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GIS and Remote Sensing-Based Assessment and Mapping of Industrial Pollution Impacts: A Case Study of the Kafue River, Zambia

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ABSTRACT

This study applies GIS and multi-temporal satellite remote sensing to trace the environmental signature of the February 2025 Sino-Metals tailings dam failure along Zambia's Kafue River, and considers what the resulting evidence implies for the design of a low-cost, satellite-based early-warning monitoring policy. Landsat 8/9 and Sentinel-2 imagery across six temporal windows (three pre-incident, three post-incident) were used to compute the Normalised Difference Turbidity Index (NDTI) and Normalised Difference Vegetation Index (NDVI), with the Normalised Difference Water Index (NDWI) applied as a binary water mask to separate the open-water pixels used for NDTI from the riparian land pixels used for NDVI. Mean NDTI rose sharply from a pre-incident rainy-season-onset value of −0.008 to +0.210 in March 2025, before returning to near-baseline levels (+0.018) within a month and to clear-water conditions (−0.009) by June 2025 a pattern consistent with the river's hydrological flushing capacity. Riparian NDVI, in contrast, declined from a rainy-season peak of 0.345 in December 2024 to 0.313 immediately after the spill and had not returned to that baseline five months later. Because no concurrent in-situ water-chemistry or soil heavy-metal sampling was available, and because only a single pre-incident rainy-season observation exists, these patterns are interpreted as consistent with, rather than statistically confirmatory of, pollution-driven vegetation stress. The differential recovery signatures of NDTI and NDVI are nonetheless proposed as a candidate design feature for a dual-index, satellite-based early-warning trigger for Zambia's Environmental Management Agency (ZEMA) and Water Resources Management Authority (WARMA), and the data, validation, and institutional requirements for operationalising such a system are discussed.

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1. Introduction

1.1 Background and Context

Global metal mining has expanded dramatically in recent decades and has become a major driver of environmental change through land disruption, water and air impacts, and biodiversity loss (Giljum et al., 2025). Water is a fundamental resource for human life, agriculture, industry, and ecological function, yet rivers worldwide face increasing contamination from this expansion, particularly in mineral-rich nations such as Zambia. The Kafue River is Zambia's most important waterway, flowing for over 1,500 km through the country and sustaining approximately 12 million people, around 60% of the national population. It supplies drinking water to roughly five million people, including residents of Lusaka, and supports fishing, agriculture, and industrial operations (Engineering Institution of Zambia, 2025).

On 18 February 2025, a catastrophic tailings dam failure at the Sino-Metals Leach Zambia copper facility released approximately 50 million litres of acidic, contaminated water into the Mwambashi Stream, a tributary that flows directly into the Kafue River. The spill caused extensive fish kills, water contamination, livestock losses, and a temporary shutdown of the town of Kitwe's water supply (Associated Press, 2025). It was one of three mine waste disasters on the Zambian Copperbelt within a 15-month period, an unusually high frequency attributed to a combination of ageing tailings infrastructure, rapid liberalisation-era ownership turnover, and enforcement capacity that has not kept pace with the sector's expansion (Mukumba et al., 2026). The event is not without precedent in the global mining sector: the 2015 Fundão/Samarco dam collapse in Mariana, Brazil, released between 43 and 62 million cubic metres of iron-ore tailings into the Doce River system, with ecological and socio-economic impacts still detectable more than seven years later (Fernandes et al., 2016), and the 2019 Brumadinho disaster in the same Brazilian mining region killed more than 250 people and was subsequently traced using multispectral and radar satellite imagery (Rotta et al., 2020). Globally, tailings storage facilities fail two to five times per year on average, with human factors, construction and design faults, regulatory shortcomings, and deferred maintenance increasingly recognised as more significant drivers than purely physical causes (Hudson-Edwards et al., 2024; Lin et al., 2022).

Traditional water quality monitoring relies on field sampling and laboratory analysis. The only prior systematic environmental monitoring exercise on this reach of the Kafue River, conducted by Norrgren et al. (2000), used caged fish bioassays and semipermeable membrane devices deployed over several months to trace the bioaccumulation of copper, cadmium, and pesticides downstream of Copperbelt industrial discharges. A more recent regional geochemical survey confirmed that dissolved copper and cobalt concentrations in several Kafue tributaries near major mining centres substantially exceed Zambian effluent limits, though the Kafue mainstem itself is comparatively buffered by its high neutralisation capacity, and documented historical fish kills linked to acidic discharge spikes (Kříbek et al., 2023). These approaches remain the most rigorous available for chemical and biological confirmation of contamination, but they are logistically intensive, cannot be mobilised at short notice after a sudden spill, and provide point measurements rather than basin-wide spatial coverage. Geographic Information Systems (GIS), combined with multi-temporal satellite remote sensing, offer a complementary approach: cost-effective, near-real-time, and capable of basin-wide spatial analysis (Ritchie et al., 2023).

Industrial pollution associated with mining activities remains one of the most significant environmental challenges affecting river systems globally, and tailings dam failures are particularly destructive because they release large volumes of contaminated slurry, suspended sediments, and dissolved heavy metals into surrounding ecosystems. Beyond the Mariana and Brumadinho disasters, the Catoca mine spill in Angola produced extensive transboundary pollution impacts affecting the Congo River Basin, subsequently traced using Sentinel-2 imagery (Ruppen et al., 2023), and acid mine drainage, a chronic, chemically distinct pollution pathway generated when mining exposes sulfide minerals to oxygen and water has been monitored via Sentinel-2-derived water-quality proxies in Russia's Kizel coal basin (Pyankov et al., 2021) and remains a persistent global remediation challenge in its own right (Yuan et al., 2022). In Zambia, mining has historically been concentrated in the Copperbelt Province, where decades of extraction have contributed to acid mine drainage, heavy metal contamination, and sediment loading within river systems, and satellite-derived water-index methods have separately been used to monitor legacy contamination pathways such as windborne lead dispersion from the Kabwe zinc-plant residues (Nakamura et al., 2021, 2022; Nakata et al., 2022). The Kafue River is particularly vulnerable because it traverses heavily industrialised mining zones before supplying water to agricultural, industrial, and urban populations downstream.

Satellite-derived spectral indices such as the Normalised Difference Turbidity Index (NDTI) and Normalised Difference Vegetation Index (NDVI) have proven effective for monitoring sediment transport, turbidity dynamics, and vegetation stress. NDTI exploits the spectral contrast between red and green wavelengths to identify suspended sediment concentrations, while NDVI quantifies vegetation health through the contrast between red absorption and near-infrared reflectance. Vegetation exposed to heavy-metal stress specifically has been shown to exhibit measurable reductions in chlorophyll-related reflectance in the visible and red-edge regions, distinct from but overlapping with drought-related signals (Lovynska et al., 2024) a mechanism this study returns to when interpreting the observed NDVI response in Section 4.

1.2 Research Gap and Objectives

Two gaps in the existing literature motivate this study. First, while global studies have demonstrated the use of NDTI-type indices to trace the acute turbidity signal of tailings dam failures (Crioni et al., 2023; Ruppen et al., 2023; Pyankov et al., 2021; El-Zeiny & Effat, 2019), these studies focus predominantly on the immediate water-clarity response and generally stop short of pairing it with a parallel, sub-monthly NDVI time series to characterise the distinct, longer-tail recovery trajectory of riparian vegetation from the same event. Second, no existing study has translated such paired NDTI–NDVI evidence into concrete design parameters revisit interval, index pairing, alert thresholds, institutional workflow for an operational, regulator-facing early-warning monitoring system in a Sub-Saharan African river basin. The only comparable Zambian precedent, Norrgren et al. (2000), pre-dates the operational availability of Sentinel-2 and free Landsat archives and relied entirely on in-situ methods.

This study addresses these gaps by applying multi-temporal GIS and remote sensing analysis to a 100-km segment of the Kafue River spanning the February 2025 Sino-Metals tailings dam failure. The specific objectives are: (i) to assess the spatial and temporal variability of water quality using NDTI; (ii) to assess the impacts of pollution on riparian vegetation health using NDVI; (iii) to compare the resulting satellite-derived signatures against the documented, publicly reported impacts of the spill as a form of qualitative validation, while being explicit about the limits of that validation in the absence of in-situ chemical data; and (iv) to translate the observed NDTI/NDVI recovery signatures into design considerations for a satellite-based early-warning monitoring policy for ZEMA and WARMA.

1.3 Contribution and Structure of the Paper

This study contributes to three audiences. For the academic community, it extends the tailings-failure remote-sensing literature by pairing turbidity and vegetation indices at sub-monthly resolution around a single dated event in an African basin, and by making explicit the statistical and validation limits of that evidence rather than treating satellite indices as a direct proxy for chemical water quality. For policymakers, it proposes concrete design elements, index pairing, revisit cadence, and an escalation workflow for a satellite-based early-warning capability that ZEMA and WARMA could adopt at near-zero marginal data cost, addressing a documented gap in Zambia's environmental monitoring response following the 2025 spill. For other stakeholders in the Kafue basin, including downstream water users and Copperbelt communities, it provides an evidence base for why differential recovery of water clarity and riparian vegetation matters for how long environmental risk from a single spill actually persists. The remainder of the paper is organised as follows: Section 2 details the study area, satellite data, pre-processing and index-calculation methodology, and the statistical approach used to interpret the resulting time series. Section 3 presents the NDVI and NDTI results. Section 4 discusses the findings, sets out the proposed smart monitoring policy design, and details the study's limitations. Section 5 concludes and outlines directions for future research.

2. Materials and Methods

The study employed a structured GIS and remote sensing methodology designed to capture both the immediate and residual environmental impacts of the pollution event. The overall workflow progressed from satellite image acquisition and pre-processing, through spectral index calculation, water masking, and spatial analysis, to comparative temporal assessment.

Data Collection
Landsat 8/9 and Sentinel-2 imagery from USGS and Copernicus.

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Pre-processing
Atmospheric correction, radiometric calibration, cloud masking, and clipping to a 5km buffer.

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Spectral Indices Calculation
NDTI (Turbidity), NDWI (Water extent), NDVI (Vegetation health).

↓

GIS Analysis and Mapping
Spatial and temporal analysis, statistical summaries (mean values, histograms).

↓

Validation
Qualitative comparison with ground data and reported impacts.

↓

Conclusion and Recommendations
Assessment summary and Key findings

Figure 1. Research methodology flowchart illustrating data flow from acquisition through to assessment and conclusions (Developed by the Authors).

2.1 Study Area

The study area encompasses a 100-km segment of the Kafue River in Zambia's Copperbelt Province. It extends from 20 km upstream of the Mwambashi confluence, serving as a pre-pollution control reach, through 80 km of the downstream affected zone. The Mwambashi Stream drains the Chambishi mining area, where the Sino-Metals Leach facility is located. The wider Kafue basin is characterised by miombo woodland, agricultural land, and riparian vegetation.

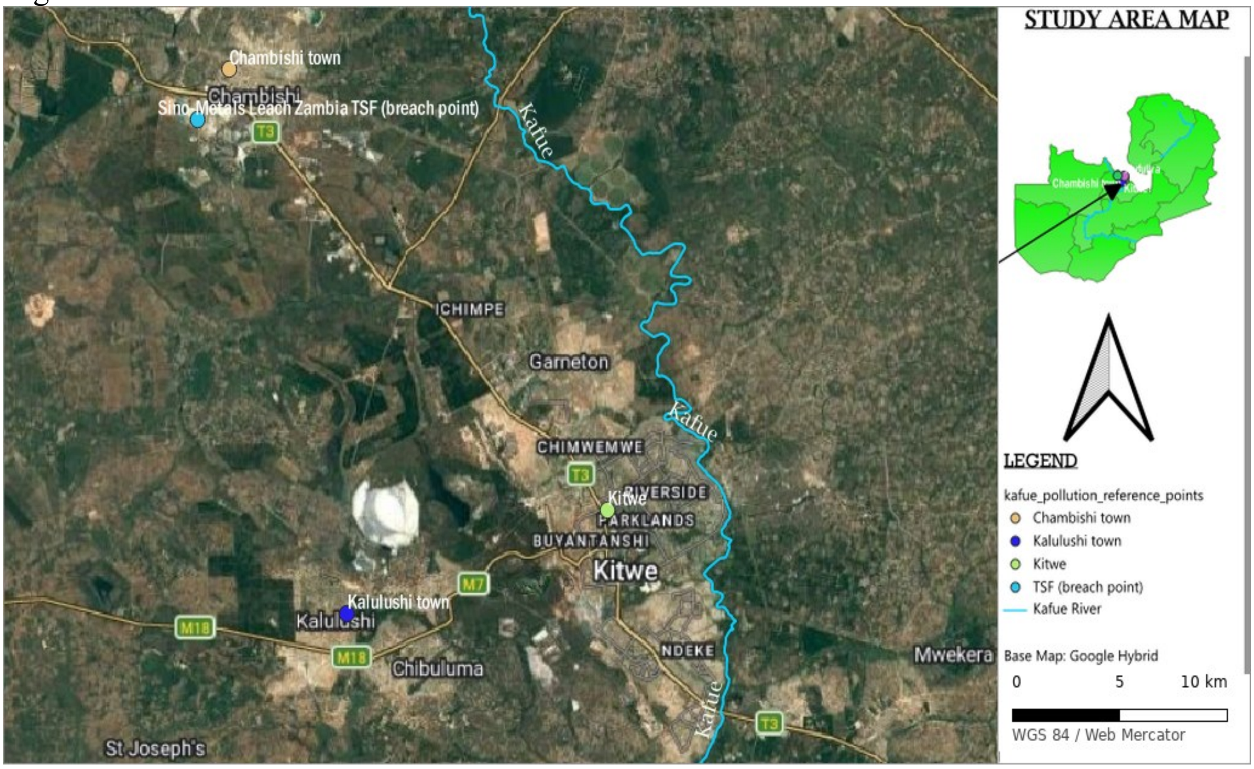

Figure 2. Study area map showing the Kafue River segment(Developed by the Authors).

2.2 Satellite Data Acquisition

Two satellite platforms were used. Landsat 8/9 (30 m spatial resolution) was sourced from the USGS Earth Explorer platform and used for long-term trend anchoring. Sentinel-2 (10–20 m resolution) was accessed via the Copernicus Open Access Hub and employed for finer-resolution post-event monitoring. Only scenes with less than 10% cloud cover were selected. Six temporal windows were analysed: three pre-incident (August 2024 late dry season baseline; September 2024 - peak dry season low; December 2024 rainy season peak) and three post-incident (March 2025 - post-disaster shock; April 2025 short-term recovery; June 2025 - lingering impact / dry season onset).

Table 1: Summary of satellite imagery used and temporal periods analysed.

Date	Platform	Resolution	Period	Purpose
August 2024	Landsat 8	30 m	Pre-incident (dry season)	Dry season baseline
September 2024	Landsat 9	30 m	Pre-incident (peak dry)	Seasonal low benchmark
December 2024	Sentinel-2	10 m	Pre-incident (rainy season)	Vegetation baseline
March 2025	Sentinel-2	10 m	Post-incident (rainy season)	Acute pollution impact
April 2025	Sentinel-2	10 m	Post-incident (recovery)	Short-term recovery assessment
June 2025	Landsat 9	30 m	Post-incident (dry onset)	Lingering impact check

Because Landsat and Sentinel-2 differ in native spatial resolution, band configuration, and radiometric calibration, direct pixel-level comparison between sensors introduces uncertainty. Following the reconciliation logic established by the NASA Harmonized Landsat and Sentinel-2 (HLS) framework (Claverie et al., 2018), Sentinel-2 bands were resampled to a common 30 m grid for cross-sensor temporal comparability. Full radiometric harmonisation in the sense of

Claverie et al. (2018), including bidirectional reflectance distribution function (BRDF) normalisation and bandpass adjustment, was not applied in this study, and the resulting residual cross-sensor uncertainty is treated explicitly as a limitation in Section 4.3 rather than absorbed silently into the reported index values.

2.3 Data Pre-processing

Sentinel-2 imagery was atmospherically corrected using the Sen2Cor processor within the Sentinel Application Platform (SNAP). Landsat imagery underwent radiometric calibration and surface reflectance conversion. All imagery was clipped to a 5 km buffer around the Kafue River centreline. Cloud masking was applied using the QA pixel band for Landsat and the Scene Classification Layer (SCL) for Sentinel-2.

2.4 Spectral Index Calculation and Water Masking

Three spectral indices were calculated in QGIS using the raster calculator. The Normalised Difference Water Index (NDWI), following McFeeters (1996), was computed as NDWI = (GREEN − NIR) / (GREEN + NIR) and used as a binary water mask (NDWI > 0.1 classified as open water) to separate the water pixels over which NDTI was subsequently computed from the riparian land pixels over which NDVI was computed. This masking step, rather than a stand-alone index reported for its own sake, is the operational role NDWI plays in the analysis. The Normalised Difference Turbidity Index (NDTI) quantifies water turbidity through the contrast between the red and green bands: NDTI = (RED − GREEN) / (RED + GREEN). The Normalised Difference Vegetation Index (NDVI) assessed riparian vegetation health: NDVI = (NIR − RED) / (NIR + RED). For Landsat, Band 5 (NIR) and Band 4 (Red) were used; for Sentinel-2, Band 8 (NIR) and Band 4 (Red).

2.5 GIS Analysis

Thematic maps were generated using colour-coded classifications for each index. NDVI categories ranged from sparse/stressed vegetation (dark yellow-brown) through moderate cover to dense healthy vegetation (dark green). NDTI classifications used dark blue for clear water (NDTI: −1 to 0), yellow for moderate turbidity (0 to 0.2), and red for high turbidity (0.2 to 1.0). Statistical summaries (mean values and histograms) were produced for each temporal period to enable quantitative comparison.

2.6 Spectral Behaviour of Polluted Water and Vegetation

Remote sensing of water quality relies on the interaction between electromagnetic radiation and optically active constituents within water bodies. Clear water strongly absorbs near-infrared radiation while reflecting relatively low levels of visible wavelengths; increased concentrations of suspended sediments, dissolved organic matter, and pollutants alter these reflectance characteristics. Highly turbid water exhibits elevated reflectance in the red wavelength region due to increased backscattering from suspended particles, which forms the basis for turbidity estimation using NDTI. Positive NDTI values generally indicate increased turbidity, while negative values correspond to clearer water conditions.

Vegetation monitoring relies primarily on the spectral behaviour of chlorophyll. Healthy vegetation absorbs visible red light for photosynthesis while strongly reflecting near-infrared radiation due to leaf cellular structure. Moisture deficit, and where present heavy-metal-induced physiological stress, both reduce chlorophyll concentration and photosynthetic activity, and both can lower NDVI values; the two stressors are not spectrally distinguishable from NDVI alone (Lovynska et al., 2024), a point this study returns to when interpreting the vegetation results.

2.7 Statistical Analysis and Validation Approach

The dataset comprises six temporal composite values per index rather than pixel-level replicate samples, and only a single pre-incident observation falls within the rainy season (December 2024). This structure does not support formal parametric inferential testing (e.g., a paired t-test) of the post-incident change, and no such test is reported here. Two more limited, defensible steps were taken instead. First, post-incident NDVI values are compared against the observed pre-incident seasonal pattern rather than against a single fixed baseline so that a value such as the March 2025 reading is described as a decline relative to the immediately preceding rainy-season observation, not as falling outside the full annual range (it does not). Second, for future work with a longer, denser time series, a non-parametric Mann-Kendall trend test combined with a Theil-Sen slope estimator is identified as the appropriate method for formally testing the significance and magnitude of any post-incident trend (Neeti & Eastman, 2011); this is not applied to the present six-point series because a meaningful trend test requires more observations than are available, and is flagged as a specific direction for follow-on monitoring in Section 5.

3. Results

3.1 Vegetation Health Analysis (NDVI)

The NDVI analysis revealed a seasonal cycle interrupted by the February 2025 pollution event. During the late-dry-season baseline in August 2024, the mean NDVI was 0.160, reflecting natural vegetation stress due to moisture deficit. By September 2024, mean NDVI marginally increased to 0.173, the expected peak dry-season low point.

In December 2024, coinciding with the peak rainy season, mean NDVI rose to 0.345, the highest value recorded across the study period and the only pre-incident rainy-season reference point available. Following the February 2025 tailings dam failure, the March 2025 NDVI declined to 0.313 a drop of 0.032 units relative to the December observation, at a point in the rainy season when sustained or rising values would ordinarily be expected. With only one prior rainy-season observation, this comparison cannot rule out the possibility that some of the decline reflects natural inter-monthly or inter-annual variability rather than the spill; it is reported here as consistent with, rather than statistical proof of, an anomalous disturbance.

By April 2025, partial recovery occurred, with mean NDVI rising to 0.334, yet this remained below the December 2024 baseline of 0.345, indicating incomplete recovery within the study window. By June 2025, with the onset of the dry season, mean NDVI fell to 0.239 — broadly consistent with typical dry-season values, though the absence of a second rainy-season baseline means this study cannot distinguish a genuinely accelerated seasonal decline from ordinary dry-season onset.

Table 2: Multi-temporal NDVI values along the Kafue River riparian zone, 2024–2025.

Period	Date	Mean NDVI	Classification	Notes
Pre-incident (dry baseline)	August 2024	0.160	Sparse / stressed vegetation	Natural dry season low
Pre-incident (peak dry)	September 2024	0.173	Moderate stress	Expected seasonal minimum
Pre-incident (rainy peak)	December 2024	0.345	Healthy, dense vegetation	Only pre-incident rainy-season reference
Post-incident (immediate)	March 2025	0.313	Moderate, below expected	Decline relative to Dec. 2024; single-year baseline limits attribution

Post-incident (short-term)	April 2025	0.334	Partial recovery	Below Dec. 2024 baseline
Post-incident (dry onset)	June 2025	0.239	Seasonal decline	Cannot separate from ordinary dry-season onset

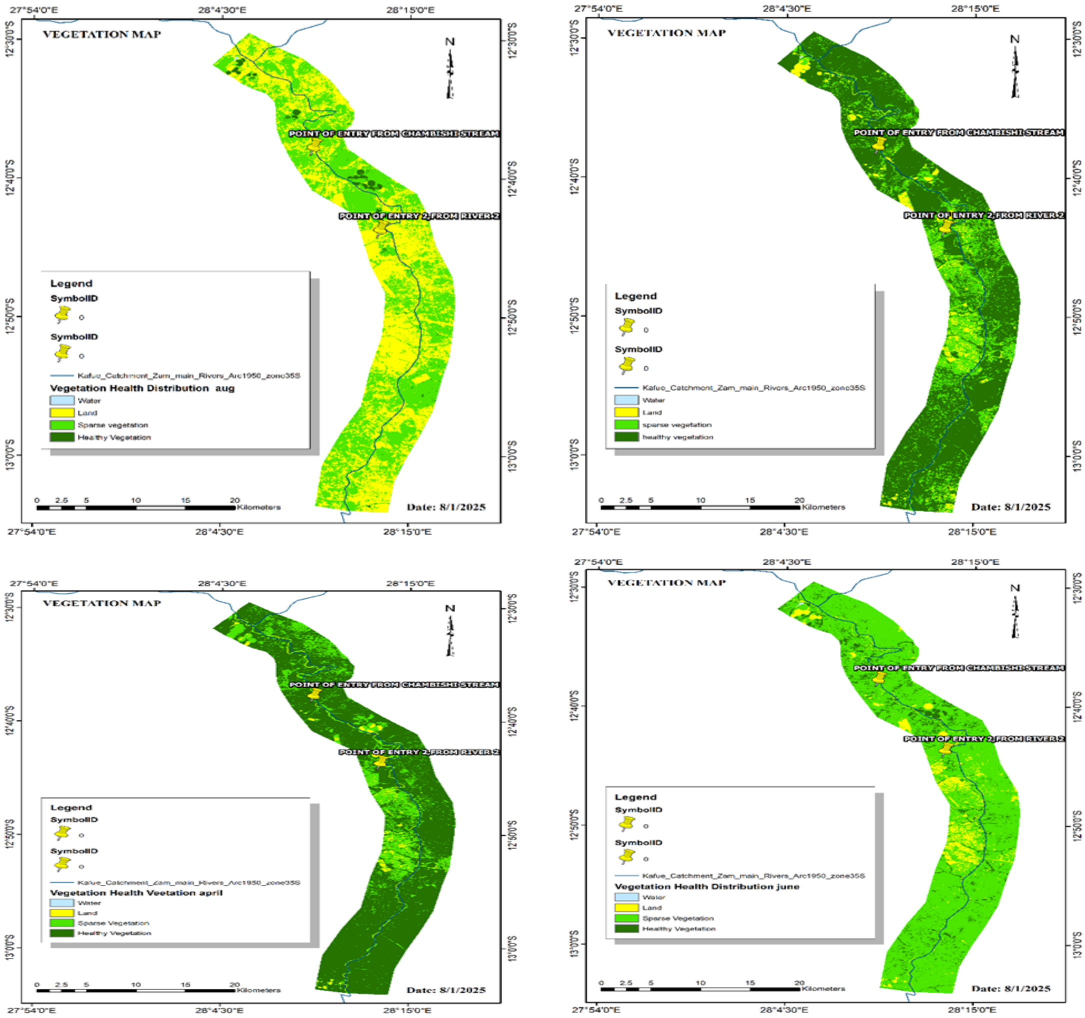

Figure 3. Multi-temporal NDVI thematic maps showing riparian vegetation health from August 2024 to June 2025 (Developed by the Authors).

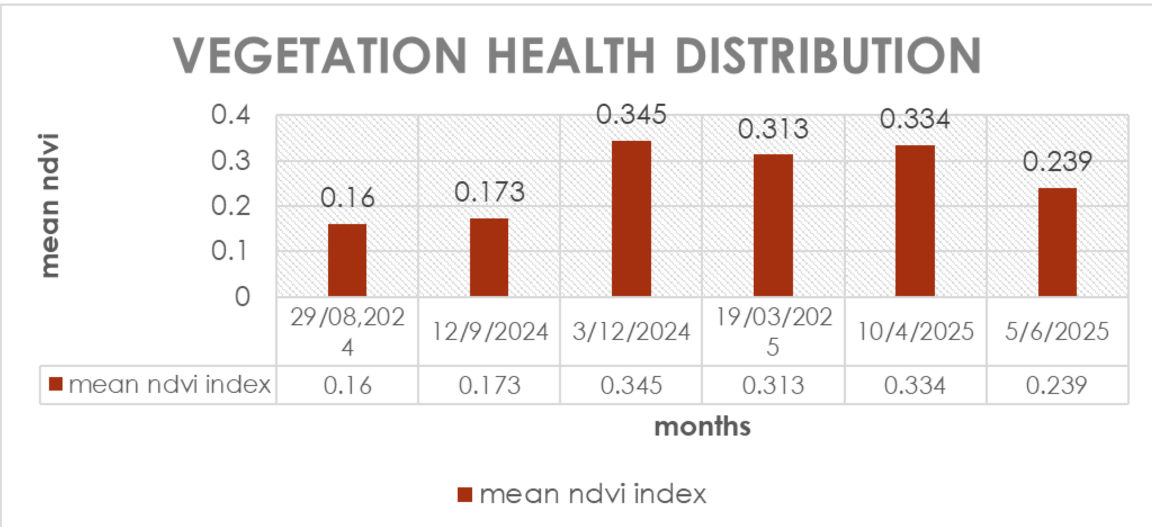

Figure 4. Summary graph of mean NDVI values across all six temporal periods illustrating the pollution impact and partial recovery trajectory (Developed by the Authors).

3.2 Water Turbidity Analysis (NDTI)

The NDTI analysis captured a pronounced turbidity signal in the Kafue River following the February 2025 tailings dam failure. During the August 2024 dry-season baseline, mean NDTI was −0.013, with values clustered around zero and negative figures, consistent with clear, low-turbidity water typical of the dry season. September 2024 showed a marginal increase, reflecting natural concentration of suspended particles as water levels dropped, and December 2024 showed moderate turbidity associated with early rainy-season runoff and sediment mobilisation from the catchment.

March 2025 the month immediately following the tailings dam failure showed a sharp spike in mean NDTI, with high-turbidity zones (NDTI > 0.20) extending substantially downstream from the Mwambashi confluence. This spatial pattern is consistent with the reported trajectory of the pollution plume. By April 2025, mean NDTI had returned to near-baseline levels, consistent with the river's hydrological flushing capacity, and by June 2025 NDTI values had reverted to clear-water levels. This reversion indicates recovery of the optically detectable turbidity signal specifically; because NDTI responds to suspended particulates and not to dissolved constituents, it does not by itself confirm recovery of dissolved chemical water quality parameters such as dissolved heavy metals, which would require in-situ chemical sampling to establish.

Table 3: Multi-temporal NDTI values for the Kafue River study segment, 2024–2025.

Period	Date	Mean NDTI	Turbidity Class	Notes
Pre-incident (dry baseline)	August 2024	−0.013	Clear water	Low sediment, pre-disaster baseline
Pre-incident (peak dry)	September 2024	−0.008	Clear to very low turbidity	Expected seasonal sediment increase
Pre-incident (rainy season)	December 2024	+0.042	Moderate turbidity	Normal early rainy-season runoff
Post-incident (acute)	March 2025	+0.210	High turbidity (pollution spike)	Tailings plume clearly visible
Post-incident (recovery)	April 2025	+0.018	Low turbidity	Rapid hydrological flushing
Post-incident (dry onset)	June 2025	−0.009	Clear water	Turbidity signal recovered

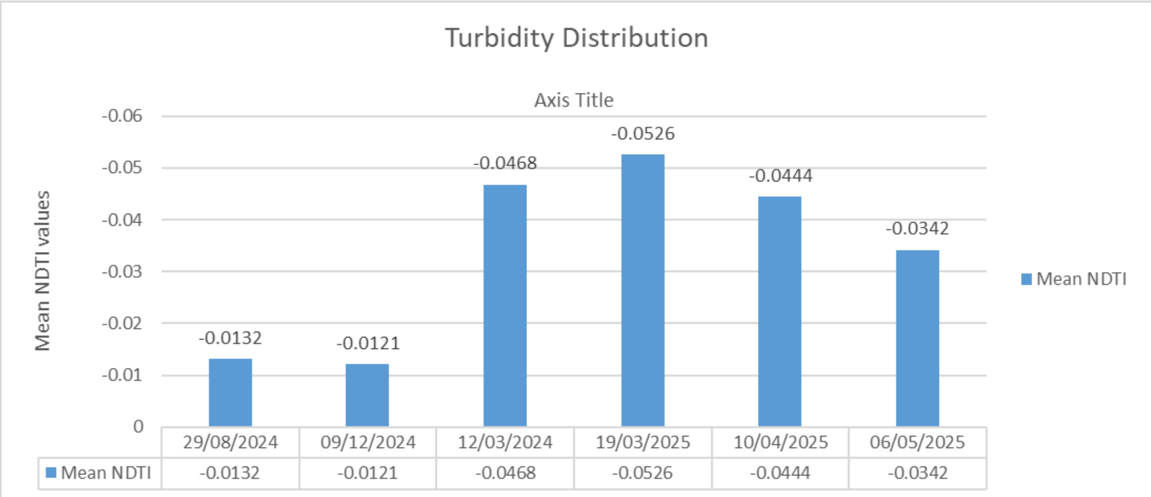

Figure 5. Summary graph of mean NDTI values across all temporal periods, showing the spike and subsequent recovery of turbidity (Developed by the Authors).

4. Discussion and Policy level implication

4.1 Contrasting Recovery Patterns

The multi-temporal NDTI and NDVI analysis provides a spatially explicit, quantitative record of the environmental signature of the February 2025 Sino-Metals tailings dam failure. Two contrasting patterns emerge: comparatively rapid recovery of water turbidity, against a more persistent suppression of riparian vegetation health.

Water quality, as measured by NDTI, showed a pronounced acute response in March 2025 with high-turbidity values extending substantially downstream from the Mwambashi confluence followed by a return to near-baseline levels within one to two months. This pattern is consistent with the river's hydrological flushing capacity and the dilution effects of rainy-season flows, and aligns with the global literature on turbidity dynamics following tailings dam failures (Crioni et al., 2023; Ruppen et al., 2023).

Riparian vegetation health, measured by NDVI, exhibited a more prolonged response, declining from the single available rainy-season baseline and remaining below it five months later. One plausible explanation is the persistence of heavy-metal contamination in riparian soils after turbidity levels normalise a pattern noted in studies of the Catoca mine tailings spill in Angola (Ruppen et al., 2023) and mechanistically consistent with the reflectance changes documented in heavy-metal-stressed vegetation more broadly (Lovynska et al., 2024). This study did not, however, collect soil or water heavy-metal data, and NDVI decline is also produced by drought stress, so this explanation should be read as a plausible hypothesis consistent with the evidence, not as a confirmed causal finding; Section 4.3 returns to what would be needed to confirm it.

Taken together, the results suggest that satellite-based spectral indices can trace the downstream signature of a tributary-sourced pollution event on a major river system, and that NDTI and NDVI provide complementary rather than redundant information: NDTI captures the acute, comparatively rapidly reversible water-clarity signal, while NDVI reflects a slower-moving, more persistent riparian response. Relying on either index alone would give an incomplete picture of the event's environmental footprint.

4.2 Towards a Smart Environmental Monitoring Policy Design

The findings point to specific, implementable design elements for a satellite-based early-warning capability that ZEMA and WARMA could integrate into their operational frameworks, rather than to a general case for remote sensing in the abstract.

First, index pairing: because NDTI and NDVI capture different failure modes with different recovery timescales, an operational system should compute both in parallel rather than relying on a single index, using NDTI as the fast-acting acute-event trigger and NDVI as a slower-moving confirmatory and extended-impact indicator. Second, revisit cadence: the combined Landsat 8/9 and Sentinel-2 constellation used in this study offers a revisit interval of a few days under clear-sky conditions, which is sufficient to detect an acute turbidity spike of the kind observed in March 2025 within days rather than weeks, provided cloud-cover screening is automated. Third, alert thresholds: the pre-incident NDTI values observed here (−0.013 to +0.042) provide an initial empirical basis for a site-specific alert threshold (for example, NDTI values sustained above +0.15 across a defined river reach), though such a threshold should be calibrated against a longer historical baseline than the six windows analysed here before operational deployment. Fourth, an institutional workflow: a phased response automated anomaly flagging from freely available Sentinel-2/Landsat imagery, followed by rapid field verification once a flag is raised, followed by formal regulatory action would let ZEMA and WARMA use the near-zero marginal cost of Copernicus and USGS imagery to extend the reach of a field-verification capacity that cannot itself cover the full length of the Kafue basin continuously.

This design deliberately treats satellite indices as a triage and prioritisation tool that directs scarce field-verification and laboratory capacity to the right place at the right time, rather than as a replacement for in-situ chemical monitoring, which remains the only way to confirm dissolved contaminant levels.

A satellite-based trigger of this kind would also directly address a documented institutional gap: Zambia's Environmental Management Agency currently maintains a permanent presence in only a small fraction of the country's districts, and a recent assessment of three Copperbelt mine waste disasters, including the Sino-Metals failure examined here, found little transparency around tailings risk and no evidence of disaster-response or recovery plans co-developed with affected communities (Mukumba et al., 2026). The Global Industry Standard on Tailings Management, introduced after the 2019 Brumadinho disaster, calls for public geolocation and risk-assessment disclosure for tailings facilities (ICMM, 2020; Kemp et al., 2021), and a satellite-derived anomaly layer of the kind proposed here could give ZEMA and WARMA an independent, low-cost means of verifying that disclosure rather than relying solely on operator self-reporting. More broadly, the framing of satellite monitoring as one input into a smart, data-driven regulatory system is consistent with the wider literature on smart and sustainable urban and environmental governance, which similarly emphasises that technological monitoring capability only translates into better outcomes when paired with the institutional capacity to act on it (Bashir et al., 2025).

4.3 Limitations

Several limitations qualify the findings and are stated explicitly rather than left implicit. First, no in situ water chemistry or soil heavy-metal sampling was available during this study period, so satellite-derived index values could not be validated against direct chemical measurements; validation here is limited to comparisons with publicly documented impacts (fish kills, water-supply shutdowns, reported contamination). Second, the dataset contains only a single pre-incident rainy-season observation (December 2024), which limits the ability to distinguish an anomalous disturbance from ordinary inter-annual variability in the March 2025 NDVI decline, and the same limitation applies to the June 2025 dry-season reading. Third, combining Landsat 8/9 and Sentinel-2 introduces residual cross-sensor uncertainty: this study resampled Sentinel-

2 to a common 30 m grid but did not apply full BRDF and bandpass harmonisation of the kind implemented in the NASA HLS product (Claverie et al., 2018), and the 30 m Landsat pixel size in particular may not resolve fine-scale spatial heterogeneity in turbidity or vegetation stress within the riparian zone. Fourth, the six-point temporal composite structure of the dataset does not support formal parametric or Mann-Kendall trend testing, as discussed in Section 2.7; the reported patterns are descriptive rather than statistically tested for significance. Fifth, NDTI is sensitive to suspended particulates but not to dissolved contaminants, so its return to clear-water levels indicates optical turbidity recovery specifically and should not be read as confirmation of full chemical water-quality recovery. Finally, cloud cover constrained the temporal density of usable scenes, particularly during the peak rainy season, limiting the study to six discrete windows rather than a continuous time series. It is also worth noting that the Sino-Metals tailings facility that failed in February 2025 was a legacy structure whose walls had been raised repeatedly rather than replaced (Mukumba et al., 2026) — a pattern consistent with the broader global finding that historical, under-assessed waste legacies are disproportionately implicated in tailings failures (Marais et al., 2024; Rana et al., 2022) which means the satellite-derived alert thresholds proposed in Section 4.2 would need to be calibrated separately for other Copperbelt facilities rather than assumed to transfer directly from this single case.

5. Conclusion

This study shows that GIS and satellite remote sensing can provide a cost-effective, basin-wide record of the acute and medium-term environmental signature of an industrial pollution event, even across a complex, interconnected river system, while also making clear what such a record can and cannot establish on its own. The February 2025 Sino-Metals tailings dam failure was associated with two contrasting patterns in the satellite record: a pronounced but comparatively short-lived turbidity spike, with NDTI returning to clear-water levels within the five-month study window, and a more persistent suppression of riparian vegetation health that had not returned to its pre-incident rainy-season baseline by the end of that window.

The study's contribution is to pair NDTI and NDVI at sub-monthly resolution around a single dated event in a Sub-Saharan African river basin, and to translate the resulting differential recovery signature into concrete design elements: index pairing, revisit cadence, threshold calibration, and institutional workflow for a satellite-based early-warning monitoring capability for ZEMA and WARMA, rather than treating the case study as an end in itself.

The evidence presented here is nonetheless limited by the absence of in situ chemical validation and by a single-year seasonal baseline. Future research should prioritise three things: concurrent in-situ water sampling and heavy-metal analysis to directly validate satellite-derived indices against dissolved and particulate contaminant concentrations; extension of the monitoring period across multiple annual cycles so that Mann-Kendall trend testing and Theil-Sen slope estimation (Neeti & Eastman, 2011) can be applied with adequate statistical power; and piloting the proposed alert-threshold and escalation workflow with ZEMA and WARMA on a defined river reach to test its operational feasibility ahead of wider deployment.

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Conflicts of Interest
The authors report no conflicts of interest.

Data availability statement
The Landsat and Sentinel-2 imagery underlying this study are freely available from the USGS Earth Explorer platform and the Copernicus Open Access Hub respectively. The derived NDTI, NDVI and NDWI raster products and summary statistics are available from the corresponding author, M.S., upon reasonable request.

Institutional Review Board Statement
Not applicable. This study involved satellite remote sensing and GIS analysis only and did not involve human participants, human data or animal subjects.

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