Integrating UAV Photogrammetry and Multispectral Remote Sensing for High-Resolution Topographic Mapping, Land Cover Characterisation, and Solar PV Site Suitability in Kariba, Zimbabwe

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Key words: UAV Photogrammetry, Multispectral Remote Sensing, DEM, Land Cover Classification, Solar PV Siting

Summary

Accurate topographic mapping and up-to-date land cover information are central to environmentally responsible infrastructure planning yet in many African countries the cost and limited availability of high-resolution geospatial data constrain decision-making (Woldai, 2002). This paper presents an integrated methodological framework that combines Unmanned Aerial Vehicle (UAV) photogrammetry and multispectral satellite remote sensing to support high-resolution terrain modelling, land cover mapping and solar photovoltaic (PV) site suitability assessment in Kariba, Zimbabwe. Kariba lies within the Zambezi Valley near Lake Kariba where semi-arid climatic conditions, complex relief and sensitive drainage networks require careful siting of large energy infrastructure. The approach uses UAV imagery processed through Structure-from-Motion (SfM) and Multi-View Stereo (MVS) workflows to generate Orthomosaics and digital elevation products suitable for slope and drainage analysis. Multispectral satellite imagery (e.g., Sentinel-2/Landsat-class) complements UAV outputs by enabling consistent repeatable land cover classification over broader extents supporting exclusion of unsuitable land (e.g., water, built-up areas, and ecologically sensitive zones). A GIS-based suitability model is then applied, incorporating topographic constraints and infrastructure buffers. (Westoby et al., 2012; Eltner et al., 2016)

Using the Kariba Proposed Solar Plant slope analysis output as an applied case layer, the framework demonstrates how suitability screening can incorporate hydrological protection (drainage buffering), reservoir safety buffers, road offsets and high-voltage powerline corridors. The mapped candidate blocks indicate four proposed areas of approximately 239.892 ha, 223.254 ha, 249.446 ha, and 64.794 ha (total 777.386 ha) under a common reference system (WGS84 UTM Zone 35S). The study concludes that integrated UAV-multispectral workflows can substantially strengthen evidence-based siting by improving terrain fidelity, clarifying land cover constraints and enabling transparent reproducible spatial decision support for renewable energy planning in Kariba and similar environments.

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1. Introduction

Solar PV deployment is increasingly prioritised across Southern Africa to diversify generation portfolios and reduce vulnerability related with climate sensitive hydropower (Van Vliet, 2016). In Zimbabwe, the Kariba hydropower scheme has strategic national status, yet the surrounding Zambezi Valley is characterised by strong seasonal rainfall variability and recurrent drought risk, reinforcing the need for harmonising renewable energy options and careful siting of new projects (Magadza & Brief, 2006). Renewable energy planning at utility scale requires spatially explicit evidence on terrain suitability (e.g., slope, drainage, cut-and-fill risk), land cover constraints (e.g., water bodies, settlements, vegetation), and proximity to enabling infrastructure (e.g., powerline corridors, substations, access roads) (Block & Lane, 2019).

Conventional satellite-only approaches often struggle to represent micro-topography and fine-scale drainage pathways critical for engineering layout and environmental safeguards. Conversely, UAV photogrammetry can provide centimetre-scale orthomosaics and dense point clouds, but typically over limited extents (Stott, Williams, & Hoey, 2020). Integrating UAV and multispectral satellite remote sensing offers a practical compromise UAV products enhance local accuracy and engineering relevance, while multispectral imagery supports consistent land cover mapping and repeat monitoring at broader scales (Reinprecht & Kieffer, 2025). The integration is particularly beneficial in heterogeneous landscapes where pixel-only classification may be less reliable and where topographic detail governs stormwater behaviour and erosion risk.

This paper therefore develops and documents a verifiable integrated framework for:

(i) high-resolution topographic mapping using UAV SfM/MVS;
(ii) land cover classification using multispectral imagery and machine learning
(iii) GIS-based solar PV suitability screening using terrain, hydrological, and infrastructure constraints.

The study is anchored in Kariba, Zimbabwe, and demonstrates application using a slope analysis output prepared for a proposed solar plant site, including explicit buffers for drainage, dam/reservoir proximity, roads, and a 330 kV powerline corridor.

2. Study Area: Kariba, Zimbabwe

Kariba is in Mashonaland West Province, Zimbabwe, within the Zambezi Valley close to the Kariba Dam and Lake Kariba near the Zambia border. The area experiences hot conditions and strong seasonality in rainfall typical of semi-arid to arid valley environments, with pronounced wet-season concentration and intra-season dry spells. Terrain is locally complex, with hills and incised drainage lines that influence runoff concentration and erosion potential especially where vegetation cover is disturbed for construction. For engineering-grade mapping and siting, Kariba's setting presents three recurring spatial planning challenges. Topography and drainage sensitivity small slope breaks and ephemeral channels can dominate stormwater routing, so siting requires fine-scale elevation modelling and defensible drainage buffers. Infrastructure corridors and safety buffers proximity to existing high-voltage transmission infrastructure is beneficial for grid connection yet must respect corridor offsets and environmental safeguards. Land cover and environmental constraints proximity to the lake/dam system, built-up land and vegetated areas requires screening to reduce ecological and social impacts and to improve permitting readiness. The slope analysis case layer provided for the proposed solar plant is referenced to WGS84 UTM Zone 35S and includes mapped drainage networks and multiple infrastructure buffers used for suitability screening.

3 Data Analysis and Methods

3.1 Overview of the integrated workflow

The methodological workflow contains three linked components,
UAV photogrammetry to generate high-resolution Orthomosaics, point clouds and elevation models suitable for slope, drainage and earthworks screening. Multispectral remote sensing to create land cover classes and exclusion layers at landscape for instance water, built-up and dense vegetation. GIS-based suitability modelling that integrates terrain derivatives (slope), hydrological constraints (drainage buffers), infrastructure corridors (roads, powerlines, substations) and reservoir/dam buffers into a transparent decision surface.

3.2 UAV data acquisition (recommended specification for Kariba)

UAV imagery acquisition should be planned to balance resolution, coverage, and topographic complexity for Kariba's variable relief and drainage density, the following are recommended as a defensible baseline for engineering-grade mapping,
– Nadir image capture with high forward/side overlap (typically ≥75%/≥65%) to support stable SfM reconstruction.
– Consistent lighting conditions (late morning) to reduce shadow artefacts across valley slopes.
– Ground Control Points (GCPs) distributed to cover elevation ranges and site extents, measured with survey-grade GNSS to enable robust georeferencing.

3.3 UAV photogrammetric processing (SfM/MVS)

UAV images are processed using an SfM/MVS pipeline, typically including,
– Image alignment and sparse reconstruction (camera pose estimation)
– Dense point cloud generation
– Surface modelling to produce a Digital Surface Model (DSM)
– Filtering/ground classification (where appropriate) to derive a Digital Terrain Model (DTM)
– Orthomosaic generation

This pipeline has been widely validated for producing high-resolution terrain and surface models in geoscience and engineering applications when supported by sufficient overlap and well-distributed control.

3.4 Multispectral imagery and preprocessing

Multispectral imagery (e.g., Sentinel-2 or Landsat-class) is used to classify land cover and generate indices that separate vegetation, bare ground, built-up surfaces, and water. Standard preprocessing typically includes,
– Cloud and shadow masking

– Atmospheric correction or use of surface reflectance products
– Calculation of indices such as NDVI for vegetation and other spectral features supporting separation of built-up and bare surfaces

3.5 Land cover classification approach
A supervised machine learning approach is recommended, with Random Forest (RF) providing a strong baseline due to robustness to non-linearity, ability to handle mixed predictors, and performance in multi-class remote sensing classification. Training data may be derived from field observations, existing maps, and high-resolution UAV orthomosaics (to improve label quality). Where very high-resolution data are used, an object-based image analysis (OBIA/GEOBIA) option can be applied to reduce salt-and-pepper noise by classifying image objects rather than individual pixels. (Breiman, 2001)

3.6 Suitability analysis for solar PV siting
Suitability modelling follows a constraint-and-opportunity logic, Hard constraints (exclusions) areas removed from consideration (e.g., within specified buffers of drainage lines, dam/reservoir, or restricted infrastructure corridors). Soft constraints (ranking) continuous or categorical scoring (e.g., lower slopes score higher; closer proximity to grid connection may score higher, subject to safety offsets).
The provided slope analysis output explicitly shows the following mapped elements and buffers:

- Drainage network with 15 m buffer
- Dam/reservoir with 400 m buffer
- Road with 5 m buffer
- **330 kV powerline with 60 m buffer**
- Proposed substation and geotechnical boreholes
- Proposed candidate areas and proposed boundary polygons

These constraints are consistent with standard practices in infrastructure siting, where drainage and reservoir buffers support hydrological protection, and corridor offsets manage safety and access requirements.

3.7 Accuracy assessment and quality control
Two validation layers are recommended
Topographic accuracy RMSE evaluation using independent check points (not used as control), reporting horizontal and vertical accuracy.
Classification accuracy confusion matrix and class-wise metrics (overall accuracy, producer's/user's accuracy, F1-score) using stratified validation samples.

3.8 Software environment and reproducibility
A reproducible workflow should document image acquisition parameters, GCP coordinates and measurement standards, processing settings for SfM/MVS, satellite preprocessing steps, classification model configuration (features, hyperparameters), and GIS suitability rules and

weights (if multi-criteria scoring is applied). This supports auditability during technical review and permitting.

4. Results

4.1 Terrain and slope outputs for siting

The slope analysis output for the Kariba proposed solar plant provides a terrain-informed screening layer overlaid with drainage lines, contours, road access, and major transmission infrastructure. The mapped product indicates that suitability is not only slope-driven but also controlled by hydrological protection and infrastructure corridors, reflecting integrated engineering and environmental safeguards.

Figure 1: Kariba Proposed Solar Plant – Slope Analysis (WGS84 UTM 35S, May 2025).

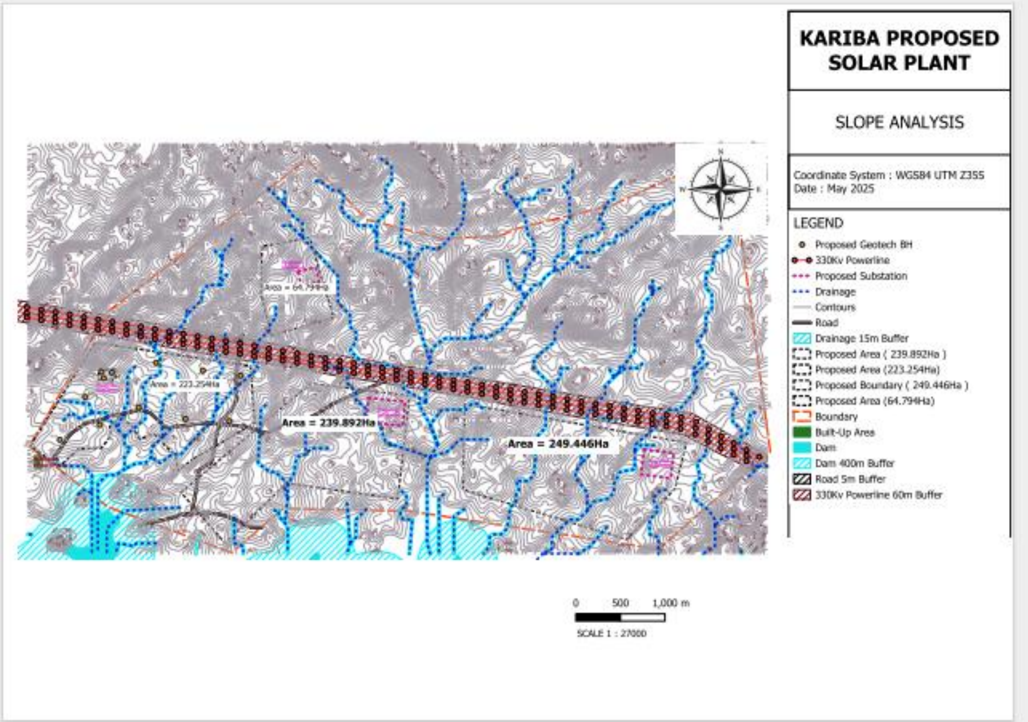


Figure 2: Kariba Slope Proxy Heatmap

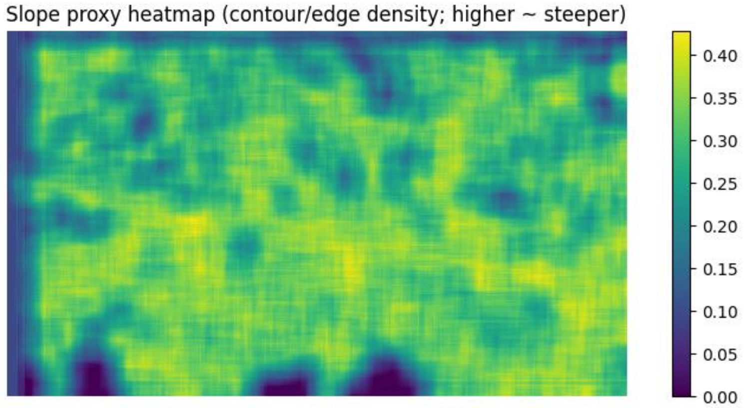


Figure 3: Kariba Regression Results

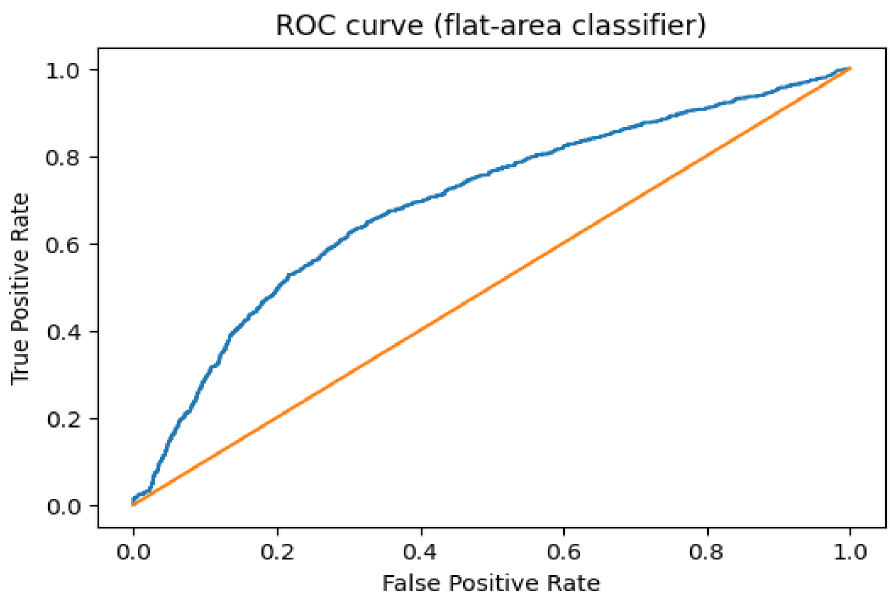


Figure 4: Showing Logistic Regression

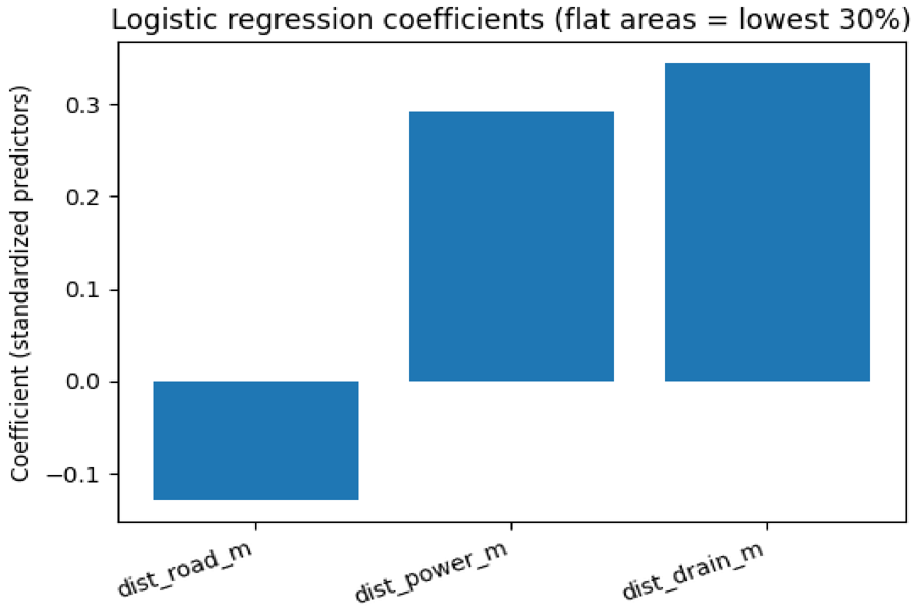
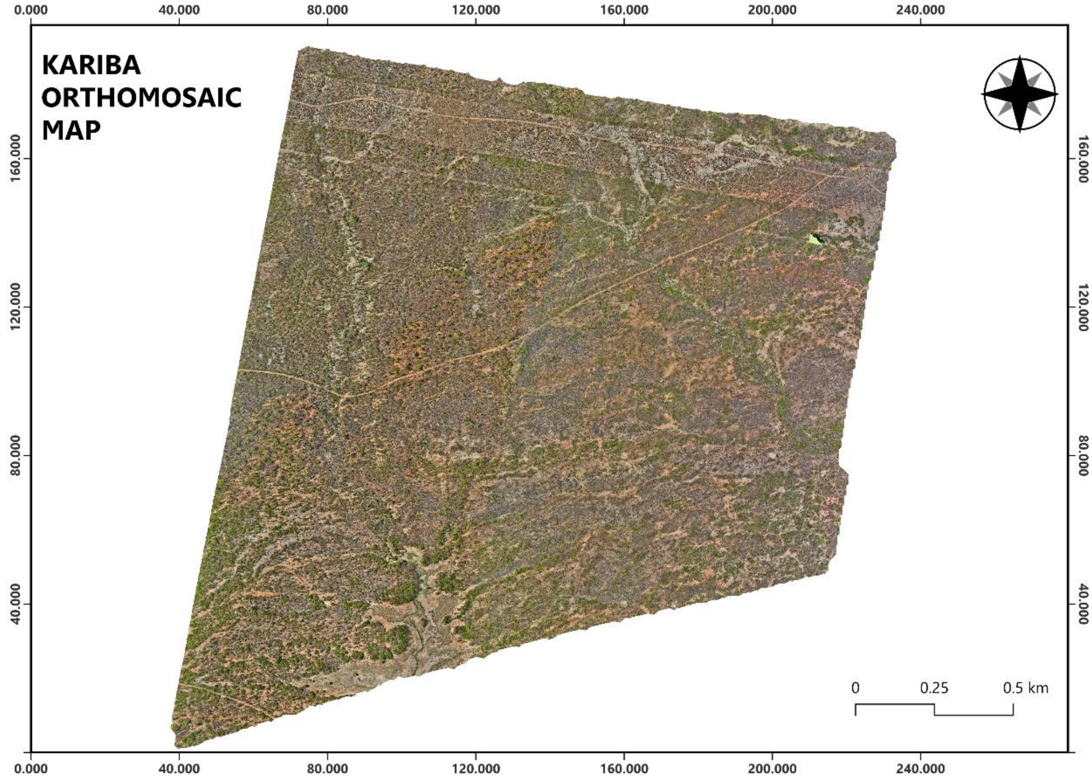


Figure 5: Showing Orthomosaic Map of Kariba



4.2 Explicit constraints visible in the Kariba slope analysis layer

The provided map includes constraint layers that function as exclusion masks in a siting model:
– Drainage 15 m buffer (hydrological protection)
– Dam 400 m buffer (reservoir/dam safeguarding)
– Road 5 m buffer (corridor management and access)
– 330 kV powerline 60 m buffer (safety offset and corridor integrity)

These constraints reduce exposure to flood routing, erosion concentration zones and reservoir-adjacent sensitivities while ensuring compatibility with road and transmission infrastructure.

4.3 Candidate suitable blocks and area accounting

The slope analysis map labels four candidate polygons as proposed areas. Their areas (as shown on the map) are summarised below.
To be placed
Table 1 shows proposed solar areas interpreted from the Kariba slope analysis map (May 2025)

Area ID	Mapped Label (ha)
A1	239.892 ha
A2	223.254 ha
A3	249.446 ha
A4	64.794 ha
Total	777.386 ha

The total candidate land footprint of 777.386 ha represents a substantial envelope for subsequent design optimisation, where detailed micro-siting would typically refine arrays, internal access roads, drainage structures, and substation placement based on finer topographic derivatives and land cover exclusions.

4.4 How UAV–multispectral integration strengthens these results

While the provided slope analysis already expresses key terrain and buffer constraints, an integrated UAV–multispectral workflow strengthens the evidence base in three practical ways: Improved micro-topography, UAV-derived DEMs can resolve local slope breaks and micro-channels that are commonly smoothed in coarser DEMs, improving drainage design and reducing earthworks risk. The land cover exclusions multispectral classification provides defensible screening of land cover types (water, built-up, dense vegetation) supporting environmental assessment and layout optimisation. The confidence in permitting transparent constraint layers, traceable methods and quality control metrics improve technical defensibility for stakeholder review.

5. **Discussion**

5.1 Planning relevance for Kariba's physical setting

Kariba's valley setting makes slope and drainage constraints non-negotiable for large-scale infrastructure. The inclusion of a drainage buffer (15m) and a reservoir buffer (400m) in the provided siting layer demonstrates appropriate caution in managing flood routing, sediment mobilisation, and potential downstream impacts. In semi-arid environments, intense rainfall events can generate rapid runoff and gully formation, so siting and design must anticipate hydrological extremes despite low annual rainfall totals.

5.2 Why the integrated approach is technically defensible

UAV photogrammetry using SfM/MVS provides low-cost, high-resolution surface reconstruction compared to traditional airborne campaigns, if image geometry and ground control are adequate. When combined with multispectral mapping, the workflow improves both the engineering realism of terrain constraints and the ecological/social realism of land cover constraints. Machine learning classification (e.g., Random Forest) is well suited for complex class boundaries and mixed predictors, and object-based approaches can further improve results in high-resolution environments.

5.3 Limitations and risk management

Three limitations should be explicitly managed in a Kariba deployment.
Temporal mismatch UAV and satellite acquisitions must be aligned seasonally where possible, because vegetation and water extent vary strongly across the year. Shadow and relief artefacts steep relief can create shadowing in both UAV imagery and satellite reflectance; careful acquisition timing and preprocessing are essential. Ground truth availability classification accuracy depends on training and validation data quality. UAV Orthomosaics can improve label confidence, but field checks remain important for ambiguous classes.

5.4 Operational recommendations for solar PV design teams

The project teams progressing from suitability screening to detailed design, the following are recommended. The use UAV derived DEMs to refine internal drainage routing and avoid placing infrastructure across ephemeral channels not represented in coarse datasets. Integrate land cover exclusions early to reduce redesign risk during environmental review. Maintain a documented GIS rule set (buffers, thresholds, weights) to ensure transparency and replicability for technical reviewers.

6. Conclusions and Recommendations

This paper presented an integrated UAV–multispectral remote sensing framework for high-resolution topographic mapping, land cover characterisation and solar PV siting in Kariba, Zimbabwe. The Kariba slope analysis case layer demonstrates how terrain-based screening combined with hydrological and infrastructure buffers can identify candidate development blocks that are more likely to be technically feasible and environmentally defensible. The mapped candidate blocks total 777.386 ha, referenced to WGS84 UTM Zone 35S and explicitly include drainage (15 m), dam/reservoir (400 m), road (5 m), and 330 kV powerline (60 m) buffers.
The study recommends that future site refinement in Kariba adopt UAV-derived elevation products to improve micro-topographic realism and combine these with multispectral land

cover classifications to strengthen exclusion mapping and monitoring. Together, these methods provide a cost-effective, transparent, and scalable geospatial basis for renewable energy planning in Kariba and comparable semi-arid valley environments.

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