KNOWLEDGE BRIEF

Strengthening Critical Mineral Supply Chain Resilience through Multi-Scale Geospatial Monitoring

SATELLITE MONITORING, ESG RISK MAPPING, DISPLACEMENT-BASED TRANSPORT VULNERABILITY ANALYSIS, AND MULTI-SCALE GEOGRAPHIC CONTEXT MAPPING

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EXECUTIVE SUMMARY

Critical materials such as lithium, copper, and rare earth elements are essential for the global energy transition. However, the supply chains that connect mines, transport corridors, and export infrastructure are increasingly exposed to environmental hazards, infrastructure disruptions, and governance challenges. Many existing risk assessments conducted by governments, industry, and international organisations focus primarily on geopolitical and market risks. In contrast, spatially explicit risks—such as exposure of mining sites and transport corridors to environmental hazards, infrastructure constraints, and local social conditions—remain less systematically assessed. Integrating these spatial risks is crucial to inform policies aimed at improving supply security and the sustainability of the sector.

This briefing presents a novel multi-scale geospatial monitoring framework for assessing critical mineral supply chain resilience and proposes its integration into existing risk assessment approaches. The framework combines satellite monitoring of mining activity, spatial environmental, social, and governance (ESG) indicators, transport network modelling, and the use of internal displacement data to identify areas exposed to disruption risks. These components are implemented within the Critical Mineral Dashboard, an interactive WebGIS platform designed for decision-makers, infrastructure planners, and supply chain analysts.

The dashboard enables users to identify high-risk locations along mineral supply chains and to validate potential disruptions using high-resolution satellite imagery. This workflow links risk identification with targeted validation, supporting more informed and evidence-based decision-making.

Case studies in Zambia and Malawi demonstrate the practical value of the approach. In Zambia, satellite-derived mine expansion is closely associated with copper production trends, enabling near real-time monitoring of mining activity. In Malawi, transport network analysis identifies alternative road corridors that can maintain export flows when primary infrastructure is disrupted. Spatial ESG indicators highlight mining sites with elevated environmental and social exposure, while displacement data, measured as numbers of internally displaced people (IDPs) associated with past disasters and conflict, are used to identify transport segments that are repeatedly exposed to disruption.

These findings demonstrate how the framework can support both mineral-producing countries (e.g. infrastructure planning and governance) and downstream users of critical materials (e.g. supply chain risk assessment and diversification). The results also reflect a broader pattern of accelerating mineral development across southern Africa. For instance, this includes rapid lithium expansion in Zimbabwe, increasing copper production ambitions in Zambia, and emerging rare earth opportunities in Malawi.

The analytical approach is based largely on open geospatial datasets and replicable methods, making it readily applicable to other regions. By enabling spatially explicit risk identification and validation, the framework provides a practical tool for strengthening the resilience, transparency, and sustainability of critical mineral supply chains.

Key Recommendations

→

Integrate spatially explicit risk analysis into critical mineral supply chain assessments alongside geopolitical and market risk.

→

Use satellite monitoring routinely to track mine expansion, detect operational change, and validate reported production trends.

→

Prioritise resilience investment and contingency planning on critical transport bottlenecks, while developing alternative export corridors.

→

Apply Local Impact Area ESG screening to identify mines with elevated environmental and social exposure and target mitigation accordingly.

→

Deploy integrated dashboard-based monitoring workflows that connect risk identification with targeted validation and action.

Introduction

As global demand for critical materials accelerates, securing reliable and resilient supply chains has become a central concern for governments, industry, and international development institutions. Studies suggest that achieving climate targets will significantly increase demand for minerals required in energy technologies; for example, solar photovoltaic and battery technologies are expected to drive substantial growth in demand for materials such as lithium, copper, and rare earth elements [7, 1, 6, 8]. These materials are essential for low-carbon technologies, including renewable energy systems, electric vehicles, and energy storage, and their demand is projected to increase rapidly as countries scale up clean energy deployment [9, 11, 16, 17, 18, 3, 14]. At the same time, the geographical concentration of mineral production and processing raises concerns regarding supply security and strategic dependencies.

Critical mineral supply chains extend far beyond individual mine sites. They include interconnected systems of extraction, transport infrastructure, processing facilities, and export corridors linking inland production areas to global markets. Disruptions at any stage of these systems can have significant economic and strategic consequences for stakeholders along the supply chain. While mineral supply risk analyses—commonly conducted by governments, industry, and international organisations—highlight the importance of assessing vulnerabilities across entire supply chains [11], they often focus primarily on geopolitical and market risks [7, 8].

In contrast, spatially explicit risks—such as exposure of transport infrastructure to flooding, proximity to conflict-affected regions, or local environmental and social conditions—remain less systematically integrated into supply chain analysis. This gap is particularly relevant in regions where mineral production is expanding rapidly and infrastructure systems are exposed to multiple types of disruption.

Southern Africa provides a clear example of this challenge. Lithium production in Zimbabwe and emerging rare earth opportunities in Malawi depend on cross-border transport corridors connecting inland mining areas to Mozambican ports, particularly Beira and Nacala. These corridors traverse regions that are frequently affected by cyclones, flooding, and conflict, making them vulnerable to disruption. Understanding where and how such risks affect supply chains requires spatially explicit analysis that links infrastructure, environmental hazards, and socio-political dynamics.

Geospatial data and satellite observations provide new opportunities to address this challenge. Advances in remote sensing, open geospatial datasets, and spatial analysis techniques enable monitoring of mining activity, infrastructure networks, environmental conditions, and population dynamics across multiple spatial scales.
In particular, combining these datasets allows the identification of infrastructure segments that are both critical for supply chains and exposed to disruption risks.

This briefing presents a multi-scale geospatial monitoring framework designed to assess and strengthen critical mineral supply chain resilience and demonstrates its application to the Malawi–Zimbabwe–Mozambique transport corridor. The framework integrates several complementary analytical components. High-resolution satellite imagery is used to monitor mine expansion and operational activity. Spatial ESG indicators derived from open geospatial datasets provide insight into local conditions around mining sites. Transport network analysis identifies critical infrastructure corridors and evaluates alternative routes. Internal displacement data associated with past conflict and natural disaster events are incorporated as a proxy for infrastructure disruption risk, capturing locations where disruptions have had significant real-world impacts on populations and infrastructure. Finally, thematic geospatial layers provide broader environmental and socio-economic context. These components are not applied independently but form a unified analytical framework, where ESG-based Local Impact Area analysis provides site-level context that complements transport network modelling and displacement-informed risk assessment across supply chains.

These analytical components are made available and visualised within the Critical Mineral Dashboard[1], an interactive WebGIS platform that enables users to explore geospatial datasets related to mining activity, infrastructure networks, environmental indicators, and population distribution [13]. The dashboard provides access to precomputed datasets, including global lithium, copper, cobalt, and nickel mines and processing facilities. It also includes environmental and social layers at the global scale, enabling users to analyse spatial relationships and identify potential vulnerabilities.

By linking satellite observations, spatial indicators, and infrastructure analysis within a single framework, this approach enables decision-makers to identify, assess, and manage risks in critical mineral supply chains. The Malawi–Zimbabwe–Mozambique case study presented in this briefing illustrates how such analysis can provide actionable, place-based insights for strengthening supply chain resilience in regions exposed to both environmental and socio-political disruptions.

Finally, national and regional thematic maps provide broader geographic context for understanding mineral supply chains within their environmental and socio-economic settings, with additional examples presented in Annex A4 and Annex A5.

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[1] Available at: https://gsdr.n-kov.com/cmd/

Geospatial Monitoring of Critical Mineral Supply Chains

Critical mineral supply chains operate across multiple spatial scales, from individual mine sites to regional transport corridors and export infrastructure [2]. This approach enables the identification of spatial vulnerabilities across mineral supply chains and supports evidence-based decision-making through the Critical Mineral Dashboard.

Satellite Monitoring of Mining Activity

Satellite imagery provides an effective tool for monitoring mining activity and identifying changes in mine infrastructure over time, which is essential for assessing exposure and vulnerability of mining operations to environmental and operational risks [10]. High-resolution imagery allows the delineation of open-pit boundaries and other surface features associated with mining operations [15].

Mine area change can be mapped using lower-resolution satellite imagery through automated processing, while higher-resolution imagery typically requires supervised analysis or manual digitisation of mine boundaries. Time series of mine extent are then derived by calculating the area of delineated mine polygons for each observation period.

Medium-resolution satellite datasets such as Landsat (30m resolution) can further support long-term analysis of mining development. Using an NDVI[2]-based, unsupervised classification approach (i.e. without training data), vegetated areas are removed and non-vegetated surfaces associated with mining (e.g. pits, waste dumps, and tailings) are identified over time. This is achieved by constructing yearly composites of Landsat imagery and applying a vegetation mask derived from NDVI thresholds, allowing consistent separation of mine and non-mine areas. This approach enables reconstruction of historical mining expansion patterns across multiple sites over several decades.

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[2] The Normalized Difference Vegetation Index

Figure 1 illustrates how annual open-pit boundaries derived from PlanetScope imagery[3] reveal clear expansion patterns at the Kansanshi copper mine in Zambia. Comparison of satellite-derived mine area with reported production data indicates a strong relationship between mine expansion and copper production. In particular, a substantial increase in mine area between 2023 and 2024 is followed by a corresponding increase in production during 2024–2025, based on reported production data from S&P Global. These observations demonstrate that satellite monitoring can provide near real-time indicators of mining activity and production dynamics.

Spatial ESG Indicators Around Mining Sites

As part of the proposed geospatial framework, spatial ESG indicators are used to capture local environmental and social conditions around mining sites. Mining operations generate impacts that extend beyond the boundaries of individual sites, affecting surrounding ecosystems and communities. These local conditions are directly relevant to supply chain resilience, as mines located in densely populated or infrastructure-constrained areas may be more exposed to disruption risks, regulatory pressures, or social conflict.

This component of the framework provides a practical mechanism for systematically capturing and comparing such local conditions across mining sites and integrating them into supply chain risk assessment. To operationalise this, we adopt the concept of a Local Impact Area (LIA), defined as a 10km buffer around the centre of each mining operation, consistent with the site-level assessment framework developed in [5].

Within each LIA, spatial indicators derived from open geospatial datasets are used to operationalise environmental and social dimensions of ESG assessment. The selection of indicators follows [5], where site-level conditions are quantified using infrastructure and demographic proxies. Specifically, the following indicators are used:

These indicators are aggregated into a composite ESG score that reflects local environmental and social conditions and enables comparison across mining sites. As demonstrated in [5], this scoring highlights spatial variability in vulnerability, where lower scores indicate a higher potential for mining activities to generate negative impacts on surrounding communities and environments, which may in turn increase the likelihood of operational disruption.

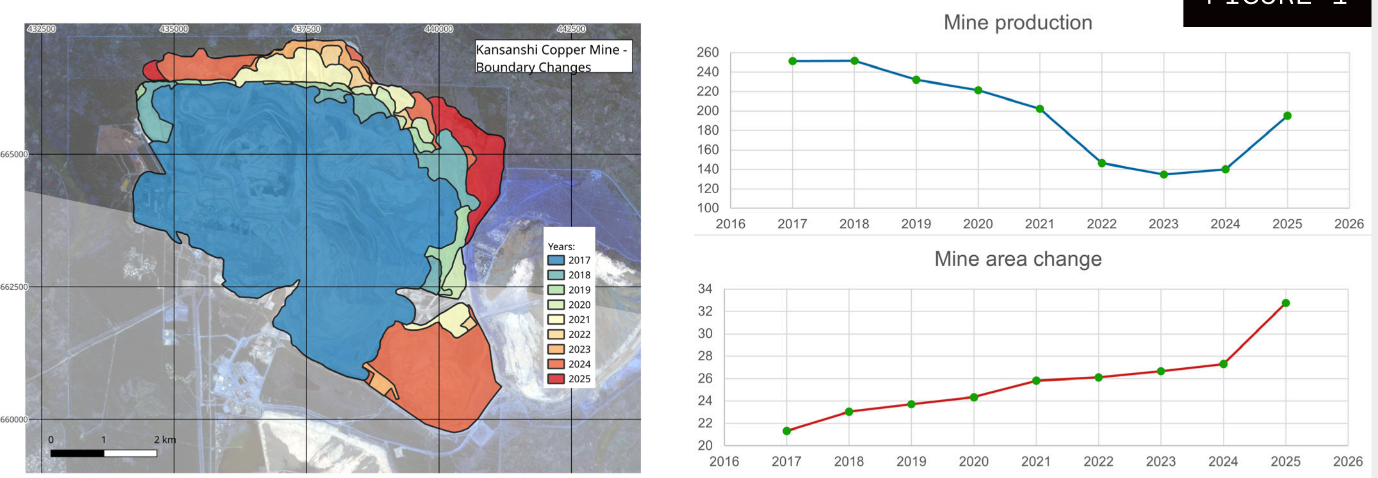
In addition to social indicators, environmental processes such as land-use change and water flow pathways can be analysed within the same LIA framework to identify areas at risk of deforestation and downstream contamination. This enables identification of critical zones where mitigation measures, such as monitoring infrastructure, can be most effectively deployed.

By combining these spatial indicators within a consistent LIA framework, the approach translates abstract ESG principles into measurable, site-specific metrics. This supports systematic monitoring of environmental and social exposure, facilitates comparison between mining sites, and provides a basis for targeted, evidence-based strategies to reduce risks and improve supply chain resilience.

INDICATOR	DESCRIPTION
Building density	Proxy for settlement intensity and population presence within the LIA.
Road network density	Indicator of accessibility, connectivity, and potential exposure pathways.
Population	Total population within the LIA, representing potential exposure to mining-related impacts.
Proximity to amenities	Functional feature or service provided for the convenience or necessity of a community - e.g., restaurants, schools, car parks, ATMs, post offices, toilets, etc.). Proxy for social infrastructure, measuring accessibility to key services within the LIA.
Healthcare facilities	Indicator of access to healthcare services and capacity to respond to environmental and social risks.
Educational facilities	Indicator of access to education and long-term community development capacity.

TABLE 1: SPATIAL ESG INDICATORS USED WITHIN LIAS, ADAPTED FROM [5].

FIGURE 1

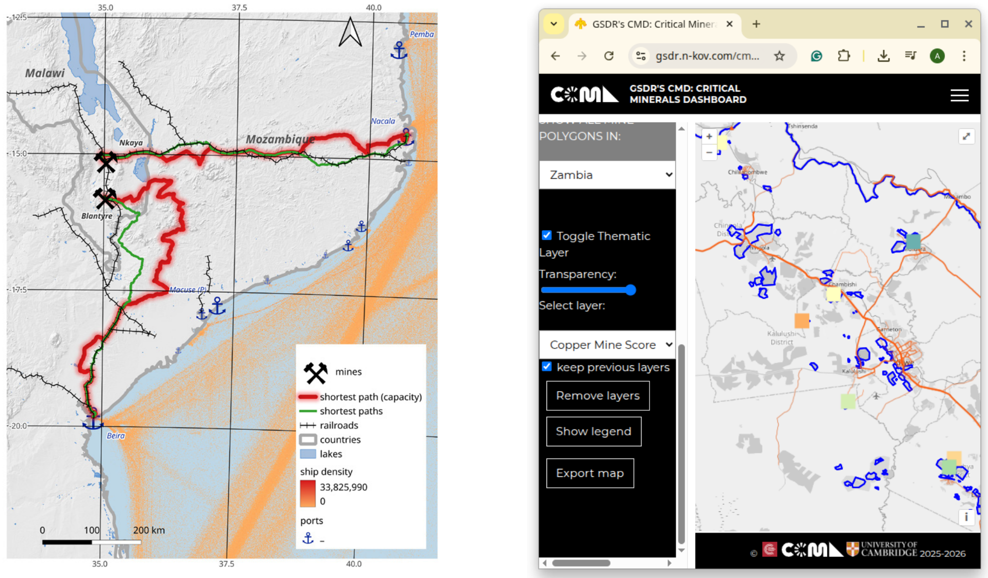


(A) ANNUAL OPEN-PIT BOUNDARIES DERIVED FROM PLAN-

(B) ANNUAL COPPER PRODUCTION THOUSANDS METRIC TONS ETSCOPE IMAGERY (3M RESOLUTION). (TOP) AND MINE AREA IN SQ. KILOMETRES (BOTTOM).

FIGURE 1: SATELLITE MONITORING OF MINE EXPANSION AT THE KANSANSHI COPPER MINE IN ZAMBIA. THE COMPARISON BETWEEN SATELLITE-DERIVED MINE AREA AND REPORTED COPPER PRODUCTION DEMONSTRATES THAT CHANGES IN MINE AREA PROVIDE A STRONG PROXY INDICATOR FOR MINING ACTIVITY AND PRODUCTION DYNAMICS.

FIGURE 2



(A) POTENTIAL EXPORT CORRIDORS FOR RARE EARTH ELEMENTS FROM MALAWI TO MOZAMBICAN PORTS. RAILWAYS REPRESENT THE PRIMARY EXPORT ROUTES, WHILE ROAD-BASED NETWORK ANALYSIS IDENTIFIES ALTERNATIVE TRANSPORT CORRIDORS THAT MAY IMPROVE SUPPLY CHAIN RESILIENCE.

A)AVAILABLE AT: HTTPS://GSDR.N-KOV.COM/CMD/ COUNTRIES.HTML

(B) CRITICAL MINERAL DASHBOARD (CMD)/COUNTRIESA, AN INTERACTIVE WEBGIS PLATFORM INTEGRATING MINING DATA, INFRASTRUCTURE NETWORKS, ENVIRONMENTAL INDICATORS, AND POPULATION DATASETS. THE COLOURS ON THE MAP REPRESENT CALCULATED ESG SCORES FOR COPPER MINES IN ZAMBIA, RANGING FROM 0 TO 9, WHERE LOWER SCORES INDICATE POORER CONDITIONS AND ARE SHOWN IN RED, FOLLOWED BY ORANGE, YELLOW, GREEN, AND BLUE FOR PROGRESSIVELY HIGHER SCORES. TO REPRODUCE THIS MAP, OPEN THE DASHBOARD LINK, SELECT THE COPPER MINE SCORES LAYER, AND PRESS SHOW LEGEND TO DISPLAY THE SCORE CLASSIFICATION.

FIGURE 2: GEOSPATIAL ANALYSIS AND DIGITAL INTEGRATION OF CRITICAL MINERAL SUPPLY CHAINS. (A) TRANSPORT NETWORK MODELLING IDENTIFIES RESILIENT EXPORT CORRIDORS FOR RARE EARTH EXPORTS FROM MALAWI. (B) THE CRITICAL MINERAL DASHBOARD PROVIDES AN INTERACTIVE PLATFORM FOR EXPLORING SPATIAL DATASETS RELATED TO MINING ACTIVITY AND INFRASTRUCTURE SYSTEMS, INCLUDING ESG SCORE VISUALISATION FOR ZAMBIAN COPPER MINES.

Transport Corridor Resilience and Integrated Monitoring

Transport infrastructure plays a central role in connecting mineral production regions to processing facilities and export ports. Disruptions affecting transport corridors can therefore have significant impacts on the reliability of mineral supply chains. Spatial network analysis can help identify alternative transport routes and evaluate infrastructure resilience.

Figure 2 illustrates how geospatial analysis and digital platforms can support monitoring of mineral supply chains. The example on the left (a) shows potential export corridors for rare earth elements from Malawi to Mozambican ports. Railways connecting Blantyre to Beira and Nkaya to Nacala represent the primary export routes. However, network analysis of the regional road system reveals several alternative routes that may provide redundancy if rail infrastructure becomes disrupted. This analysis is based on shortest-path calculations using both geometric distance and estimated road capacity, combined with network centrality metrics to identify routes that are critical for maintaining connectivity between mining regions and export ports.

Infrastructure disruptions are often associated with environmental disasters or regional instability. Integrating displacement records associated with disasters and conflict with transport network analysis makes it possible to identify infrastructure segments exposed to elevated disruption risk. Historical displacement events provide a spatial record of where major disruptions have occurred, such as flooding or conflict-related instability. Areas with repeated displacement patterns are therefore interpreted as locations with higher likelihood of future disruption, particularly where critical transport infrastructure intersects with these zones. When combined with network criticality metrics, such analyses highlight transport corridors that are both strategically important and vulnerable to disruption.

The Critical Mineral Dashboard shown in Figure 2 (b) integrates these analytical components within an interactive WebGIS environment. The platform enables users to explore spatial datasets related to mining activity, infrastructure networks, environmental indicators, and population distribution. By combining satellite observations, infrastructure data, and socio-environmental indicators within a single interface, the dashboard provides a practical decision-support tool for analysing mineral supply chains and identifying potential vulnerabilities.

A key component of the framework is the integration of displacement data, measured as numbers of internally displaced people (IDPs), as a proxy for disruptive events such as natural disasters and conflict. Unlike hazard datasets that describe the physical extent of events, displacement data capture their actual societal impact, reflecting where disruptions are severe enough to affect populations and, by extension, infrastructure and transport systems. In this approach, IDP events are georeferenced and linked to transport infrastructure, allowing the identification of road segments that are both critical for supply chains and historically exposed to disruption. For example, in the Malawi–Zimbabwe–Mozambique region, displacement events associated with cyclones (e.g. Idai, Freddy) and conflict in Cabo Delgado are spatially aligned with transport corridors leading to the port of Beira. By combining IDP intensity with network centrality measures, the tool highlights infrastructure segments with elevated disruption risk.

Decision Support and Applications

The analyses presented in this brief demonstrate how multi-scale geospatial monitoring can support decision-makers in identifying, assessing, and managing risks in critical mineral supply chains, by enabling intuitive exploration of spatial indicators and event data through an interactive dashboard. By integrating satellite observations, spatial ESG indicators, transport network modelling, and displacement-based risk proxies within a single analytical framework, the approach provides actionable insights across multiple stages of the supply chain.

Satellite-based monitoring enables continuous observation of mining activity, allowing decision-makers to track mine expansion, identify changes in production dynamics, and verify reported trends using independent data sources. This is particularly valuable in regions where reporting may be delayed or incomplete, as satellite-derived indicators provide near-real-time evidence of operational changes. Although such data are increasingly available, they often require significant technical expertise to access and process; platforms such as the Critical Mineral Dashboard help address this challenge by making these datasets more accessible and easier to interpret.

Transport network analysis supports infrastructure planning by identifying critical corridors and evaluating alternative routes. Rather than relying solely on existing infrastructure configurations, the tool allows users to explore redundancy within transport systems by comparing shortest paths and capacity-constrained routes. This enables identification of bottlenecks and supports decisions on infrastructure investment, corridor diversification, and resilience planning.

A key insight from the framework is the ability to identify transport infrastructure that is both critical for mineral supply chains and exposed to disruption risks. In the Malawi–Zimbabwe– Mozambique region, the analysis highlights corridor segments near Beira that are particularly vulnerable to flooding, as well as northern routes that may be affected by conflict-related instability. These insights enable decision-makers to prioritise monitoring, maintenance, and resilience investments in specific high-risk locations rather than applying uniform strategies across entire corridors.

This information is operationalised within the Critical Mineral Dashboard, where users—particularly decision-makers, infrastructure planners, and supply chain analysts—can visualise transport networks together with displacement patterns and derived vulnerability scores. High-risk segments can then be investigated further using high-resolution satellite imagery, enabling assessment of the actual impact of specific events (e.g. flooding of road infrastructure during cyclone events). This workflow supports evidence-based decision-making by linking risk identification with targeted validation.

Spatial ESG indicators further complement this analysis by providing site-level insights into environmental and social exposure around mining operations. By combining infrastructure, population, and service accessibility data within Local Impact Areas, decision-makers can gain place-based insights into mining contexts, identifying sites located in sensitive or densely populated regions and prioritising monitoring or mitigation actions accordingly.

Finally, the integration of all datasets within an interactive WebGIS platform enables users to explore spatial relationships between mining activity, infrastructure, environmental conditions, and social factors on a single platform. This supports scenario analysis, rapid screening of risk hotspots, and communication of complex spatial information to stakeholders.

Overall, the framework shifts the role of geospatial data from descriptive mapping to decision support, enabling decision-makers and practitioners to move from identifying risks to prioritising actions aimed at improving supply chain resilience.

Application of the Geospatial Framework: The Malawi–Zimbabwe–Mozambique Transport Corridor

This section demonstrates the application of the proposed geospatial monitoring framework to a critical mineral transport corridor in the Malawi–Zimbabwe–Mozambique region. Lithium production in Zimbabwe and potential rare earth exports from Malawi rely heavily on transport routes connecting inland mining areas to Mozambican ports, particularly Beira and Nacala. As a result, mineral supply chains in this region depend on cross-border infrastructure systems spanning multiple countries and a relatively limited number of rail and road connections.

The analysis shows that disruption risks are not uniform across the corridor: specific segments are exposed to different types of disruption and therefore require differentiated strategies.

The integrated analysis reveals that disruption risks along the corridor are spatially heterogeneous. In north-eastern Mozambique, displacement is primarily driven by the Cabo Delgado conflict, which has caused repeated population movements since 2020. In contrast, central and southern Mozambique, Malawi, and eastern Zimbabwe are predominantly affected by disaster-related displacement, particularly cyclones and flooding events such as Idai (2019), Eloise (2021), Ana and Gombe (2022), Freddy (2023), and Chido (2024). This distinction is critical, as it indicates that different segments of the corridor are exposed to different disruption mechanisms.

Using the geospatial framework, transport network analysis combined with displacement data identifies infrastructure segments that are both critical for mineral exports and historically exposed to disruption. Export routes are concentrated along a limited number of rail and road connections, creating bottlenecks in the regional logistics system. In particular, several coastal and river-crossing segments near Beira are repeatedly exposed to flood-related risk, while the northern corridor to Nacala lies closer to areas influenced by conflict.

To validate these modelled vulnerabilities, high-resolution PlanetScope imagery was acquired for a highly vulnerable road segment on the N6 corridor near the Pungwe River, approximately 54 km north-east of Beira, during the period of Cyclone Idai. Figure 3 shows RGB and NDVI imagery before, during, and after the flood event. The NDVI imagery clearly delineates floodwater as dark purple to blue, allowing the spatial extent of inundation to be assessed at 3 m resolution. Although the surrounding landscape was extensively flooded, the road itself remained intact. This demonstrates that the combined approach can distinguish between hazard exposure and actual infrastructure failure. In this case, the resilience of the road segment may be related to its elevation, engineering design, or drainage capacity, which limited structural damage despite extensive surrounding flooding. Identifying such factors is important for informing future infrastructure design and prioritising investments in construction standards and maintenance practices that enhance resilience to similar events.

The application of the framework provides actionable insights for decision-makers. For example, flood-prone road and bridge segments in the Beira corridor should be prioritised for monitoring, maintenance, and disaster preparedness. In contrast, transport planning in northern Mozambique should account for proximity to conflict-affected areas.

More broadly, this case study demonstrates how combining displacement-based risk screening with targeted satellite imagery enables a scalable workflow for identifying, validating, and prioritising infrastructure vulnerabilities. This supports more precise and evidence-based decision-making for strengthening critical mineral supply chain resilience.

FIGURE 3

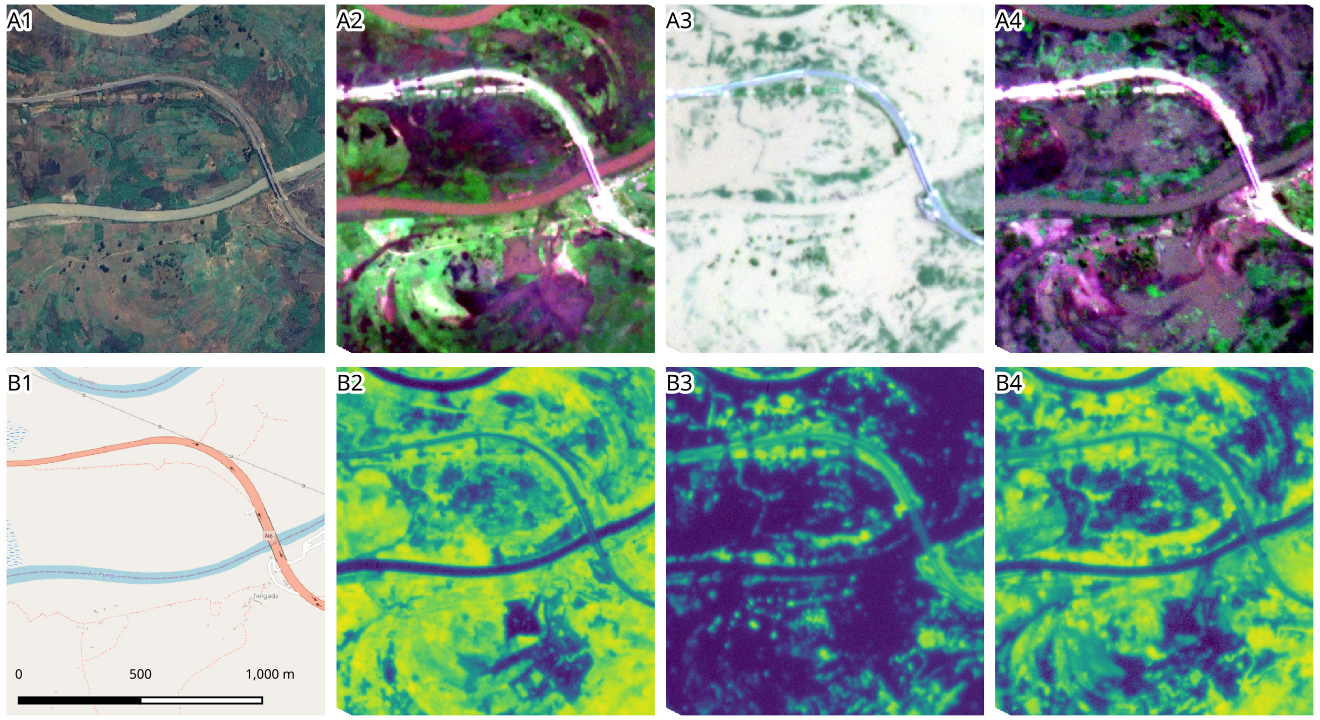


FIGURE 3: TARGETED HIGH-RESOLUTION PLANETSCOPE IMAGERY FOR A HIGHLY VULNERABLE ROAD SEGMENT ON THE N6 CORRIDOR NEAR THE PUNGWE RIVER, MOZAMBIQUE (E34.533, N-19.447), APPROXIMATELY 54 KM NORTH-EAST OF BEIRA. UPPER ROW: A1 – GOOGLE IMAGERY; A2 – PLANETSCOPE RGB ON 2023/01/05; A3 – PLANETSCOPE RGB ON 2023/03/19; A4 – PLANETSCOPE RGB ON 2023/04/24. LOWER ROW: B1 – OPENSTREETMAP; B2 – PLANETSCOPE NDVI ON 2023/01/05; B3 – PLANETSCOPE NDVI ON 2023/03/19; B4 – PLANETSCOPE NDVI ON 2023/04/24. PLANETSCOPE SPATIAL RESOLUTION IS 3 M. NDVI IS SHOWN USING THE QGIS VIRIDIS COLOUR RAMP, WHERE DARK PURPLE TO BLUE INDICATES VERY LOW VEGETATION INDEX VALUES ASSOCIATED HERE WITH OPEN WATER AND FLOOD INUNDATION. THE IMAGERY SHOWS EXTENSIVE FLOODING AROUND THE ROAD SEGMENT DURING THE EVENT, WHILE THE ROAD ITSELF REMAINED INTACT.

Conclusions

The growing importance of critical minerals for the global energy transition has intensified the need for resilient and transparent supply chains. While much attention has focused on geopolitical and market risks, spatial dimensions of mineral supply chains remain less systematically incorporated into policy analysis. This brief presents a novel multi-scale geospatial modelling framework and applies it to real-world case studies in southern Africa, demonstrating how spatial data can be systematically integrated to analyse mining activity, infrastructure systems, and regional vulnerabilities as a low-cost tool for monitoring and decision support.

The case studies illustrate the practical value of this approach. Satellite observations reveal strong relationships between mine expansion and production dynamics at copper mines in Zambia. Network analysis highlights alternative transport routes that may strengthen export resilience for rare earth elements in Malawi. Displacement-informed risk assessments identify vulnerable infrastructure segments in the Zimbabwe–Malawi–Mozambique region and distinguish between different disruption mechanisms, such as flooding and conflict-related instability.

These analytical components are made available within the Critical Mineral Dashboard, an interactive WebGIS platform designed to support exploration of spatial datasets related to mineral supply chains. By enabling users to combine satellite observations, infrastructure data, and socioenvironmental indicators within a single environment, the platform provides a practical decision support tool for identifying high-risk areas, prioritising infrastructure investments, and evaluating potential mitigation strategies.

For policymakers and decision-makers, this approach enables a shift from high-level risk assessments to spatially explicit, evidence-based planning. The framework allows users to identify where vulnerabilities are located, understand the underlying drivers of potential disruption, and assess whether risks translate into actual infrastructure impacts through targeted satellite observations. This supports more effective prioritisation of resources, improved monitoring strategies, and more resilient design of critical mineral supply chains.

As demand for critical minerals continues to increase, improving the transparency and resilience of supply chains will remain an important policy challenge. Multi-scale geospatial monitoring provides a scalable and transferable approach for identifying emerging vulnerabilities and supporting more informed decision-making in mineral governance, infrastructure planning, and supply chain management.

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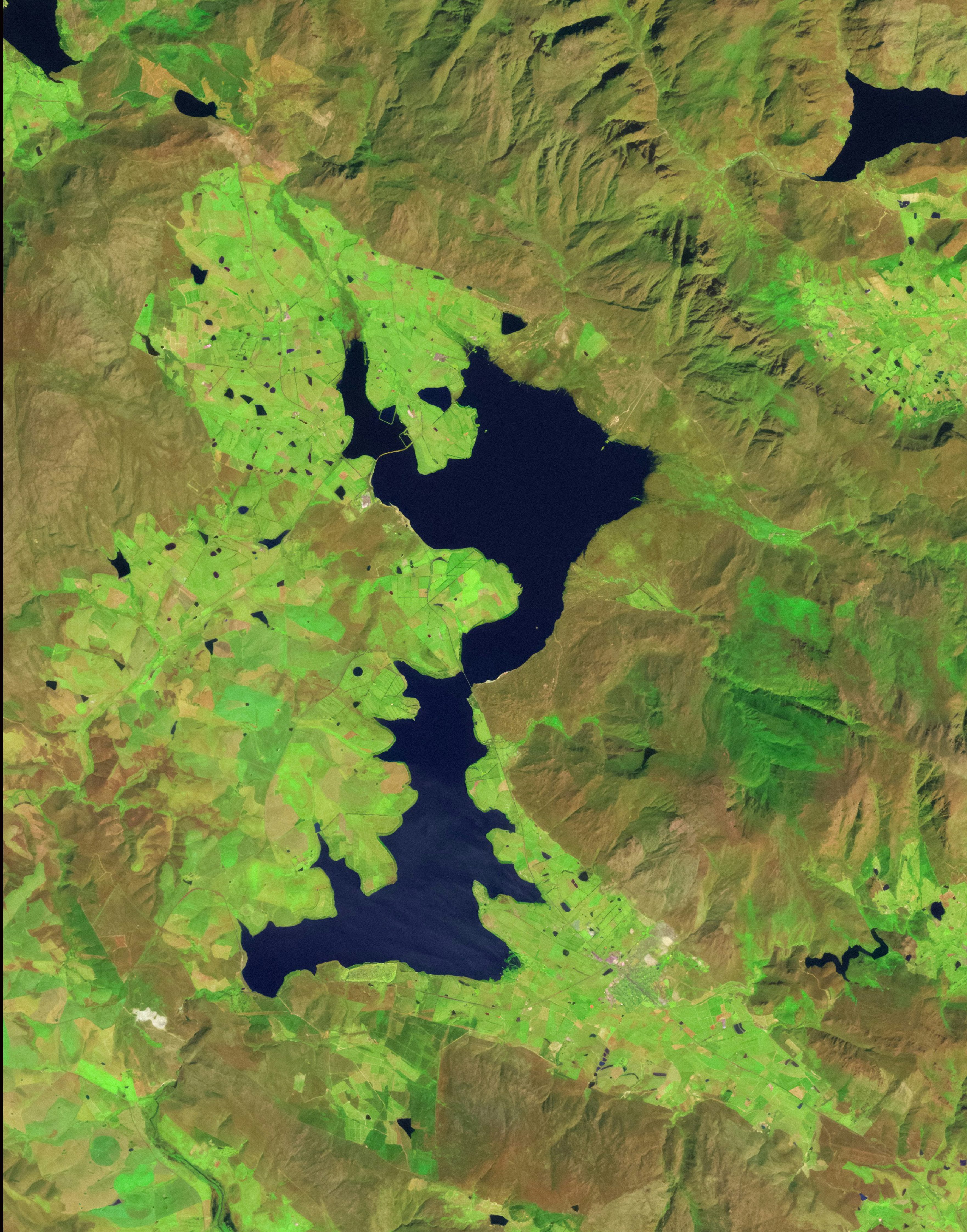

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Annex A: Supporting Figures for the Geospatial Monitoring Framework

This annex provides additional figures supporting the geospatial monitoring framework presented in the main text. These figures illustrate methodological components and regional case studies that complement the analyses discussed in Section 2. Together, they demonstrate how satellite monitoring, spatial ESG indicators, transport network modelling, displacement data, and regional thematic mapping can be combined to analyse critical mineral supply chains across multiple spatial scales.

A1 Long-term Landsat-based mine monitoring

Long-term mine expansion can be assessed using Landsat imagery. Figure 4 shows the results of unsupervised land-use classification distinguishing mine and non-mine areas at Kansanshi copper mine.

FIGURE 4

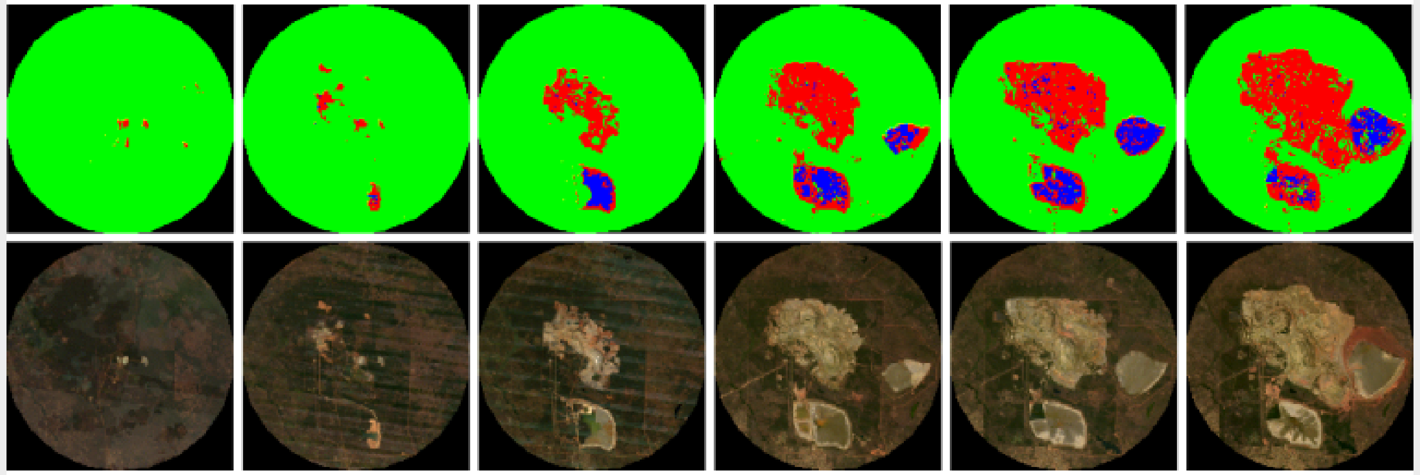


FIGURE 4: LONG-TERM LAND-USE CLASSIFICATION FOR KANSANSHI MINE USING LANDSAT IMAGERY. THE TOP ROW SHOWS MINE/NON-MINE CLASSIFICATION RESULTS, WHILE THE BOTTOM ROW SHOWS THE CORRESPONDING RGB IMAGERY. THE ANALYSIS COVERS THE PERIOD 2000–2025 AT FIVE-YEAR INTERVALS.

In this analysis, mine areas include open pits, waste dumps, and tailings or water ponds associated with mining operations. The classification results illustrate the progressive expansion of mining areas over the past two decades. The same methodology was applied to multiple copper mines in Zambia to assess long-term mining dynamics.

A2 Spatial ESG indicator methodology

Spatial ESG indicators were calculated using publicly available geospatial datasets. Figure 5 illustrates the methodology used to compute these indicators around mining sites.

FIGURE 5

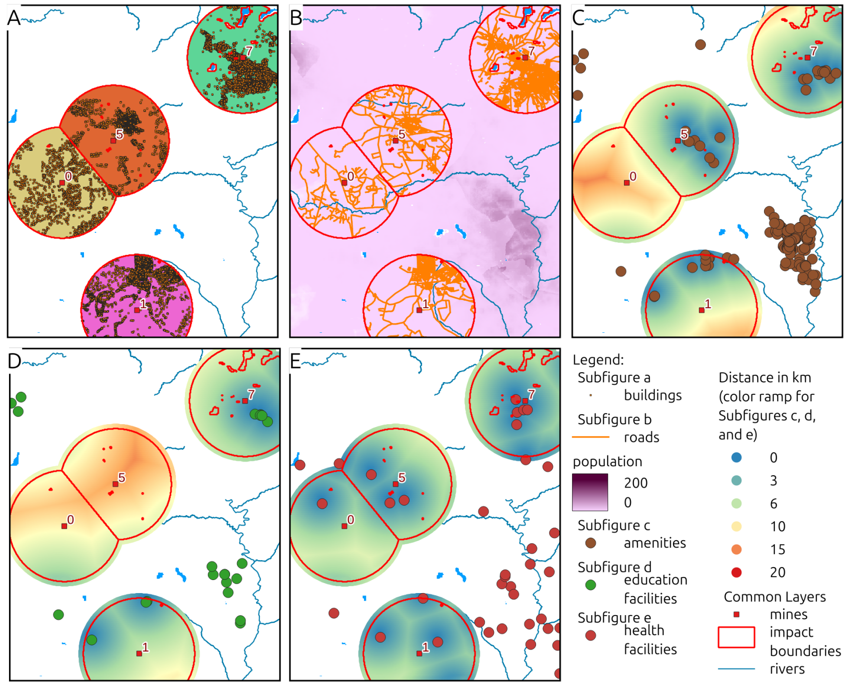


FIGURE 5: METHODOLOGICAL FRAMEWORK FOR CALCULATING SPATIAL ESG INDICATORS AROUND MINING SITES. RED SQUARES INDICATE MINE LOCATIONS AND RED OUTLINES REPRESENT LOCAL IMPACT AREAS (LIAS), DEFINED AS 10 KM BUFFERS AROUND MINE CENTRES.

Each mine is associated with a Local Impact Area (LIA), defined as a 10 km buffer around the mine centre. Within this zone, multiple spatial indicators are calculated, including building density, road network density, and distances to key services such as education facilities, healthcare facilities, and other amenities. These indicators provide a spatially explicit framework for identifying mines with potentially higher environmental and social exposure.

A3 Displacement-informed transport vulnerability analysis

Internal displacement data were incorporated into transport network analysis as a proxy for disruption risk. Figure 6 illustrates the resulting vulnerability analysis for the Zimbabwe–Malawi–Mozambique region [12].

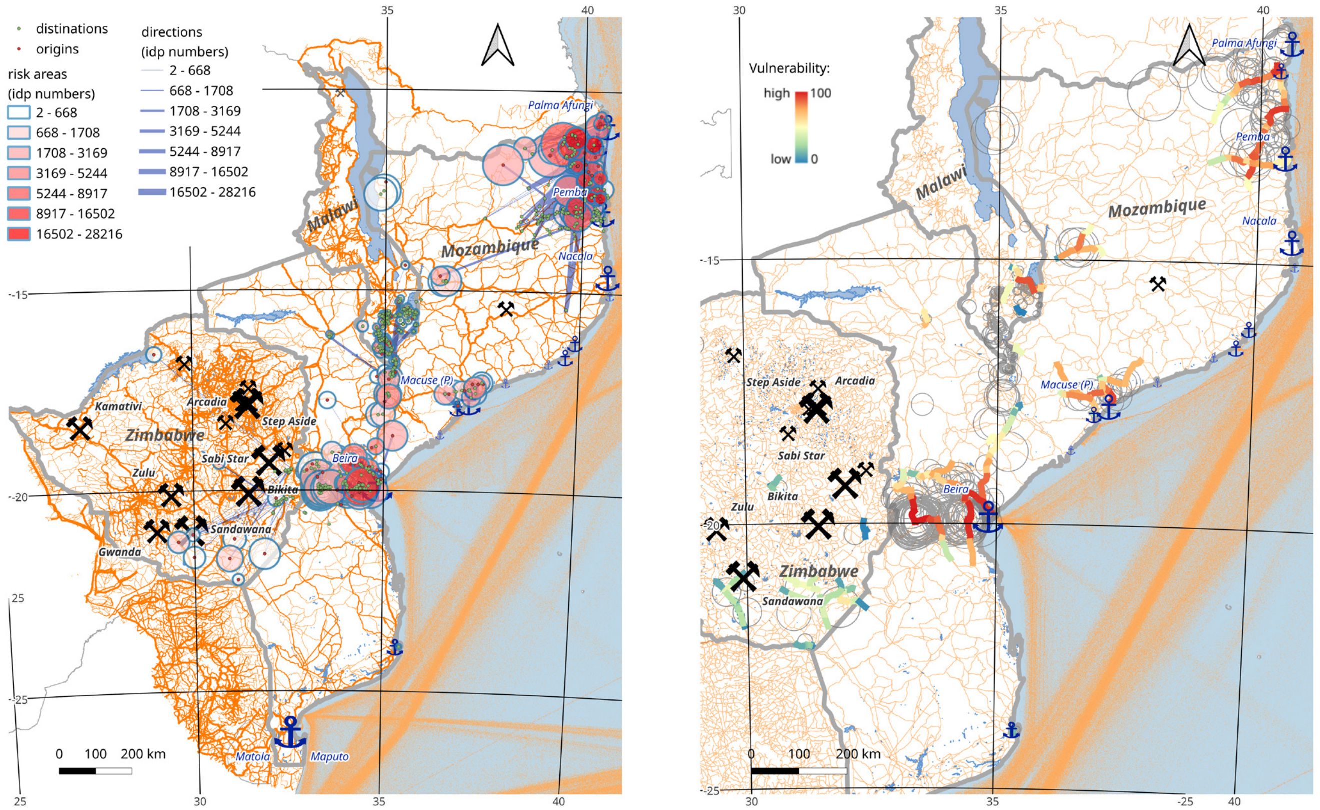
Historical displacement records associated with both natural disasters and conflict were integrated with transport network analysis to identify vulnerable infrastructure segments. Combining displacement data with network criticality metrics allows strategically important road segments exposed to disruption risk to be identified. High-resolution satellite imagery can then be used to investigate specific disruption events. Using this workflow, flooded road segments near the port of Beira were detected with daily temporal precision.

A4 National-scale geographic context mapping

National-scale thematic maps provide geographic context for mining systems and infrastructure networks. Figure 7 presents examples for Vietnam.

These maps integrate multiple spatial datasets including mines, transport infrastructure, population density, and administrative boundaries. Such contextual maps support high-level mineral policy analysis by placing mining activities within their broader geographic and infrastructure environment.

FIGURE 6

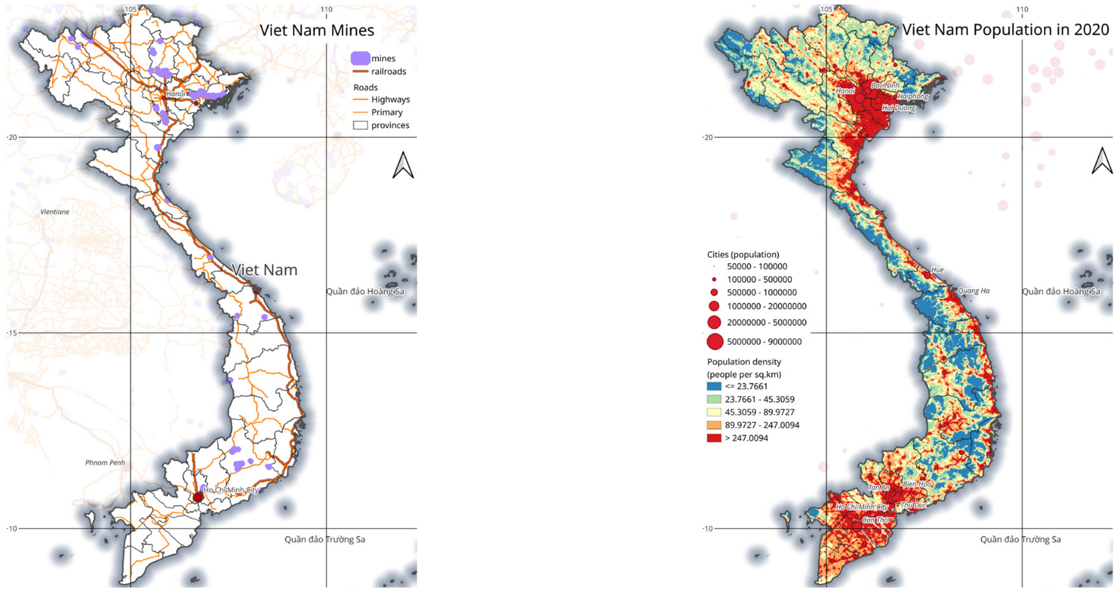


(A) LITHIUM MINES, PORTS, ROADS, AND INTERNAL DIS-

(B) ROAD SEGMENT VULNERABILITY BASED ON NETWORK PLACEMENT EVENTS. CRITICALITY AND DISPLACEMENT RISK.

FIGURE 6: TRANSPORT VULNERABILITY ASSESSMENT USING DISPLACEMENT DATA AS A PROXY FOR SUPPLY CHAIN DISRUPTION RISK.

FIGURE 7



(A) MINES, TRANSPORT ROUTES, ADMINISTRATIVE BOUND-

(B) POPULATION DENSITY AND MAJOR CITIES. ARIES, AND MAJOR CITIES IN VIETNAM.

FIGURE 7: MULTI-THEMATIC GEOGRAPHIC CONTEXT MAPS FOR VIETNAM USING UPDATED ADMINISTRATIVE BOUNDARIES AND ISLAND GROUP GEOMETRIES PROVIDED BY VIETNAMESE PARTNERS.

A5 Regional infrastructure context

Regional thematic maps provide broader infrastructure context across Southeast Asia. Figure 8 presents the regional transport network across ASEAN countries [4].

The ASEAN transport map integrates multiple spatial datasets to illustrate regional connectivity and infrastructure distribution. Such regional perspectives help contextualise national mining supply chains and transport corridors within broader economic and geographic systems.

FIGURE 8

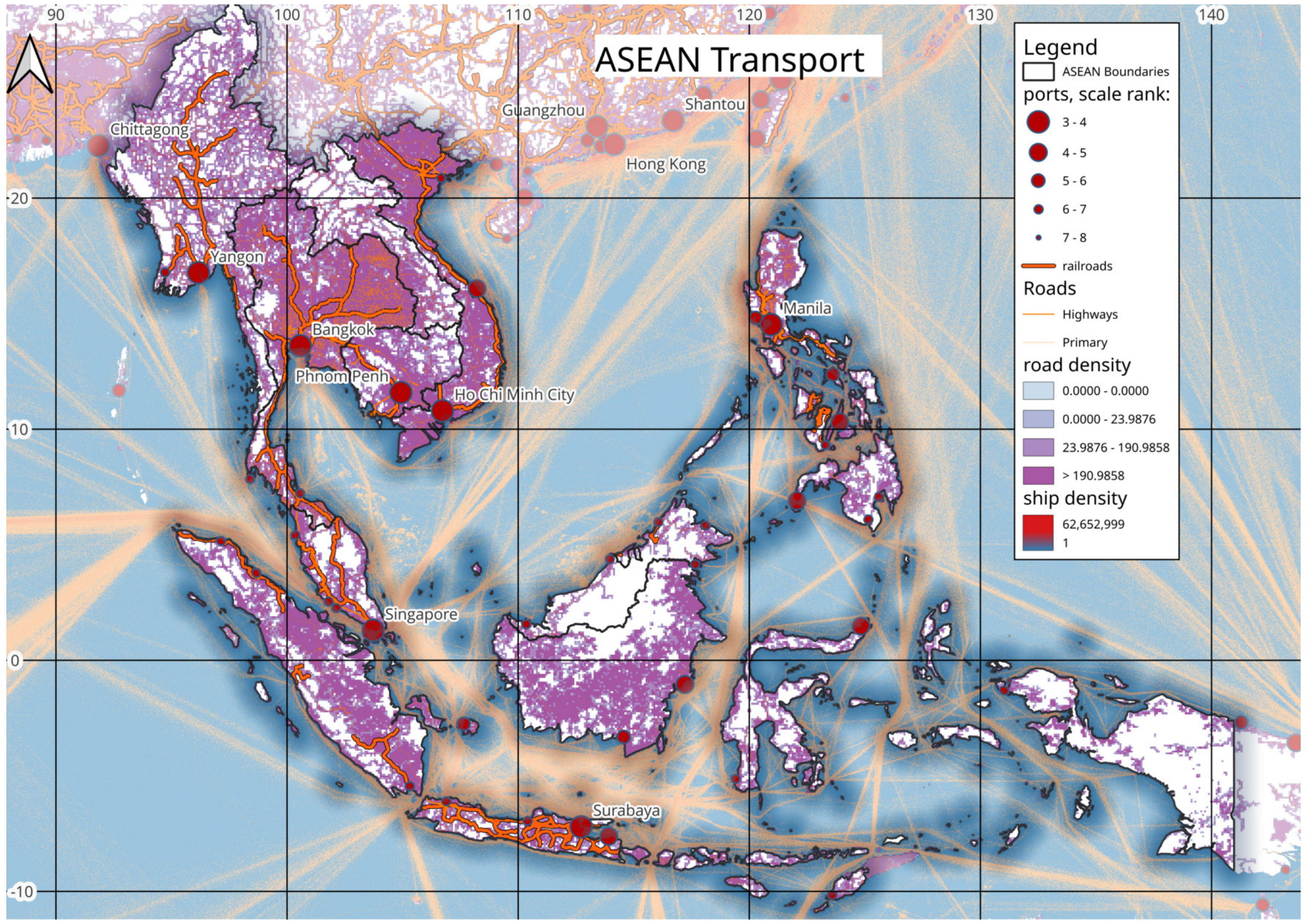


FIGURE 8: REGIONAL TRANSPORT INFRASTRUCTURE ACROSS ASEAN COUNTRIES, INCLUDING ROAD DENSITY, SHIPPING DENSITY, RAILWAYS, MAJOR ROADS, COUNTRY BOUNDARIES, AND MAJOR CITIES.

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WHO WE ARE

CAMBRIDGE CRITICAL MATERIALS LAB

We believe the energy transition must be equitable and inclusive. That means mineral-rich countries and their communities should benefit fully from their resources. By co-creating information platforms, producing rigorous research, and building tools for better decision-making, we work to strengthen equity in how critical materials are used to ensure no one is left behind.

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HOW WE WORK

We combine independent, interdisciplinary research with close collaboration across the Global South to ensure mineral governance is technically sound, socially just, and climate-compatible. By integrating engineering, policy, and social sciences, we create actionable insights that empower governments and communities to defend their rights, advance their interests, and navigate the complex environmental, social, and economic challenges of the energy transition.

OUR TEAM

Blending engineering, policy, and social sciences, our team finds innovative solutions to complex challenges.