented analogous increases in ASGM footprints in Brazil and Ghana, linking mining growth to deforestation, habitat fragmentation, drinking water resources and food security. The uniformity observed across different geographies highlights ASGM's function as a widespread catalyst for socioeconomic and environmental changes. The observed expansion aligns with broader socioeconomic dynamics, notably the surge in global gold prices and geopolitical shifts, such as South Sudan's 2011 secession and ongoing conflict in Sudan, which destabilized local economies and spurred migration into mining sectors (Ahmed et al.,

Table 2

Accuracy metrics of binary Random Forest classifications in 2016, 2021, and 2024 (ASGM: Artisanal Small-scale Gold Mining, UA = user's accuracy, PA = producer's accuracy, OA= overall accuracy).

Year	Dataset	OA	Class	UA	PA	F1-score
2016	Training	0.95	ASGM	0.880	0.910	0.890
			Non-ASGM	0.970	0.960	0.960
	Testing	0.87	ASGM	0.857	0.857	0.857
			Non-ASGM	0.983	0.983	0.983
2021	Training	0.94	ASGM	0.820	0.890	0.850
			Non-ASGM	0.960	0.950	0.955
	Testing	0.92	ASGM	0.612	0.678	0.644
			Non-ASGM	0.962	0.950	0.956
2024	Training	0.91	ASGM	0.740	0.800	0.740
			Non-ASGM	0.940	0.930	0.935
	Testing	0.87	ASGM	0.562	0.573	0.514
			Non-ASGM	0.916	0.940	0.928

Table 3

Accuracy assessment of multi-class Random Forest classification in 2016, 2021 and 2024 (ASGM: Artisanal Small-scale Gold Mining, V: vegetation, W: water, MA: meta-andesit, MB: meta-basalt; UA = user's accuracy, PA = producer's accuracy, OA= overall accuracy).

Year	Dataset	Class	UA	PA	F1-score
2016	Training	ASGM	0.940	0.950	0.945
		V	0.960	0.930	0.945
		W	0.950	0.970	0.960
		MA	0.910	0.890	0.900
		MB	0.980	0.960	0.970
		OA	0.950		
	Testing	ASGM	0.850	0.900	0.850
		V	0.940	0.790	0.860
		W	0.770	0.940	0.850
		MA	0.940	0.690	0.800
		MB	0.940	0.940	0.940
		OA	0.870		
2021	Training	ASGM	0.960	0.930	0.945
		V	0.970	0.910	0.940
		W	0.930	0.970	0.950
		MA	0.910	0.930	0.920
		MB	0.880	0.940	0.910
		OA	0.960		
	Testing	ASGM	0.940	0.770	0.985
		V	0.940	0.790	0.861
		W	0.790	0.940	0.860
		MA	0.940	0.790	0.860
		MB	0.610	0.860	0.710
		OA	0.840		
2024	Training	ASGM	0.950	0.920	0.935
		V	0.960	0.920	0.940
		W	0.940	0.970	0.950
		MA	0.920	0.930	0.925
		MB	0.850	0.910	0.880
		OA	0.950		
	Testing	ASGM	0.940	0.770	0.980
		V	0.940	0.790	0.860
		W	0.790	0.940	0.850
		MA	0.94	0.790	0.860
		MB	0.610	0.840	0.700
		OA	0.840		

2019; Fadlallah et al., 2020). The combination of these factors and the scarcity of alternative sources of income have strengthened the ASGM's role as an essential source of economic support and ecological stress.

Gold extraction practices within ASGM areas cause environmental and occupational health risks at various processing stages (Achina-Obeng and Aram, 2022; Mestanza-Ramón et al., 2022). Elwaleed et al. (2024) tested the Hg content in soil, tap water from the Nile, and groundwater to evaluate the human health risks from ASGM activities and assess contamination levels within the study area and found extreme pollution levels in areas of tailings, and low to moderate pollution levels in agricultural areas. However, although Hg is widely



Fig. 7. Areas of ASGM and non-ASGM classes determined by the binary approach between 2016-2024.

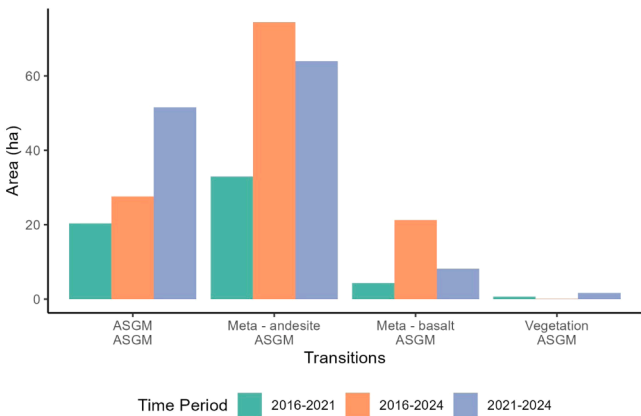


Fig. 8. Geological units and land cover transitions to ASGM in the years 2016, 2021, and 2024.

used in gold extraction, Ali et al. (2017) did not find detectable amounts in the investigated soil samples, probably due to evaporation during the analysis (i.e., an inappropriate method to detect; thus, it does not mean that Hg was not present in the soil). They also called attention to the presence of other metals, such as Pb and Zn, which were attributed to ASGM activity according to the enrichment factor of >2, in the vicinity of ASGM sites and in the Nile River terrace. Our spatial analysis also confirmed that much of the ASGM expansion between 2016 and 2024 occurred within the proximity of the Nile River and its tributaries, increasing the risk of pollutant transfer via surface runoff and erosion. These changes are both spatial and ecological, as they directly affect critical riparian ecosystems and downstream water quality.

The ASGM expansion in the Nile River area from 2016 to 2024, especially the penetration into previously undisturbed areas, calls attention to both socio-economic and geological dynamics. The preference for mining meta-andesite reflects its perceived gold potential, but the underlying social drivers include poverty, conflict-related displacement, lack of employment, and governance challenges, which is in line with the results of Achina-Obeng and Aram (2022), who arrived at the same conclusion as ASGM activities in Ghana. Each district may face different combinations of pressures. In areas close to the Nile, displacement due to water insecurity may be a factor, whereas in southern districts, the influx of migrant miners and lack of regulation may have larger roles. ASGM provides income opportunities for local populations but often at the cost of long-term environmental and social stability. There is a growing need to balance the economic benefits of ASGM with the risks of environmental degradation and threats to public

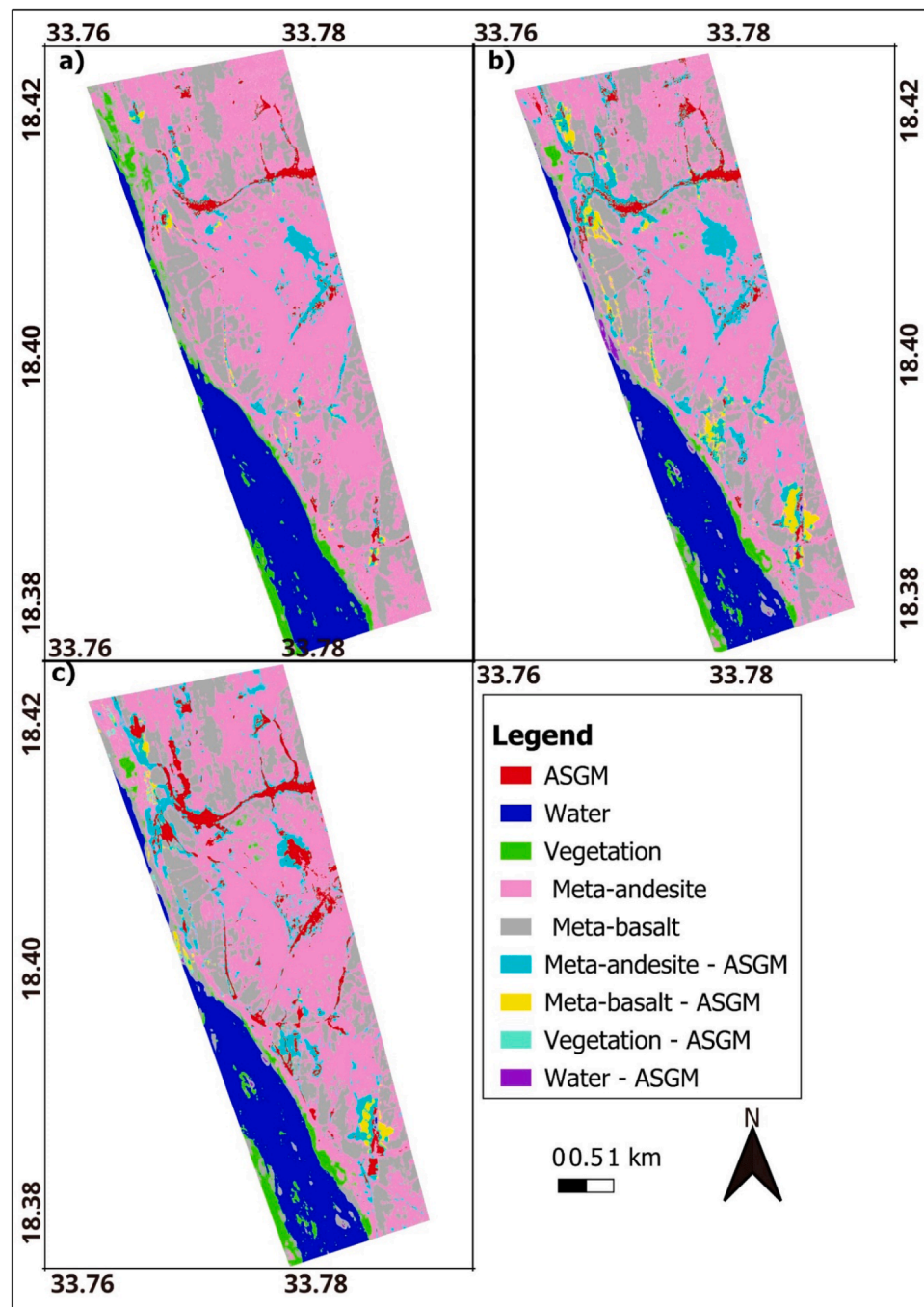


Fig. 9. Spatial distribution of the transition to ASGM for geological units and land cover types (a: 2016, b: 2021, c: 2024).

health. Moreover, the proximity of several ASGM sites to tributaries of the Nile River system raises significant environmental and public health concerns. According to [Ondayo et al. \(2024\)](#), based on an extensive literature analysis of 71 papers, Hg was the most reported potential risk factor for ASGM. As reported by [Elwaleed et al. \(2024\)](#), the use of Hg and other metals in gold extraction poses a substantial risk of contaminant runoff into surface waters, as can be found in the Nile. Given that the Nile is the primary water source for agriculture, livestock, and human consumption across northeastern Sudan, Ethiopia, and Egypt, such contamination can have cascading effects, polluting irrigation channels, degrading soil quality, and introducing toxic substances into the food chain. In the long term, toxic metals may bioaccumulate in plants and animals, posing a risk to humans through biomagnification.

Beyond its immediate environmental and socioeconomic

implications, the expansion of ASGM in the study area also threatens its academic and long-term economic value. As part of the Arabian-Nubian Shield (ANS), this region represents a metallogenic-rich province with a high potential for future mineral exploration. The ANS is globally recognized for its complex tectonic history and economically significant mineral deposits ([Abu-Fatima et al., 2021](#)). However, as we pointed out the disrupting influence of ASGM on the natural drainage system, unregulated ASGM activities rapidly alter or destroy key geological features, such as lithological boundaries, faults, and structural orientations, which are vital for reconstructing the geological history of the area. The obliteration of these features due to uncontrolled excavation not only complicates academic research into the region's geological evolution but also hinders precise geological mapping and future resource assessment. This may lead to the loss of important scientific data and

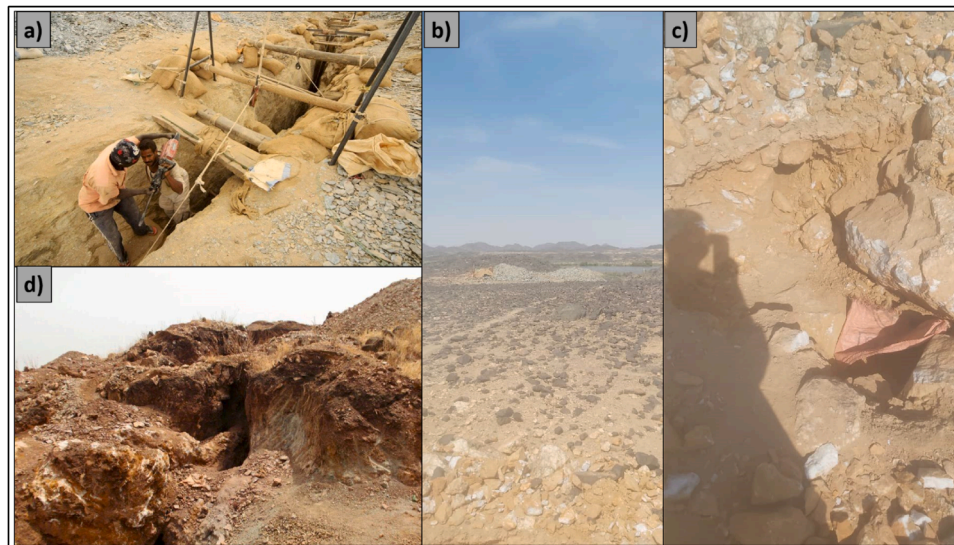


Fig. 10. Environmental issues of artisanal small-scale mining (a: mining pit, b: scattered debris, c: collapsed mining pit, d: abandoned mining site).



Fig. 11. Gold extraction practices in ASGM areas (a: miners around a small artificial pool filled with water for ore washing and panning; b: breaking rocks generates dust clouds; c: improper waste disposal; d: manual amalgamation of gold using mercury in a pan filled with muddy water).

hinder informed exploration strategies.

The integration of remote sensing and machine learning in sustainable development monitoring has gained momentum with advancements in high-resolution satellite data (Burke et al., 2021; Nyamekye et al., 2021). Our study contributes to this growing field by applying a pixel-based RF classification that achieves >92% OA with the binary approach, which outperformed the object-based method used by Simonato et al. (2021). The fine-scale spectral variability captured by pixel-based methods proved to be particularly efficient in our sparsely vegetated and geologically complex desert setting. Compared to CNN approaches (Gallwey et al., 2020b), RF was also more practical for a smaller reference dataset. Our findings align with those of Barenblitt et al. (2021), who used coarser-resolution Landsat imagery in Ghana, although our results showed a slightly higher binary classification accuracy. Nonetheless, the lower performance at the class level, meta-volcanics in particular, underscores the inaccuracies of relying solely on VNIR data to distinguish between spectrally similar lithologies, such as meta-andesite and meta-basalt (Othman and Gloaguen, 2017; Mishra and Rao, 2023). Despite these challenges, the multiclass RF

model can reasonably distinguish between land cover types, including ASGM, meta-andesite, meta-basalt, vegetation, and water, with a notable decline in classification accuracy from 2016 to 2024. We attributed this trend to the expanding footprint of the ASGM, which disrupts geological features and increases spectral confusion between classes.

Considering these findings, we recommend a comprehensive approach to ASGM management in Sudan, drawing from the successful elements of other countries' policies. First, there is an urgent need for awareness campaigns targeting miners and local communities to highlight the harmful effects of Hg use, land degradation, and the importance of sustainable practices. This is particularly vital given Sudan's lack of formal safety and environmental regulations, unlike countries such as Ghana and Tanzania, which mandate licenses and promote legal ASGM operations through structured frameworks such as Community Mining Schemes (CMS) and Primary Mining Licenses (PML) (Fisher, 2007). Second, Sudan needs to develop and implement coherent land management and mining policies that designate specific zones for mining, agriculture, and habitation to reduce environmental conflict, as seen in

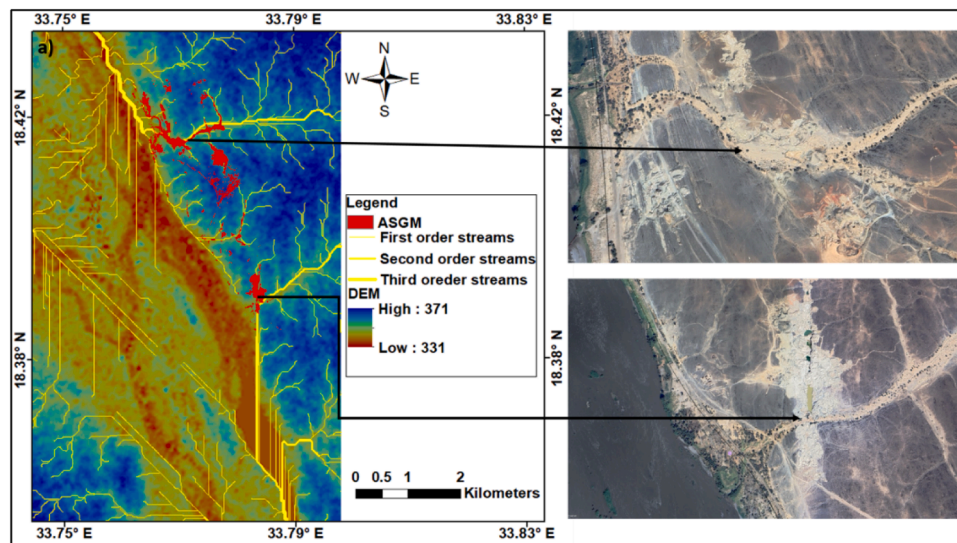


Fig. 12. Drainage systems with potential impacts of artisanal and small-scale gold mining (ASGM) operations (a: terrain height and drainage system with highlights of ASGM activities; b: high-resolution Google Earth imagery with regions where intense mining activity disrupts the drainage system).

Indonesia's designated 'People's Mining Areas' under Law No. 4/2009. Integrating high-resolution satellite imagery such as PlanetScope into national ASGM monitoring systems would considerably improve the detection of mining expansion, similar to Brazil's use of remote sensing for formal oversight via the National Mining Agency (de Theije and Heemskerk, 2009). Finally, sustained collaboration among government institutions, environmental experts, and local communities is essential for enforcing regulations and achieving long-term sustainability, a model adopted in Chile and South Africa, where government agencies engage miners through technical support and inclusive policy reforms (Fritz et al., 2018; Schwartz et al., 2021). Given Sudan's current informal mining structure and fragile regulatory framework, these comparative models offer valuable policy pathways for formalization, sustainability, and environmental protection.

Although our study provides valuable insights into the spatial and temporal dynamics of ASGM expansion using remote sensing and machine learning, several limitations remain. The absence of historical socio-economic data, such as the number of miners, mining co-operatives, and estimated gold production, limits our ability to fully correlate observed land changes with on-the-ground mining activity. Similarly, the lack of environmental pollution datasets, including mercury levels in water, soil, and air, constrains our assessment of ASGM's ecological and public health impacts of the ASGM. Future research should integrate these socioeconomic and environmental indicators to offer a more holistic evaluation of ASGM trends. Establishing partnerships with local institutions and environmental monitoring agencies can facilitate access to such data and improve the temporal validation of remote sensing observations. Due to logistical challenges, we were unable to conduct formal GPS-based ground surveys, which represents a limitation of this study. Future work should incorporate systematic in situ measurements to enable quantitative validation of satellite-based classifications and strengthen the reliability of temporal trend analyses.

5. Conclusions

We aimed to investigate the efficiency of PlanetScope data capabilities in mapping and monitoring ASGM development over a study area in Sudan, using binary and multiclass RF classifiers. Our findings confirmed that PlanetScope's high spatial resolution data, combined with machine learning, effectively detected and mapped ASGM sites despite the absence of the shortwave infrared portion of the electromagnetic spectrum, which is essential for mapping lithologically related

features such as ASGM. Although PlanetScope efficiently identified ASGM sites in both binary and multiclass classifications, its performance was notably better in binary classification. The accuracy of multiclass mapping was lower, demonstrating superior capability in identifying water and vegetation compared to ASGM and rock. ASGM, meta-andesite, and meta-basalt were the main sources of misclassification because of their spectral similarities and inhomogeneous nature. ASGM development near the Nile River poses profound environmental challenges, primarily land degradation, drainage system disruptions, and potential River Nile water pollution. Through visual inspection, field observations, previous studies, class level, and overall accuracy analysis, we strongly recommend the integration of RF with PlanetScope data for ASGM monitoring studies. Furthermore, the likelihood of the implications of our results is high in future studies related to ASGM development, mainly in areas where ASGM replaces forest and vegetation.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT, Quillbot, and PaperPal in order solely to improve the writing and clarity of certain paragraphs in this manuscript. After using ChatGPT, the author(s) reviewed and edited the content as needed and took (s) full responsibility for the content of the publication.

CRediT authorship contribution statement

Abdelmajeed A. Elrasheed: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Data curation, Conceptualization. **Yousif Y. Obaid:** Validation, Software, Data curation. **Szilárd Szabó:** Writing – review & editing, Visualization, Validation, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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