Evidence-Based Spatial Planning through Drone-Derived Geospatial Intelligence in South Africa (14036)

Muhammed Shaakir DEAL and Stephanus MINNIE, Republic of South Africa

Key words: drone technology, remote sensing, geospatial intelligence, spatial planning, informal settlements, ortho-mosaics, digital surface models, digital terrain models, 3d mesh models, geoinformation

1. SUMMARY

The National Department of Land Reform and Rural Development (DLRRD) has launched a Drone Programme aimed at transforming service delivery and spatial planning through near-real-time geospatial intelligence. Compliant with South African Civil Aviation Authority (SACAA) regulations, the Programme leverages multirotor and VTOL (Vertical Take-Off and Landing) fixed-wing drone technology. These drones are equipped with advanced sensor payloads, including RGB, Oblique and Multispectral sensors to collect high-resolution data. This data is used to produce geospatial products such as ortho-mosaics, 3D meshes, point clouds, contours, Digital Terrain Models (DTMs), and Digital Surface Models (DSMs). These products support evidence-based planning and accelerate interventions across rural and urban landscapes. They provide insights into land use, infrastructure, and environmental conditions.

This paper provides an overview of the Programme's establishment and operational framework. It outlines the workflow, which includes aerial surveys, sensor-based data acquisition utilizing a RGB payload, and subsequent processing and analysis using Geographic Information Systems (GIS) and Geospatial Artificial Intelligence (GeoAI) techniques. Through case studies from informal settlements and small towns, the paper illustrates how drone-derived datasets can inform targeted interventions and improve planning for decision-making. It demonstrates how high-resolution imagery and 3D models deliver insights that enable dynamic spatial analysis and foster a data-driven approach to spatial planning.

The Drone Programme exemplifies how innovative geospatial technologies can revolutionize spatial planning in South Africa. By combining near-real-time remote sensing with advanced analytics, it promotes responsive, inclusive, and sustainable development strategies. The significance of this work lies in its potential to scale across regions, offering a replicable model for other government departments and agencies seeking to modernize service delivery through geospatial intelligence.

Evidence-Based Spatial Planning through Drone-Derived Geospatial Intelligence in South Africa (14036)

Muhammed Shaakir DEAL and Stephanus MINNIE, Republic of South Africa

2. INTRODUCTION

Access to near-real-time high-resolution geospatial information has long been a constraint for spatial planning and land-use management in South Africa. Traditional planning processes frequently relied on outdated datasets or lengthy outsourced data-acquisition cycles, delaying service delivery and limiting evidence-based decision-making. To address these gaps, the National Department of Land Reform and Rural Development (DLRRD) established the Drone Programme as a strategic initiative to institutionalize near-real-time geospatial intelligence within government operations.

The Programme leverages multirotor and fixed-wing VTOL drones equipped with advanced sensor payloads to generate timely, high-resolution imagery, 3D models, terrain information, and analytic products. These datasets aid spatial planning processes, enhance disaster-response capabilities, and support more responsive land-use management.

Beyond acquiring near-real-time geospatial datasets, the Programme is built on a foundation of regulatory compliance, governance, operational standardization, and capacity building. By meeting SACAA requirements and integrating GIS, GeoAI and cloud-based processing tools, the Programme ensures that drone-derived intelligence is accurate, interoperable, accessible, and aligned with national legislation such as SPLUMA and the SDI Act.

This paper outlines the Programme's design, operational framework, current data-processing workflows, and governance mechanisms, supported by case studies demonstrating real-world impact in informal settlements and small towns. The work illustrates how drone-derived geospatial intelligence can transform planning and service delivery.

3. PROGRAMME DESIGN AND OPERATIONAL FRAMEWORK

The DLRRD Drone Programme is rooted in the Constitution and aligned with the National Development Plan, ensuring compliance with key legislation such as the Spatial Planning and Land Use Management Act (SPLUMA, 16 of 2013) and Spatial Data Infrastructure Act (SDIA, 54 of 2003). Additionally, all regulatory requirements of the South African Civil Aviation Authority (SACAA) are met. It is not only about technology, it's about transforming land management, improving service delivery, and institutionalizing accountability through accurate, timely geospatial data that supports informed decision-making across government.

For the legal operation of drones, there are three primary requirements that need to be met, namely,

- **Registered Drones:** Annual registration, system safety approval and up to date maintenance,
- **Certified Pilots:** Skilled professionals with remote pilot licences, medical clearance, and valid aviation security training) and the
- **Unmanned Aircraft System Operating Certificate (UASOC):** Operation manuals, Quality Management, Safety Management, Security Management, Drone Limitations and Maintenance.

Section 4 highlights the policy, regulation and institutional context of the Programme in more detail. To ensure that the department is able to render drone operations throughout the country, drone pilots and drones are stationed in every province. Figure 1 below outlines the number of pilots, number of drones and types of drones as of 14 October 2025.

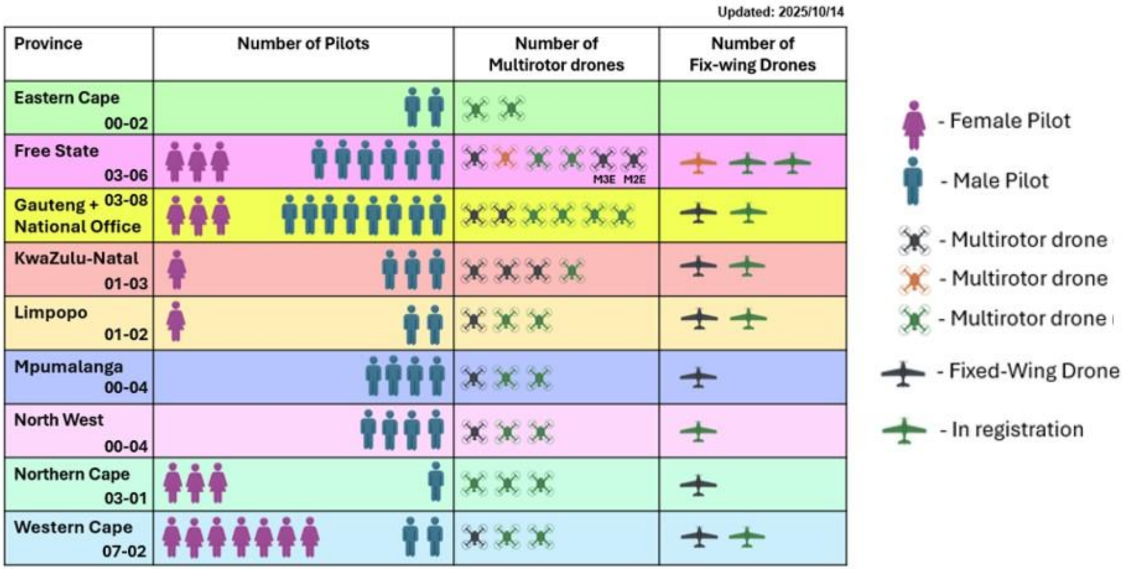

Figure 1: Drone Programme Footprint (14/10/2025)

Within the Drone Programme, pilots are recruited on a voluntary basis. A key factor contributing to its success is that each pilot has their primary role (for example, GISc Practitioner, Land Surveyor, Spatial Planner, Rural Infrastructure Specialist, or Project Manager) within the department while supplementing their core responsibilities with drone piloting expertise.

DLRRD Drone pilots are spread across the country, making centralized communication critical for success. Currently, this is achieved by utilizing an integrated Esri-Microsoft stack as shown in Figure 2. Web services allow for public access to multiple resources such as drone operations dashboard to view all activities, a drone operation request survey form to request a drone operation and additional resources regarding the Drone Programme. Managing the National Drone Programme requires strong communication to ensure the good coordination. Additional web services such as internal SharePoint sites are utilized for daily communication, project files storage, industry updates, managing client requests, resource allocation and mission planning.

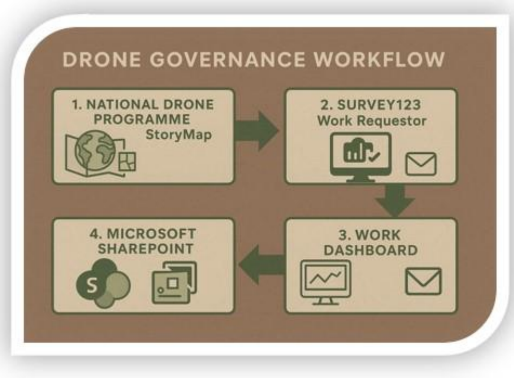

Figure 2: Drone Governance Workflow

In Figure 3 below, a high-level workflow is illustrated on how drones and geospatial intelligence transform raw data into actionable insights, moving from drone operation in the field, processing, create geospatial products using specialized software and to informed planning decisions. The role of the GISc professionals is essential in turning imagery into knowledge. Within the Drone Programme, using specialized software, accurate geospatial datasets are achieved that is essential for spatial planning. Currently, the Esri suite processes captured images into geospatial products and insights, while GeoAI advances automation, detecting patterns, predicting trends, and classifying features.

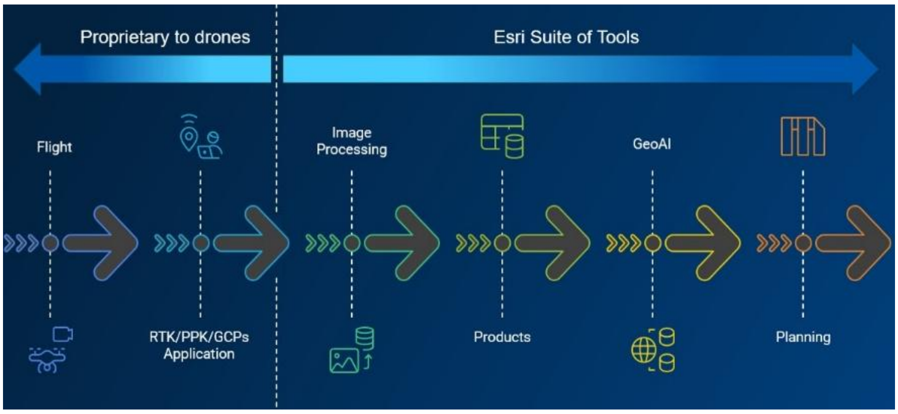

Figure 3: :High Level Work flow Drone Governance Workflow

Lastly, collaboration within government is key for the success of the Drone Programme. One of the objective is to ensure that a captured dataset from a single drone operation can be utilized multiple times within different sectors of government. Instead of duplicating efforts, the data, insights, and infrastructure is shared to ensure public value. By aligning with the SDI Act, innovation can be unlocked while ensuring compliance.

4. POLICY, REGULATION AND INSTITUTIONAL CONTEXT

The National DLRRD Unmanned Aircraft Systems (UAS) Operations Manual (DLRRD, 2025a) was approved from 31 August 2024. It frames the UAS operations as a formally controlled aviation activity, governed through a defined compliance system (manual control, regulator approvals, safety, security, and quality oversight), and executed through clearly allocated operational accountabilities within the UAS Operating Certificate (UASOC).

The UAS Operating Certificate (UASOC) was approved on 1 September 2025 which is the official date from where we may operate independently. We did however contract aviation experts under which we operated since 2023 (DLRRD, 2025b).

This section highlights the SACAA compliance strategy, the governance structure, and the institutional position of the DLRRD Drone Programme.

4.1 SACAA Compliance Strategy

NDLRRD's UAS Operations Manual (UOM) positions UAS operations as a formally controlled aviation activity, run through a compliance system that ties operational practice to legislative and regulatory requirements, and to the permissions and limitations of the UASOC (DLRRD, 2025a, p. 20).

The Manual frames compliance as a conservative, judgement-based responsibility, requiring personnel to apply the most defensible interpretation whenever instructions or limitations are not fully explicit. Compliance is further strengthened through formal document-control processes that ensure the UOM is reviewed, amended, and distributed in a controlled manner so outdated procedures cannot be used. It distinguishes between internal updates and changes that remain proposals until external approval is granted, linking operational authority to regulatory acceptance where required.

Quality assurance supports compliance through planned audits with defined scope and criteria, covering both operational and supporting functions. The UASOC must be audited at least annually, with frequency adjusted according to operational size, risk, and performance indicators. Audit criteria include regulatory and standards compliance, conformance with the UOM and associated procedures, and checks against external technical references such as manufacturer documentation. Findings follow a structured reporting and corrective-action cycle to ensure verification and closure.

The Manual also embeds Safety Management System practices, including hazard identification, reporting expectations, investigation procedures, and risk assessment as part of operational change management. Compliance is operationalized through centralized electronic recordkeeping, enabling traceability, oversight, renewal tracking, and verification across activities.

4.2 Governance Structure

The SACAA-approved Operations Manual assigns governance through nominated post holders with clear reporting lines.

The **Safety Manager**, reporting to the Accountable Manager, is responsible for safety meetings, safety communication, hazard management, regulatory reporting, and may stop any unsafe or unreliable operation (DLRRD, 2025a, pp. 1–23).

The **Responsible Person: Flight Operations (RP: FO)** reports to the Accountable Manager and ensures operations comply with the UOM and SA-CARs/SA-CATS. The role manages scheduling, license oversight, fatigue risk, document revisions, and may prohibit unsafe operations (DLRRD, 2025a, pp. 1–24).

The Responsible Person: Aircraft (RP: A) also reports to the Accountable Manager. This role ensures safe maintenance, aircraft airworthiness, maintenance scheduling, and compliance with manufacturer service bulletins, with authority to stop unsafe or unreliable operations (DLRRD, 2025a, pp. 1–25).

The **Quality Manager** leads compliance monitoring and assurance, oversees internal quality controls, and may intervene whenever safety or reliability concerns arise (DLRRD, 2025a, pp. 1–26, 1–27, 5–35, 5–36, 5–37).

The **Security Manager**, reporting to the Accountable Manager, develops and updates security procedures, conducts security evaluations, oversees security-related training, reports unlawful interference, and may halt unsafe operations (DLRRD, 2025a, pp. 4–4).

Operational roles support daily delivery. **Remote Pilots** ensure safe flight, separation, site supervision, documentation, and compliance with the UOM and RP: FO controls. **UA Observers** assist in E-VLOS operations through continuous visual monitoring and communication. **Maintenance Technicians (UASMT holders)** report to RP: A and conduct maintenance per manufacturer requirements, maintain records, and report maintenance occurrences.

4.3 Institutional Position

Institutionally, the Manual frames UAS capability as a departmental function delivered through a regulated operating certificate construct, rather than an informal technical capability, with accountability consolidated at senior level through the Accountable Manager role (DLRRD, 2025a, pp. 1–20).

The Manual's acceptance and governance language places the Accountable Manager within senior oversight structures, including reference to reporting to the board of directors of the national department, signaling that UAS operations are positioned within executive accountability rather than purely technical management (DLRRD, 2025a, pp. 1–22).

Operational control is reinforced through direct reporting lines from key post holders (Safety Manager, RP: FO, RP: Aircraft, and Security Manager) to the Accountable Manager, which supports a single point of accountability while preserving role-specific authority to prevent unsafe or unreliable operations (DLRRD, 2025a, pp. 1–23, 1–24, 1–25, 4–4).

The Manual also links institutional positioning to organisational governance routines through quality management practices, including management review considerations and quality records, which connect audit results, corrective actions, and compliance maintenance to internal decision-making processes (DLRRD, 2025a, pp. 5–44).

Lastly, the recordkeeping requirements, including retention of regulatory approvals, insurance, ICASA-related documentation, flight planning artefacts, risk assessments, and landowner permissions, imply that the UASOC sits at the intersection of aviation compliance and public-sector accountability, where operational legitimacy depends on demonstrable administrative control as much as flight execution (DLRRD, 2025a, pp. 1–45, 1–47).

5. DATA COLLECTION AND PROCESSING WORKFLOW

5.1 Types of Drones

The Programme utilizes two (2) types or drones, either a multirotor or fixed-wing VTOL hybrid.

5.1.1 <u>Multirotor drones (DJI Mavic 3M)</u>

For smaller areas, multirotor drones are deployed covering about 40 hectares per flight with a single battery. The multi-rotor is supplied with 4 batteries. Each battery can operate up to 20 minutes. Multirotor drones within the Programme are equipped with RGB, thermal, and multispectral sensors. The end product of the drone operation are Geotagged images. It is important to note, when not utilizing Ground Control Points (GCPs), the multirotor drone geotags images in an autonomous/hovering coordinate reference system that is not tied to the National Control Network. To ensure the drone operation is tied to the National Control Network, Ground Control Points must be observed in real-time which is achieved by setting up a GNSS receiver in Real-Time Kinematic (RTK) mode above a point with known position and height within the National Control Survey Network. The GNSS receiver communicates with the drone through the drone controller.

5.1.2 <u>Fixed-wing VTOL drones (Trinity F90+)</u>

For larger areas, fixed-wing VTOL drones are deployed covering 200-400 hectares per flight. The fixed wing is supplied with 3 batteries. Each battery can operate for 1 hour 30 mins. Their hot swappable sensor feature allows switching of sensors without having the need to purchase multiple drones. With SACAA, the drone needs to be registered and not the sensor. This reduces costs significantly. The end product of the drone operation is non-geotagged images. It is important to note, GCPs are required to geotag the images. To ensure the drone operation is tied to the National Control Network or any other known system, GCPs must be observed in Post Processing Kinematic (PPK) mode and later processed in specialised software to obtain geotagged images. In the field, there is no communication between the drone and GNSS receiver.

5.2 Processing Workflow

Drone pilots are recruited on a voluntary basis from various professional backgrounds within the department. For this reason, a software that provides accurate output, has a simplistic workflow and allows for viewing, sharing and interacting with the processed data is required. Within the Drone Programme, ESRI SiteScan is one of the primary software packages that is currently utilized to process geotagged images into geospatial products, allowing pilots with minimal experience to produce an outcome. Figure 4 shows a simplistic workflow using ESRI SiteScan.

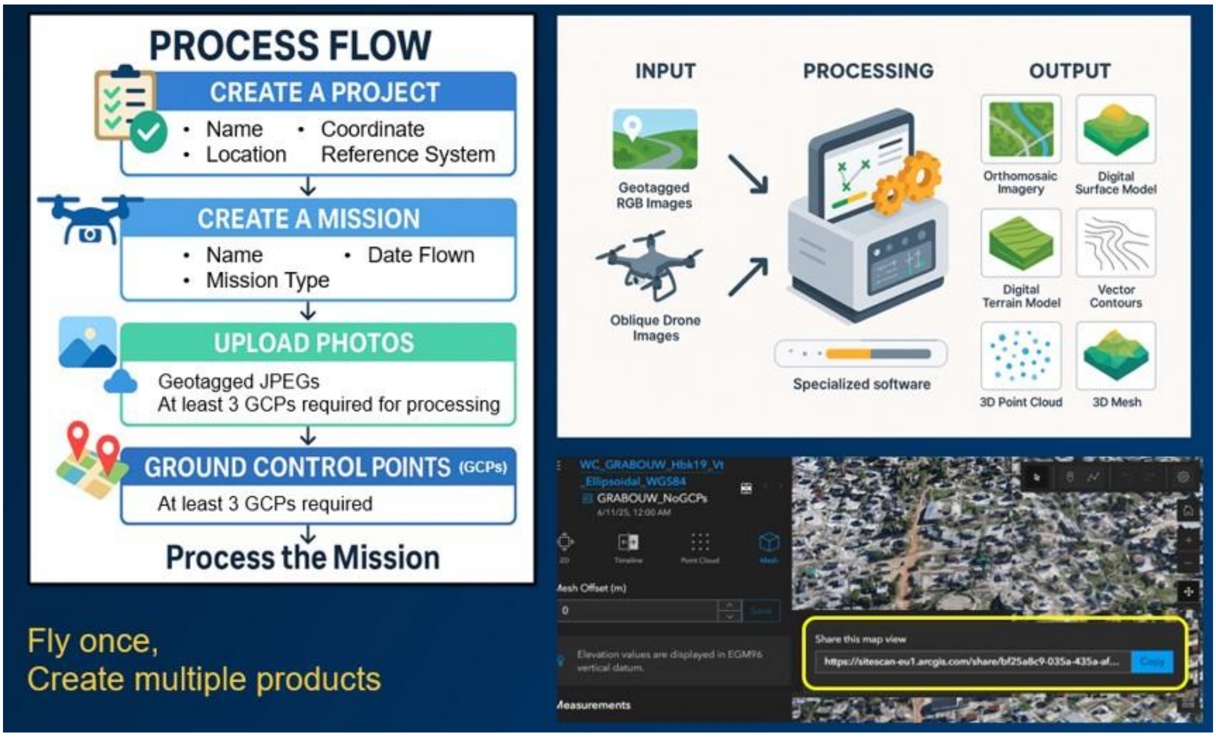

Figure 4: Simplistic Workflow using ESRI SiteScan

6. DRONE PRODUCTS

Using ESRI SiteScan, each processed mission includes a detailed accuracy report, giving us confidence in the images collected during the drone operation. A simple drone mission flown with a RGB sensor and 80% image overlap can generate ortho-mosaics, digital terrain and surface models, point clouds and 3D meshes. These drone products offer near-real-time visibility, which is crucial for planning, monitoring, and decision-making. As a cloud-based platform, SiteScan makes these products instantly accessible, downloadable, and shareable, enhancing collaboration across teams. Figure 5 below shows samples of geospatial products generated from a simple RGB flight with 80% overlap.

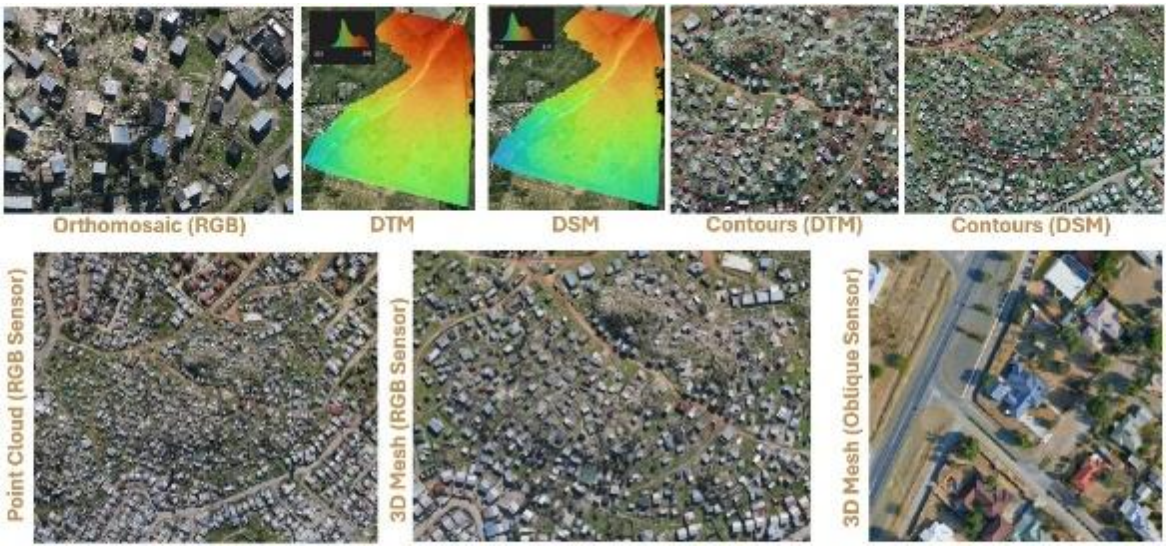

Figure 5: Geospatial products generated from a simple RGB flight with 80% overlap.

Storage is an important factor to consider when working with drone datasets. Figure 6 below demonstrates the data storage requirements for four (4) projects that were flown & processed. Each mission generated large volumes of raw data, depending on project size and sensor type. For example, Victoria West Town (No. 2) with eight missions produced over 10,766 images, totaling 384 GB after processing. It is important to note, from a data management perspective, the raw images are much bigger datasets than the processed geospatial products.

No.	Project Name	Number of Missions	Sensor [RGB, Oblique, Lidar, Multispectral]	Number of Raw Photos/Images	Product Sizes (Gb)						Total Project Size (Gb)
					Raw data (images only)	Ortho-mosaic Image (single/multiple missions)	Digital Surface Model (DSM)	Digital Terrain Model (DTM)	3D Point Cloud	3D Mesh	
1.	Victoria West Town	8	Oblique	10766	238.00	72.82	42.26	1.96	15.71	13.38	384.13
2.	Victoria West Church	1	Oblique	347	1.50	0.25	0.10	0.01	0.60	0.38	2.83
3.	Zweletemba	1	RGB	2324	80.00	16.35	10.50	0.47	4.09	3.64	115.05
4.	Villiersdorp	1	RGB	4408	54.5	4.25	2.79	0.13	2.41	1.32	65.40

Figure 6: Drone products data storage requirements

7. CASE STUDIES AND APPLICATIONS

This section illustrates the contribution of drone-derived geospatial information to spatial planning by

- outlining the planning challenge addressed,
- detailing the drone technologies employed, and
- highlighting the resulting impact of the generated geospatial products.

One advantage of RGB drone-derived datasets, images collected from a single drone operation can produce multiple 2D and 3D products. The 2D datasets ortho-mosaics, DTMs and DSMs. The 3D datasets are point clouds and Meshes.

7.1 Informal Settlements, Theewaterskloof Local Municipality, Western Cape

The Human Settlements Department of the Theewaterskloof Local Municipality submitted a drone operations request via the 'Drone Work Request' survey on the Drone Programme online platform. The request sought near-real-time ortho-mosaics covering all informal settlements. Despite challenges posed by adverse weather conditions and concurrent disaster-response activities, the resulting geospatial datasets were essential for supporting the municipality's efforts to motivate for potential funding and resource allocation.

7.1.1 Villiersdorp Informal Settlement

The informal settlements of Villiersdorp are located on steep slopes adjacent to the formal township area (see Figure 7). These terrain conditions pose significant challenges for emergency response and service delivery, particularly when municipal teams lack accurate information on access routes and the spatial distribution of structures. To address these constraints, the Trinity F90+ VTOL drone was deployed to survey the extensive area efficiently and safely.

Figure 7: 3D Mesh - Informal Settlement, Villiersdorp

High-resolution imagery captured by the drone was processed into a near-real-time ortho-mosaic, providing a detailed representation of settlement layout, infrastructure footprints, and potential access pathways. Complementing this, a 3D mesh model enabled the municipality to visualize slope gradients, assess the condition and positioning of structures, and identify hazardous or high-risk zones that were not apparent from the ortho-mosaic alone.

Together, these geospatial products significantly enhanced situational awareness for municipal planners and disaster-management teams. The datasets supported more informed decision-making regarding service-delivery planning, risk mitigation, and emergency-response routing, while also strengthening the municipality's motivation for securing additional funding for infrastructure and disaster preparedness.

7.1.2 Grabouw Informal Settlement

The informal settlements of Grabouw are situated on slopes both adjacent to and interspersed within the formal township area (see Figure 8). As in Villiersdorp, the complex topography and dispersed settlement pattern present significant challenges for emergency response, infrastructure planning, and the delivery of basic services. To address these operational constraints and to support more informed decision-making, the Trinity F90+ VTOL drone was deployed to generate near-real-time, high-accuracy geospatial datasets for the entire area.

The resulting products provide complementary insights essential for spatial analysis and risk assessment. The **RGB ortho-mosaics** deliver high-resolution visual depictions of structures, roads, pathways, and vegetation, making them valuable for field verification, planning consultations, and stakeholder engagement. **Digital Terrain Models (DTMs)** reveal the bare-earth elevation and drainage patterns, supporting flood-risk modelling, infrastructure alignment, and the identification of erosion-prone zones. **Digital Surface Models (DSMs)** capture the height of buildings and vegetation, enabling analysis of urban density, fire-risk exposure, and emergency access constraints. **Vector contours** derived from these models offer simplified elevation information suitable for engineering design, slope-stability assessments, and land-use planning.

Figure 8: 3D Mesh – Settlements, Grabouw

Figure 9 illustrates how the integration of these datasets produces a multi-layered understanding of the spatial environment.

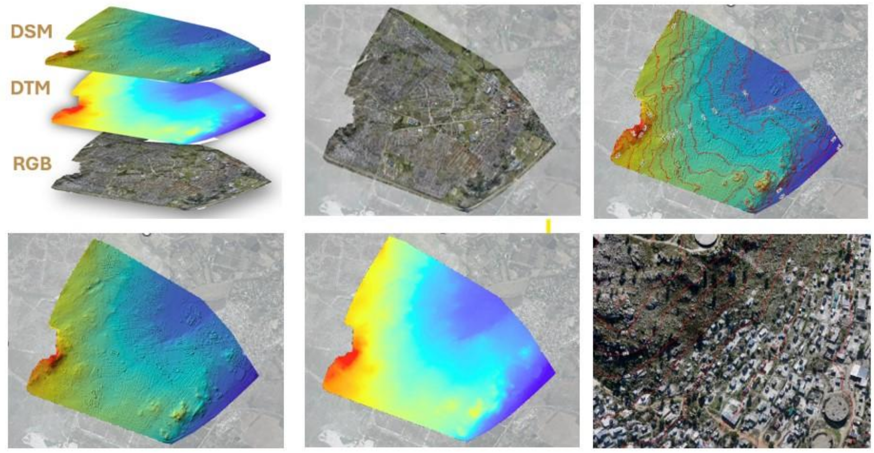

Figure 9: Combined Geospatial Datasets

When viewed collectively, the products provide a comprehensive picture of terrain conditions, built-up areas, and access networks. This enhanced situational awareness equips the municipality with the evidence base required for effective service-delivery planning, disaster preparedness, and prioritization of interventions. In particular, the insights gained support rapid response strategies, highlight vulnerable zones, and strengthen the municipality's ability to substantiate funding applications for infrastructure upgrades and risk-mitigation measures.

Feature Detection using GeoAI: In Figure 10, The Left image shows manually digitalised points, in red, representing structures. The right image shows points, in red, representing structures identified using a deep learning tool. In comparison, the deep learning tool correctly identified approximately 78% of the manually digitized structures. With further refinement through visual inspection and dataset cleaning, the accuracy could further improve. Overall, implementing GeoAI offers a powerful alternative to manual digitisation, enabling faster, repeatable, and cost-effective mapping of structures, which is crucial for planning and service delivery.

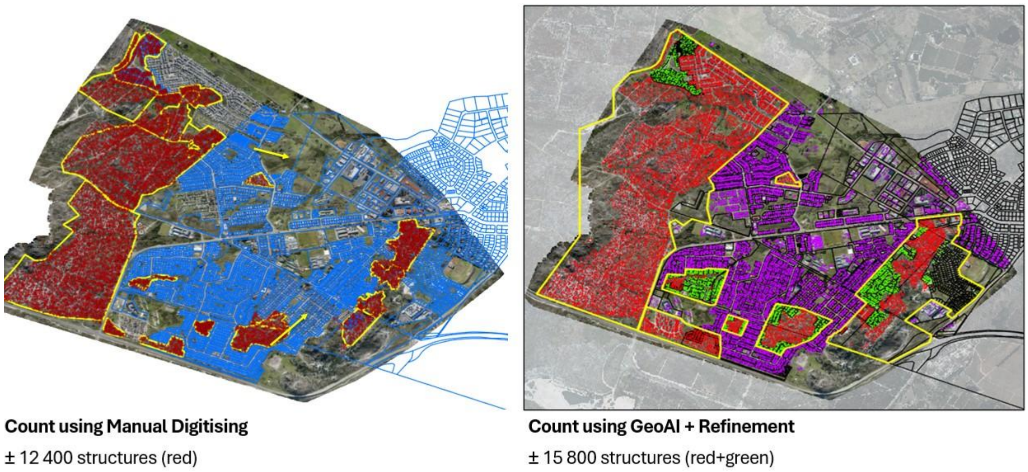

Figure 10: Manual vs GeoAI (Deep Learning tool)

7.2 Zweletemba, Western Cape

7.2.1 Land Cover Mapping (Classifying Pixels)

Disparities in urban development can create significant social inequities, leading to heightened exposure for marginalized communities. Figure 11 demonstrates how an ortho-mosaic drone image captured over an area of 200-hectares at a 3cm resolution can be classified using a tool in ArcGIS Pro. In under 10 minutes, a land cover classification was generated using a deep learning tool. While the classification is not flawless, it delivers highly actionable insights.

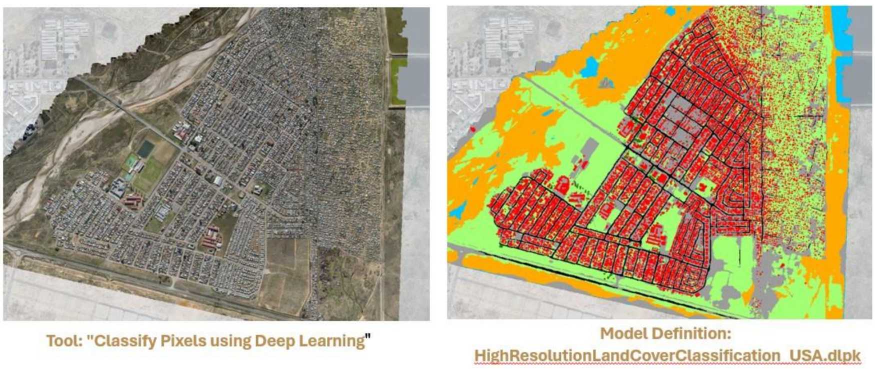

Figure 11: Pixel Classification using GeoAI

7.2.2 Feature Detection using GeoAI Techniques

Image resolution has an impact on feature detection using deep learning tools. An ortho-mosaic with 3cm resolution was resampled to 15, 25, and 50 centimeters. For structure detection, the 15cm resolution image produced more accurate results. While some errors were detected, for example some shadows and cars were misidentified, most likely impacted by the prompt keywords, the deep learning tool still provided valuable insights.

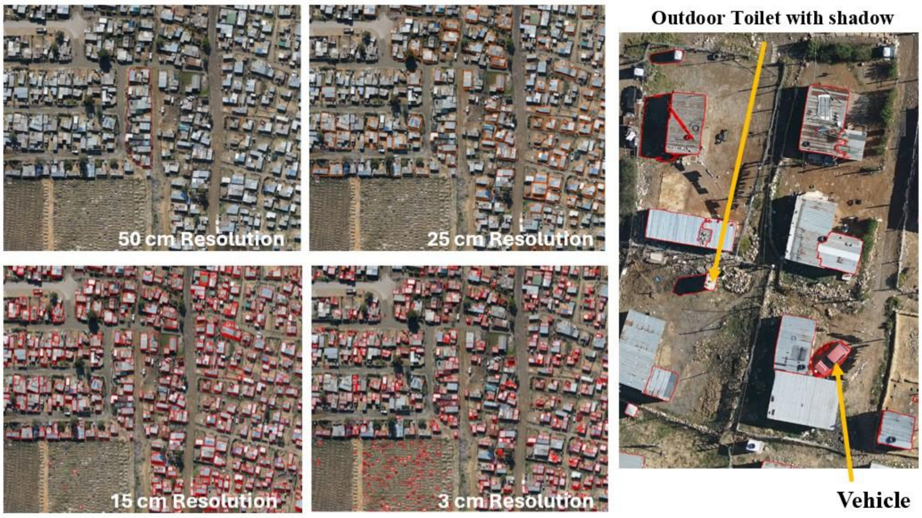

Figure 12: Feature Detection using GeoAI

8. CONCLUSION

The National Drone Programme demonstrates how drone-derived geospatial intelligence can fundamentally transform spatial planning, land management, and service delivery in South Africa. By moving from ad-hoc and outsourced data acquisition to an institutionalized, compliant, and technically robust in-house capability, the Programme has enabled faster access to high-resolution spatial information, improved decision-making, and enhanced operational efficiency across government sectors.

Through a combination of advanced sensors, standardized workflows, GIS and GeoAI processing, and a strong governance framework, the Programme delivers geospatial products that support evidence-based interventions in both urban and rural contexts. Case studies show the value of high-resolution imagery, 3D models, land-cover classification, and GeoAI-based feature detection in addressing planning challenges such as informal settlement upgrading, infrastructure planning, and land-use compliance.

As the Drone Programme continues to evolve, its scalable design and emphasis on interoperability, collaboration, and public-sector capacity building position it as a replicable model for other government departments. Ultimately, the Programme strengthens accountability, promotes cost-effective governance, and supports more inclusive and sustainable spatial development.

REFERENCES

DLRRD, 2025a. DLRRD Unmanned Aircraft System Operations Manual.
DLRRD, 2025b. DLRRD Unmanned Aircraft System Operating Certificate.

BIOGRAPHICAL NOTES

Mr. Muhammed Shaakir Deal, Chief GISc Professional (Directorate: Spatial Planning and Land Use Management Services – Western Cape) / Research and Development Lead (DLRRD National Drone Programme), Department of Land Reform & Rural Development. SAGC Registered Geomatics Professional: Geographic Information Science and Geomatics Professional: Land Surveying. Holder of a Aviation Security (AVSEC) Awareness UAS Operations Certificate. With 14 years of experience in the geo-spatial industry acquired in spatial data collection, analysis, modelling, management, mapping, cadastral surveying, topographic surveying, research, technical support, training and python coding.

Mr. Stephanus (Fanie) Minnie, Director, Spatial Planning and Land Use Management Services / National Drone Programme Department of Land Reform & Rural Development. SAGC Registered Professional GISc Practitioner, SACAA Certified Unmanned Aircraft pilot with BVLOS rating and Aviation Safety Management System (SMS) accredited. With 36 years of experience in the built environment related to infrastructure planning, telecommunication engineering projects, GISc projects and Urban and Regional Planning projects and entrusted in 2022 with leading the National Drone Programme, a transformative initiative that enhances spatial analysis and monitoring through cutting-edge remote sensing. Leveraging 3D Oblique imagery, LiDAR, and multispectral mapping, I oversee complex drone operations aligned to ICAO standards that generate actionable insights for spatial planning, applications.

CONTACTS

Mr. Muhammed Shaakir Deal
Department of Land Reform & Rural Development (DLRRD),
600 Lilian Ngoyi Street, Pretoria, 0002
REPUBLIC OF SOUTH AFRICA
+27 82 334 3802
Shaakir.Deal@dlrrd.gov.za
https://www.dlrrd.gov.za/

Mr. Stephanus Minnie
Department of Land Reform & Rural Development (DLRRD)
600 Lilian Ngoyi Street, Pretoria, 0002
REPUBLIC OF SOUTH AFRICA
+27 82 827 0644
Stephanus.Minnie@dlrrd.gov.za
https://www.dlrrd.gov.za/