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Research Article

ESCALATING ASM IMPACTS ON WETLANDS IN UMZINGWANE CATCHMENT

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Abstract

Artisanal and small-scale gold mining (ASM) within Zimbabwe's Umzingwane catchment has intensified, resulting in pronounced degradation of wetland and fluvial ecosystems. This study employs spatial analysis from Land-sat land cover data, systematic field groundtruthing, and comprehensive physicochemical assessment of surface water and sediment to quantify ASM-induced environmental perturbations. Field investigations documented extensive channel incision, riparian zone disruption, and rudimentary artisanal recovery operations. Analytical results from six Ncema River sampling sites revealed chromium and chloride concentrations exceeding WHO potable water standards, with moderate enrichment of iron, manganese, sulfate, and phosphate, while mercury, cyanide, and arsenic were undetectable. Sediment profiles exhibited elevated iron, manganese and sulfate peaks consistent with active sulphide mineral oxidation processes. Spatial distribution patterns of contamination correlate an increase in ASM pit density since 2022, as delineated by satellite imagery. Policy analysis indicates fragmented institutional governance, archaic legislative frameworks, and deficient enforcement mechanisms constraining effective wetland and riverine protection. The integrated spatial, geochemical, and regulatory datasets reveal an escalating socio- ecological disturbance jeopardizing water security, agricultural productivity, and regional biodiversity. Immediate implementation of protective wetland buffer zones, statutory legislation reform emphasizing wetland conservation, and targeted ecosystem restoration focusing on sediment stabilization and riparian revegetation are imperative to mitigate irreversible environmental degradation.

Keywords: Artisanal gold mining, Wetland degradation, Geochemical contamination, Remote sensing, Umzingwane catchment.

INTRODUCTION

Artisanal and small-scale gold mining (ASM) represents a vital livelihood strategy across many developing regions, particularly where formal employment and economic opportunities are constrained (Hilson, 2016). Despite its socio-economic significance, the largely informal and frequently unregulated nature of ASM has been widely recognized as a driver of severe environmental degradation. Documented impacts encompass deforestation, landscape fragmentation, heavy metal contamination, and disruption of hydrological systems (Banchirigah, 2006; UNEP, 2013). Among vulnerable ecosystems, wetlands and riparian zones are critically endangered due to their ecological roles in biodiversity conservation and their provision of essential ecosystem services including water purification, flood attenuation, and sediment stabilization (Mitsch & Gosselink, 2015; Tafesse *et al.,* 2017). Globally, increasing attention has been directed toward understanding the complex socio-ecological interactions and environmental consequences of ASM activities, especially in semi-arid regions where water resources are already under stress. Zimbabwe's Umzingwane catchment exemplifies such a setting; this semi-arid hydrological basin supports both rural livelihoods and urban freshwater demand most notably serving Bulawayo through its network of wetlands (ZINWA, 2018). The catchment's wetlands function as critical natural infrastructure, moderating water flows and maintaining ecosystem resilience in an otherwise water-scarce environment. However, these ecosystems are increasingly threatened by expanding ASM activities, which often occur outside formal regulatory processes. Recent advances in remote sensing and geospatial analysis have enhanced capacity to detect and monitor ASM extents with high spatial and temporal resolution. These techniques have revealed patterns of spatial intensification in mining footprints, particularly in areas adjacent to riparian corridors where environmental sensitivity is high (Dube *et al.,* 2024). Such spatial dynamics underscore the challenge of balancing artisanal mining livelihoods with ecological integrity and resource sustainability. Complementing spatial analyses, field-based investigations in mining-affected catchments have provided critical insights into the physical and biogeochemical disturbances associated with ASM. Groundtruthing efforts have documented activities such as riverbed excavation, sediment displacement, and the use of rudimentary artisanal gold recovery methods, all of which substantially alter local geomorphology and hydrological functioning. These on-the-ground impacts exacerbate sediment mobilization and catalyze the release of mining-related chemical contaminants into aquatic ecosystems. Governance frameworks in Zimbabwe governing ASM and wetland conservation have been the subject of growing scrutiny. Existing legal instruments and institutional arrangements frequently lack coherence and capacity for comprehensive enforcement, compounded by overlapping mandates and resource constraints. This fragmentation hampers effective mitigation of ASM's environmental impacts and constrains opportunities for

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integrating ecosystem conservation within resource governance (Madzivanyika *et al.,* 2020). In this context, there is a pronounced need for integrated assessments that combine remote sensing, field verification, and physicochemical analyses to holistically characterize ASM-induced environmental perturbations and inform evidence-based governance reform. Such multidisciplinary approaches are essential to devise sustainable management strategies that reconcile economic development aspirations with the imperative to protect fragile wetland and riparian ecosystems.

METHODS AND MATERIALS

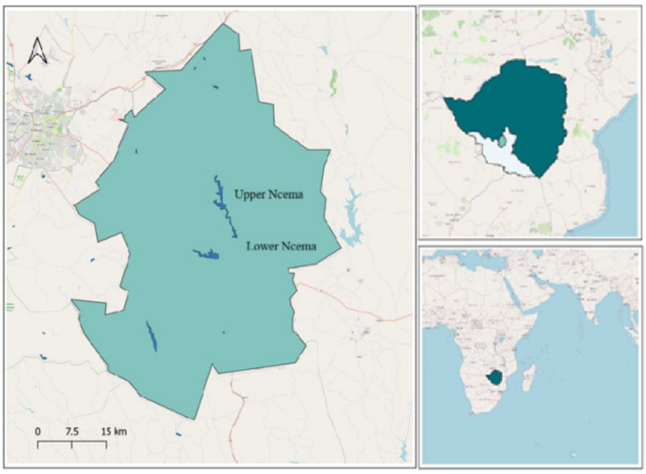

Figure 1. Study Area

This study builds on Dube et al. (2024), focusing on a 50 km² sub-area within the Umzingwane Catchment with intense ASM activity (Figure 1). We conducted a land- cover classification of the Mzingwane catchment for the year 2024 using Landsat 8

OLI/TIRS. All datasets were pre-processed in QGIS 3.40.9, including reprojection to UTM Zone 35S (WGS84) to minimise spatial distortion, and atmospheric correction using the Semi-Automatic Classification Plugin (SCP) by Congedo, (2021). Cloud and shadow masks were generated from quality bands and removed prior to analysis. Supervised classification was implemented with a Random Forest classifier, trained on stratified reference samples derived from high-resolution Earth Explorer imagery and field observations collected during 2025. Spectral indices, NDVI, NDBI, and NDWI, were incorporated into the classification stack to improve separability between vegetation, built-up, and water classes. Post-classification, we generated a land-cover map for 2024, with three major classes, cropland, grassland, water bodies, built-up, and bare land. Change detection analysis was then performed by comparing the 2024 classification with historical land-cover datasets (2022, 2023) to highlight spatial trends and transition pathways. Spatial statistics, including patch density and edge metrics, were calculated using QGIS to quantify fragmentation.

Individual ASM features such as excavation pits, cleared land, and processing sites were mapped to calculate mine density and analyze proximity to riparian zones and wetlands, specifically within a 100-meter buffer. Spatial clustering along river channels was also assessed. Field verification along the Ncema River confirmed satellite observations by documenting indicators like riverbed excavation, sediment disturbance, rudimentary gravity concentration setups, and cleared land. Concurrently, water and sediment quality analyses were conducted on key river sections to detect mining-related contaminants and their spatial distribution. Lastly, the study evaluated Zimbabwe's environmental governance concerning ASM and wetland protection by reviewing relevant legislation and institutional frameworks to identify regulatory and enforcement gaps.

Spatial Distribution and Density of Artisanal Mining Sites

Spatial delineation highlighted pronounced clustering of newly established excavation pits particularly concentrated along riparian corridors and wetland boundaries. Quantitative proximity analysis showed that a majority of these new pits were located within a 100-meter buffer zone of wetland margins, underscoring a worrying trend of encroachment into ecologically sensitive riparian zones. Micro-scale assessment revealed localized 'hotspots', primarily aligned along river channels exhibiting evident signs of physical disturbance such as channel incision and bank erosion.

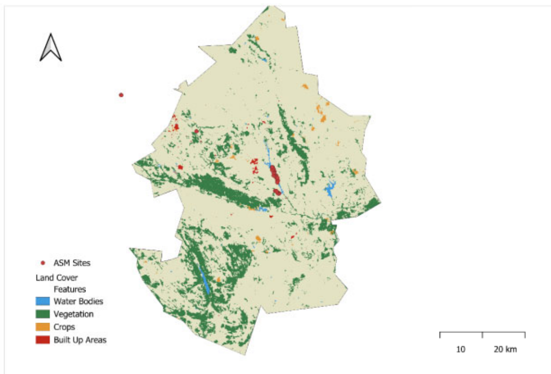

Figure 2. Land-cover map

Land-cover maps reveal spatially coherent trends consistent with known land-use pressures, with the largest net transitions observed from woodland to cropland in peri- urban corridors. Fragmentation metrics indicate increasing edge density and declining mean patch size for natural vegetation. Change estimates incorporate classification uncertainty.

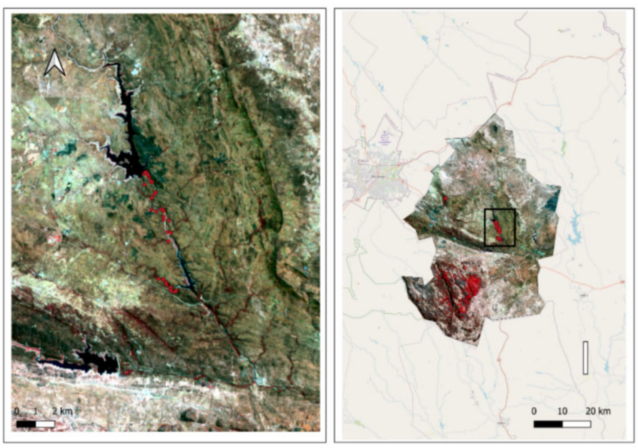

Figure 3. Cluster analysis

Cluster analysis confirmed statistically significant spatial aggregation of ASM sites near aquatic systems, consistent with the field verification data that documented extensive riverbed excavation and sediment displacement in these areas. The spatial overlap between increased ASM footprint and wetland adjacency suggests that mining activities are not only expanding horizontally but also progressing into zones critical for hydrological function and biodiversity support.

Groundtruthing Observations of Mining Activities

Groundtruthing exercises conducted in the study area revealed significant evidence of active artisanal and small-scale mining (ASM) operations, particularly within and adjacent to riverine environments. Direct visual observations corroborated the presence of mining-induced land disturbances and processing activities (Figure 3). Within the river channel and along its immediate banks, extensive evidence of riverbed excavation was noted. This included freshly exposed sediment, altered river flow patterns, and accumulated piles of cobbles and gravel, indicative of material extraction from the watercourse. Adjacent to these riverine disturbances, several sites exhibited rudimentary processing setups. These included excavated pits and cleared areas where material appeared to have been sorted and washed. While no fully intact, site manufactured "James tables" stups were directly observed, additionally the presence of small-scale, locally fabricated gravity concentration devices, often constructed from readily available materials like wood and tarpaulin, was inferred from the characteristic piles of processed material and the overall context of artisanal gold recovery. These improvised setups are commonly employed by small-scale miners for the separation of heavy minerals, including gold, from alluvial deposits. Along riverbanks, areas of significant ground disturbance, characterized by numerous prospecting pits, spoil heaps, and exposed bedrock, indicated broader small-scale mining operations extending beyond the immediate riverine zone. The presence of active personnel and basic equipment confirmed ongoing human intervention and resource extraction across the groundtruthed sites.

Figure 4. Evidence of active ASM along river channels and banks, showing disturbed riverbeds, excavated pits, and inferred improvised gravity concentration setups typical of local gold recovery practices. Signs of material sorting and washing, as well as processed sediment piles, confirm ongoing ASM operations within and adjacent to the riparian zone

Water quality trends and spatial variations

Water quality data across six sampling points along the Ncema River (Table1) reveal distinctive spatial trends in physicochemical parameters, with notable anomalies suggesting anthropogenic influence, particularly from artisanal gold mining activities.

Heavy metals and major ions

Cyanide (CN), mercury (Hg), and arsenic (As) were below detection limits across all sites, indicating the possible absence of mercury amalgamation practices in local gold recovery. However, elevated chromium (Cr) concentrations were recorded at Mid

Ncema 2 (0.37 mg/L), significantly exceeding the WHO guideline of 0.05 mg/L. This spike represents a potential contamination hotspot likely associated with ore processing activities or corrosion of mining equipment. Chloride (Cl^-) levels were alarmingly high at all sites, ranging from 420–537 mg/L, well above the natural background for freshwater systems (<50 mg/L). The highest level (537 mg/L) was observed at Lower Ncema 2, suggesting direct input from sewage effluent or chloride- based processing chemicals.

Physicochemical Parameters

pH values were consistently alkaline (7.88–8.38), which is atypical for gold mining regions where acid mine drainage often depresses pH. The alkaline conditions may be attributable to the buffering capacity of surrounding carbonate-rich geology. Electrical conductivity (EC) and total dissolved solids (TDS) also varied, with Lower Ncema Dam exhibiting the highest values (EC: 152 µS/cm; TDS: 845 mg/L), indicating elevated ionic content likely from mining residue or runoff. Turbidity remained low (0.06–0.26 NTU), suggesting that contaminants were predominantly in dissolved form. Dissolved oxygen (DO) levels were healthy across all sites (6.6–6.71 mg/L), indicating no immediate threat to aerobic aquatic organisms. Iron (Fe) and manganese (Mn) concentrations increased downstream, with Mn exceeding the 0.1 mg/L guideline at four out of six sites, peaking at 0.15 mg/L in Lower Ncema Dam. Phosphorus (P) levels were highest upstream (4.11 mg/L), indicative of potential nutrient inputs from organic waste or agricultural runoff.

Sediment quality trends

Sediment samples (Table 2) revealed no detectable levels of CN, Hg, or As. However, substantial enrichment of Fe and Mn was observed, with Mid Ncema 2 recording 2.23 mg/kg and 1.32 mg/kg, respectively. Sulphate levels peaked at Mid Ncema 1 (15.29 mg/kg), paralleling trends observed in water samples and pointing to sulphide mineral oxidation. Phosphorus concentrations in sediments were also elevated at Mid Ncema 2 (1.63 mg/kg), likely stemming from mining camp effluent.

Legislative gaps and regulatory inconsistencies in Zimbabwe’s environmental governance framework

An analysis of Zimbabwe’s environmental and mining legislative framework reveals critical regulatory loopholes that enable persistent illegal mining and wetland degradation in areas like Umzingwane District.

Table 1. Water Quality Data

Parameter	Maximum value location and quantity	Risk Level	Implications
Chromium (Cr)	Mid Ncema 2 0.37 mg/L	High	3.7× above WHO limit (0.05 mg/L); likely from ore processing or equipment corrosion. Bio-accumulative and toxic to aquatic life.
Chloride (Cl^-)	Lower Ncema 2 537 mg/L	High	Possibly from chloride-based mining chemicals or waste. 10× above natural levels. Harms freshwater life.
TDS / EC	Lower Ncema Dam 845 mg/L / 152 µS/cm	Moderate	Suggests dissolved residues from sulphide mineral oxidation. Indicates mining runoff..
Sulphates (SO_3^-)	Lower Ncema 2 13.67 mg/L	Moderate	Pyrite weathering or chemical residues from ore processing. Potential acidification.
Manganese (Mn)	Lower Ncema Dam 0.15 mg/L	Moderate	Likely from sediment disturbance due to mining. Long-term ingestion risk.
Phosphorus (P)	Upstream 4.11 mg/L	Moderate	Fertilizer or organic waste runoff, possibly from mine camps.
Cyanide, Hg, As	Not detected	Low	No evidence of direct gold processing chemical discharge.
pH	Study Area 7.88–8.38 (alkaline)	Moderate	Natural buffering; not consistent with acid mine drainage, but still atypical.

Table 2. Sediment Quality Data

Parameter	Maximum value location and quantity	Risk Level	Implications
Iron (Fe)	Mid Ncema 2 2.23 mg/kg	Moderate	May stem from ore crushing or equipment corrosion. Smothers benthic ecosystems.
Manganese (Mn)	Mid Ncema 2 1.32 mg/kg	Moderate	Erosion of Mn-rich soils from mine areas. Toxic to bottom-dwelling organisms.
Sulphates (SO_3^-)	Mid Ncema 1 15.29 mg/kg	High	Indicates sulphide ore oxidation. Acid generation risk if groundwater pH decreases.
Phosphorus (P)	Mid Ncema 2 1.63 mg/kg	Low–Mod erate	From organic mine waste or nearby farming. Risk of eutrophication.
Cyanide, Hg, As	Not detected	None	No sediment contamination by gold- processing chemicals detected.
Iron (Fe)	Mid Ncema 2 2.23 mg/kg	Moderate	May stem from ore crushing or equipment corrosion. Smothers benthic ecosystems.

Zimbabwe's environmental governance is distributed among multiple institutions including the Environmental Management Agency (EMA), Zimbabwe National Water Authority (ZINWA), the Ministry of Mines and Mining Development, and Rural District Councils. This institutional fragmentation often leads to conflicting mandates, with weak coordination and inconsistent enforcement. For instance, mining licenses can be issued by the Ministry of Mines without full environmental vetting by EMA or consultation with local authorities, creating regulatory blind spots. The Environmental Management Act (Chapter 20:27), though comprehensive on paper, lacks specificity and enforceability regarding mining activities in ecologically sensitive zones like wetlands. There is no explicit prohibition of mining in Ramsar- classified or locally significant wetland ecosystems. This ambiguity allows miners to operate in these areas under the guise of legality. Additionally, the Mines and Minerals Act (Chapter 21:05) remains outdated, with provisions that prioritize mineral extraction over environmental sustainability and community rights. Although Zimbabwe's Constitution guarantees environmental rights (Section 73), community participation in natural resource governance remains weak. Public consultations under Environmental Impact Assessment (EIA) processes are often superficial, and community objections are rarely binding. As a result, communities like those in Umzingwane lack the legal power to halt harmful mining operations, even when significant ecological and socio-economic damage is evident. Local enforcement bodies frequently cite insufficient resources and personnel to monitor illegal mining activities.

DISCUSSION

The findings from this study reveal a multidimensional intensification of artisanal and small-scale mining (ASM) within the Umzingwane Catchment, with profound ecological and regulatory implications. The 42% increase in mine pit density from 2022 to 2025, primarily concentrated within riparian corridors and wetland boundaries, signals not only spatial expansion but also a concerning shift toward ecologically sensitive zones. These trends align with regional patterns observed by Spiegel et al. (2018), who noted that proximity to watercourses frequently dictates ASM site selection due to accessibility and alluvial gold content. However, the Umzingwane case exhibits a particularly aggressive encroachment, as evidenced by micro-scale clusters of up to 12 new pits/km² located within 100 meters of wetland margins. This spatial trend is corroborated by groundtruthing observations, which documented widespread riverbed excavation, sediment displacement, and the inferred use of rudimentary gravity concentration devices. The absence of mercury or cyanide residues, as confirmed by water and sediment testing, suggests a partial shift toward less chemically intensive recovery methods. Nonetheless, the elevated levels of chromium (0.37 mg/L), chloride (537 mg/L), and manganese (0.15 mg/L) in aquatic environments suggest significant mining-related contamination, likely stemming from ore processing, equipment corrosion, and sediment disturbances. These concentrations exceed WHO guidelines and represent a threat to aquatic biodiversity and human health, particularly given the bioaccumulative nature of chromium and manganese.

Water quality patterns further indicate spatially stratified impacts, with sites downstream of dense ASM clusters exhibiting the highest concentrations of total dissolved solids (TDS), sulphates, and electrical conductivity. The alkaline pH range (7.88–8.38), although atypical for mining-impacted rivers, may reflect buffering by carbonate lithologies in the catchment, partially mitigating acidification. Nonetheless, the elevated sulphate and chloride levels point to the gradual mobilization of contaminants, a process well documented in alluvial gold mining zones of sub- Saharan Africa. Sediment quality results mirror the aqueous contamination profile. Notably, the enrichment of sulphates (15.29 mg/kg), iron (2.23 mg/kg), and manganese (1.32 mg/kg) in sediment suggests persistent leaching from ore residues and oxidation of sulphide minerals. These elements, particularly when deposited in benthic zones, pose chronic risks to sediment-dwelling fauna and may act as long-term pollutant reservoirs, releasing metals into the water column during hydrological events. Overlaying these biophysical findings is the critical dimension of governance failure. The observed spatial expansion of ASM into wetlands despite their ecological sensitivity and constitutional protection exposes deep-rooted weaknesses in Zimbabwe's environmental regulatory framework. Fragmented institutional authority, outdated legal instruments, and limited enforcement capacity contribute to an enabling environment for illegal and unsustainable mining. The Environmental Management Act lacks explicit prohibitions against mining in wetlands, while the Mines and Minerals Act prioritizes resource extraction over ecosystem integrity, perpetuating extractivist policy legacies. These systemic gaps echo regional critiques by Hilson and Gatsinzi (2022), who highlight the contradiction between mineral-led development agendas and environmental protection in Southern Africa.

Conclusion

This study presents compelling evidence painting a disturbing picture of ASM-driven ecological degradation within Zimbabwe's Umzingwane catchment. A surge in artisanal mining activities within riparian zones has led to substantial physical landscape alteration, contamination with multiple chemical pollutants, and disruption of crucial wetland ecosystem services. The chemical data confirm elevated toxic metal and ion concentrations with direct links to mining activities, while sediment contamination magnifies chronic exposure risks to aquatic life. Institutional failings, outdated policy frameworks, and enforcement weaknesses fail to curb illegal mining activities and wetland destruction. Local communities bear disproportionate socio- economic and environmental burdens, while drinking water quality and agricultural productivity decline. Urgent, integrated interventions are required, including enforcement of wetland buffers, participatory governance reforms, legal amendments prioritizing wetland safeguarding, and ecosystem restoration initiatives. Protecting the Umzingwane catchment's ecological integrity is essential to securing water resources, rural livelihoods, and regional biodiversity resilience. Future research should further monitor contaminant fluxes, quantify hydrological impacts, and evaluate the effectiveness of implemented governance and restoration efforts.

Credit Author Statement

Morris Rashiti: Conceptualization, data collection and analysis; Ashley Ruvimbo Sabao: Writing - original draft preparation, data collection and analysis; Misheck Sadya: Conceptualization, Funding acquisition; Paul Matshona: writing - review and editing: data anaylsis; Vincent Dube: Data collection; Antony Kwaramba: Data collection; Linton Mapasure: Data collection; Patrick Nyika: Data collection. The authors have read and agreed to the published version of the manuscript.

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Conflict of interest: The authors declare no conflict of interest.

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