AI and Drone-Based Monitoring in Mining: Redefining Environmental Baselines, Plantation Strategy, and Post-Closure Accountability

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ABSTRACT

Mining and associated activities are pivotal in India's economic development, contributing over 2.5% to the national GDP and employing approximately 11 million people. However, Environmental degradation from mining has resulted in substantial ecosystem loss all over India. Between 1994 and 2022, India’s eastern coal belt witnessed a 7.3–17.6% loss in forest cover, a 5–10% reduction in water bodies, and a 3–5% drop in agricultural land. From 1991 to 2021, vegetation cover in mining zones declined from 40.17% to 31.20%, while mining land expanded to 9% of the regional footprint. As a result of this, mining PSUs have set a target of planting 60–75 million trees across 24,000–30,000 hectares by 2030.

This paper explores current practices and possible interventions across three critical environmental dimensions of mining: (a) baseline environmental data collection during new mine allocations, (b) site selection strategies for ecological rehabilitation, and (c) mechanisms for Monitoring, Reporting, and Verification (MRV) during operations and post-closure phases. The analysis draws from MoEF and IBM guidelines, global standards such as the IEEE for EIA, and insights from green cover data and land-use change assessments using Aereo, a GIS and AI native solution, which automates data ingestion, orthomosaic, LULC, drainages analysis, canopy cover, afforestation area and change detections - replacing manual, error-prone methods with fast, scalable, and auditable insights with harvesting power of AI. The study concludes by advocating the institutional adoption of AI-integrated MRV frameworks, real-time plantation validation, and centralized data repositories within India’s mining regulations.

1.0 INTRODUCTION

India's mines covers varied geographical areas across multiple geological setting, in key mineral-rich states like Jharkhand, Chhattisgarh, Odisha, Karnataka, Rajasthan, and Goa. The operations of these mines are quite large in scale, ranging from small-scale, traditional mines with the utilization of locals to large-scale, mechanized mines with the use of advanced technology and machinery. The mining sector is a major contributor to the Indian economic system, contributing about 2.5% of the country's GDP. Additionally, it is a major source of employment, sustaining the livelihood of millions directly and indirectly (Indian Bureau of Mines, 2023).

The future of India's mining sector is bright. The government is encouraging the auction of more than 500 discovered mineral blocks, including the country's major and the green initiative minerals like lithium, cobalt, and nickel. These minerals are critical to the country's energy transition and tech-driven economic growth (Ministry of Mines, 2023). To speed up the release of mining projects, the government has offered several measures. These are a single-window clearance system, digital land record management systems, and quick environmental and forest clearances. These reforms are aimed at minimizing delays and maximizing transparency (Ministry of Environment, Forest and Climate Change, 2023). These measures are likely to attract more investment, allow sustainable growth, and greatly enhance India's mining output in the coming decades.

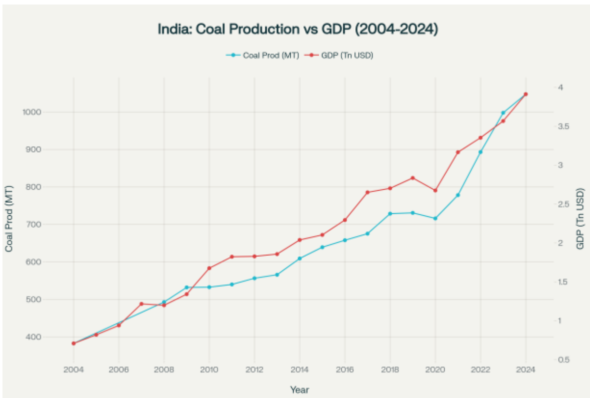

Figure 1: Coal Production VS GDP of India from 2004 to 2024 (Sources: Ministry of Coal: Production and Supplies; Ministry of Coal: Statistical Report)

The relationship between mining and the environment is complex, involving critical stages from initial baseline environmental studies through ongoing operations to reclamation and final closure. Baseline studies play a crucial role by establishing the initial environmental conditions of a site, providing essential benchmarks against which all future impacts can be measured and managed. Despite stringent regulatory safeguards designed to mitigate environmental harm, mining activities typically lead to significant ecological consequences such as deforestation, habitat destruction, water and air pollution, soil erosion, biodiversity loss, and land degradation. These environmental concerns often result in significant project delays or complete stalls, particularly when there are conflicts regarding the credibility or comprehensiveness of baseline environmental assessments. Additionally, the rigorous demands of continuous environmental monitoring, reporting, and validation place substantial burdens on mining companies and regulatory authorities alike. Any failures in these areas can exacerbate ecological damage, undermine public trust, and result in costly legal and operational consequences.

The global outlook on mining is increasingly shaped by ESG (Environmental, Social, and Governance) and compliance priorities, with sustainability and decarbonization now central to corporate strategies. According to McKinsey, mining companies are under growing pressure to create "zero-carbon mines," aligning with climate goals and societal expectations for greener operations. Similarly, EY's 2025 risk and opportunity report highlights how ESG-linked issues—such as environmental stewardship, license to operate, and climate change—consistently rank at the top of board-level agendas. Capital access is now tied to sustainability performance, and companies recognize that long-term competitiveness hinges on balancing growth with responsible resource use, stakeholder trust, and regulatory alignment. In essence, mining's global future is one where ESG commitments are no longer optional but a defining factor of operational success and risk management.

2.0 METHODOLOGY

2.1 Environment Orientated Process in Mining Value Chain

During the inception of a new mining site, conducting comprehensive baseline studies is crucial. In India, baseline environmental studies form the foundation for Environmental Impact Assessments (EIA), mandated under the Environment (Protection) Act, 1986, and the EIA Notification, 2006. These studies involve systematic data collection on existing conditions such as air and water quality, biodiversity, soil characteristics, socio-economic parameters, and land use patterns. The EIA process typically includes screening, scoping, data collection through baseline studies, impact prediction, mitigation planning, and public consultation before obtaining environmental clearances from the Ministry of Environment, Forest and Climate Change (MoEFCC). Despite their importance, baseline studies in India often encounter several challenges. These include limited availability of historical environmental data, inconsistencies in data collection methodologies, and insufficient expertise or resources among smaller mining companies conducting these studies. Additionally, there may be disputes related to the accuracy, transparency, or perceived biases of the studies, which can cause delays or rejections during the clearance process. The complex regulatory environment, coupled with stakeholder conflicts and administrative inefficiencies, further complicates and prolongs the inception stage of mining projects in India.

2.2 Planning for Afforestation Activities during Mining Operational and Reclamation Stage

Planning for afforestation activities during mining operational and reclamation stages is an integral part of sustainable mining practices in India, guided by stringent regulatory frameworks including the Forest (Conservation) Act, 1980, and the guidelines provided by the Ministry of Environment, Forest and Climate Change (MoEFCC). Mining companies are required to develop and adhere to comprehensive afforestation and reclamation plans approved by respective regulatory authorities, specifying clear commitments regarding species selection, area coverage, survival rates, and timelines for implementation. The standard process involves systematic identification of suitable land, preparation of nursery and plantation plans, species selection (preferably indigenous and ecologically compatible), plantation execution, and ongoing maintenance activities such as watering, weed control, and protection from grazing and fires. Monitoring of these activities typically involves periodic assessments conducted by both internal teams and external regulatory bodies, including state forest departments and environmental compliance committees, to ensure adherence to stipulated survival rates and ecological performance targets. Despite these well-defined procedures, several challenges persist, including difficulties in procuring suitable indigenous species, variability in soil and climatic conditions affecting plantation success, limited expertise in ecological restoration among some mining operators, and inadequate long-term maintenance and monitoring capabilities. These limitations sometimes result in lower-than-desired survival rates of planted saplings, reduced biodiversity recovery, and delays in ecological restoration, thus affecting overall environmental sustainability goals in mining operations.

2.3 Monitoring, Reporting and Verification of Environment Measures and Compliances.

Monitoring, Reporting, and Verification (MRV) of environmental measures and compliances is a critical component of mining governance in India, mandated under the Environmental Protection Act, Forest (Conservation) Act, Air and Water Acts, and governed by institutions such as the Ministry of Environment, Forest and Climate Change (MoEFCC), State Pollution Control Boards (SPCBs), and Central Ground Water Authority (CGWA). During active mining and reclamation phases, mining leaseholders are required to carry out regular monitoring of air and water quality, noise levels, biodiversity, soil stability, and afforestation progress using a combination of field sampling, remote sensing (e.g., drones and satellite imagery), and automated sensor-based tools. These observations feed into mandatory yearly submissions such as the Annual Environmental Statement (Form V), half-yearly EC/CTO compliance reports, groundwater monitoring returns, and afforestation survival rate assessments, which are uploaded to centralized portals like PARIVESH and submitted to regulatory bodies for verification. Compliance is further evaluated through periodic inspections, third-party audits, and cross-verification with baseline Environmental Impact Assessment (EIA) and Environmental Management Plan (EMP) data. Despite this structured framework, implementation faces several challenges including lack of skilled personnel, delays in regulatory processing, limited use of modern environmental monitoring technologies, and insufficient post-closure monitoring. Strengthening institutional capacity, encouraging digital MRV systems, and promoting proactive environmental stewardship among mining operators are essential to improving compliance outcomes and achieving sustainable mining goals in India.

3.0 INCORPORATION OF DRONE BASED SURVEY SYSTEMS

3.1 Evolution of Drone Based Survey and Application Programs

The inception of drones in India began with their initial adoption in defence and surveillance, gradually expanding into civilian domains as technology matured and regulatory clarity improved. The Directorate General of Civil Aviation (DGCA) has established comprehensive drone regulations under the Drone Rules, governing registration, operation, safety standards, and airspace management, while ensuring an enabling environment for industry growth. To further promote a robust drone ecosystem, the government has introduced various incentives, including the Production-Linked Incentive (PLI) scheme, which supports domestic manufacturing, research, and deployment of drones and their components. India’s rapidly evolving tech ecosystem has embraced the introduction of advanced survey-grade drones, equipped with high-precision GNSS (PPK/RTK) systems, aerial sensors, and extended flight endurance, tailored for professional geospatial mapping. These survey-grade drones are actively deployed in government initiatives such as Swamitva (for rural property mapping), Indian Bureau of Mines (IBM) surveys, Ministry of Environment, Forest and Climate Change (MoEF) projects, Ministry of Coal (MOC) assessments, and Large Scale Mapping (LSM) efforts, enabling high-accuracy data collection for land records, environmental monitoring, and mining regulation. Technically, survey-grade drones stand out for their higher payload, longer endurance (often exceeding 50min), centimeter-level positional accuracy, and integration with professional-quality cameras and LiDAR sensors, compared to consumer drones which are limited by basic GPS, reduced flight time, and lower data resolution. While consumer drones can suffice for simple visualization and hobby mapping, survey-grade drones are essential for statutory, large-area, and precision-driven projects critical to India’s sustainable development and regulatory compliance.

3.2 Processing of Drone Data for Generation of Basic Deliverables

Once drone data is captured over a mining area, the transformation from raw imagery into actionable geospatial products requires a carefully designed photogrammetric processing workflow. This process begins with importing the geo-tagged images along with positional corrections derived from GNSS logs, particularly when using PPK (Post-Processed Kinematics) or RTK (Real-Time Kinematics) enabled UAVs. Ground Control Points (GCPs), if available, are used to enhance absolute positional accuracy during alignment. Advanced software platforms apply Structure-from-Motion (SfM) algorithms to identify common features across overlapping images, triangulating their positions to generate a sparse point cloud. This is followed by dense matching techniques that build a high-resolution 3D point cloud, which is then filtered and classified to distinguish ground from non-ground features.

The result is a suite of foundational deliverables essential for mining workflows. These include orthomosaics (true-to-scale stitched images), Digital Surface Models (DSMs), and Digital Terrain Models (DTMs) that represent surface elevation and bare earth topography respectively. Contour maps are also extracted from DTMs to aid in drainage planning and slope classification. When overlaid with operational boundaries or compliance zones, these outputs enable automated volumetric estimations of overburden dumps, coal stockpiles, or excavation progress. The entire processing chain can now be performed in cloud-native platforms, drastically reducing turnaround times and facilitating seamless access across departments.

Drone-based surveying has been rigorously validated in peer-reviewed literature as a reliable scientific tool for topographic mapping, volumetric estimation, and infrastructure monitoring. In topographic survey applications, UAV photogrammetry—with carefully planned missions involving ≥70% forward and lateral image overlaps—can achieve centimeter-level accuracy (horizontal RMSE ≈ 0.087 m, vertical RMSE ≈ 0.177 m at 4 cm GSD), even in vegetated terrains by incorporating low-altitude oblique imagery to minimize vegetation-induced errors (Rusli et al., 2022). Volumetric estimations derived from drone photogrammetry have demonstrated high reliability, typically with errors below ±3%, comparable to traditional survey methods. For instance, quarry stockpile volume assessments using drones exhibited errors around 2.6%, closely matching traditional ground-based survey errors of approximately 1.3% (Xu et al., 2022). Additionally, studies employing low-cost drones (e.g., DJI Phantom series) have successfully reduced volumetric measurement errors to around 5% by optimizing image overlap (≥95%) and deploying at least four Ground Control Points (GCPs) (Yilmaz et al., 2018). Collectively, these studies indicate that drone-based photogrammetric methods, supported by precise GCP placement and meticulous flight planning, constitute a scientifically robust and effective approach for generating accurate orthomosaics, digital terrain models (DTMs), dimensional measurements, and volumetric assessments across various surveying applications.

3.3 General Application of Drone Based Deliverables

Drone-based surveys have revolutionized geospatial data acquisition, offering rapid, safe, and highly accurate deliverables across diverse applications. In topographic surveys, UAV photogrammetry produces detailed orthomosaics, Digital Surface Models (DSM), and contour maps with centimeter-level accuracy, making it invaluable for terrain analysis, planning, and environmental monitoring. The high resolution 3D models enable virtual inspection with close-range visual analysis of infrastructure, mining pits, dump slopes, and vegetation zones—minimizing human exposure to hazardous or inaccessible areas while ensuring high-resolution documentation Drones also support precise measurements of distances, areas, and features such as benches, haul roads, or vegetation patches, streamlining fieldwork and post-processing. For volumetric estimation, drone imagery processed via Structure-from-Motion (SfM) techniques allows accurate quantification of stockpiles, excavation volumes, and overburden dumps, with errors typically within 3–5% when properly georeferenced. These capabilities make drone surveys an essential tool in sectors such as mining, construction, forestry, and infrastructure development.

3.4 Advanced Drone Based Analytics for Environment Management at Mining Sites

.The integration of high-resolution unmanned aerial systems (UAS) with geospatial analytics has transformed environmental monitoring in mining domains. Recent advancements in drone technology—including real-time kinematic (RTK) and post-processed kinematic (PPK) GNSS positioning, multispectral and RGB imaging, and autonomous flight systems—have facilitated large-scale spatial data acquisition with centimeter-level accuracy. These technologies enable the systematic automation of traditionally manual geographic information system (GIS) workflows through photogrammetric reconstruction, terrain modelling, and feature extraction.

The deployment of cloud-native AI engines represents a critical evolution in the post-processing of drone-derived geospatial data. These platforms support high-performance rendering, vectorization, and analytics directly within a web-accessible interface, removing the dependency on traditional desktop GIS infrastructure.

Such systems are designed to handle terabyte-scale orthophotos, digital terrain models (DTM), and vegetation indices while offering automated layer generation, version control, and batch export functionalities. Importantly, cloud-based architectures enable task-specific access through role-based controls and ensure compliance with data governance frameworks such as ISO 27001 and MEITY cloud hosting standards. The integration of cloud processing significantly reduces turnaround time for geospatial deliverables and enhances inter-departmental access to synchronized, audit-ready datasets.

- Device-agnostic access to orthomosaics, terrain models, and vector overlays
- Instant generation of exportable formats (SHP, KML, DXF, PDF)
- Automated alerts for environmental non-compliance or vegetation loss

3.5 Use of AI/ML for Data Quality Control (QC)

Artificial intelligence (AI) and machine learning (ML) algorithms are increasingly embedded in drone survey pipelines to perform real-time data quality assessment. These models utilize supervised and unsupervised learning techniques to evaluate imagery quality, detect anomalies in spatial geometry, and validate georeferencing accuracy.

Key applications include:

- Pixel-level analysis for blur and exposure anomalies
- Geospatial residual checks against control points using error propagation models
- Point cloud density validation for DSM/DTM consistency

Automated QC processes ensure that input data meets predefined thresholds for spatial accuracy, spectral fidelity, and completeness. This quality assurance framework reduces the need for manual inspection and forms the foundation for reliable downstream analytics.

3.6 Use of AI/ML for Data Interpretation and Automation of Manual GIS Workflows

The application of artificial intelligence (AI) and machine learning (ML) in environmental geospatial analysis offers significant advancements in automating manual GIS workflows. These intelligent systems enhance accuracy, reduce manual effort, and enable high-frequency monitoring across large mining landscapes. Key implementations include:

1. Tree Count Detection

- **Objective:** Quantify individual trees for plantation monitoring and afforestation audits.
- **Methodology:**
    - o Use of high-resolution orthomosaics (≤10 cm GSD).
    - o Application of convolutional neural networks (CNNs) to detect tree crowns via image segmentation.
    - o Centroid-based quantification for total count.

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- **Outcome:**
  - Enables accurate, large-scale assessment of tree survival rates.
  - Supports vegetation inventory for ecological restoration and compensatory afforestation.

2. Water Body Identification

- Objective: Detect and classify stagnant and flowing water bodies, including ephemeral features.
- **Methodology:**
  - Application of AI classifiers on spectral and topographic signatures.
  - Integration of hydrological modeling using DSM/DTM-derived depression analysis.
  - Use of temporal change detection (pre- vs. post-monsoon surveys) for seasonal mapping.
- **Outcome:**
  - Accurate identification of water bodies and flood-prone zones.
  - Supports drainage design, waterlogging risk mitigation, and monsoon planning.

3. Canopy Cover Identification

- **Objective:** Estimate and classify vegetation canopy cover for ecological compliance and reporting.
- **Methodology:**
  - Use of NDVI/VARI indices for spectral classification of green cover.
  - DSM-DTM subtraction to extract vertical canopy structure.
- Deep learning models classify canopy into threshold-based categories:
  - Dense Forest: >40% canopy density
  - Open Forest: 10–40% canopy
  - Scrub: <10% canopy
  - Bare Soil / Reclaimed Land: 0% canopy
- **Outcome:**
  - Provides quantifiable canopy maps for FC/EC (Forest/Environmental Clearance) reporting.
  - Supports mine closure planning and long-term land-use restoration evaluation.

3.7 Integrated Benefits of AI/ML-Driven GIS Automation

- Replaces Manual GIS Digitization: Enables faster and more consistent feature extraction compared to manual vector drawing.
- Improves Accuracy and Repeatability: AI ensures uniform classification logic across large spatial extents and time series datasets.
- Enhances Decision-Making: Outputs feed into compliance dashboards, vegetation health monitoring systems, and regulatory submissions.
- Supports Audit-Ready Documentation: Generates traceable, reproducible data products aligned with regulatory formats (e.g., DGMS, MoEF&CC).

3.8 Application of Drone Data for Different Stages of Mining Process.

High-resolution drone surveys and geospatial analysis have become foundational tools for conducting baseline studies in mining regions, particularly during the exploration phase and prior to Environmental Impact Assessment (EIA) submissions. By generating accurate orthomosaics, terrain models, and land use classifications, these technologies establish a robust spatial baseline for regulatory documentation and facilitate informed decision-making in early-stage project development. The availability of high-resolution data ensures precise delineation of existing vegetation, drainage patterns, and anthropogenic features, thus supporting comprehensive environmental assessments.

In the context of afforestation planning, drone-derived datasets are used to identify ecologically and topographically suitable zones for plantation activities. Through canopy analysis, slope modeling, and surface roughness detection, these platforms guide the spatial allocation of plantation blocks, optimize tree spacing, and assist in the development of micro-watershed-based green cover strategies. Remote sensing indices such as NDVI and VARI are further employed to characterize vegetation health and prioritize intervention zones based on degradation levels.

Monitoring and validation of afforestation work are operationalized through periodic drone flights and AI-based feature detection algorithms. These systems enable automated tree counting, canopy change detection, and spatial verification of planted zones against approved plans. By quantifying vegetative growth and survivability, stakeholders can validate afforestation outcomes, ensure compliance with compensatory afforestation mandates, and generate audit-ready reports for forest and environmental authorities.

Reclamation planning is similarly enhanced through the use of digital terrain models and slope analytics. Reclaimed landforms—such as overburden dumps, benches, and slope profiles—are designed using GIS-based interpretations of elevation, runoff potential, and soil drainage. The ability to simulate post-mining landform stability and optimize drainage pathways contributes to sustainable closure planning and alignment with mine closure guidelines under regulatory frameworks.

Progress monitoring of reclamation work is achieved through time-series analysis of orthophotos and elevation datasets. These outputs allow for quantitative assessment of backfilling activities, slope reformation, and vegetation regeneration over time. By comparing surveyed surfaces with designed reclamation models, project teams can evaluate the pace and quality of ecological restoration, ensuring that land use transitions meet intended post-mining land utility objectives.

Finally, surface runoff and contamination control are managed through hydrological modeling integrated with drone-derived elevation maps. These analyses identify natural flow paths, potential erosion zones, and sedimentation hotspots, facilitating the design of functional drainage and containment systems. Predictive modeling of surface water dynamics also supports proactive interventions to prevent waterlogging, mitigate contaminant leachate spread, and ensure environmental protection of downstream ecosystems.

4.0 CASE STUDY

Site: An Open Cast Coal Mining Project, Northern Coalfield Limited, Singrauli, Madhya Pradesh.

The Opencast Coal Mine, operated by Northern Coalfields Limited (a subsidiary of Coal India Limited), is among the most productive and advanced coal mining projects in India. Located in the Singrauli district of Madhya Pradesh, the mine spans over 3,000 hectares and has an approved capacity of 22.5 million tonnes per annum (MTPA). It is rich in thermal coal reserves (~504 million tonnes), with a well-developed infrastructure including draglines, high-capacity dumpers, and integrated conveyor and rail-based dispatch systems. The mine plays a vital role in supporting nearby power plants, especially NTPC' Super Thermal Power Station.

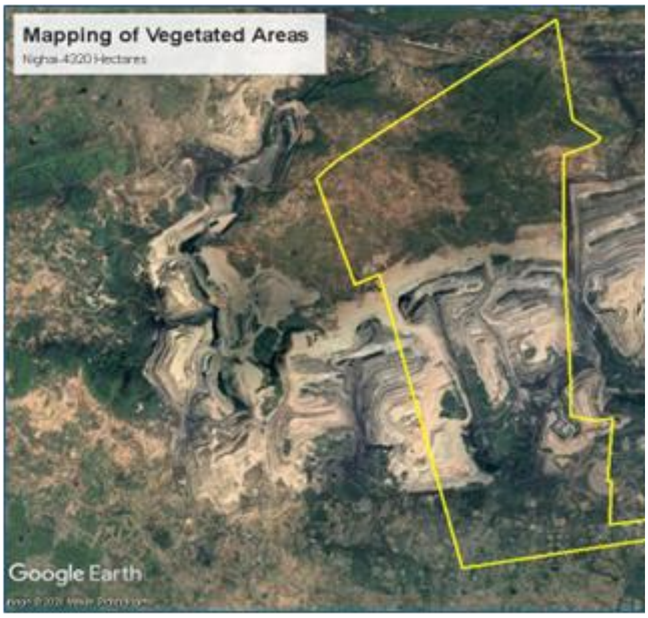


Figure 2: Lease Area of Opencast Coal Mine

The Opencast Coal Mine has adopted structured environmental management practices to address the ecological sensitivity of the region. More than 2,300 hectares have been afforested, over 7 million saplings planted, and mine water is largely reused or recycled. Post-mining land use planning includes water body creation and greenbelt development, aiming for long-term ecological stability. The mine reflects a balance between energy production and environmental responsibility, contributing significantly to the region's economy and energy security.

4.1 Drone Model and Specification

Fig 3: Aereo INP Drone designed and manufactured by Aarav Unmanned Systems, Bangalore

Details	**Parameter**
Operation Capability	Full Autonomous
Weight	3.3 Kg
Endurance	>40 Mins
GPS Correction Technology implemented	Post Processing Kinematics (OnBoard PPK)
Payload (RGB Camera)	APSC CMOS Sensor 24 MP

Table 1: Drone Specifications

4.2 Software Model and Specification

Component	Description
Platform Name	Aereo Cloud
Developer	Aereo (formerly Aarav Unmanned Systems Pvt. Ltd.)
Overview	A MEITY-compliant, web-based cloud platform for drone data processing, visualization, and analytics in mining and infrastructure domains.
Core Purpose	To enable faster decision-making, plan execution tracking, and real-time monitoring using high-resolution drone survey data.
Visualization Features	- 2D/3D data views (orthomosaics, DSM, DTM, contours) - Bench toe/crest tracking - Slope and haul road analysis
Analytics Capabilities	- ML-driven deviation detection - Volume computations (OB, coal, dump, stockpile) - Change detection - Safety compliance metrics
Dashboard Functionalities	- Department-wise dashboards for Planning, Production, Safety, Environment, Land, and Leadership - KPI tracking and alerts
Data Access	- Real-time, cloud-based access - Role-based user permissions - Support for multiple stakeholders and devices
System Integration	Integrates with mine planning tools (Minex, AutoCAD), ERP, GIS, and FMS platforms
Scalability	- 1,000,000+ hectares processed/month - 960+ mines and 1,200+ stockyards served
Turnaround Time	Typically 48–72 hours from flight to final report

Table 2: Overview of data processing and capabilities of software used

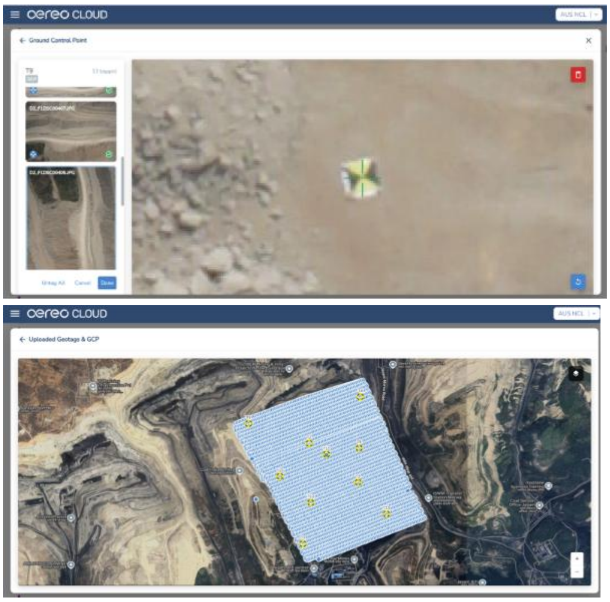


Figure 4: Screengrabs of Processing module, GCP Marking, Geotags etc

4.3 Process Followed

The entire aerial survey exercise is systematically divided into four key stages—Planning, Capturing, Processing, and Analysis & Report Preparation—ensuring accuracy, consistency, and operational efficiency across mining use cases.

Figure 5: Overall workflow

Phase	Description
Planning	AOI Finalization: The Area of Interest (AOI) was delineated using Google Earth. - Ground Reconnaissance: Site visits were conducted to understand terrain, accessibility, and risks. - Flight Planning: UAV Ground Control Software was used to design flight grids with inputs such as GSD, front & side overlap, and flight direction.
Capturing	Site Setup: Optimal flight locations were selected considering safety and coverage. - Flight Execution: Multiple drone flights were conducted using PPK-enabled survey-grade UAVs. - Quality Checks: Post-flight validation

	of images, PPK logs, and base station data ensured high data fidelity.
Processing	Photogrammetric Processing: Raw drone data including images, PPK logs, and GCP values were processed in specialized software. - Outputs Generated: • Orthomosaics (GeoTIFF) • 3D Point Cloud (LAS/LAZ) • Digital Terrain Models (DTM/DSM)
Analysis & Reporting	Data Utilization: Processed datasets were used for: • Volumetric Calculations (OB, dumps, stockpiles) • Slope and Stability Assessments • Vegetation & Canopy Mapping • Structure Digitization and UID tagging - Reporting: Analytical results and maps were compiled into structured reports and uploaded to Aereo Cloud for stakeholder access.

Table 3: Workflow adopted

4.4 Outputs generated

Category	Output Type	Format(s)
Geospatial Maps	Orthomosaic Map	GeoTIFF, PNG, JPEG
	Digital Terrain Model (DTM) / Digital Surface Model (DSM)	GeoTIFF
	Contour Map	DXF, DWG, SHP
	Slope Map	PDF, PNG, GeoTIFF
	Surface Plan (for statutory compliance)	DXF, DWG
3D Models	3D Georeferenced Point Cloud	LAS, LAZ
	3D Mesh Models (for visualization and inspection)	OBJ, STL, 3D PDF
Volumetric Analysis	Cut and Fill Volume Calculations	PDF, Excel, Web Dashboard
	OB, Coal, Dump Volume Reports	PDF, Excel
	Stockpile Inventory Reports	PDF, Excel

Table 4: Outputs generated

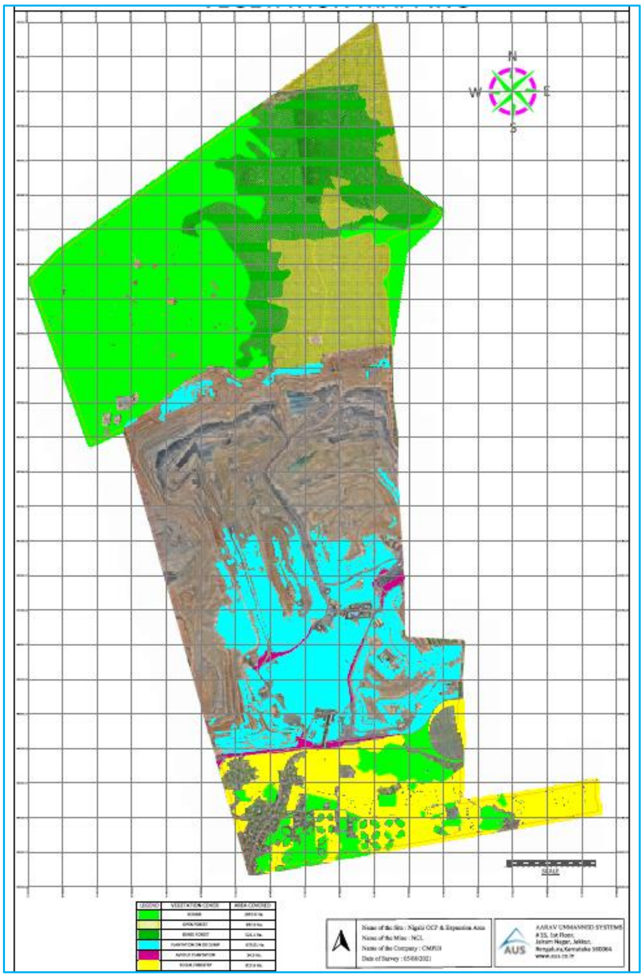
Environmental Use Case	**Output Type**	**Format(s)**	**Purpose**
Vegetation & Green Cover Mapping	- Classified canopy cover map - Plantation progress map	PDF, SHP, GeoTIFF	To monitor afforestation progress, OB dump greening, and compliance with mine closure plans
Drainage and Surface Runoff	- Drainage line map - Critical stream identification - Flow accumulation map	GeoTIFF, SHP, PDF	For monsoon preparedness, waterlogging prevention, and improving mine drainage infrastructure
Slope and Dump Stability	- Dump slope map - Mine-wide slope classification map	DXF, PDF, PNG	To assess slope safety, identify unstable zones, and comply with DGMS regulations
Land Use & Land Cover (LULC)	- LULC classification map - Change detection layers	SHP, GeoTIFF, PDF	To detect encroachments, monitor land use transitions, and support IBM submissions
Environmental Plan Overlay	- Overlay of environmental buffer zones and green areas on drone maps	DXF, PDF, Web Viewer	For compliance validation, planning of environmental buffer zones
Pre/Post-Monsoon Comparisons	- Wet season vs dry season surface comparison layers	PDF Reports, Web Visualization	To identify seasonal changes in vegetation and water pathways

Table 5: Environmental use cases and outputs generated

Figure 6: Entire Lease hold Orthomosiac of the AOI Generated

Figure 7: 3D Digital twin of the AOI

Figure 8: Canopy Cover map of the AOI



LEGEND	VEGETATION COVER	AREA COVERED
	SCRUBS	1057.6 Ha.
	OPEN FOREST	397.9 Ha.
	DENSE FOREST	521.1 Ha.
	PLANTATION ON OB DUMP	473.01 Ha.
	AVENUE PLANTATION	14.3 Ha.
	SOCIAL FORESTRY	317.3 Ha.

Figure 9: Vegetation Cover Map

Figure 10: Drainage Analysis

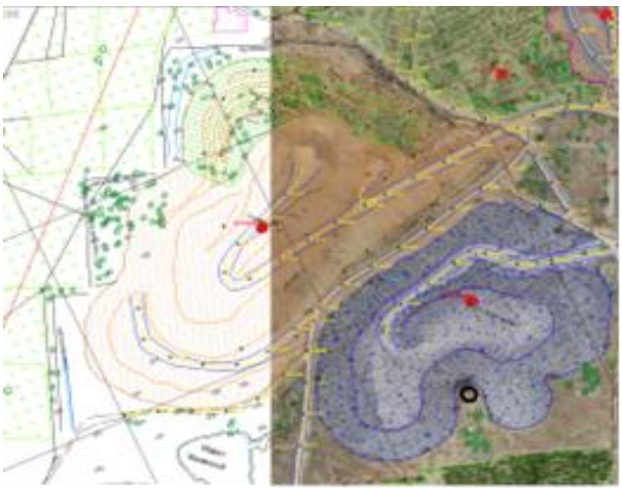


Figure 11: Land Use Land Cover Map

4.5 Validation of Vegetation Cover and Drainage Analysis Accuracy

The accuracy of drone-derived outputs for vegetation mapping and drainage assessment was validated using ground-truthing, spatial correlation techniques, and remote sensing benchmarks. The results substantiate the technical reliability and practical application of these layers for environmental monitoring and operational planning.

1. Vegetation Cover Mapping Accuracy

- **Methodology:** Drone-captured orthomosaics (3 cm/pixel GSD) were classified into vegetation types based on canopy density and spatial patterns, following Forest Survey of India (FSI) classification standards. Categories included: Dense Forest, Open Forest, Scrub, OB Plantation, Avenue Plantation, and Social Forestry.
- **Validation Techniques:**
  - Ground Truthing: 45 field reference plots were surveyed to validate vegetation class boundaries and patch accuracy.
  - Satellite Comparison: Vegetation maps derived from drones were cross-referenced with recent Sentinel-2 satellite imagery (10 m resolution). While satellite data provided broader canopy zones, drone data captured finer distinctions and accurately delineated smaller plantation clusters on OB dumps and internal roads.
- **Observed Accuracy:**
  - Overall classification accuracy: ~92.3%
  - Kappa coefficient: 0.87
  - Improvement over satellite-based detection: Drone data resolved ~25–30% more vegetation patches than satellite analysis, especially for patches <0.1 hectare.
- **Operational Impact:** Enabled precise reporting for green cover compliance, afforestation audits, and tracking vegetation progress on reclaimed land.

2. Drainage and Runoff Analysis Accuracy

- **Methodology**: High-resolution DTMs generated from drone data were used to derive hydrological layers like flow accumulation, stream networks, and water retention zones. Rainfall intensity data was incorporated to simulate runoff patterns.
- **Validation Techniques:**
  - On-Ground Verification: Critical drainage channels and low-lying accumulation areas identified in the analysis were verified by site teams.

  - Comparison with historical infrastructure maps: Helped identify missing or blocked drainage structures.
- **Observed Accuracy:**
  - Critical stream detection accuracy: >90%
  - Alignment deviation with ground flow: <5 m for major runoff paths
- **Operational Impact:** Data was adopted by monsoon preparedness teams across SECL and NCL to improve waterlogging prevention and update internal drainage infrastructure plans.

5.0 CONCLUSIONS

This study demonstrates that integrating drone-based aerial surveys with AI-powered analytics presents a transformative leap in how mining operations manage environmental responsibilities—from baseline assessments to post-closure compliance. By capturing centimeter-level terrain data, automating critical GIS workflows, and offering rapid, repeatable, and audit-ready outputs, drone-based solutions address many of the long-standing challenges in mining governance: accuracy of environmental data, timeliness of monitoring, and transparency of reporting.

The results from the case study affirm the high reliability of drone-derived datasets for vegetation classification (92.3% accuracy), drainage analysis (>90% stream detection), and volumetric estimation (within ±1.5% deviation). Compared to traditional or satellite methods, drones offer unmatched resolution, coverage efficiency, and operational safety—enabling environmental planning that is not only compliant but proactive and predictive.

Looking ahead, the institutionalization of such technologies—through centralized cloud platforms like Aereo Cloud, integration with ERP and GIS systems, and alignment with IBM, DGMS, and MoEFCC guidelines—can pave the way for a digital-first environmental governance framework. To unlock its full potential, mining agencies and regulators must invest in:

- Establishing AI-integrated MRV systems at scale;
- Enabling capacity building across mine-level and headquarters teams;
- Promoting standardized drone data usage in EC, FC, and EMP workflows;
- Strengthening post-closure monitoring through automated analytics.

By adopting these digital innovations, India's mining sector can lead globally in demonstrating that growth and environmental stewardship are not mutually exclusive—but inherently complementary.

6.0 REFERENCES

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7.0 APPENDIX

Abbreviation	Full Form
AI	Artificial Intelligence
ML	Machine Learning
GIS	Geographic Information System
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
GNSS	Global Navigation Satellite System
PPK	Post-Processed Kinematics
RTK	Real-Time Kinematics
GSD	Ground Sampling Distance
DSM	Digital Surface Model
DTM	Digital Terrain Model
SfM	Structure from Motion
GCP	Ground Control Point
RMSE	Root Mean Square Error
NDVI	Normalized Difference Vegetation Index
VARI	Visible Atmospherically Resistant Index
OB	Overburden
CTO	Consent to Operate
EC	Environmental Clearance
FC	Forest Clearance
EMP	Environmental Management Plan
EIA	Environmental Impact Assessment
LULC	Land Use and Land Cover
DGCA	Directorate General of Civil Aviation
MoEFCC / MoEF&CC	Ministry of Environment, Forest and Climate Change
SPCB	State Pollution Control Board
CGWA	Central Ground Water Authority
IBM	Indian Bureau of Mines
DGMS	Directorate General of Mines Safety
MOC	Ministry of Coal
LSM	Large Scale Mapping
PLI	Production Linked Incentive
MRV	Monitoring, Reporting, and Verification
UID	Unique Identification
SHP	Shapefile (GIS format)
DXF	Drawing Exchange Format
DWG	Drawing (AutoCAD) Format
KML	Keyhole Markup Language
PDF	Portable Document Format
LAS / LAZ	LiDAR Point Cloud Format (Uncompressed / Compressed)
OBJ	3D Object File Format
STL	Stereolithography File Format
MEITY	Ministry of Electronics and Information Technology
PARIVESH	Pro Active Responsive facilitation by Interactive and Virtuous Environmental Single-window Hub
NTPC	National Thermal Power Corporation
ERP	Enterprise Resource Planning
FMS	Fleet Management System
APSC	Advanced Photo System type-C (sensor format)
CMOS	Complementary Metal-Oxide Semiconductor (image sensor type)
MTPA	Million Tonnes Per Annum
AOI	Area of Interest
RGB	Red Green Blue (image channel combination)
3D	Three-Dimensional
ISO 27001	International Standard for Information Security Management