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Abstract: Gold mining is a significant strategic sector for local, regional, and national economies. The rapid development of coexisting camp-type artisanal and small-scale gold mining (C-ASGM) and large-scale mining (LSM) accelerates the environmental and health risks associated with mercury pollution; however, transformations of coexisting sites have not been well quantified. This study used remote sensing (the PlanetScope smallsat constellations systems) to investigate the development of coexisting C-ASGM and LSM sites in Gorontalo, Indonesia, from 2019 to 2022. The results show a positive increase in the extent of barren land across all study zones, resulting from a road network construction connecting the southern port to major mining sites. Notably, greater landcover transformations in the C-ASGM sites after 2020 were attributed to the dumping of underground soils excavated using a shaft-mining method. The findings of this study expand our understanding of the rapid development of coexisting mining operations and quantify significant mining-induced environmental changes. These findings are anticipated to assist in timely monitoring and identification of development areas, rates, and volumes, together with the existing C-AGSM's reactions associated with LSM's massive developments. This also helps to detect possible local-level socioenvironmental impacts from massive land shape changes, leading to human disasters, including landslides and floods.

Keywords: landcover transformation; largescale mining; PlanetScope; smallsat constellations; smallscale gold mining

1. Introduction

Gold mining is a significant strategic sector for local, regional, and national economies. This sector can be categorized into two sub-sectors, namely, large-scale mining (LSM) and artisanal and small-scale gold mining (ASGM). The LSM can be defined as a domain of various mining enterprises with mechanized operations consisting of small to medium-scale mining [1], whereas ASGM comprises informal, unregistered, and often illegal activities [2], undertaken by 70–80% of informal small-scale workers worldwide [3]. This ASGM sector is a significant source of gold production globally, with the poor mainly seeking poverty alleviation and socio-economic benefits [2,4]. Regardless of economic benefits, the substantial harmful environmental and health risks associated with mercury pollution are destructive on a large scale [5–7]. Significantly, the coexistence of ASGM and LSM sectors exacerbates environmental and health risks. Furthermore, massive landcover transformations (LCTs) due to rapid developments possibly follow land shape changes [8–12], leading to other mining-induced human disasters, such as landslides and floods.

The mining sector in Indonesia is a significant gold producing industry, and also produces significant amounts of bauxite, coal, copper, nickel, and tin [13]. In particular, the country's gold production was the 7th highest worldwide in 2020 [14]. There is an extensive ASGM sector throughout the country, which has grown exponentially over the



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Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). last two decades [15]. LSM businesses obtained a legal license and agreement of Contract of Work (CoW) from the Ministry of Energy and Mineral Resources (MEMR) for the country's mineral deposit development [16]. The CoW was made between the MEMR and the Indonesia-incorporated mining company, describing each project stage requirement from the general survey to production, including taxation [17]. Concession area and project life depend on the minerals, which are defined by the Indonesian mineral law No. 4 of 2009 on mineral and coal mining [18] (Table 1). The mining business licenses (IUP), which are required to avail mining business rights, comprise two types—exploration (Exploration IUP) and production operation (Production Operation IUP) [18]. The former provides the right to conduct exploration activities, including a general survey, exploration, and feasibility study, while the latter provides the right to conduct production-related activities, including construction, mining, processing/refining, development, transportation, and sale [18]. A total of 805 IUP of mineral materials have been issued as of July 2022, of which 8 and 797 cover the mineral exploration and the mineral production processes, respectively [19]. For instance, in the gold mining sector, 30 year CoWs have been provided to Freeport–Mac MoRan (the United States mining company in Grasberg, Papua) [20], Newcrest (an Australian mining company in Gosowong, North Maluku) [16], Antam (a state-owned company in Pongkor, West Java), and Bumi Resources Minerals (BRMS: the largest Indonesian company operating in Gorontalo) [21].

Table 1. Terms by mining products.

Mining Product	Exploration IUP		Production Operation IUP		
	Term	Area (Max. in ha.)	Term	Area (Max. in ha.)	
Metal minerals	8 years + 1 year per extension (ext.)	100,000	20 years + 2 exts. (of 10 years each) 30 years + 10 years per ext. with integrated processing and/or refining facilities	25,000	
Non-metal Minerals (N-MMs)	3 years 7 years for certain N-MMs	10 years + 2 exts. (of 5 years each)25,00020 years + 2 exts. (of 10 years each) fo certain N-MMs		5000	
Rocks	3 years	5000	5 years + 2 exts. (of 5 years each)	1000	
Coal	7 years + 1 year per ext.	50,000	20 years + 2 exts. (of 10 years each) 30 years + 10 years per ext. with integrated development and/or utilization activities	15,000	

Northern Sulawesi has a geologic bedrock consisting of a series of Late Cenozoic calc-alkaline magmatic arcs that rest on Early Cenozoic tholeiitic volcanic basalt above an underlying oceanic crust [22]. This includes several mineral deposits from the predominantly Late Miocene-Pliocene age, including high-, intermediate-, and low-sulphidation epithermal gold (Au)- Silver or Electrum (a solid solution made of Au-Ag) (Ag), porphyry copper (Cu)-gold \pm Molybdenum, intrusion-related base metal-Au, sediment-hosted Au, skarn, and volcanogenic massive sulfide styles of mineralization [22]. Mining activities are widespread because of this rich mineralization system, including ASGM in conserved areas [23,24], negatively affecting biodiversity and human health [25]. Moreover, the coexistence of the LSM and ASGM sectors is assumed to accelerate changes in biogeographic conditions, deforestation, geomorphology, high mercury contamination, hydrological regimes, and river courses. Simultaneously, it may cause conflicts between these parties because of the regulatory environment for mining and land access [26].

Remote sensing technologies are widely used to characterize physical objects or natural features on the land surface using various spatial, temporal, and spectral resolution datasets. The use of openly available datasets allows for long-term monitoring of spatial transforma-

tions; however, acquiring cloud-free datasets, particularly in tropical regions with heavy rainstorms, is a significant challenge [10,11,23,24]. Previous studies on the transformation of camp-type ASGM (C-ASGM), in which miners live and perform mining activities at rural-remote informal worksites, have used remote sensing technologies [10,11,23,24]. Regardless of the availability of long-term analysis with openly available moderate resolution datasets, higher cloud coverage in the tropical region makes timely and detailed assessments of rapid informal mining developments difficult [23,24]. The rapid growth of coexisting C-ASGM and newly operated LSM operations is expected to accelerate environmental and health risks at various levels and on a larger scale. Therefore, efficient monitoring of such coexisting mining sites is critical.

To facilitate our understanding of the rapid development of coexisting gold mining operations at the two scales, high spatiotemporal observation, may be a key to identifying details, such as development pace and mining activity-induced environmental changes at local, community, and regional levels. Powerful high spatiotemporal commercial observation smallsats are emerging. For example, Planet (Planet Labs, Inc., San Francisco, California, USA) has operated the largest earth-imaging smallsat constellations (SSCs) since 2016 [27]. Approximately 130 PlanetScope (PS) smallsats, such as Doves, are functioning as of July 2022. These PS SSCs have a daily collection capacity of 200 million km² with approximately 3 m spatial resolutions, capturing multispectral imagery [27]. Thus, using SSCs facilitates our qualitative and comprehensive understanding of the rapid developments of the coexisting two scales' mining operations and associated socioenvironmental changes. Therefore, this study primarily investigated the transformations of coexisting C-AGSM and LSM sites in Bone Bolango Regency, Gorontalo Province, Indonesia, from 2019 to 2022 using PS SSC datasets.

2. Materials and Methods

2.1. Overall Methodological Workflow

Figure 1 shows the methodological workflow employed in this study. This workflow comprised four main steps to achieve our primary objective of investigating the transformations of coexisting C-AGSM and LSM sites from 2019 to 2022. First, the histories of the mining sites were reviewed. Second, the LSM's mining sites were identified using georeferencing of LSM's project concession blocks. Third, the LCTs of the study area were assessed using PS SSCs time-series (2019–2022). Fourth, LCTs were computed using target zones. This study discusses based on the findings described above. The methods used in each step are described in the following sections.

2.2. Study Area

The mineralization in the study area is represented by a high-sulphidation Lepantostyle Cu-Au system [22]. The Gorontalo Minerals' (GMs) project concession block I is located on the west side of Bogani Nani Wartabone National Park (BNWNP), which is designated as a nature reserve and nature conservation area. Cabang Kanan, Cabang Kiri, Kayu Bulan, Mohutango, Motomboto East (MTMBT-E), Motomboto West (MTMBT-W), Sungai Mak, and Tulabolo deposits are located in the north of concession block I, the limited production forest area (Figure 2). Concession block I is located approximately 30 km southeast of Gorontalo city in Bone Bolango Regency, Gorontalo Province, North Sulawesi. The GMs is a joint venture company with 80% of shares owned by BRMS and 20% by Aneka Tambang [28]. These mining sites were initially developed by several foreign mining companies in the late 20th century [22] but were closed in 1991 because of the BNWNP development and it overlaps with the mining sites [29]. The closure of the former mining site triggered the residents to engage in informal mining activities [29]. Over 9000 small-scale miners were reported in the BNWNP in 2003 [30]. However, an additional MTMBT–W mining site has been rapidly developed in the west of the MTMBT–E since 2019 with large influxes of miners [23,24].



Figure 1. Overall methodology.



Figure 2. Study area.

The georeferencing company reports identified the GMs' deposits [31], which were plotted with the MTMBT–W site [23,24]. The study zones were divided into three categories, namely, north (MTMBT–E, Mohutango, Tulabolo, Sungai Mak), MTMBT–W, and south zones (Cabang Kanan, Cabang Kiri sites, and Kayu Bulan).

2.3. PlanetScope Imagery and Data Processing

PS Ortho Scene-Analytic-Level 3B products acquired between 2019 and 2022 were used [32]. The PS SSCs consist of three satellite generations comprising multiple satellite

groups, such as Dove Classic (image availability: 2016–April 2022), Dove-R (March 2019– April 2022), and SuperDove (March 2020–current) [27]. PS SSCs have a daily collection capacity of approximately 3-m spatial resolutions, capturing multispectral imagery [27]. Subsequently, the normalized difference vegetation index (NDVI) was generated using Equation (1) and added to each composite. Furthermore, the elevation and slope data acquired from the Advanced Land Observation Satellite World 3D-30m were added to the same composite to improve the classification quality. Consequently, the data were normalized to a range of 0–1. As a result, eight sets of PS imagery of 2019 (February and August), 2020 (February and October), 2021(January and October), and 2022 (January and June) were obtained with a ground resolution of 3 m in the World Geodetic System 84 Universal Transverse Mercator coordinate system Zone 51. The main specifications of the imagery and sensors utilized in this study are summarized in Table 2.

$$NDVI = (NIR - Red)/(NIR + Red)$$
(1)

Table 2. Main specification of PS imagery used in the study.

Instrument Name	Instrument Type	Acquisition Date	Spatial Res. (m)	Temporal Res. (days)
Dove Classic	PS2	9 February 2019	3	Daily
Dove–R	PS2.SD	10 August 2019		
Dove Classic	PS2	7 February 2020		
		30 October 2020		
SuperDove	PSB.SD	29 January 2021		
		7 October 2021		
		31 January 2022		
		3 June 2022		

2.4. Land Cover Classification and Accuracy Assessment

Land cover (LC) was categorized into the following four classes: barren, built-up, grassland, and trees. The spatial distribution of built-up and barren areas can be a significant indicator for transforming invisible mining sectors because the study area is in a remote-rural location and shaft-mining is used [23,24]. Supervised classification was used for the time-series LCT analysis. Here, ground control points for the classification were determined on a pixel basis by image to improve classification quality. A simple random forest (RF) classifier with 50 decision trees was used. RF classification is a decision tree-based machine learning method, which is a hierarchical classifier that compares data with various properties [33]. Subsequently, the classification accuracy of the produced maps was assessed using the overall accuracy (OA) obtained from confusion matrices, comparing predicted and actual values. We aimed for more than 90% OA per imagery. The ground control point, classifier and accuracy assessment were implemented in Google Earth Engine, resulting in the generation of eight LC maps. Subsequently, the total extent of built-up and barren areas were computed separately for LCT comparison in each study zone. However, Planet has continuously upgraded sensor instrumentation over generations, indicating radiometric and geometric incompatibility, making precise spectral analyses, such as reliable time-series, difficult [34]. Despite slight differences in bandwidths and placements, SuperDoves (PSB.SD) and Dove-R (PS2.SD) remain compatible [34]. Therefore, we particularly focused on the results from the PS2.SD and PSB.SD datasets for the LCT comparisons. Consequently, trends in built-up and barren areas were evaluated statistically using non-parametric Mann–Kendall and Sen's Slope tests with significance at the 90% confidence level.

3. Results

3.1. History of Large-Scale Mining-Based Mineral Exploration in Bone Bolango

The government of the Netherlands East Indies started mineral exploration in Sulawesi at the end of the 19th century [22]. This entry period was much later than Java, Sumatra, and Borneo because of Sulawesi's high geographical inaccessibility, unpacified condition, and unknown mineral endowment [22]. Later, Newmont (the world's largest gold-producing

company, located in the USA) began exploring porphyry-Cu deposits in Sulawesi's north arm in 1967 and 1969 [22].

After the porphyry search was completed, the mineral exploration focused on gold. In the 1970s, several foreign mining companies continued to explore the Cabang Kiri, Kayu Bulan, and Sungai Mak, and Motomboto sites [22]. GMs currently holds a 24,995-ha concession in this region [28] (Figure 2). A feasibility study in this area was approved in 2014. Estimated resources in the concession area were 392.3 million tons (Mts) ore of 0.49% Cu and 0.43 g/t Au from the Sungai Mak, Cabang Kiri, MTMBT–E, Tulabolo, and Kayu Bulan sites [21] (Table 3). Furthermore, estimated reserves reach 105 Mt of ore grading 0.7% Cu and 0.33 g/t Au [35]. The MEMR granted three-year and thirty-year permits under the CoW in February 2019 for infrastructure and processing facility development, and production, respectively [21].

Table 3. Estimated resources by mining deposits.

Site	Cut of Grade	Mts	Cu (%)	Au (g/t)	Ag (g/t)
Tulabolo	0.5 g/t Au	4.0	1.04	2.57	55.12
Motomboto East	0.5 g/t Au	6.1	0.33	1.12	29.92
Sungai Mak	0.2 g/t Au and 0.2% Cu	165.1	0.55	0.30	1.49
Cabang Kiri	0.2 g/t Au and 0.2% Cu	151.0	0.40	0.55	-
Kayu Bulan	0.3 g/t Cu	66.2	0.52	0.29	-
Total Resources		392.3	0.49	0.43	1.60

For the initial production stage, BRMS, holding GMs' 80% shares, has allocated enormous budgets for operations and infrastructure development. For example, 29 million US dollars (MUSDs) have been allocated for building a gold ore processing plant with a capacity of 2000 tons/day. Moreover, 21 MUSDs were allocated for mining support facilities construction, such as waste dump, sediment pond, power supply, fuel storage, and base camps [36]. Furthermore, 24 MUSDs were assigned for drilling in two gold prospects at the MTMBT–E and Tulabolo sites to increase reserves by an annual 10 Mts of ores [36]. Another 24 MUSDs have been allocated to build a 30-km mining road from Tombililato port, the most southern port in concession block I, to the target mines. Moreover, 10 MUSDs were assigned to build a waste treatment facility and another 3 MUSDs to purchase heavy and mining equipment [36]. A stable power supply would hasten this GMs' operation. A memorandum of understanding (MoU) between GMs and the National Electric Company, a state-owned power company, was signed in April 2022, to support minerals downstream in Indonesia [37]. According to this MoU, 100 megavolt-amperes will be supplied to GMs, and a new power plant of 7381 mega Watt with transmission and substation facilities will be built in 2021–2030 [37].

Foreign investments in mineral exploration in the past triggered a massive entry of informal miners into profitable gold mining activities. The development of built-up areas in Tulabolo and MTMBT–E sites was mostly observed in 2013 and 2015, respectively [23]. However, the MTMBT–W camps have been rapidly developing since 2019 [23]. These camps run on 24-h shift operations. Time-series analysis of night-time light intensity, indicating mining activity volume, also showed positive growth from 2014 to 2020, of which MTMBT–W's growth was significant [24]. Although the formal explorations of mineral resources were halted in 1991 because of the BNWNP development [29], informal mining activities have continued with the massive entry of informal migrant miners into the region [23,24,29]. Furthermore, these informal miners built up an alternative MTMBT–W mining camp and have significantly expanded their C-ASGM activities, indicating the coexistence of the C-ASGM and LSM sites in the formal LSM concession black.

3.2. Time-Series Landcover Transformations of Coexisting Camp-Type Artisanal and Small-Scale Gold Mining and Large-Scale Mining Sites

Planet operates the largest SSCs with a daily collection capacity; however, this study demonstrated eight LC maps with OA of the confusion matrices of 95.5% (February 2019), 95.8% (August 2019), 96.2% (February 2020), 96.2% (October 2020), 94.1%

(January 2021), 94.4% (October 2021), 95.2% (January 2022), and 92.0% (June 2022), respectively. Figures 3 and 4 show time-series LCTs by study zone. Although PS2 datasets are incompatible, visual interpretation based on individual image classification can help understand the LCT tendency. For example, Mohutango and MTMBT–E sites in the north zone remain stable. In contrast, built-up areas in the Tulabolo site were expanded toward the MTMBT–W site in January 2022. Notably, extension of the barren areas were observed in the southwest part of the MTMBT–W site in February 2020, alternating with grassland. A barren-based unpaved road connecting Tulabolo, MTMBT–E to Sungai Mak sites was identified in January 2022. An increase in built-up and barren areas in the Sungai Mak site with an unpaved road construction was observed in June 2022. LCT appeared in the Kayu Bulan site in the south zone in January 2021 but remained steady. The Chabang Kiri and Chabang Kanan sites also remained steady. Notably, a road from the south was connected to the Chabang Kiri sites in October 2021. This road went around the west side of the south zone connected to the Kayu Bulan and Sungai Mak sites in June 2022.



Figure 3. Landcover classification using PlanetScope series. (**a**–**h**) Landcover transformations in the north and Motomboto West zones (2019–2022); (**i**) overview of the target zones.



Figure 4. Landcover classification using PlanetScope series. (**a**–**g**) Landcover transformations in the south zone (2019–2022); (**h**) overview of the target zone.

The mining zones' built-up and barren areas were graphed using PS2.SD and PSB.SD datasets (Figure 5). The appearance of the transformation rate varies across the zones. No significant change in built-up extent was found in any zones. However, notable positive increases in the extent of the barren areas were observed in all zones in different periods. Particular peak changes occurred in October 2021 (0.08 km² in the south zone) and January 2022 (0.14 km² in MTMBT–W and 0.18 km² in the north zones). The extent of the barren south zone increased again in June 2022 while the MTMBT–W and north zones decreased. According to the statistical test described in Section 2.4, the built-up areas in the north and south zones showed slightly negative (-0.004) and positive (0.003) slopes, respectively. The MTMBT–E was not statistically available. Positive slopes for barren areas were identified in all mining zones, such as north (0.043), MTMBT–W (0.019), and south (0.015). A trend was found only in the north zone.



Figure 5. Built-up and barren extent transformations by zones.

4. Discussion

Although mercury pollution-associated risks to human health and the environment in the C-ASGM sector are significant, the coexistence of rapidly growing C-ASGM and LSM sites would accelerate harmful pollution. Meanwhile, rapid development is expected to change the land shape and negatively influence the vegetation, as well as topography, geology, soils, and water quality of the forest. This would increase vulnerability to landrelated disasters, such as landslide, collapse, or floods that cause sediment discharges or collapses. The time-series analysis contributes to revealing a pattern of rapid development of coexisting operations, which aids in recognizing mining-related activities, infrastructure developments, human settlements/mobilities, and estimating possible socioenvironmental impacts. Furthermore, it provides significant insight into coexisting C-ASGM sector's reactions associated with the accelerated LSM's massive operations.

According to the results, positive LCTs, particularly in the extent of barren areas, were found in all zones (Figures 3 and 4). Notably, larger barren areas in the MTMBT–W zone were observed in February 2020, transforming into grassland and barren condition alternately over an increasing area (Figure 3). The MTMBT–W site has been rapidly developed since 2019 [23]. The LCT showed that underground soils excavated with a shaft-mining method, which was used in this region, were dumped, then turned into grassy areas, and this process was repeated. Furthermore, unpaved road networks connecting most mining sites, except the Mohutango site, were identified in the north (January 2021, Figure 3g) and south zones (June 2022, Figure 4g). This road construction would be the result of the 24 MUSD investment for a 30-km mining road development connecting the Tombililato port. Although the extent of barren areas in the north and MTMBT–W zones decreased in October 2021, this is attributed to a shift in the main road construction from the north and MTMBT–W zones to the south zone in June 2022, transforming barren areas on roads into grassy areas (Figure 3g,h and Figure 4g). It is assumed that this road network will undergo further development with construction of the gold ore processing plant builtup, mining support facilities, drilling, the waste treatment facility [36], and the power supply [37].

To date, few studies have quantified the ASGM sector's transformation using high spatiotemporal remote sensing technology. The use of SSC technology allows for high spatiotemporal monitoring of rapid and massive transformations of coexisting mining operations. Previous studies have demonstrated annual C-ASGM developments and their activity volume mainly using Landsat [23,24] and Sentinel series [10,11] with ground resolutions of 30 and 10 m, respectively. In contrast, our study quantified the transformation of coexisting C-ASGM and LSM developments using high spatiotemporal SCC series, revealing more detailed operational developments, even in inaccessible rural-remote mountainous areas. This high spatiotemporal observation overcomes the limitations of medium spatiotemporal resolution satellites, such as Landsat or Sentinel series, even in tropical regions prone to heavy rainstorms. Therefore, the utilization of the PS SSC datasets could be more appropriate for the investigation than traditional satellites. Although the interface between LSM and artisanal and small-scale mining was qualitatively explored in Ghana [26], quantitative visualizations would contribute to a better understanding.

In Section 3.2, an example of the two-period of LCT images in a year was demonstrated. However, the PS's SSC series (the daily, weekly, and monthly available products) can quantify mining-induced socioenvironmental changes in shortened periods. For instance, the amount of available imagery (PSB.SD Ortho tile) with less than 20% cloud and 100% area coverage in the north zone in 2021 was approximately nine times more (35 imagery sets, partially unavailable due to clouds) [32] than that of Landsat8 (4 imagery, partially unavailable) [38]. This frequent image availability allows for effective weekly, monthly, and seasonal time-series analyses depending on purposes [39]. Gradual changes in the global environment, such as deforestation and sea level rise, can be observed every few years. However, monitoring and analyzing extreme and rapid environmental changes under massive mining developments should be done in a much shorter time frame. Therefore, monitoring target sites with high spatiotemporal resolution observations and quantifying their changes would be a powerful tool for providing significant insights into community and environmental management.

5. Conclusions

This study used SSC datasets to investigate the development of coexisting C-AGSM and LSM sectors in Bone Bolango Regency, Gorontalo Province, Indonesia, from 2019 to 2022. The results show that positive increases in the extent of barren land were found in all study zones, resulting from the road networks connecting the southern port to significant mining sites in June 2022. Furthermore, greater LCTs in MTMBT–W were due to underground soil excavated with a shaft-mining method because of the rapid C-ASGM development in 2019. Therefore, high spatiotemporal resolution observation is a powerful tool for quantifying advantageous spatiotemporal information. These quantitative analysis results contribute to a better understanding of the rapid development of coexisting mining operations, including mining activities, infrastructure developments, and human settlements/mobility. Recognizing such developments also aids in the prediction and alerting of possible socioenvironmental impacts at the local and regional levels because of massive changes in land shape, leading to human disasters, such as landslides and floods. These findings are expected to aid in timely high spatiotemporal monitoring, even in tropical regions that frequently experience heavy rainstorms, for recognizing development areas, rates, and volumes, as well as the C-AGSM's reactions associated with the LSM's massive developments.

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