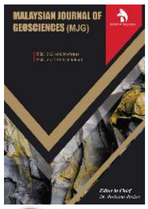
ZIBELINE INTERNATIONAL PUBLISHING
ISSN: 2521-0920 (Print)
ISSN: 2521-0602 (Online)
CODEN: MJGAAN

Malaysian Journal of Geosciences (MJG)

DOI: http://doi.org/10.26480/mjg.01.2025.28.34



CrossMark

RESEARCH ARTICLE

ASSESSING THE EFFECTS OF GOLD MINING ACTIVITIES IN THE OPA RIVER BASIN, SOUTHWEST NIGERIA, USING GOOGLE EARTH ENGINE AND MEDIUM-RESOLUTION LANDSAT DATA

D.A. Akinbode[a], B.A. Tukura[b], I.O. Olaniyi[a], A.A. Adewoyin[c], O.E. Olanrewaju[d], F. O. Tijani[e], F. T. Akinwumi[e], I.T. Oluwatuyi[c], A.O. Eludoyin[a*]

[a]Department of Geography, Obafemi Awolowo University, Ile-Ife, Nigeria
[b]Department of Geography, Federal University, Birnin Kebbi, Nigeria
[c]Institute of Ecology and Environmental Studies, Obafemi Awolowo University, Ile-Ife, Nigeria
[d]Department of Public Health, University of Calabar. Nigeria
[e]Department of Soil Science and Land Resources Management, Obafemi Awolowo University, Ile-Ife, Nigeria.
**Corresponding Author Email: oaeludoyin@yahoo.com*

ARTICLE DETAILS

Article History:

Received 15 February 2025
Revised 23 March 2025
Accepted 28 March 2025
Available online 30 April 2025

ABSTRACT

This study evaluated the environmental effects of gold mining in the Opa River Basin of Southwestern Nigeria, employing multi-temporal Landsat imagery alongside Google Earth Engine. It also examined changes in land use and cover, as well as NDVI and NDWI from 1991 to 2024. Results reveal significant transformations in the landscape, including the growth of mining hotspots, deforestation, and a decline in vegetation health. Statistical analysis of NDVI indicates a reduction in vegetation vigor near mining areas, pointing to ecological disturbances. Furthermore, NDWI analysis establishes a connection between mining activities and increased water turbidity, reflecting higher levels of suspended sediments. This research underscores the essential role of open-access remote sensing data in developing countries with limited research budgets. By accurately identifying mining hotspots and quantifying environmental degradation, it demonstrates the effectiveness of Landsat data for remote monitoring. The findings stress the urgent necessity for comprehensive regulatory frameworks and sustainable management strategies to mitigate the detrimental effects of gold mining, ensuring the ecological integrity of the basin and the welfare of local communities. The reliance on publicly accessible satellite data provides a cost-efficient and replicable methodology, empowering researchers in resource-constrained settings.

KEYWORDS

Gold Mining, Land Use/Cover Change, Remote Sensing, Environmental Impact, Opa River Basin

1. INTRODUCTION

Gold mining is a crucial economic endeavor in many regions; however, it brings significant environmental and social challenges (Ofosu et al., 2020; Worlanyo & Jiangfeng, 2024; Yu et al., 2024). The widespread occurrence of artisanal and small-scale mining, especially in remote and ecologically vulnerable areas, intensifies these challenges, resulting in considerable environmental and social repercussions (Ofosu et al., 2020; Hentschel et al., 2022; Ngom et al., 2023). Numerous reports have consistently pointed out serious environmental problems in key gold-producing African nations, including Nigeria, Kenya, Ghana, South Africa, Sudan, Mali, and Burkina Faso. Both governmental and non-governmental organizations have increasingly focused on raising awareness and implementing mitigation strategies (Fishlock, 2011; Hook, 2019; Bechir-Mahamat, 2024). Empirical research (e.g., Mutanga, 2018; Kameri-Mbote et al., 2024; Eludoyin et al., 2024) has revealed alarming levels of toxic heavy metals, such as mercury, lead, and arsenic, in various gold mining regions across Africa. These findings highlight the pressing need for improved regulatory frameworks and sustainable mining practices to address the detrimental environmental and health effects associated with gold mining activities.

Research has identified various methods for assessing the effects of mining on impacted environments, which include both in-situ and ex-situ techniques. The in-situ method mainly consists of field studies that typically involve ecological sampling for subsequent laboratory analysis (Roullion et al., 2017; Kuppusamy et al., 2016; Kumpiene et al., 2019). Although this approach yields direct insights into specific site conditions, it may not be feasible in areas with security risks or challenging landscapes. As a result, the ex-situ method, particularly remote sensing techniques, often emerges as the more viable option (Cetin et al., 2023; Shikhov et al., 2023). Cetin et al. (2023) pointed out the difficulties in evaluating the impact of mining on soil organic carbon at the hard-to-reach Altintepe gold mine in Turkey using conventional field methods. This challenge led them to implement "a practical and alternative approach that circumvents the need for fieldwork and allows for rapid estimations based on existing data comparisons." Furthermore, many studies advocate for remote sensing techniques over traditional fieldwork in mining research due to their ability to monitor large geographical areas and deliver real-time or near-real-time information through satellite and aerial imagery (e.g., Mehedi et al., 2024; Albahri et al., 2024).

The Opa River Basin, situated in Osun State within the mineral-abundant Ife-Ijesa gold mining area of Southwest Nigeria, is well-known for its widespread artisanal and small-scale mining (ASM) activities, which are fueled by the high market demand for gold (Adeoye, 2016; Eludoyin et al., 2017; Fatoye et al., 2018; Adesipo et al., 2020; Eludoyin et al., 2024). These ASM operations are generally informal and lack regulation, leading to significant environmental harm and frequent incidents of insecurity. In contrast, larger mining enterprises, while also impacting the environment,

Quick Response Code	Access this article online	
	Website: www.myjgeosc.com	**DOI:** 10.26480/mjg.01.2025.28.34

Cite The Article: D.A. Akinbode, B.A. Tukura, I.O. Olaniyi, A.A. Adewoyin, O.E. Olanrewaju, F. O. Tijani, F. T. Akinwumi, I.T. Oluwatuyi, A.O. Eludoyin (2025). Assessing The Effects Of Gold Mining Activities In The Opa River Basin, Southwest Nigeria, Using Google Earth Engine And Medium-Resolution Landsat Data. *Malaysian Journal of Geosciences, 8(1): 28-34.*

benefit from more stringent regulatory oversight. Nevertheless, aside from the Segilola Gold Project (Olade, 2019; Elufisan, 2024), which remains under close public scrutiny, such larger operations are relatively limited in the region under study.

The interplay between artisanal and large-scale mining operations has resulted in notable changes in land use and land cover within the basin, alongside a rise in reported kidnapping cases. These issues highlight the critical role of remote sensing technologies, which serve as an essential resource for tracking these transformations over time (Ayegbusi, 2024; Ojakorotu, 2024; Ojewale, 2024). In middle and low-income nations, open-access satellite data are favored due to their accessibility. Since the inaugural launch of the first Landsat satellite in 1972, Landsat satellites have been fundamental to Earth observation. The medium-resolution data they provide, generally at a 30-meter resolution, facilitates comprehensive analysis of changes in land use and land cover (Chatterjee et al., 2010; Khatiri, 2024). In Nigeria and various countries in the West African region, the application of Landsat data for monitoring the environmental consequences of deforestation is well-established; however, its use for mining activities is less prevalent compared to many regions in Asia and South Africa. This indicates a pressing need for further research in this area to enhance capacity building within the West African region (Rajaee et al., 2015; Dethier et al., 2023; Masolele, 2023).

2. Research Problem

The Opa River Basin in Osun State exemplifies the complex effects of gold mining, particularly through artisanal and small-scale operations, which are crucial for local economies but also present considerable environmental and social issues. Despite this, most research has concentrated on the Ijesa area of the gold mining sector (Adeoye, 2016; Eludoyin et al., 2017; Fatoye et al., 2018; Adesipo et al., 2020; Eludoyin et al., 2024). Consequently, the Opa River Basin has received less attention, even though it is of great importance. While the basin has been thoroughly investigated regarding its morphometric features and water quality—critical for the region's domestic water supply (Eludoyin et al., 2004; Akindele & Adeniyi, 2013; Adesakin et al., 2017; Adewole & Eludoyin, 2020; Aliu et al., 2020; Babatimehin et al., 2022; Ogunkoya & Ogbole, 2024)—recent studies (Adewole & Eludoyin, 2020; Aliu et al., 2020; Babatimehin et al., 2022; Ogunkoya & Ogbole, 2024) have identified contamination from both diffuse and particulate pollutants linked to poorly documented mining activities in the basin, underscoring the necessity for this research.

Additionally, conventional field-based techniques in the mining sector of the Opa River Basin face significant limitations due to challenging terrain and security concerns, which necessitate the adoption of alternative methods such as remote sensing. This trend is increasingly observed in various regions of Nigeria and elsewhere, where security issues may hinder research efforts. Therefore, this study aims to establish a practical framework for monitoring environmental changes over time, especially in vast and isolated areas, by utilizing multi-date, medium-resolution, open-access Landsat imagery in conjunction with Google Earth Engine. As a result, the specific goals of this research are to evaluate changes in land use and land cover and to pinpoint mining hotspots within the Opa River Basin. The study is grounded in the hypothesis that mining activities have led to significant changes in land use and land cover within the basin, and that these alterations can be effectively detected and monitored through medium-resolution Landsat data.

3. Materials And Methods

3.1. Study Area

The Opa River Basin, located in Southwestern Nigeria, acts as a tributary to the larger River Osun. It is geographically positioned between latitudes 7°26′56′′ and 7°35′5′′ N, and longitudes 4°24′53′′ and 4°39′13′′ E (Figure 1). Within this basin, significant streams such as the Amuta, Obubu, and Esinmirin flow through various land-use areas (Akinbuwa & Adeniyi, 1996; Eludoyin et al., 2004). The basin includes four Local Government Areas (LGAs): Atakumosa West, Ife Central, Ife East, and Ife North. A prominent feature of the basin is the Opa Dam, which was built in 1978 to provide water to Obafemi Awolowo University and nearby communities. It was estimated that by 2015, the dam would serve over 644,000 individuals (Adediji, 2005). The reservoir covers a catchment area of about 68 km^2 and has a capacity of 675,000 m^3, supplying water for domestic, agricultural, and research needs.

The region is characterized by a tropical climate, specifically classified as Köppen's Af type, which features a rainy season from April to October and a dry season from November to March. The average annual precipitation ranges from 206 cm to 232 cm, with temperatures fluctuating between a low of 23.0°C in August and a high of 33.8°C in February (Akinbuwa & Adeniyi, 1996). Seasonal wind patterns vary, with southwesterly winds prevailing during the wet season and northeasterly winds during the dry season.

Historically, the basin was predominantly covered by tropical rainforest; however, much of this has been transformed into secondary vegetation due to agricultural development. From 1986 to 2016, around 23.8% of the original vegetation was replaced by urbanization, agricultural land, and bare surfaces (Eludoyin & Adewole, 2020). By 2016, the proportion of built-up areas had increased from 5% to 18% of the basin's total area (Adesakin et al., 2017). The main soil types in the region are the Egbeda and Iwo series, which are typical of tropical ferruginous soils associated with Basement Complex geology. The geological composition of the basin mainly includes granites, schists, and pegmatites (Adediji, 2005).

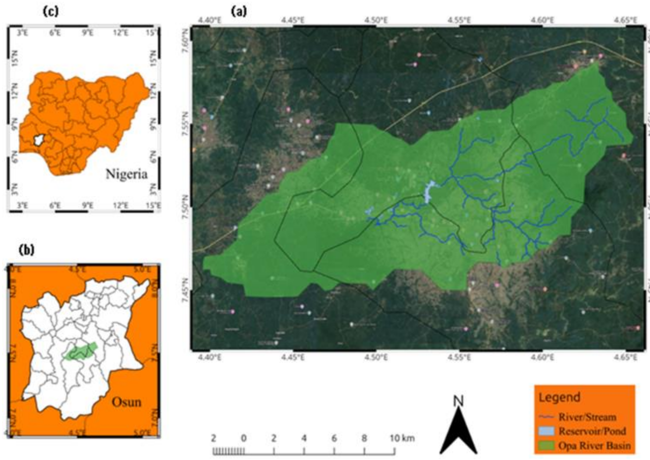


Figure 1: Opa River Basin (a) located in Osun State (b) in Southwestern Nigeria (c)

3.2. Data

This research employed Landsat satellite images with a spatial resolution of 30 meters, sourced from the United States Geological Survey (USGS) website, covering the years 1991, 2002, 2011, 2021, and 2024 (path 190, row 55). The datasets included Landsat 4 (TM) for January 5, 1991, Landsat 7 (ETM+) for January 3, 2011, and January 3, 2022, as well as Landsat 8 and 9 OLI for December 17, 2021, and January 16, 2024, respectively, all maintaining the 30-meter resolution. For land use and land cover classification, ArcGIS Pro 2.8.3 was utilized, while QGIS 3.4 was chosen for calculating the Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI) due to its open-access nature. Google Earth Pro facilitated the validation of coordinates for the mining enclaves and adjacent areas, addressing security concerns in the mining region. The satellite datasets underwent supervised image pre-processing, which included geometric and radiometric corrections. The subsequent data analysis involved image classification through the maximum likelihood classification algorithm. Land Use/Land Cover (LU/LC) change (Table 1) detection was conducted using Geographic Information System (GIS) analysis and a post-classification comparison of the satellite imagery. This process entailed independently classifying images from various time points and performing a comparative analysis to create a change matrix (Lu et al., 2004). The annual rate of change, encompassing both increases and decreases for each LU/LC class, was calculated using absolute and percentage change methods (Wegmann et al., 2016). The Normalized Difference Vegetation Index (NDVI) was computed using equations 1 and 2.

$$NDVI = \frac{Band\ 4 - Band\ 3}{Band\ 4 + Band\ 3} \quad (1)\ \text{Landsat 4-7,}$$

$$NDVI = \frac{Band\ 5 - Band\ 4}{Band\ 5 + Band\ 4} \quad (2)\ \text{Landsat 8-9,}$$

Furthermore, the Normalized Difference Water Index (NDWI) was calculated using eq. 3

$$NDWI = \frac{Near\ Infrared - Shortwave\ Infrared}{Near\ Infrared + Shortwave\ Infrared} \quad (3)$$

Each enhanced image underwent processing for supervised classification utilizing the Maximum Likelihood Classifier. This classification process was informed by the USGS Level I classification system (Anderson, 1976), expert insights regarding the study area, and field observations. The classification scheme employed in this study is presented in Table 2. The Maximum Likelihood Classifier was chosen for its assumption of normally distributed statistics for each class across the various bands, which

Cite The Article: D.A. Akinbode, B.A. Tukura, I.O. Olaniyi, A.A. Adewoyin, O.E. Olanrewaju, F. O. Tijani, F. T. Akinwumi, I.T . Oluwatuyi, A.O. Eludoyin (2025). Assessing The Effects Of Gold Mining Activities In The Opa River Basin, Southwest Nigeria, Using Google Earth Engine And Medium-Resolution Landsat Data. Malaysian Journal of Geosciences, 8(1): 28-34.

facilitates the computation of pixel membership probabilities. Pixels were allocated to the class with the highest probability, contingent upon meeting a specified probability threshold. This approach is advantageous as it incorporates the covariance matrix and relies on established methodologies (Swain and Davis, 1981; Oyinloye & Oloukoi, 2013). Following this, land use/land cover (LU/LC) changes from 1991, 2002, 2011, 2021, and 2024 were evaluated using a change detection technique as outlined by Rawat & Kumar (2015).

Table 1: Identified land use/cover class and the interpretation

Class of Landuse/cover	Description
Mature forest	Areas dominated by dense forest cover or clusters of lush and abundant plant life
Light vegetation	Areas with scattered trees, shrubs, or degraded vegetation.
Waterbody	Rivers, streams, or reservoirs where water is the dominant feature
Built-up	Places reflecting human activities and infrastructure, including houses, roads, and pathways
Open space/bareland	Regions with little to no vegetation, such as exposed soil, rocks, or barren land.
Gold mine hotspot	Areas identified as active or former gold mining sites, often associated with soil disruption

The evaluation of the land use/land cover (LULC) classification's accuracy was conducted through a confusion matrix, which juxtaposes the classified LULC categories with reference (ground) data. The overall accuracy, indicating the proportion of accurately classified samples to the total sample size, was determined to be 79.12%. Additionally, the Kappa coefficient was calculated at 0.75, or 75%, signifying a strong level of concordance between the classification outcomes and the ground data (see Table 2).

Table 2: Land classification accuracy assessment with a confusion matrix table and Kappa coefficient

Classified as ↓ / Actual →	Thick vegetation	Open Space/ Bareland	Light vegetation	Gold Mine Hotspot	Waterbody	Built-up
Mature forest	50	3	5	0	0	2
Open Space/ Bareland	3	38	5	7	1	3
Light vegetation	6	4	45	0	2	1
Gold Mine Hotspot	0	3	1	37	0	4
Waterbody	0	2	3	0	25	0
Built-up	1	2	2	4	0	48
Total Ground truth	60	52	61	48	28	58
User Accuracy	83	73.1	73.8	77.1	89.3	82.8
Producer Accuracy	83	63.7	77.6	82.2	83.3	84.2
Overall accuracy	79.12					
Kappa accuracy (no unit)	0.75					

4. Results

4.1. Temporal changes in land use/cover, including the gold mine hotspot

Table 3 provides a summary of the land use and cover changes in the Opa River Basin from 1991 to 2024, highlighting significant alterations in the landscape due to urban development, environmental changes, and the recent onset of mining operations. The area designated for built-up structures consistently expanded, rising from 14.10 km² in 1991 to 58.86 km² in 2024. The most rapid growth occurred between 2011 and 2021, with an increase of 110.33%, which then decelerated to 22.33% from 2021 to 2024. Light vegetation experienced variability: it initially grew from 50.82 km² in 1991 to 74.04 km² in 2002 (a rise of 45.68%), followed by a decline to 41.17 km² by 2021 (a decrease of 37.25%), and then rebounded to 52.20 km² by 2024 (an increase of 26.79%). The area of open space or bare land first decreased from 52.79 km² in 1991 to 42.57 km² in 2002 (a reduction of 19.37%), then saw a significant rise to 72.91 km² by 2021 (an increase of 67.99%), before experiencing a slight decline to 67.70 km² (a decrease of 7.14%) between 2021 and 2024.

Table 3: Land use/cover distribution and percentage change (1991 - 2024)

Class of Landuse/cover	The total area occupied in area (in sq. km)					Percentage Change				Overall change (%)
	1991	2002	2011	2021	2024	1991—2002	2002—2011	2011—2021	2021—2024	1999-2024
Mature forest	115.55	95.87	101.54	66.89	52.57	-17.03	5.91	-34.12	-21.41	-16.66
Light vegetation	50.82	74.04	65.64	41.17	52.20	45.69	-11.35	-37.28	26.79	5.96
Waterbody	0.45	0.34	0.25	0.24	0.23	-24.44	-26.47	-4.00	-4.17	-14.77
Built-up area	14.10	20.89	22.88	48.12	58.86	48.16	9.53	110.31	22.32	47.58
Open space/bareland	52.79	42.57	43.41	72.91	67.70	-19.36	9.53	67.96	-7.15	10.86
Gold mine hotspot	0.00	0.00	0.00	4.39	2.13	0.00	0.00			

Mature forests experienced a continuous decline from 115.55 km² (1991) to 52.57 km² (2024), with the most significant loss between 2011 and 2021 (-34.13%) and a further reduction of 21.41% by 2024. Water bodies steadily decreased from 0.45 km² (1991) to 0.23 km² (2024). Gold mining emerged as a new land use in 2021, occupying 4.39 km² and decreasing to 2.13 km² by 2024.

In addition, Figures 2a-e show the spatial distribution of the landuse/cover changes across the same periods, including the emergence and evolution of a designated goldmine hotspot. In 2021, this hotspot was located within a region predominantly characterized by Mature Forest, interspersed with patches of light vegetation. By 2024, the hotspot was centrally situated within the mapped area, away from the peripherally concentrated built-up areas. Water bodies were observed around the goldmine hotspot, while open space/bare land was more prevalent along the edges of Mature Forest and interspersed with built-up areas. This spatial distribution in 2024 indicates substantial mining activity within a previously vegetated area, suggesting deforestation and vegetation removal. A comparison of the maps from 1991, 2002, 2011, 2021, and 2024 (Figures 2a-e) reveals a clear trend of escalating impact of gold mining. The 1991, 2002, and 2011 maps show a landscape dominated by Mature Forests with minimal open space/bareland, primarily confined to peripheral and built-up areas. Critically, no goldmine hotspot is present during this period.

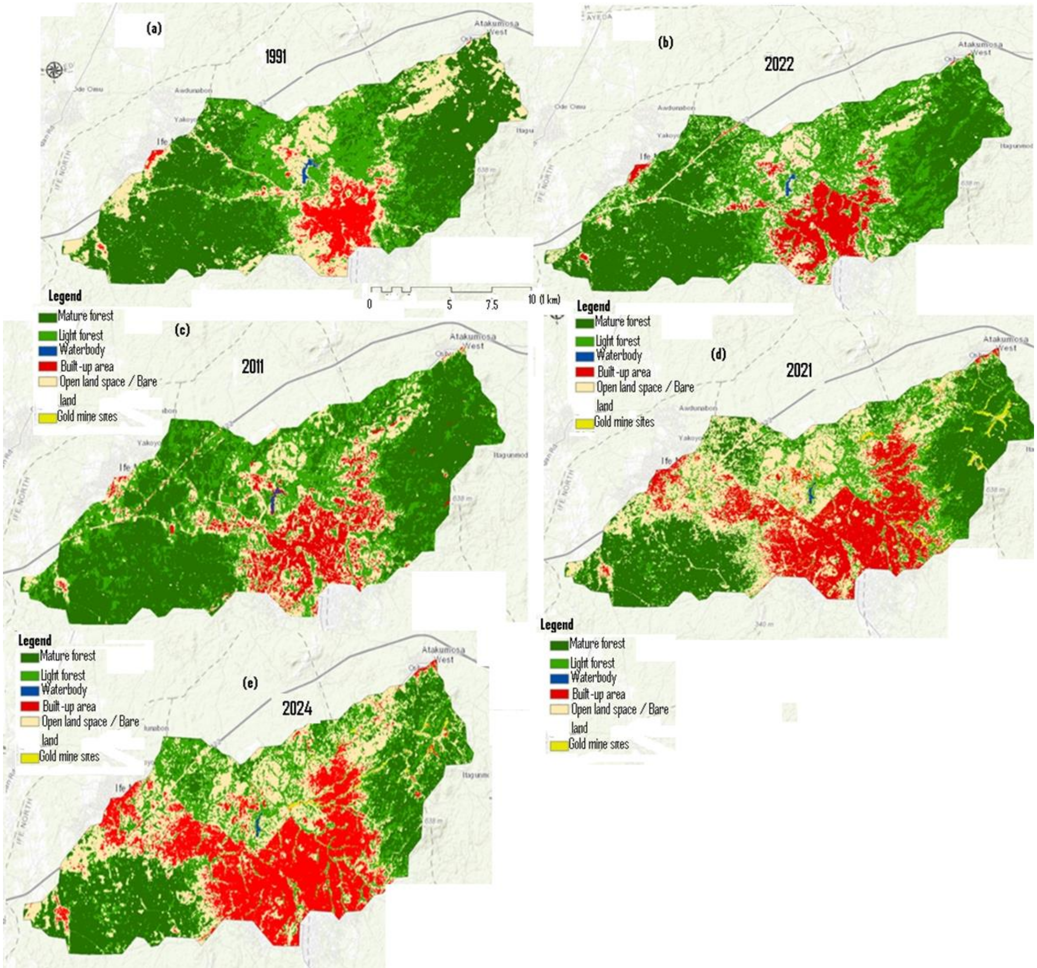


Figure 2a-e: Spatial distribution of land use/cover as at 1991, 2002,2011, 2021 and 2024

The 2021 map marks the emergence of the goldmine hotspot within the former Mature Forest, initiating significant mining-related land use change. By 2024, the hotspot had substantially expanded, accompanied by further Mature Forest reduction and increased open space/bareland, demonstrating intensified mining and greater land disturbance. This progression—emergence, expansion, and intensification—has significant implications, most notably deforestation and habitat loss, impacting local biodiversity (Lambin et al., 2001).

4.2. Change in vegetal response

Figure 3a-e presents a visual narrative of the basin's evolving vegetation health, as captured through the Normalized Difference Vegetation Index (NDVI) from 1991 to 2021. The NDVI, a widely recognized measure of vegetation density and vigour derived from the reflectance of red and near-infrared light, provides a valuable lens through which to examine environmental change (Tucker, 1979). In 1991, as shown in Figure 3a, the basin exhibited a landscape largely characterized by robust vegetation cover, with expansive swathes of high NDVI values, indicated by the pervasive green tones. This suggests a healthy and relatively undisturbed ecosystem. However, even at this baseline, subtle variations exist, with localized areas of lower NDVI, represented by yellow-orange hues, likely reflecting natural features such as water bodies, exposed soil, or less dense vegetation patches.

Moving forward to 2002 (Figure 3b), a distinct shift becomes apparent. The previously dominant green tones, indicative of high vegetation density, begin to recede, yielding to an expansion of yellow-orange areas, particularly along the main river channel and within specific regions of the basin. This transition signals a decline in vegetation health or cover, potentially attributable to the escalating gold mining activities that are known to have intensified during this period.

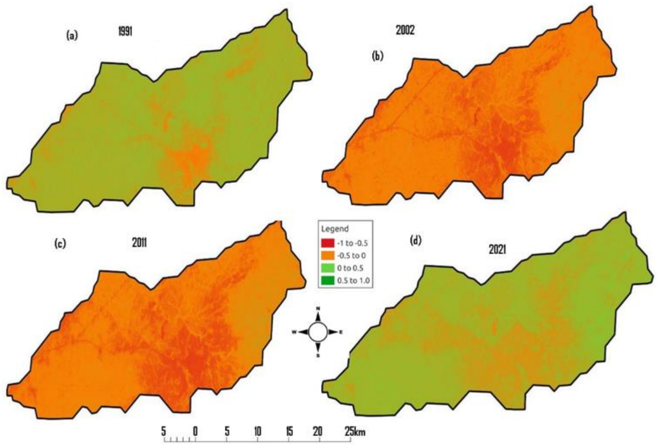


Figure 3: Patterns of NDVI in 1991, 2002, 2011 and 2021.

The spatial correlation between the observed NDVI changes and the expansion of mining operations is striking, aligning with established

Cite The Article: D.A. Akinbode, B.A. Tukura, I.O. Olaniyi, A.A. Adewoyin, O.E. Olanrewaju, F. O. Tijani, F. T. Akinwumi, I.T . Oluwatuyi, A.O. Eludoyin (2025). Assessing The Effects Of Gold Mining Activities In The Opa River Basin, Southwest Nigeria, Using Google Earth Engine And Medium-Resolution Landsat Data. Malaysian Journal of Geosciences, 8(1): 28-34.

research that documents the detrimental impact of vegetation clearing associated with such activities (LaJeunesse et al., 2016). By 2011, the trend of declining NDVI values became even more pronounced (Figure 3c). The reduction in high NDVI areas and the corresponding expansion of lower NDVI zones persist, painting a picture of sustained environmental stress. The spatial patterns reveal a concentration of vegetation loss along river courses and in areas directly affected by mining, suggesting a direct causal link between the intensification of mining and the observed ecological degradation (Oluwafemi, 2018). The impact of the mining operations is very clear in this figure, and the reduction of the green areas is very noticeable.

The 2021 map, (Figure 3d), introduces a more nuanced scenario. While some areas continue to exhibit low NDVI values, indicating ongoing disturbances, a notable resurgence of high NDVI values is observed in other parts of the basin. This suggests a potential recovery or a shift in the factors influencing vegetation dynamics. Possible explanations include a reduction in mining intensity in certain areas, allowing for partial vegetation regeneration, or a relocation of mining activities to other parts of the basin.

4.3. Change in surface water coverage

The temporal sequence of NDWI maps in Figure 4, spanning from 1991 to 2021, indicates evolving surface water characteristics within the Opa River Basin, Osun state, Nigeria. In 1991, the basin presented a relatively undisturbed state, evidenced by the predominantly brown and grey tones, indicative of low NDWI values. This suggests a baseline condition of relatively clear water and potentially limited surface water coverage, reflective of the forest-dominated landscape seen in the corresponding land use map (Figure 2a). However, this initial state is markedly altered in subsequent years. By 2002, a distinct shift became apparent, with the emergence and expansion of blue areas, particularly along the main river channel. This surge in NDWI values, signalling increased surface water storage, its associated turbidity and sedimentation, directly corresponds with the documented expansion of gold mining sites during this period (Figure 2b). The clearing of vegetation and disturbance of soil, inherent to mining operations, likely led to increased sediment runoff, thereby elevating turbidity levels. This observation aligns with established research demonstrating the detrimental impact of land disturbance on sediment export in tropical ecosystems (Schaffelke et al., 2017). The trend of increasing NDWI values persists into 2011, with a further expansion of blue areas across the basin. This sustained rise in turbidity reflects the cumulative impact of ongoing and intensifying mining activities, mirroring the continued deforestation and expansion of bare land observed in the land use maps (Figure 2c). The increased bare land and disturbed soil surfaces, directly associated with mining operations, contribute to higher sediment loads in the waterways, exacerbating the turbidity problem and potentially impacting aquatic biodiversity.

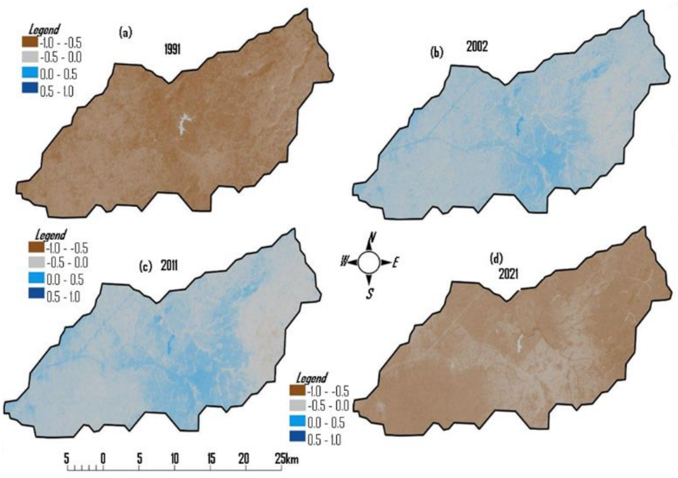


Figure 4: Patterns of NDWI in 1991, 2002, 2011 and 2021

However, the 2021 map (Figure 4d) introduces a more complex scenario. While some areas maintain high NDWI values, indicating the persistence of mining impacts, a substantial portion of the basin exhibits a decline, reverting towards lower NDWI values. This shift suggests a potential reduction in turbidity, possibly due to a combination of factors. The most easily erodible materials might have been depleted, localized recovery may have occurred due to reduced mining intensity, mining operations might have shifted to other areas within the basin, or changes in precipitation patterns could have influenced NDWI values. Nevertheless, the lingering presence of high NDWI values underscores the enduring environmental challenges posed by gold mining in the Opa River basin.

The combined analysis of the NDWI and land use maps highlights the direct link between mining activities and the hydrological characteristics of the basin, which has been of interest to researchers including the authors. The expansion of mining operations has led to significant deforestation and soil disturbance, resulting in increased turbidity and sediment load in the waterways, with direct implications for water quality and the well-being of the local community. Potential impacts on access to clean drinking water, agricultural productivity, and the health of aquatic ecosystems that support local livelihoods are of concern. The long-term sustainability of water resources in the region is thus inextricably linked to the management of mining activities and the restoration of degraded landscapes.

5. Discussion

This research presents an examination of the environmental consequences of gold mining in the Opa River Basin, located in Southwestern Nigeria, utilizing medium-resolution Landsat data within the Google Earth Engine platform. It effectively fills a significant void in the current body of literature, which has largely concentrated on the Ijesa region, by emphasizing the notable changes taking place in the Opa River Basin. The documented temporal shifts in land use and cover, especially the rise and growth of gold mining hotspots, indicate a direct link between mining operations and ecological harm. The shift from a landscape dominated by mature forests to one marked by increased open spaces and diminished vegetation aligns with the recognized understanding that deforestation is a major outcome of resource extraction (Lambin et al., 2001). The study's conclusions are further bolstered by the analysis of NDVI, which reveals a distinct decline in vegetation health and vitality over time, particularly in areas near mining operations. This observation supports the ecological disturbance theory, which posits that human activities disrupt natural ecosystems, resulting in a loss of biodiversity and ecosystem services (McDonnell & Pickett, 1990; Mathewos et al., 2024). The variations in NDVI, including signs of potential recovery in certain regions, indicate a complex interaction between environmental factors and mining activities, highlighting the need for further exploration into the resilience and recovery capabilities of the impacted ecosystems.

The evaluation of the Normalized Difference Water Index (NDWI) offers essential insights into the hydrological effects of mining, establishing a clear connection between mining operations and the rise of turbid water-filled surface depressions in the Opa River Basin. The increase in NDWI values, especially near mining hotspots, highlights the substantial sediment load resulting from deforestation and soil disruption. This observation is consistent with existing knowledge regarding sediment transport and the deterioration of water quality in affected watersheds (Schaffelke et al., 2017). Variations in NDWI, which may include potential decreases in turbidity, could indicate changes in mining activity, sediment depletion, or shifts in rainfall patterns. Nevertheless, the consistently high NDWI values emphasize the ongoing environmental challenges associated with mining, particularly in relation to the sustainability of water resources. The ramifications of these findings go beyond immediate ecological effects, raising significant concerns about the long-term viability of water resources and the welfare of local populations. The potential consequences for access to clean drinking water, agricultural output, and aquatic biodiversity highlight the urgent need for effective environmental management strategies.

The methodology employed in this study, which incorporates multi-date Landsat imagery alongside Google Earth Engine, presents an effective and economical strategy for monitoring environmental changes in remote and difficult terrains, overcoming the challenges associated with conventional field-based techniques. This method reflects the increasing acknowledgment of remote sensing as a vital instrument for environmental monitoring and management (Turner et al., 2003). Additionally, the research serves as a significant framework for evaluating the environmental consequences of artisanal and small-scale mining, a crucial source of income in numerous developing nations. The findings contribute to the larger conversation surrounding sustainable resource management, emphasizing the necessity of reconciling economic growth with environmental preservation. The changes observed can be associated with the environmental Kuznets curve, which posits that initial economic activities may result in environmental harm, yet with appropriate regulation, environmental quality can be restored. Nevertheless, in the context of the Opa River Basin, the study indicates that the existing regulatory measures may be insufficient, resulting in ongoing environmental degradation. Furthermore, the research implicitly references the 'tragedy of the commons' theory, which suggests that individuals acting in their own self-interest can deplete shared resources (Hardin, 1968), specifically the land and water resources within the basin.

6. Conclusion And Recommendations

This research has highlighted the significant environmental consequences of gold mining in the Opa River Basin, located in Southwestern Nigeria, by utilizing multi-temporal Landsat data and the Google Earth Engine platform. The identified trends, such as the rapid expansion of mining hotspots, extensive deforestation, and declining vegetation health, along with increased water turbidity, collectively indicate a serious disruption to the ecological balance of the basin. This situation poses long-term risks to the sustainability of water resources and the livelihoods of local populations. Importantly, this study emphasizes the vital role of open-access remote sensing data in developing nations, especially where research funding is limited. The use of freely accessible Landsat data offers a cost-effective and replicable approach, facilitating essential environmental evaluations in contexts with scarce resources.

In light of these findings, we strongly advocate for the prompt implementation of comprehensive strategies to address the environmental degradation resulting from gold mining in the Opa River Basin. First and foremost, establishing a strong regulatory framework is essential to oversee mining activities, ensuring compliance with sustainable practices and minimizing ecological harm. This should include mandatory environmental impact assessments and the enforcement of rehabilitation initiatives. Additionally, promoting alternative livelihood opportunities is critical to lessen reliance on environmentally harmful mining, thereby encouraging economic diversification and sustainable development. Furthermore, ongoing environmental monitoring, employing both remote sensing and field-based techniques, is crucial for tracking changes and guiding adaptive management strategies. This monitoring should significantly depend on open-access remote sensing data, which is vital for ongoing environmental oversight in developing countries. Collaborative efforts among government agencies, local communities, and research institutions are essential for successfully implementing these measures.

Acknowledgements

The authors acknowledge the former Executive Director of the Central Office of Research, Obafemi Awolowo University, Ile Ife, Nigeria, Prof. Morenike O. Ukpong, for organising the June 19-21, 2024's Manuscript Writing Workshop at the Conference Hall of ACE Park. This publication is a product of Group 2.

References

Adediji, A. (2005). Reservoir sedimentation: The case of the Opa Reservoir catchment, Southwestern Nigeria. *South African Geographical Journal, 89*(2), 123–128.

Adeoye, N. O. (2016). Land degradation in gold mining communities of Ijesaland, Osun State, Nigeria. *GeoJournal, 81*, 535–554.

Adesakin, T. A., Adedeji, A. A., Aduwo, A. I., & Taiwo, Y. F. (2017). Effect of discharges from re-channeled rivers and municipal runoff on water quality of Opa Reservoir, Ile-Ife, Southwest Nigeria. *African Journal of Environmental Science and Technology, 11*(1), 56–70.

Adesipo, A. A., Akinbiola, S., Awotoye, O. O., Salami, A. T., & Freese, D. (2020). Impact of mining on the floristic association of gold-mined sites in Southwest Nigeria. *BMC Ecology, 20*, 1–13.

Akinbuwa, O., & Adeniyi, I. F. (1996). Seasonal variation, distribution, and interrelationships of rotifers in Opa Reservoir, Nigeria. *African Journal of Ecology, 34*(4), 351–363.

Akindele, E. O., & Adeniyi, I. F. (2013). A study of the physico-chemical water quality, hydrology, and zooplankton fauna of Opa Reservoir catchment area, Ile-Ife, Nigeria. *African Journal of Environmental Science and Technology, 7*(5), 192–203.

Albahri, A. S., Khaleel, Y. L., Habeeb, M. A., Ismael, R. D., Hameed, Q. A., Deveci, M., ... & Alzubaidi, L. (2024). A systematic review of trustworthy artificial intelligence applications in natural disasters. *Computers and Electrical Engineering, 118,* 109409.

Aliu, O. O., Akindele, E. O., & Adeniyi, I. F. (2020). Biological assessment of the headwater rivers of Opa Reservoir, Ile-Ife, Nigeria, using ecological methods. *The Journal of Basic and Applied Zoology, 81*, 1–8.

Anderson, J. R. (1976). A land use and land cover classification system for use with remote sensor data (Vol. 964). *US Government Printing Office*.

Ayegbusi, T. R. (2024). Armed Banditry and Kidnapping in Nigeria. In *The Political Economy of Kidnapping and Insecurity in Nigeria: Beyond News and Rumours* (pp. 105–134). Cham: Springer Nature Switzerland.

Babatimehin, O. I., Eludoyin, A. O., Ekundayo, O. O., & Ekwere, N. J. (2020). Water quality and perception on use in Obafemi Awolowo University, Ile-Ife, Nigeria. *Interdisciplinary Environmental Review, 20*(2), 100–117.

Bechir-Mahamat, B. (2024). Do conflict mineral disclosures financially matter? (Doctoral dissertation, Loughborough University).

Cetin, M., Isik Pekkan, O., Bilge Ozturk, G., Cabuk, S. N., Senyel Kurkcuoglu, M. A., & Cabuk, A. (2023). Determination of the impacts of mining activities on land cover and soil organic carbon: Altintepe Gold Mine Case, Turkey. *Water, Air, & Soil Pollution, 234*(4), 272.

Chatterjee, A., Michalak, A. M., Kahn, R. A., Paradise, S. R., Braverman, A. J., & Miller, C. E. (2010). A geostatistical data fusion technique for merging remote sensing and ground-based observations of aerosol optical thickness. *Journal of Geophysical Research: Atmospheres, 115*(D20).

Dethier, E. N., Silman, M., Leiva, J. D., Alqahtani, S., Fernandez, L. E., Pauca, P., Çamalan, S., Tomhave, P., Magilligan, F. J., Renshaw, C. E., & Lutz, D. A. (2023). A global rise in alluvial mining increases sediment load in tropical rivers. *Nature, 620*(7975), 787–793.

Eludoyin, A. O., Ike, F., Onanuga, M. Y., Omosuyi, O. S., & Adewoyin, A. A. (2024). Gold mining activities and impact on Osun River Basin in Southwestern Nigeria. In *The Palgrave Encyclopedia of Sustainable Resources and Ecosystem Resilience* (pp. 1–12). Cham: Springer International Publishing.

Eludoyin, A. O., Ofoezie, I. E., & Ogunkoya, O. O. (2004). The effect of Oja-titun market effluent on the chemical quality of the receiving OPA reservoir in Ile-Ife, Nigeria. *Journal of Environmental Management, 72*(4), 249–259.

Eludoyin, A. O., Ojo, A. T., Ojo, T. O., & Awotoye, O. O. (2017). Effects of artisanal gold mining activities on soil properties in a part of Southwestern Nigeria. *Cogent Environmental Science, 3*(1), 1305650.

Elufisan, P. T. (2024). Geospatial assessment of the effect of gold mining in Atakunmosa East Local Government Area, Osun State. *African Journal on Land Policy and Geospatial Sciences, 7*(5).

Fatoye, A. O., Adebayo, A. O., & Tomori, W. B. (2018). Multivariate analysis and contamination studies of elemental profile in Ife/Ijesa goldmine tailings, Southwestern Nigeria. *Sustainable Geoscience and Geotourism, 35*.

Fishlock, J. (2011). But the white man peeked: Impacts, opportunities, and dilemmas within social development and private sector cooperation in the international mining sector in Sub-Saharan Africa. *Library and Archives Canada=Bibliothèque et Archives Canada, Ottawa*.

Hardin, G. (1968). The tragedy of the commons: The population problem has no technical solution; it requires a fundamental extension in morality. *Science, 162*(3859), 1243–1248.

Hentschel, T., Hruschka, F., & Priester, M. (2002). Global report on artisanal and small-scale mining. *Mining, Minerals and Sustainable Development, 70*(January). Retrieved from https://www.iied.org/sites/default/files/pdfs/migrate/G00723.pdf

Hook, A. (2019). Fluid formalities: Insights on small-scale gold mining dynamics, informal practices, and mining governance in Guyana. *Resources Policy, 62,* 324–338.

Kameri-Mbote, P., Kamunge, I., & Yatich, J. K. (2021). Country report for Kenya. In *African Soil Protection Law* (pp. 177–294). Nomos Verlagsgesellschaft mbH & Co. KG. Retrieved from https://www.ielrc.org/content/a2103.pdf

Khatri, D. (2024). Remote sensing approach for estimating agroforestry area, suitability mapping, and carbon sequestration potential of agroforestry systems in Solan District Of Himachal Pradesh (Doctoral dissertation, Dr. Yashwant Singh Parmar University of Horticulture and Forestry). Retrieved from https://egranth.ac.in/items/d5fd0186-f3a7-4457-a34a-2d278e453e79/full

Kumpiene, J., Antelo, J., Brännvall, E., Carabante, I., Ek, K., Komárek, M., Söderberg, C., & Wårell, L. (2019). In situ chemical stabilization of trace element-contaminated soil–Field demonstrations and barriers to transition from laboratory to the field–A review. *Applied Geochemistry, 100,* 335–351.

Kuppusamy, S., Palanisami, T., Megharaj, M., Venkateswarlu, K., & Naidu, R. (2016). In-situ remediation approaches for the management of contaminated sites: A comprehensive overview. *Reviews of Environmental Contamination and Toxicology, 236,* 1–115.

LaJeunesse, T. C., Forsman, Z. H., & Wham, D. C. (2016). An Indo-West Pacific 'zooxanthella' invasive to the western Atlantic finds its way to the Eastern Pacific via an introduced Caribbean coral. *Coral Reefs, 35,* 577–582.

Lambin, E. F., Turner, B. L., Geist, H. J., Agbola, S. B., Angelsen, A., Bruce, J. W., Coomes, O. T., Dirzo, R., Fischer, G., Folke, C., & Xu, J. (2001). The causes of land-use and land-cover change: Moving beyond the myths. *Global Environmental Change, 11*(4), 261–269.

Lu, D., Mausel, P., Brondizio, E., & Moran, E. (2004). Change detection techniques. *International Journal of Remote Sensing, 25*(12), 2365–2401.

Masolele, R. N. (2023). Assessing land use following tropical deforestation: Combining remote sensing and deep learning (Doctoral dissertation, Wageningen University and Research).

Mathewos, Y., Abate, B., Dadi, M., & Mathewos, M. (2024). The nexus between spatiotemporal land use/land cover dynamics and ecosystem service values in the Wabe River catchment, Omo Gibe River Basin, Ethiopia. *Environmental Challenges, 17*, 101053.

McDonnell, M. J., & Pickett, S. T. (1990). Ecosystem structure and function along urban-rural gradients: An unexploited opportunity for ecology. *Ecology, 71*(4), 1232–1237.

Mehedi, I. M., Hanif, M. S., Bilal, M., Vellingiri, M. T., & Palaniswamy, T. (2024). Remote sensing and decision support system applications in precision agriculture: Challenges and possibilities. *IEEE Access.*

Mutanga, S. S. (2018). Cleaning up after mines are long gone. In S. Valiani (Ed.), *The Future of Mining in South Africa: Sunset or Sunrise?* African Books Collective.

Ngom, N. M., Baratoux, D., Bolay, M., Dessertine, A., Abass Saley, A., Baratoux, L., Mbaye, M., Faye, G., Yao, A. K., & Kouamé, K. J. (2023). Artisanal exploitation of mineral resources: Remote sensing observations of environmental consequences, social, and ethical aspects. *Surveys in Geophysics, 44*(1), 225–247.

Ofosu, G., Dittmann, A., Sarpong, D., & Botchie, D. (2020). Socio-economic and environmental implications of Artisanal and Small-scale Mining (ASM) on agriculture and livelihoods. *Environmental Science & Policy, 106*, 210–220.

Ogunkoya, O. O., & Ogbole, A. S. (2024). Estimation of suspended sediment balance of a small catchment in Southwestern Nigeria. *Environmental Monitoring and Assessment, 196*(3), 292.

Ojakorotu, V. (2024). The implications of insurgencies and illegal gold mining for sustainable development in Nigeria. *African Journal of Development Studies, 14*(3), 261.

Ojewale, O. (2024). Shadow of death: The criminal economy of banditry and kidnapping in northwest Nigeria. *Security Journal, 37*(4), 1680–1710.

Olade, M. A. (2019). Solid mineral deposits and mining in Nigeria: A sector in transitional change. *Achievers Journal of Scientific Research, 2*(1), 1–16.

Oluwafemi, O. K. (2018). Development of a mathematical model considering nutrients kinetics for assessing uMgeni River water quality. Retrieved from https://core.ac.uk/reader/268998660

Oyinloye, R. O., & Oloukoi, J. (2013). An assessment of the pull between land use and land cover in Southwestern Nigeria and the ensuing environmental impacts. *FIG Working Week 2013 Environment for Sustainability*, Abuja.

Rajaee, M., Obiri, S., Green, A., Long, R., Cobbina, S. J., Nartey, V., Buck, D., Antwi, E., & Basu, N. (2015). Integrated assessment of artisanal and small-scale gold mining in Ghana—Part 2: Natural sciences review. *International Journal of Environmental Research and Public Health, 12*(8), 8971–9011.

Rawat, J. S., & Kumar, M. (2015). Monitoring land use/cover change using remote sensing and GIS techniques: A case study of Hawalbagh block, district Almora, Uttarakhand, India. *The Egyptian Journal of Remote Sensing and Space Science, 18*(1), 77–84.

Rouillon, M., Taylor, M. P., & Dong, C. (2017). Reducing risk and increasing confidence of decision making at a lower cost: In-situ pXRF assessment of metal-contaminated sites. *Environmental Pollution, 229,* 780–789.

Schaffelke, B., Collier, C., Kroon, F., Lough, J., McKenzie, L., Ronan, M., Uthicke, S., & Brodie, J. (2017). 2017 Scientific Consensus Statement: Land use impacts on the Great Barrier Reef water quality and ecosystem condition, Chapter 1: The condition of coastal and marine ecosystems of the Great Barrier Reef and their responses to water quality and disturbances. Retrieved from https://researchonline.jcu.edu.au/50117/

Shikhov, A., Ilyushina, P., Makarieva, O., Zemlianskova, A., & Mozgina, M. (2023). Satellite-based mapping of gold-mining-related land-cover changes in the Magadan Region, Northeast Russia. *Remote Sensing, 15*(14), 3564.

Swain, P. H., & Davis, S. M. (1981). Remote sensing: The quantitative approach. *IEEE Transactions on Pattern Analysis & Machine Intelligence, 3*(06), 713–714.

Tucker, C. J. (1979). Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment, 8*(2), 127–150.

Turner, B. L., Kasperson, R. E., Matson, P. A., McCarthy, J. J., Corell, R. W., Christensen, L., Eckley, N., Kasperson, J. X., Luers, A., Martello, M. L., Polsky, C., & Schiller, A. (2003). A framework for vulnerability analysis in sustainability science. *Proceedings of the National Academy of Sciences, 100*(14), 8074–8079.

Wickware, A., & Howarth, D. (1981). Change detection in the Peace-Athabasca delta using digital Landsat data. *Remote Sensing of Environment, 11*, 9–14.

Worlanyo, A. S., & Jiangfeng, L. (2021). Evaluating the environmental and economic impact of mining for post-mined land restoration and land-use: A review. *Journal of Environmental Management, 279,* 111623.

Yu, M., Wang, Y., & Umair, M. (2024). Minor mining, major influence: Economic implications and policy challenges of artisanal gold mining. *Resources Policy,* 91,104886.