

Assessing the impacts of artisanal and small-scale mining on rehabilitated land

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Abstract

Progressive rehabilitation is vital for successful mine closure and reducing long-term liabilities (International Council on Mining and Metals [ICMM] 2025). It helps demonstrate the success and sustainability of the closure plans, which is vital in getting the buy-in of stakeholders, especially regulators and the host communities.

The Siguiri Gold mine in north-eastern Guinea, a region historically tied to artisanal and small-scale mining (ASM), managed to rehabilitate about 50% of its 25 waste rock dumps between 2015 and 2019. However, after gold prices rose in 2015, ASM activities surged, leading to extensive damage to rehabilitated areas and forcing the mine to halt rehabilitation in 2020.

Since then, the mine has taken steps to mitigate the ASM impact and explore other more sustainable closure alternatives for the dumps. In 2022 internal studies, including fieldwork and mapping, estimated that 30% of the rehabilitated areas had been damaged by ASM activities. However, following the recommendations of that study, in 2024 the mine commissioned a more detailed, independent assessment. The project aimed to map ASM damage, remodel landforms and estimate the extent of repairs required. Using topographical devices, geospatial technology and field surveys, the assessment re-mapped the site and quantified the extent of damage.

The 2024 study estimated that the damage was about three times higher by cost and area than the 2022 initial estimate. The 2022 assessment only considered disturbed hectares, while the 2024 study accounted for landform and topography changes. Remodelling requires cutting undisturbed areas to fill disturbed ones, resulting in a larger impact than initially expected. Time-series mapping from 2014 onwards also helped track ASM disturbances and vegetation regrowth.

Key lessons include recognising that ASM impacts should be assessed from a landform perspective (3D) and not just areas disturbed (2D), and that mapping alone can be misleading due to vegetation regrowth. In regions with historical ASM activity, alternative land use options should be explored, and government support is crucial for success.

Keywords: *artisanal and small-scale mining, progressive rehabilitation, disturbance, closure estimate*

1 Introduction

Artisanal and small-scale mining (ASM) traditionally involves informal, labour-intensive mining practices carried out by individuals, families or small groups with basic tools and limited machinery. Predominantly found in rural areas of developing countries, ASM serves as a vital source of employment and income for economically disadvantaged communities (Hilson & Gatsinzi 2014). However, its informal and often unregulated nature leads to significant environmental, health and social issues, sometimes linking ASM to organised crime and armed conflict (Hilson & Maconachie 2020). Despite its challenges, ASM remains crucial in areas with limited alternative livelihoods.

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Over the years, ASM has evolved, particularly in regions like West Africa, where traditional tools have been replaced by modern equipment such as crushers and metal detectors (Doubouya et al. 2024). This mechanisation has expanded mining capabilities, allowing ASM to target deeper and more diverse ore sources. These advancements have outpaced traditional village-level governance structures, as ASM operations have extended beyond village boundaries, consequently rendering ineffective the traditional processes meant to govern these activities. Additionally, the demographic of ASM participants has shifted, with unemployed youth increasingly viewing ASM as a lucrative opportunity, unlike its previous role as a supplementary income for subsistence farmers.

What sets ASM apart from commercial mining is that ASM focuses on ore that is typically deemed unprofitable for large-scale commercial mining operations. In West Africa – particularly in Guinea’s Boure region – ASM has historically concentrated on shallow alluvial and eluvial deposits, where gold is present as nuggets mixed within gravel (Doubouya et al. 2024). However, with recent technological advancements, ASM has begun to access areas within commercial mining concessions, targeting waste rock dumps (WRDs) and inactive pits. These areas generally contain low-grade ore that is uneconomical for large-scale operations but remains viable for ASM.

Amongst the commercial mining companies located in the Boure region is Siguiri Gold mine (also known as Société AngloGold Ashanti de Guinée, or SAG). ASM in the Boure region has a rich history dating back centuries and has been coexisting with SAG. However, rising in gold prices and ASM technological advancements have led to encroachment and damage on rehabilitated WRDs and inactive pits at SAG. Damage to rehabilitated WRDs re-exposes the waste material to the elements, resulting in dust nuisance to neighbouring communities, susceptibility of the landform to water erosion and gullying, which will potentially become a safety risk for humans and animals accessing these areas. On the other hand, damage to inactive pits often results in destabilising the pit walls, making them prone to failure, while water quality in the pit lake is compromised due to ore processing by ASM. These risks highlight the need for robust measures to address ASM impacts, with lessons from such experiences serving as valuable insights for mitigating future challenges in ASM and industrial mining interactions.

2 Methodology

2.1 Study area

The Siguiri Gold mine is situated in the remote Siguiri district, approximately 850 km northeast of Conakry, the capital of Guinea, in West Africa (Figure 1). Between 2015 and 2019 the mine was able to rehabilitate almost half (i.e. 12 of the 25) of the WRDs established since SAG’s inception in 1997 (Figure 2). However, in 2020 SAG decided to stop the rehabilitation of WRDs due to the extensive disturbance of these areas by ASM.



Figure 1 Location of the Siguiri Gold mine

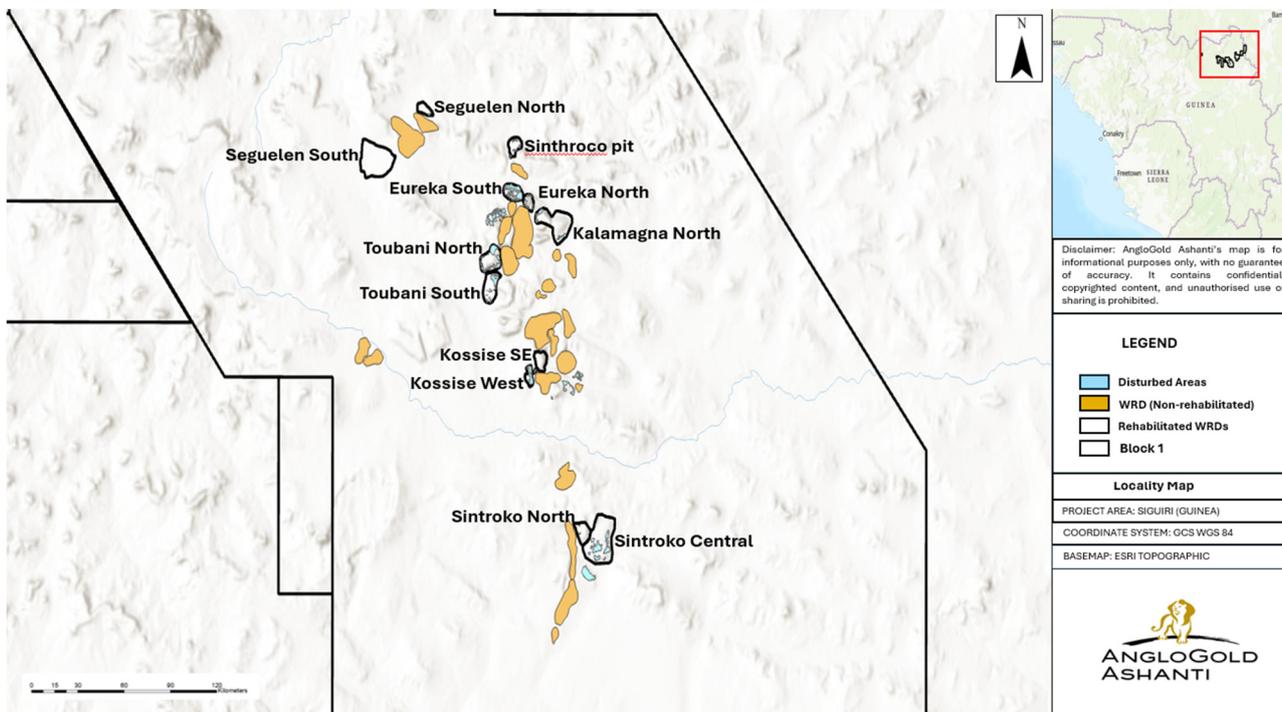


Figure 1 Location of the rehabilitated (black outline) and non-rehabilitated (brown) waste rock dumps in Block 1 at the Siguiri Gold mine

2.2 Data collection and processing

2.2.1 *Internal audit*

To better understand the extent of damage by ASM on rehabilitated sites, SAG carried out an internal audit of the 12 rehabilitated WRDs between February and October 2022 using visual assessment. This involved conducting fieldwork, during which the damaged WRDs were visually examined to quantify the damage and determine its potential origins, represented as a percentage.

In February 2024, another internal audit was conducted on the same WRDs utilising geospatial technology. The objective of this audit was to create a digital map of the disturbed areas to estimate the impact of ASM activities on the WRDs and compare this with the previous audit in 2022. Satellite imagery with 50 cm spatial resolution was utilised to map these areas, providing a basis for assessing the extent of the damage. Following the audit, recommendations were proposed, including the engagement of an independent specialist contractor to conduct a more comprehensive survey and evaluation of the affected regions.

2.2.2 *External survey*

The independent contractor conducted a comprehensive survey involving an onsite evaluation of each of the 12 rehabilitated WRDs, utilising tools such as the Stonex S911 differential GPS to collect data points. This advanced topographic instrument is specifically designed for volume calculations. Additionally, a Mavic Air 2 drone was employed to capture images of the WRDs. The collected data was processed using various software programs including Covadis, AutoCAD Civil 3D, Global Mapper and Excel.

2.2.3 *Time-series mapping*

To supplement both surveys and to capture any significant changes in ASM damage between the time the assessments were conducted, a time-series map was created by an independent contractor. The time-series analysed changes in disturbances from 2007 to 2024, utilising various satellite images with a 50 cm spatial resolution. The different images included Worldview 2, Quickbird, GeoEye and Pleiades. A normalised difference vegetation index (NDVI) was also computed to map the vegetation extent on the WRDs. An NDVI was calculated from satellite imagery using the red and near-infrared light reflected by vegetation. The maps were computed in ArcGIS Pro.

3 Results

3.1 Internal audit

The 2022 internal audit revealed that at least 30% of the rehabilitated WRDs had been re-disturbed by ASM since rehabilitation efforts ceased in 2020 (Table 1). This finding was supported by both the visual assessment, which estimated damage of 32.1% and the maps derived from satellite imagery, which indicated 27.9% damage. While most of the disturbances were attributed to ASM, the disturbances at two WRDs (i.e. Kossisse Southwest WRD and Toubani South WRD) were believed to be because of natural factors such as soil erosion, as no evidence of ASM activity (e.g. random shallow-to-deep excavations and general disturbance of the topography) was observed in these areas during the assessment.

Table 1 Estimated artisanal and small-scale mining (ASM) disturbance of rehabilitated waste rock dumps (WRDs) during Siguiri Gold mine's (SAG's) 2022 internal audits

Name of WRD	Area (ha)	Year of rehabilitation	ASM disturbance – visual assessment as of Dec 2022	ASM disturbance – satellite imagery as of Feb 2024	Comments
Eureka North	59.5	2015	8.4%	21%	Damage due to ASM
Eureka West	25.21	2020	16%	45%	Damage due to ASM
Kalamagna North	39.0	2016	18%	6%	Damage due to ASM
Kossisse Southwest	43.0	2016			Natural disturbance due to erosion
Kossisse West	13.9	2019	66%	42%	Damage due to ASM
Santchoro Pit backfill	25.0	2014	28%	79%	Damage due to ASM
Sanu-tinti	24.0	2018	10%	41%	Damage due to ASM
Seguelen North	14.0	2018	64%	2%	Damage due to ASM
Sintroko Central	74.0	2016	95%	18%	Damage due to ASM
Sintroko North	22.0	2018	8%	2%	Damage due to ASM
Toubani North	41.2	2018	7%	24%	Damage due to ASM
Toubani South	24.4	2018			Natural disturbance due to erosion
Average			32.1%	27.9%	

The visual assessment revealed that the severity of damage to the rehabilitated landforms varied significantly (Figures 3 and 4). In some areas the destruction was relatively minor, involving small-scale excavations and limited uprooting of vegetation coupled with natural erosion (Figure 3). However, in other locations, the damage was far more severe, characterised by extensive excavations, the complete removal of vegetation and the digging of deep wells, some exceeding 15 metres in depth (Figure 4). These observations highlighted the range of disturbances impacting the rehabilitated areas, from localised disruptions to widespread and profound degradation.



Figure 3 Extent of artisanal small-scale miners' disturbance at Toubani North (see area highlighted in red)



Figure 4 Extent of artisanal small-scale miners' disturbance at Sanu-tinti

Although all 12 WRDs were evaluated, the most significant damage (especially per the visual assessment) was found at Sintroko Central WRD, which is why the majority of our findings for this paper focus on this WRD. Sintroko Central WRD spans 74 hectares and was constructed using oxide waste material from the Sintroko Pit, with rehabilitation efforts completed in 2016. The oxide material is inherently unstable, presenting serious environmental challenges such as dust generation during dry periods and high susceptibility to water erosion during the rainy season. These issues are further aggravated by the local climate at SAG. The region experiences long dry spells, with Harmattan winds blowing from December to March, followed by heavy rainfall from June to November. To mitigate these risks, the closure strategy for Sintroko Central WRD and other WRDs within SAG's concession involved covering the waste material with layer of topsoil or laterite at least 300 mm-thick and planting vegetation. This method aimed to stabilise the surface, reduce erosion from wind and water, and encourage ecosystem recovery. SAG successfully applied this strategy to its WRD and presented the Sintroko Central WRD as a model of effective rehabilitation to key stakeholders, including government authorities and local communities.

Since the start of ASM destruction of rehabilitated areas (around 2015) within SAG's concession, Sintroko Central and other rehabilitated WRDs have been significantly affected. As a result, the previously covered oxide material at Sintroko Central has been exposed, large gullies have formed due to erosion and the landscape has experienced substantial changes (Figure 5).



Figure 5 Status of the Sintroko Central waste rock dump as of January 2024 after artisanal and small-scale mining disturbance

Although differences were observed between the results of the visual and satellite imagery assessments (Table 1), the most notable difference was at Sintroko Central. The visual assessment estimated 95% damage, while the satellite imagery indicated only 18% damage. This significant variation is likely attributed to the timing of the assessments as they were conducted in different seasons. The visual assessment took place in December 2022, during the height of the dry season when sparse vegetation left the ground more exposed. In contrast, the satellite imagery was captured in February 2024, a few months after the rainy season, when denser vegetation likely obscured many of the damaged areas, reducing the apparent extent of disturbance. The time difference between the two assessments did not seem to have an impact as no significant difference in ASM damage was observed in the time-series mapping between December 2022 and February 2024 (see Section 3.3 below).

Based on these and other findings, the internal audit recommended the engagement of an independent consultant to perform a thorough assessment of the rehabilitated sites, with consideration for seasonal and other variations. Instead of relying on potentially subjective estimates, the audit advised incorporating precise survey methods, such as topographic reprofiling and associated cut-and-fill volume calculations, for each rehabilitated WRD. This approach would provide a more accurate and objective evaluation of the extent of damage on rehabilitated sites.

3.2 External survey

The general trend in ASM activities across the 12 rehabilitated WRDs, as observed in the external survey, was similar to the findings of the internal audit. However, unlike the internal audit (which focused mainly on assessing the disturbed areas), the external survey assessed the topography of the whole WRD and attributed all the disturbances to ASM as the evidence of ASM activities, including deep excavations which had been covered by vegetation regrowth, were found on all sites (Table 2). Moreover, due to the utilisation of topographic techniques, the external survey revealed that the damage to the WRDs was more extensive than initially reported in the internal audit. For instance, WRDs such as Kalamagna North WRD, Seguelen North WRD and Eureka West WRD showed 100% damage, which was higher than previously assessed.

Table 2 Estimated artisanal and small-scale mining (ASM) disturbance of rehabilitated waste rock dumps (WRDs) during external audits

Name of WRD (12)	Area (ha)	ASM disturbance – survey as of Jan 2025	Observation during field assessment
Eureka North	59.5	69.0%	Presence of ASM. Severe damage largely due to erosion
Eureka West	25.21	100%	Presence of ASM
Kalamagna North	39	100%	Presence of ASM. Severe damage largely due to erosion
Kossisse Southwest	43	100%	Presence of ASM with increasingly modern equipment for exploitation. Severe degradation largely due to erosion
Kossisse West	13.9	100%	Presence of ASM with increasingly modern equipment for exploitation. Some community members have illegally constructed houses on sections of the WRD. Severe degradation largely due to erosion
Santchoro Pit Backfill	25	21%	Presence of ASM
Sanu-tinti	24	100%	Presence of ASM with increasingly modern equipment (excavators, trucks, tricycles etc.) for exploitation
Seguelen North	14	100%	Presence of ASM with increasingly modern equipment (excavators, trucks, tricycles etc.) for exploitation
Sintroko Central	74	100%	Presence of ASM with increasingly modern equipment (excavators, trucks, tricycles etc.) for exploitation
Sintroko North	22	86%	Presence of ASM with increasingly modern equipment (excavators, trucks, tricycles etc.) for exploitation. Severe damage largely due to erosion
Toubani North	41.2	57%	Presence of ASM with increasingly modern equipment for exploitation. Severe damage largely due to erosion
Toubani South	24.4	49%	Presence of ASM with increasingly modern equipment for exploitation. Severe damage largely due to erosion
Average		81.8%	

The external survey estimated almost three times more damage (i.e. disturbed area) than that found during the internal audit (Tables 1 and 2). This finding can be explained by the difference in assessment methods utilised between the internal audit and the external survey. Unlike the internal audit, which only estimated the ASM damage based on hectares disturbed, the external survey went further to look at how the disturbance had impacted the overall topography and remodelled the landform into stable and free-draining facilities (Figure 6). Further to this, some of the ASM disturbance had resulted in the complete deformation of the landscape and removal of significant material, so fixing and reprofiling of these areas would require importing large amounts of material. The importation of material would mean potentially disturbing intact areas. Therefore, the most feasible option proposed was cutting material from undisturbed parts of the WRD to fill damaged areas. So, depending on the type (e.g. deep/shallow excavations) and extent of damage, WRDs like Kalamagna North WRD, Seguelen North WRD and Eureka West WRD, which showed low damage in the internal audit, ended up showing huge damage in the external survey.

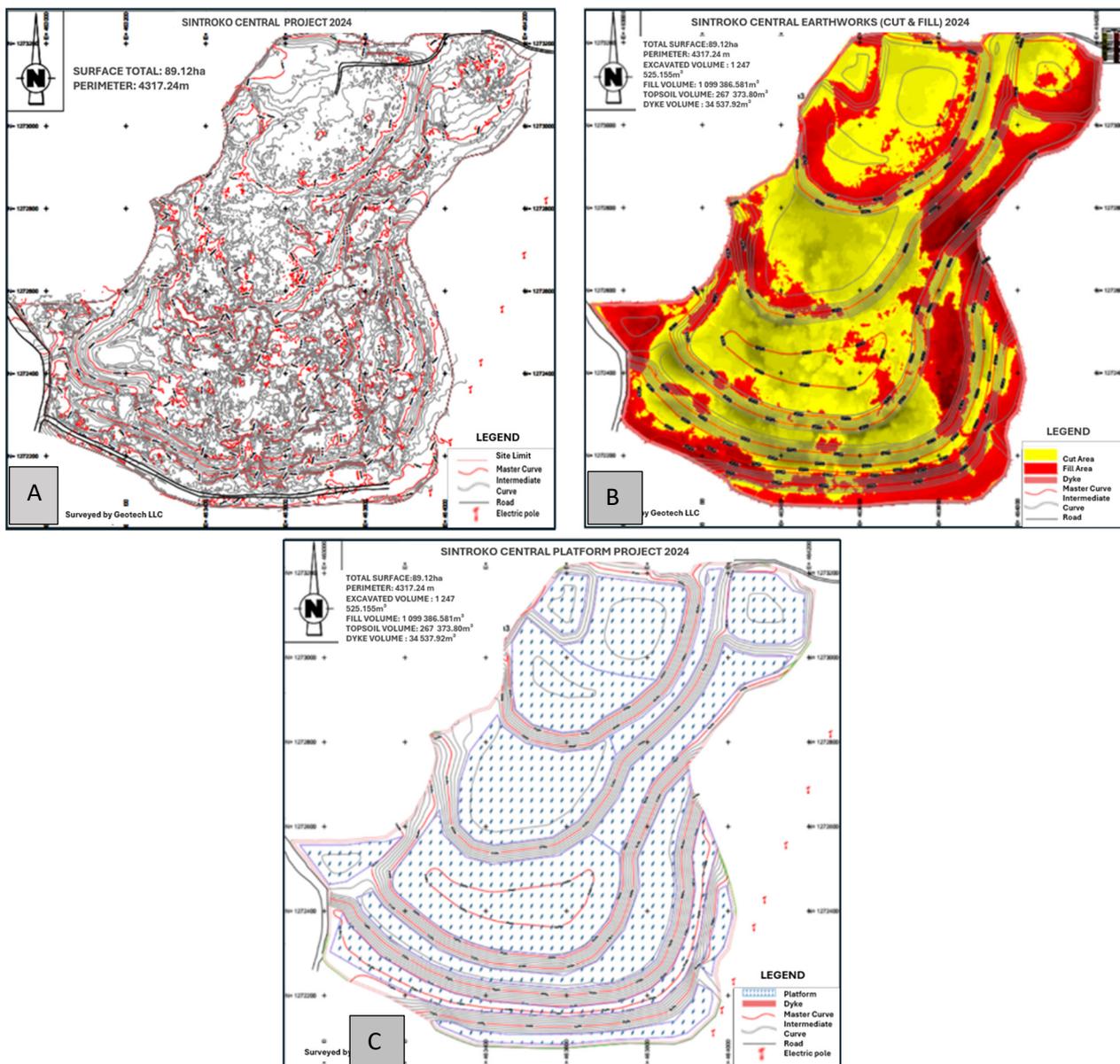


Figure 6 Survey models for Sintroko Central waste rock dump depicting: (a) The extent of artisanal and small-scale mining disturbance; (b) Areas requiring cut (yellow) and fill (red); (c) The remodelled landform

Due to the extensive and detailed nature of the external survey, the survey team also observed that some ASM disturbances were relatively more recent than others and that vegetation had started to grow on the older disturbances. This observation explains some of the variations observed between the visual and satellite imagery assessment during the internal audit. To further inform this gap, SAG worked with the internal geospatial team to develop time-series maps from 2014 to 2024. The section below summarises these results.

3.3 Time-series mapping

A time-series mapping analysis was conducted to assess the condition of WRDs both before and after rehabilitation and evaluate the extent of damage caused by ASM activities, as well as to capture any significant differences in ASM damage between the assessments. This mapping utilised high-resolution satellite imagery captured between 2014 and 2024, covering 12 WRDs. However, the results presented here will only focus on Sintroko Central WRD.

As illustrated in Figure 7, ASM activities on the Sintroko Central WRD first became noticeable around 2019 after the 2016 rehabilitation. Due to the transient nature of ASM operations, ASM miners have shifted their activities to various sections of the WRD over time, as evidenced by the changes observed in the 2022 image. Despite ongoing impacts, the 2024 image reveals that damage remains visible, particularly at the lower section of the WRD. However, natural vegetation regeneration is occurring in certain areas, indicating some degree of ecological recovery.

Since the initial ASM impact at Sintroko Central WRD in 2019, no major disturbances were observed during the subsequent assessments (i.e. visual, aerial and survey) conducted in either 2022 or 2024. However, as noted earlier, vegetation has begun to recolonise the disturbed areas, which is clearly visible in the 2023 and 2024 images shown in Figure 7. Although not detailed in this paper, similar patterns observed at Sintroko Central WRD were also evident across the other 11 WRDs, suggesting that the most significant ASM activity likely occurred between 2019 and 2022.

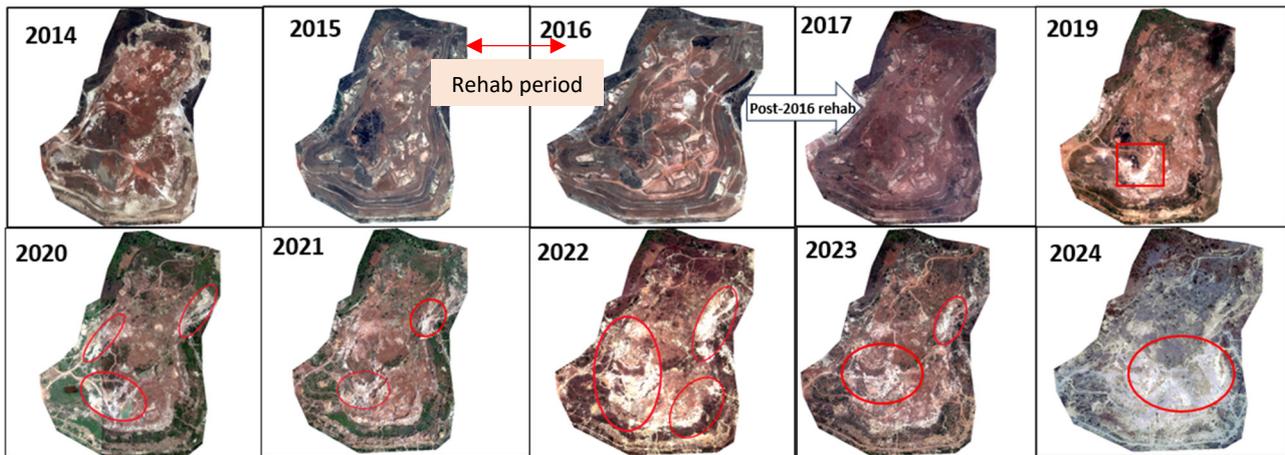


Figure 7 High-resolution images depicting the changes in Sintroko Central waste rock dump from 2014 to 2024, with artisanal and small-scale mining-affected areas highlighted in red

The NDVI images presented in Figure 8 illustrate the gradual regrowth of vegetation on the Sintroko Central WRD, despite the environmental disturbances caused by ASM activities. The 2024 image highlights this regrowth, demonstrating that plant life is beginning to recover in the affected areas. However, while vegetation is returning, the extent of the damage remains apparent as the surface still shows visible signs of degradation. Therefore, although natural regeneration occurs, the underlying risk of unstable ground, deep wells and excavation remains.

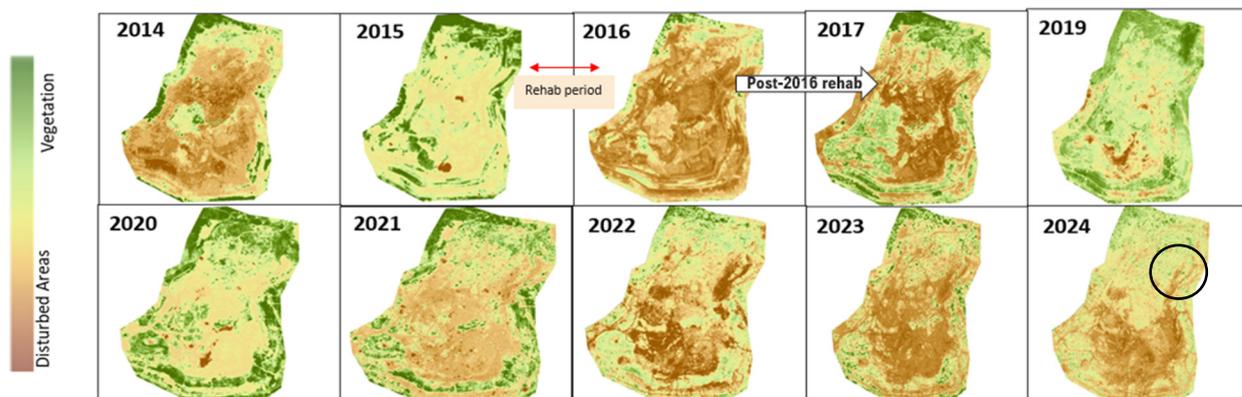


Figure 8 Normalised difference vegetation index images showing vegetation regrowth (highlighted in black) on the Sintroko Central waste rock dump following rehabilitation efforts since 2016

4 Discussion

From a technical perspective, the results from this study provide insightful information when trying to calculate the impact of ASM on landforms. The results show that measuring damage only through field measurement (i.e. per hectare) 2D satellite estimates does not suffice as a great amount of detail is missed. This is because ASM activities often do not only impact the landform surface but also alter the topography of the landform. So physically surveying and remodelling the topography and estimating the material required to reinstate the landform and make it free draining is a more accurate measure.

The results also show that due to the nomadic nature of ASM, one needs to incorporate a temporal assessment instead of only basing ASM's impact on present or recent disturbance. This is particularly important when assessing ASM-related damage using 2D imagery as areas affected by ASM activity may be overlooked due to vegetation regrowth over time. This occurred at the Kossisse Southwest WRD and Toubani South WRD sites, where the field measurements and satellite estimates attributed the disturbances in these areas to erosion. However, the subsequent survey assessment identified ASM as the true cause, revealing deep excavations that had become obscured by vegetation over time.

However, although the survey assessment is more accurate in assessing ASM impact, this method is relatively more labour intensive and expensive, and requires more experienced personnel to conduct the work. Conversely, although less accurate than the survey assessment, the field and satellite assessments can be easily implemented in-house on a mine utilising mine personnel and aerial data. Due to the ease of implementing field and satellite assessments, more frequent measurements of ASM disturbance can be done at short intervals (e.g. quarterly or annually), unlike the more involved survey assessment which might be best conducted at 3–5-year intervals. Consequently, before considering which assessment to adopt, it is best to first have a good understanding of the extent and severity of the ASM disturbance and the intended objective for conducting the assessment. For example, the survey assessment could be ideal for areas where there is extensive ASM disturbance characterised by deep excavations and severe deformation of the topography, such as those exhibited at Sintroko Central WRD (Figure 5), while the field and satellite assessments could work for areas exhibiting minor ASM disturbance, such as those at Toubani North WRD (Figure 3).

Time-series mapping has underscored the importance of temporal analysis in pinpointing periods of heightened ASM activity and acting as a control when comparing the different assessments (i.e. field, satellite and survey) measured at varying periods. Therefore, if one decided to adopt both the 2D analysis (i.e. field and satellite assessments) for short interval assessments and the 3D analysis (i.e. survey assessment) for relatively longer intervals, the time-series becomes a good tool to help compare these methods without concern about the different time periods for the assessment.

The scope of disturbances caused by ASM is vividly captured in satellite imagery, with additional validation provided by vegetation regrowth patterns shown in NDVI images. This regrowth acts as a vital marker of ecosystem recovery following ASM activities. However, the regrowth of vegetation does not nullify the inherent risks (e.g. deep holes, gullies and instability of the landform) caused by ASM re-disturbing rehabilitated areas. While to some extent vegetation regrowth can help with dust-related issues, regrowth of vegetation often reduces the visibility of the disturbed areas, thus increasing the risk of humans and animals falling in them. Therefore, time-series mapping can be utilised to keep track of ASM disturbance over time and keep a record of areas disturbed by ASM, even after vegetation has been re-established.

The methodologies employed to monitor and quantify ASM activities, and their environmental impacts, underscore the urgent need for effective management and regulation of such practices. Stakeholder engagement emerges as a cornerstone in addressing these challenges, ensuring proper control of rehabilitation efforts while assessing the environmental consequences. Equally important is recognition of the driving forces behind ASM activities. Factors like the rising price of gold, which signals sustained demand, are major contributors to the persistence and growth of ASM. This ongoing demand suggests that ASM activities will continue to affect both SAG's concessions and previously rehabilitated areas. Consequently, there is a pressing need to implement more sustainable and adaptive management strategies to mitigate these impacts and

ensure long-term environmental stability. While these strategies are being considered, monitoring of ASM disturbance should continue to ensure that no areas are overlooked due to vegetation regrowth.

5 Conclusion

ASM activities in Guinea's Boure region are expected to persist for an extended period due to several underlying factors, including persistently high unemployment rates and the rising value of gold. These socio-economic drivers make ASM an attractive livelihood option for many individuals. However, the long-term presence of these activities necessitates comprehensive efforts to monitor and assess their environmental and societal impacts.

Understanding and quantifying the effects of ASM are essential for developing effective management strategies and sustainable solutions. In this context, the study employed an innovative technique to remodel topography and estimate the material required to restore the original landform, especially in heavily impacted ASM areas. This method has yielded actionable insights, providing a practical foundation for addressing the environmental challenges posed by ASM and contributing to the formulation of evidence-based interventions. However, the field and satellite assessments still find relevance in areas with less ASM disturbance.

Progressive rehabilitation is widely regarded as best practice for minimising environmental liabilities and enhancing stakeholder confidence in agreed-upon closure strategies. However, this approach is often hindered by the evolving needs and expectations of stakeholders, making consistent implementation challenging. This has been evident in the case of Société AngloGold Ashanti de Guinée, where extensive rehabilitation efforts spanning more than a decade have been undone by ASM activities.

Given these challenges, alternative land use options like the formalisation of ASM presents a viable alternative to ensure that all stakeholders actively contribute to preventing environmental degradation. Beyond environmental benefits, formalisation could also support local communities by creating economic opportunities while helping governments and mining companies mitigate various liabilities. However, for this approach to be effective, continuous and inclusive stakeholder engagement coupled with a strong regulatory framework is essential.

Acknowledgement

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