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Unmanned Aerial Vehicle Mapping for Improving Spatial Accuracy in Rural Settlement Planning

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Abstract
Accurate spatial documentation is essential for rural settlement planning, particularly in hilly areas where conventional field surveys are time-consuming and often lack detailed topographic information. This study aims to evaluate the effectiveness of Unmanned Aerial Vehicle (UAV) mapping in improving spatial data accuracy and survey efficiency for settlement planning. The research was conducted in Puspo Hamlet, Purworejo, a rural settlement located in a complex hilly landscape with slopes of 15–35°. An exploratory case study approach based on spatial analysis was applied, integrating UAV aerial surveys, field observations, and photogrammetric processing using Structure-from-Motion techniques. The UAV survey covered approximately 35 hectares and produced high-resolution orthophotos with a ground sampling distance of 3–5 cm/pixel as well as digital elevation models (DEM) and digital surface models (DSM) datasets with horizontal accuracy of ±10 cm and vertical accuracy of ±15 cm. The results show that UAV mapping provides highly detailed spatial information while reducing survey time to about two days compared with more than one week using conventional survey methods.

***Keywords**: digital elevation model; high-resolution spatial mapping; rural settlement planning; terrain analysis; unmanned aerial vehicle photogrammetry*

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1. INTRODUCTION

The development of Unmanned Aerial Vehicle (UAV)–based remote sensing technology has significantly improved spatial data collection methods in architecture and spatial planning. Compared to conventional surveys, UAVs enable faster, more flexible, and cost-effective area documentation while producing high-resolution aerial imagery that supports detailed analysis of site conditions, land use patterns, and area morphology (Fernández-Hernandez et al., 2014; Andrew, 2020). In spatial planning and architectural design, such accurate spatial documentation provides a critical foundation for site analysis, planning formulation, and evaluation of the built environment, particularly in areas with complex topographical characteristics (Warsito, 2021; Faldi et al., 2024). This indicates the growing importance of high-resolution spatial data as a fundamental requirement for improving the quality and reliability of planning decisions.

In hilly and mountainous regions, such as many rural areas in Indonesia, spatial data collection presents considerable challenges. Conventional ground-based surveys are often time-consuming, labor-intensive, and limited in their ability to access steep slopes or areas with difficult terrain (Fernández-Hernandez et al., 2014; Tsouros et al., 2019). Moreover, existing topographic data are typically available at regional scales, which are insufficient to represent micro-topographic conditions required for detailed site analysis and context-sensitive design processes (Ferrer-González et al., 2020; Choi et al., 2023). As a result, planning decisions in such areas are frequently made based on incomplete or generalized spatial information, which may reduce the accuracy and responsiveness of spatial planning outcomes (Warsito, 2021; Faldi et al., 2024). This condition highlights a critical gap between the need for detailed spatial information and the limitations of conventional data acquisition methods in supporting effective planning practices.

Various studies show that the use of UAVs in area documentation can produce more detailed spatial data than conventional satellite imagery. UAV photogrammetry enables the acquisition of high spatial resolution aerial imagery, thereby supporting more detailed analysis of area morphology, identification of settlement structures, and mapping of environmental elements (Agate et al., 2026; Nex & Remondino, 2014). In addition, the integration of Structure-from-Motion (SfM)-based image processing techniques enables the reconstruction of three-dimensional models of the area's surface by combining a large number of overlapping aerial images to produce accurate digital topographic models (Remondino et al., 2017; Jiang et al., 2020; Cujó Blasco et al., 2023). Therefore, UAVs are increasingly being used in area mapping studies, topographic analysis, and built environment documentation at various regional scales.

Research developments in UAV mapping have also shown significant improvement over the past two decades. A number of studies show that UAVs are capable of producing geospatial products such as orthophotos, digital surface models (DSMs), and digital elevation models (DEMS) that have high resolution and can be used for various spatial analyses (Tsouros et al., 2019; Agate et al., 2026). These data products enable more detailed analysis of slope inclination, identification of water flow patterns, and evaluation of the relationship between topography and settlement patterns. In the context of regional planning, the availability of high-resolution spatial data is very important for understanding the morphological characteristics of an area and formulating regional development strategies that are more responsive to environmental conditions. However, despite these advancements, the application of UAV-derived data in supporting decision-making processes in planning practice remains limited.

Although UAV technology has been widely used in various regional mapping studies, there are still limitations in its use as an initial analysis tool in the rural area planning process. Many hilly areas in Indonesia still face limitations in terms of detailed spatial data that can be used as a basis for regional planning analysis. The available topographic data is generally on a regional scale, making it insufficient to describe the micro-topographic conditions required in the residential area design process. This situation means that the regional planning process is often carried out with limited spatial information. This gap indicates that existing studies have not sufficiently addressed how UAV-generated spatial data can be operationally integrated into planning analysis, particularly in rural areas with complex terrain.

This study is based on the hypothesis that the use of UAVs in the spatial data collection process can improve the accuracy of morphological information about an area while also increasing the efficiency of the survey process in areas with complex topography. To test this hypothesis, this study examines the use of UAVs in mapping activities in the Puspo Village, Purworejo Regency, which is part of the Southern Serayu Mountains geomorphological system. This area has a hilly topography with a network of rivers and a settlement pattern that follows the contours of the land. These conditions make this area a relevant location for evaluating the potential use of UAVs in supporting the spatial documentation process and preliminary analysis of area planning. This research contributes by proposing an integrative approach that not only evaluates the technical performance of UAV mapping in terms of accuracy and efficiency but also examines its role as an analytical tool in supporting spatial understanding and decision-making in regional planning contexts.

2. METHODS

This study uses an exploratory case study approach based on spatial analysis to evaluate the use of drones in the process of collecting site data for regional planning. The exploratory case study approach was chosen because this study seeks to understand spatial phenomena in depth in the context of a specific region with complex morphological characteristics. In regional planning and spatial analysis studies, the case study approach is often used to explore the relationship between the physical conditions of an area, spatial utilization patterns, and the dynamics of regional development on a local scale that cannot be fully explained through a macro statistical approach (Warsito, 2021; Rauzan & Yulianti, 2022). This approach allows researchers to empirically explore spatial phenomena contextually by utilizing various geospatial data sources (Andrew, 2020; Faldi et al., 2024). To ensure that the research design is grounded in established scientific practices, this study reviews previous UAV-based mapping studies and extracts their methodological implications. The synthesis is presented in Table 1 as a basis for defining the analytical approach and data processing workflow.

Table 1. Review of UAV-Based Research as a Basis for Methodological Framework

Researcher	Research Focus	Methods / Technologies	Key Findings	Relevance to This Study	Implication for Method Design
Agate et al. (2026)	UAV review for photogrammetry & remote sensing	UAV photogrammetry	UAVs produce high-resolution topographic data with high operational flexibility	Demonstrates UAV potential for spatial mapping	Supports the selection of UAV photogrammetry as the primary data acquisition method
Nex & Remondino (2014)	UAV for 3D mapping	UAV mapping and photogrammetry	UAVs are effective for 3D modeling and detailed topographic mapping	Supports UAV use in regional morphological analysis	Guides the use of UAV data for 3D spatial analysis and terrain interpretation
Remondino et al. (2017)	Status and development of UAV photogrammetry	SfM and UAV photogrammetry	UAVs produce accurate orthophotos, DSMs, and DEMs	Forms the basis of UAV mapping methodology	Establishes the use of SfM-based photogrammetric processing workflow
Tsouros et al. (2019)	Photogrammetric mapping using small UAVs	Small UAV photogrammetry	UAVs generate high-resolution geospatial data for spatial analysis	Supports UAV-based morphological analysis	Supports flight planning parameters and mapping workflow design
Jiang et al. (2020)	Efficiency of the Structure-from-Motion method	SfM processing of UAV imagery	SfM improves efficiency in surface model reconstruction	Supports data processing stage	Reinforces the selection of SfM for efficient data processing
Choi et al. (2023)	3D modeling of urban areas	UAV photogrammetry & spatial modeling	UAVs are effective for spatial analysis and built environment modeling	Relevant for settlement and morphology analysis	Supports integration of UAV data for analyzing settlement structures
Ferrer-González et al. (2020)	Accuracy of terrain mapping using UAVs	UAV photogrammetry	UAVs provide high topographic accuracy	Supports evaluation of mapping accuracy	Guides the inclusion of spatial accuracy validation in the analysis
Fernández-Hernandez et al. (2014)	UAV mapping on complex landscapes	High-resolution UAV photogrammetry	UAVs are effective in complex landscapes	Relevant to hilly terrain context	Supports the application of UAV in complex topographic conditions

In addition, high-resolution geospatial data-based spatial analysis is increasingly being used in regional planning studies to understand the relationship between land morphology, settlement structures, and regional development processes in greater detail. This approach allows for the integration of various data sources such as aerial imagery, digital topographic models, and field observations in the regional planning analysis process (Warsito, 2021; Faldi et al, 2024). In the context of UAV-based mapping, the spatial analysis approach also enables the evaluation of geospatial data accuracy and the interpretation of spatial patterns generated from photogrammetry products such as orthophotos, digital elevation models (DEM), and digital surface models (DSM) (Agate et al., 2026; Remondino et al., 2017).

The research site is located in Padukuhan Puspo, Purworejo Regency, Central Java, which is part of the Southern Serayu Mountains geomorphological system. The research area has a hilly topography with slope gradients varying between 15–35 degrees and a settlement pattern that follows the land contours. The research was conducted from April to June 2025, covering an observation area of approximately 35 hectares, which included residential areas, agricultural land, local road networks, and river systems that crossed the hamlet and the surrounding riverbanks. The existence of these hydrological elements is an important part of the observation object because the topography of the hilly area is greatly influenced by water flow patterns, slope erosion, and land use in the riverine zone.

Data collection was carried out through an integrated geospatial survey approach that combined aerial mapping using UAVs, field observations, and documentation of the condition of the area. UAV surveys were used to obtain high-resolution aerial imagery, which was then processed using photogrammetry techniques to produce orthophotos and digital topographic models of the area. Field observations were conducted to verify the topography, settlement patterns, and landscape characteristics such as slopes and river flows identified in the aerial images. Visual documentation of the area and recording of the survey's operational time and costs were carried out to support the analysis of the efficiency of the survey method used. These data collection stages are in line with the UAV mapping methodology commonly used in topographic mapping and spatial analysis studies, where the processes of aerial image acquisition, field verification, and photogrammetric processing are carried out in an integrated manner to produce accurate geospatial data (Agate et al., 2026; Remondino et al., 2017; Mesas-Carrascosa et al., 2015).

To provide a clearer operational framework, the UAV mapping process in this study was carried out through a series of systematic and sequential stages. The first stage is flight planning, which involves determining the survey boundaries, defining flight altitude, setting overlap parameters (forward and side overlap), and designing flight paths using grid-based patterns in drone mapping software. This stage ensures that the entire study area is covered efficiently and that sufficient image overlap is achieved for photogrammetric reconstruction (Tsouros et al., 2019; Mesas-Carrascosa et al., 2015).

The second stage is aerial data acquisition, in which the UAV is operated to capture aerial images following the predefined flight plan. During this stage, image acquisition is conducted at a controlled altitude with consistent flight speed to maintain image quality and overlap consistency. Multiple flight missions are performed to ensure complete coverage of the study area, particularly in areas with varying topographic conditions such as slopes and river corridors (Fernández-Hernandez et al., 2014; Nex & Remondino, 2014).

The third stage is photogrammetric data processing, which involves processing the collected aerial images using photogrammetric modeling software based on Structure-from-Motion (SfM) techniques. This stage includes image alignment, point cloud generation, mesh construction, and orthorectification processes to produce geospatial outputs such as orthophotos, Digital Elevation Models (DEM), and Digital Surface Models (DSM). These outputs provide detailed representations of the terrain and built environment (Remondino et al., 2017; Jiang et al., 2020; Cujó Blasco et al., 2023).

The fourth stage is field verification and validation, where the UAV-derived spatial data are compared with actual field conditions through direct observation. This step is conducted to ensure the consistency and reliability of the generated spatial data, particularly in identifying topographic features, settlement patterns, and environmental elements such as river flows and vegetation cover (Agate et al., 2026; Ferrer-González et al., 2020).

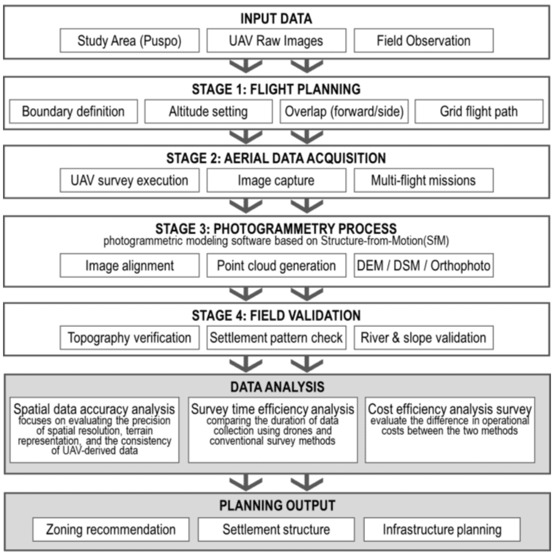

Figure 1. Research Workflow of UAV-Based Spatial Data Acquisition and Analysis

The diagram illustrates the multi-stage workflow of the study, starting from data input, UAV flight planning, aerial data acquisition, photogrammetric processing using Structure-from-Motion (SfM), field validation, spatial analysis, and final planning outputs (Fig. 1). This framework demonstrates the integration of UAV-derived geospatial data into spatial planning processes. Data analysis was conducted using three main interrelated approaches. First, spatial data accuracy analysis was performed to assess the level of accuracy of UAV mapping results compared to manual survey methods commonly used in area mapping. This analysis focuses on evaluating the precision of spatial resolution, terrain representation, and the consistency of UAV-derived data with observed field conditions. Second, survey time efficiency analysis was performed by comparing the duration of data collection using drones and conventional survey methods, including preparation, field operation, and data acquisition stages. Third, a cost efficiency analysis survey was conducted to evaluate the difference in operational costs between the two methods, including equipment usage, labor requirements, and survey duration. These three analyses were used in an integrated manner to assess the extent to which the use of UAVs can improve the effectiveness of spatial data collection processes in supporting regional planning.

3. RESULTS AND DISCUSSION

3.1. UAV Technical Data and Data Acquisition Process

The results of the study show that the use of drones can produce high-detail spatial data of the Puspo Hamlet area in a relatively short survey time. The drone used in this study was the DJI Phantom 4 Pro, a UAV commonly used in photogrammetric mapping due to its flight stability and camera sensor quality. This drone has a maximum flight duration of approximately 30 minutes per battery and is supported by one main battery and three spare batteries, allowing several flight missions to be carried out consecutively during field survey activities. The drone's operational range is around 20–50 km, depending on environmental conditions and the stability of the control system connection. These specifications enable stable aerial imaging in hilly areas with complex topography. Based on field documentation, the main take-off point is located in the courtyard of SD Puspo, which serves as the flight control center for several mapping routes (Fig. 2). The drone is equipped with a 48 MP high-resolution camera, 4K video recording capability, and a three-axis gimbal stabilization system that enables stable aerial imaging in various flight conditions.

Data collection was carried out via three main flight routes designed with consideration of the morphological conditions of the area and important objects that needed to be documented spatially. The first route followed the course of the Puspo River from the Puspo Elementary School yard to several important points identified by the local community, namely the dam, Watu Tumpeng, and bridges along the river. This route covers a distance of approximately ±2 km, with a flight altitude of around 150 m and a flight duration of around 25 minutes.

Figure 2. UAV Operation Activities During Field Surveys in Padukuhan Puspo

The second route focused on documenting residential areas, particularly cemeteries, mosques, and parking areas located around community activity centers. The flight was conducted at a distance of approximately ±500 m from the Puspo Elementary School yard, at an altitude of 50–80 m and lasted for about 15 minutes.

The third route was carried out by moving the takeoff point closer to the dam area to obtain aerial images with a higher level of detail. On this route, the drone was flown at a distance of approximately 250 m from the dam, with flight heights varying between 30–120 m and a duration of approximately 20 minutes. This approach allows for more detailed spatial documentation of the dam structure and the morphology of the surrounding area. However, this type of drone still has operational limitations, particularly in terms of relatively limited battery life (approximately 30–34 minutes per flight) and sensitivity to strong wind conditions in hilly areas (Table 2).

The data collection process was carried out in several technical stages. The first stage was flight planning using drone mapping software with a grid flight pattern to ensure that the entire research area was systematically covered. The second stage is aerial imaging at a flight altitude of approximately 120 meters and a photo overlap rate of approximately 80% (forward overlap) and 70% (side overlap) to ensure the quality of photogrammetric reconstruction. Through this survey process, approximately ±850 aerial images were obtained through three flight missions to cover the entire research area of ±35 hectares. With this flight configuration, the spatial resolution of the images or ground sampling distance (GSD) produced ranged from 3–5 cm/pixel.

Table 2. Technical Parameters of UAV Surveys in Research Areas

Survey Parameters	Value / Specifications
Types of UAVs	DJI Phantom 4 Pro
Camera resolution	48 MP
Flying altitude	30–150 m (varies depending on the route)
Maximum flight duration	Approximately 30 minutes per battery
Number of batteries	1 primary + 3 backups
Forward overlap	±80%
Side overlap	±70%
Flight route	3 routes (river, residential area, dam)
Mapping area	±35 hectares

These flight parameters follow common practices in photogrammetry-based UAV mapping, which aims to produce aerial images with high spatial resolution and sufficient overlap for the Structure-from-Motion reconstruction process. The third stage is image processing using photogrammetry software to produce orthophotos and digital topographic models of the area through the Structure-from-Motion (SfM) reconstruction process.

3.2. Obstacles and Successes in the Data Collection Process

In addition to vegetation and topography, several technical challenges also arose during the UAV flight process in the field. Based on flight operational records, during the initial stages of drone operation, there were connectivity issues marked by a "strong interference" warning on the control system. This condition required the operator to move the takeoff point to another location until the connection between the drone, remote controller, and mobile device was stable. After relocating the flight point, the system connected successfully, and the flight was able to continue normally. In addition, during one flight on the first route following the course of the Puspo River, the drone lost signal for about two minutes. However, the UAV's return-to-home system worked well, allowing the drone to automatically return to its initial flight point in the Puspo Elementary School yard without damage or data loss. This incident highlights the importance of automatic safety features on UAVs in supporting survey activities in areas with complex topography and higher potential for signal interference.

During the field data collection process, several factors affected the quality of aerial imagery acquisition. GPS signal conditions at the research site were relatively stable, allowing for smooth drone navigation. This enabled the drone to follow its planned flight path with sufficient precision.

However, in some areas with high vegetation density, especially in forests and mixed plantations, the image acquisition process becomes more challenging because part of the ground surface is covered by tree canopy. This condition has the potential to affect the readability of topographic details at some points.

The condition of slopes in the area, which have a gradient of around 15–35° and are classified geomorphologically as steep to very steep, did not pose a significant obstacle to the mapping process because drones were able to capture aerial images from various angles that were difficult to reach through ground surveys. Operational experience in the field shows that despite minor technical disturbances such as signal interference or the need to relocate takeoff points, UAV technology is still able to operate relatively stably in hilly areas. These findings indicate that automatic navigation systems, flight stabilization, and safety features such as return-to-home play an important role in maintaining the sustainability of aerial mapping operations in environments with complex topography. This shows that UAV technology has great potential for use in areas with complex land morphology.

3.3. Data Generated from the Mapping Process

Aerial image processing produced several key spatial data products (Table 3). The first product was a high-resolution orthophoto of the area that clearly showed settlement patterns, local road networks, and land use in the hamlet.

The second product is a digital topography model in the form of a digital elevation model (DEM) and digital surface model (DSM) that can visualize land contours in detail. Based on the results of photogrammetry processing, the DEM model produced has a horizontal accuracy of approximately ±10 cm and a vertical accuracy of approximately ±15 cm. This level of accuracy is sufficient for morphological analysis of hilly areas on a residential area planning scale. The resulting topographic model also allows for the identification of slope variations, water flow patterns, and the relationship between the settlement network and the topographic structure of the area. With such high spatial resolution, UAV data provides much more detailed topographic information than conventional topographic maps, which are generally available on a regional scale. The spatial data is then used as the basis for analysis in the research discussion stage.

Table 3. Spatial Data from UAV Mapping

Data Products	Resolution / Accuracy	Analysis Function
Orthophoto	±3–5 cm/pixel	Interpretation of land use, identification of settlement patterns, road networks, and spatial elements of the area
Digital Elevation Model (DEM)	Horizontal accuracy ±10 cm; vertical accuracy ±15 cm	Slope gradient analysis, identification of water flow patterns, and evaluation of residential land suitability
Digital Surface Model (DSM)	±10–15 cm	Morphological analysis of the area, the relationship between topography and settlement structure, and identification of land cover

3.4. Spatial Data Accuracy Analysis

Analysis of spatial data accuracy shows that mapping using drones can produce spatial data with higher resolution than manual survey methods based on sample point measurements. In the results of mapping an area of ±35 hectares in Padukuhan Puspo, the orthophoto produced shows spatial details down to the micro level, such as yard boundaries, neighborhood roads, small drainage networks, and changes in land surface texture on slopes and riverbanks (Fig. 3). This visual accuracy shows that high-resolution aerial imagery allows for a more detailed interpretation of the morphology of an area compared to conventional topographic data, which is generally only based on limited measurement points. This finding is in line with previous studies showing that UAV photogrammetry technology can produce high-resolution topographic data with a high level of accuracy at the regional scale and can even achieve centimeter accuracy under certain mapping conditions (Agate et al., 2026; Nex & Remondino, 2014; Remondino et al., 2017).

Figure 3. Orthophotography of the Padukuhan Puspo Residential Area, the Dam Area, and the Kali Jali River Basin, Mapped Using UAV Technology
Source: Survey Documentation, 2026.

In addition, the Structure-from-Motion (SfM) method used in UAV image processing enables accurate reconstruction of surface models of an area through the integration of various overlapping aerial images, resulting in a geometrically consistent digital surface model. This process enables the creation of digital elevation models (DEM) and digital surface models (DSM) that describe the topographical variations of hilly areas in greater detail than manual mapping. Several studies have shown that the UAV-based SfM approach can improve the quality of topographic reconstruction and land morphology analysis at various research scales, including for mapping residential areas and built environments (Jiang et al., 2020; Tsouros et al., 2019; Hu & Minner, 2023; Pham et al., 2025). In addition to improving the accuracy of spatial data, this approach also allows the integration of various types of geospatial data for more comprehensive regional planning analysis, such as slope analysis, identification of settlement development patterns, and evaluation of spatial suitability in hilly areas (Agate et al., 2026; Cujó Blasco et al., 2023; Kovanič et al., 2023; Turner et al., 2016).

The spatial data generated from UAV mapping demonstrate a high level of detail in representing terrain conditions and settlement structures. The orthophoto with a spatial resolution of 3–5 cm/pixel enables clear identification of building footprints, road networks, vegetation cover, and river boundaries, while the Digital Elevation Model (DEM) provides an accurate representation of elevation variations for interpreting slope gradients and terrain morphology. Compared to conventional survey methods, which rely on limited measurement points and generalized topographic maps, UAV-derived data offer a more consistent and detailed spatial representation. Field verification results further indicate that the UAV data are highly consistent with actual site conditions, confirming their reliability for spatial analysis in regional planning (Remondino et al., 2017; Ferrer-González et al., 2020).

3.5. Analysis of Time and Cost Efficiency of Surveys (Comparison of UAV and Conventional Survey Methods)

From an operational efficiency perspective, the use of UAVs has been proven to significantly accelerate the field data collection process while reducing the need for survey resources. Based on the results of the study, mapping an area of ±35 hectares can be completed in approximately two days through three UAV flight missions with a total of ±850 aerial images. In comparison, manual surveys of hilly areas with similar size and topography generally require more than one week, as the measurement process must be carried out gradually by collecting topographic points in the field. These findings are consistent with previous studies showing that UAV-based mapping can significantly improve the efficiency of spatial data acquisition in complex landscapes (Agate et al., 2026; Nex & Remondino, 2014).

In addition to accelerating data acquisition, UAV-based photogrammetry also enhances efficiency through digital data processing using the Structure-from-Motion (SfM) method. This approach enables systematic topographic reconstruction without requiring extensive field measurements, thereby reducing both processing time and operational complexity (Remondino et al., 2017; Jiang et al., 2020). As a result, efficiency is achieved not only during the data acquisition stage but also in the subsequent data processing phase, making UAV-based surveys more effective compared to conventional methods. This integrated workflow allows for a more streamlined transition from raw data to analytical outputs, minimizing manual intervention and potential human error during data processing. Furthermore, previous studies have demonstrated that SfM-based photogrammetry not only improves processing efficiency but also enhances the consistency and reproducibility of spatial data products across different survey conditions (Tsouros et al., 2019; Cujó Blasco et al., 2023). In the context of regional planning, this capability enables faster generation of reliable spatial information, which is essential for supporting timely and evidence-based decision-making, particularly in areas with dynamic environmental and topographical conditions (Faldi et al., 2024; Kovanič et al., 2023).

Table 4 shows that UAV-based surveys provide clear advantages over conventional survey methods across multiple operational aspects. In terms of survey time, UAV mapping significantly reduces fieldwork duration from more than one week to approximately two days. In terms of area coverage, UAV surveys are capable of capturing large areas within a single flight cycle, whereas conventional methods require gradual data collection. Furthermore, UAV surveys require fewer personnel and enable fully digital data processing, resulting in higher spatial resolution outputs such as orthophotos, DEM, and DSM. These differences demonstrate that UAV-based mapping offers a more efficient and scalable approach for spatial data acquisition, particularly in areas with complex topographical conditions.

Table 4. Comparative Analysis of the Efficiency of UAV Surveys and Conventional Surveys in Hilly Areas.

Comparative Aspects	UAV survey	Conventional Survey
Data acquisition method	Automatic aerial imaging via flight paths and photogrammetry processing	Gradual field point measurement using topographic survey equipment
Survey area coverage	Can cover a large area in a single flight cycle	The coverage area is relatively limited and must be carried out gradually.
Field survey time	Approximately 2 days to map approximately 35 hectares with 3 flight missions and approximately 850 aerial images	>1 week for similar areas and topographical conditions
Survey personnel requirements	Small team (drone operator and field observer)	Larger survey team for topographic point measurements
Data processing	Digital processing using the Structure-from-Motion method to produce orthophotos and topographic models	Data processing based on field measurement points and contour interpolation
Spatial data products	High-resolution orthophotos, DEM, and DSM with high spatial detail	Contour maps based on measurement points with more limited spatial resolution

From an operational perspective, time efficiency directly contributes to cost efficiency. UAV-based surveys require fewer personnel and shorter fieldwork duration, resulting in lower operational costs compared to conventional methods, which typically involve larger survey teams and longer survey periods. This efficiency is particularly significant in hilly areas such as Padukuhan Puspo, where terrain conditions increase the complexity and cost of manual surveys. These findings are consistent with previous studies highlighting the advantages of UAV technology in improving both time and cost efficiency in regional mapping (Tsouros et al., 2019; Ferrer-González et al., 2020; Sishodia et al., 2020). In future developments, autonomous and networked drone systems also have the potential to further enhance survey efficiency and scalability (Cabuk et al., 2022).

3.6. Implications for the Area Design Process

The implications for the area design process show that spatial data generated by drones provides important information for understanding the morphology of hilly areas. Information about slope gradients, water flow patterns, and settlement distribution enables planners to formulate development zoning strategies that are more responsive to topographical conditions. These findings are in line with various studies showing that high-resolution topographic data from UAVs can improve the quality of spatial analysis in regional planning, especially in areas with complex land morphology that are difficult to map through conventional surveys (Dadrass Javan et al., 2025; Medeiros et al., 2023; Kovanič et al., 2023). With such detailed spatial data, planners can identify the relationship between settlement structures and physical landscape conditions more accurately, thereby making the spatial planning process more site based.

This diagram (Fig. 4) illustrates how data obtained through UAV surveys (orthophotos, DEM, and DSM) is transformed through spatial analysis processes such as slope analysis, settlement pattern identification, and hydrological system analysis (Warsito, 2021; Faldi et al., 2024). The results of these analyses are then used as a basis for developing zoning strategies, designing regional infrastructure networks, and evaluating land suitability in the regional planning process.

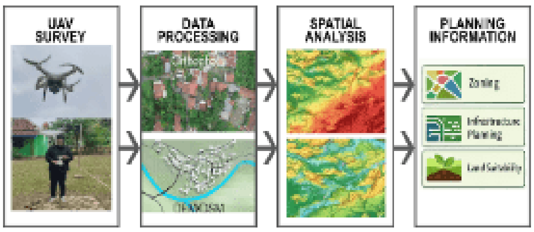

Figure 4. Framework for Transforming UAV Data into Regional Planning Information

In addition, the resulting digital topography model also assists in designing regional infrastructure systems such as road networks, drainage systems, and settlement arrangements that are adapted to the characteristics of the slopes. In the context of hillside area planning, information on elevation variations and slope gradients is an important factor in determining the direction of infrastructure development and mitigating potential environmental risks. Several studies show that the integration of UAV data with digital topography analysis can improve planners' ability to evaluate land suitability and design infrastructure that is more adaptive to terrain conditions (Turner et al., 2016; Cujó Blasco et al., 2023; Agate et al., 2026). Thus, the use of UAVs not only improves the quality of spatial data collection but also contributes directly to improving the quality of regional planning processes.

Furthermore, the availability of high-resolution spatial data from UAVs also enables the planning evaluation process to be more evidence-based. Detailed information on slope variations, landscape structures, and the relationship between settlements and local hydrological systems, including river flows and riparian zones, can be used to identify areas that are potentially at risk of environmental hazards such as slope erosion or local flooding (Faradila et al., 2024; Rauzan & Yulianti, 2022). By utilizing this data, planners can formulate more environmentally adaptive area development guidelines, for example, through the determination of safe development zones, the regulation of settlement density on slopes, and the planning of infrastructure systems that follow the natural contours of the area. This approach is in line with research findings on UAV mapping, which emphasize that the integration of UAV-based photogrammetry with spatial analysis enables a more comprehensive evaluation of landscape conditions and supports the process of making decisions based on accurate geospatial data (Tsouros et al., 2019; Ferrer-González et al., 2020; Fernández-Hernandez et al., 2014; Curcio et al., 2022; Remondino et al., 2017). Thus, the integration of UAV data in the planning process not only improves the accuracy of spatial analysis but also strengthens planners' capacity to formulate more informed and sustainable area development strategies in hilly regions.

The spatial data generated from UAV mapping, particularly the Digital Elevation

Model (DEM), provides a critical basis for understanding the morphological structure of the study area. Unlike conventional topographic data, the DEM derived from UAV photogrammetry enables detailed representation of elevation variations at a micro-topographic scale (Remondino et al., 2017; Cujó Blasco et al., 2023). This level of detail allows for more precise identification of slope gradients, terrain discontinuities, and hydrological flow patterns, which are essential for spatial interpretation in hilly settlements (Tsouros et al., 2019; Ferrer-González et al., 2020). Therefore, the DEM is not only used as a representation of terrain, but also as a primary analytical layer that supports the transformation of raw spatial data into planning-relevant information (Agate et al., 2026; Kovanič et al., 2023).

This diagram (Fig. 5) illustrates the analytical transformation of DEM-derived data into morphological understanding and planning-relevant outputs. The process begins with the extraction of elevation data from the UAV-generated DEM, which is subsequently analyzed to derive slope gradients, terrain classification, and hydrological flow patterns (Remondino et al., 2017; Jiang et al., 2020). These analytical layers enable the identification of key morphological characteristics of the area, including steep slopes, valley structures, river corridors, and relatively stable zones suitable for development (Tsouros et al., 2019; Ferrer-González et al., 2020).

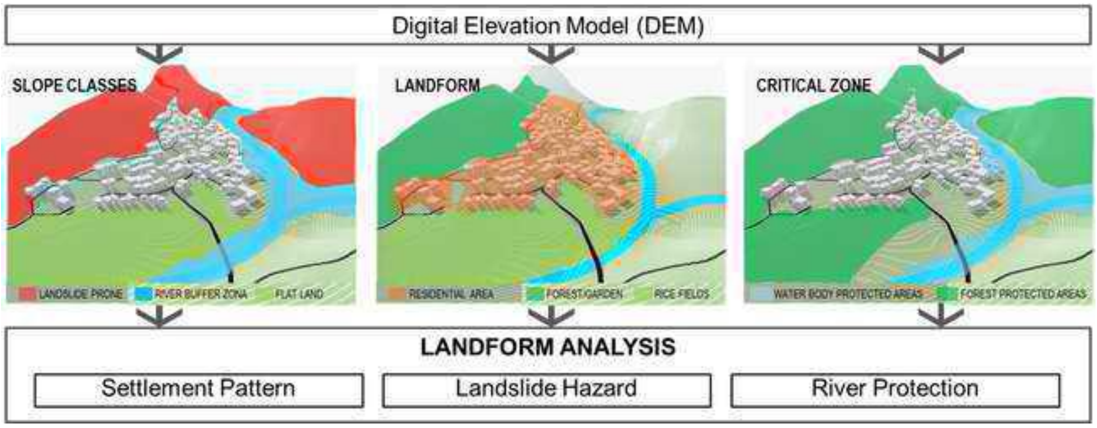

Figure 5. DEM-Based Regional Morphological Analysis Scheme

Furthermore, the integration of slope analysis and hydrological interpretation allows for a more comprehensive understanding of the spatial relationship between topography and settlement distribution (Choi et al., 2023; Cujó Blasco et al., 2023). In the case of Padukuhan Puspo, the settlement pattern is strongly influenced by terrain conditions, where built structures tend to follow contour lines and avoid areas with high slope gradients or proximity to riverbanks. This indicates that morphological constraints play a significant role in shaping spatial configurations in hilly rural settlements, particularly in environments where terrain and hydrological systems directly influence land use patterns (Fernández-Hernandez et al., 2014; Agate et al., 2026).

The results of this analysis are then translated into planning implications, including the identification of suitable zones for development, areas requiring environmental protection, and zones with potential risk related to slope instability or water flow (Kovanič et al., 2023; Faldi et al., 2024). Thus, the DEM-based analysis framework presented in Figure 4 demonstrates how UAV-derived spatial data can be systematically transformed into decision-support information for regional planning. This finding reinforces the role of UAV mapping not only as a data acquisition tool but also as a critical analytical instrument in understanding and managing complex landscape conditions (Nex & Remondino, 2014; Tsouros et al., 2019).

4. CONCLUSION

This study demonstrates that the use of UAVs in regional planning surveys effectively addresses the research gap identified in the introduction, namely the limited availability of detailed spatial data in hilly areas and the lack of empirical evaluation comparing UAV-based surveys with conventional methods. The findings confirm that UAV mapping in an area of approximately ±35 hectares in Padukuhan Puspo is capable of producing high-resolution spatial data with a ground sampling distance of 3–5 cm/pixel, as well as digital topographic models with horizontal accuracy of approximately ±10 cm and vertical accuracy of ±15 cm. These results indicate that UAV technology provides a significantly more detailed and reliable representation of terrain morphology compared to conventional survey methods, which are generally based on limited measurement points.

In addition to improving the accuracy of spatial data, this study also shows an increase in the efficiency of the survey process. The process of mapping the same area can be completed in about two days through three UAV flight missions with a total of approximately ±850 aerial images, whereas conventional surveys in areas with similar topographical characteristics generally take more than a week. These results confirm the research hypothesis that the use of UAVs in steeply contoured areas can improve the efficiency of spatial data collection while reducing the need for field survey resources.

More importantly, this study demonstrates that UAV-derived spatial data can be effectively integrated into the regional planning process. The orthophoto, DEM, and DSM produced enable a more comprehensive understanding of terrain morphology, settlement patterns, and land suitability, thereby supporting more accurate, site-responsive, and evidence-based planning decisions (Faradila et al., 2024; Liu & Suzuki, 2023). This confirms that UAV mapping not only improves data acquisition performance but also enhances the analytical capacity of planners in interpreting spatial conditions and formulating appropriate development strategies in hilly areas.

Overall, the findings of this study indicate that UAV technology plays a dual role as both a high-precision spatial data acquisition tool and a decision-support instrument in regional planning. By simultaneously improving data accuracy, survey efficiency, and analytical capability, UAV-based mapping contributes directly to enhancing the overall performance of the regional planning process in complex topographical environments.

Further research may focus on developing the integration of UAV-derived data with digital modeling systems, such as Geographic Information Systems (GIS) and Building Information Modeling (BIM), to support a more integrated and data-driven spatial planning process. In addition, the implementation of networked multi-UAV collaboration has the potential to enhance large-scale field operations by improving spatial coverage, operational efficiency, and data acquisition reliability (Cabuk et al., 2022). Moreover, the advancement of artificial intelligence–based analytical methods offers significant potential to enable automated processing of UAV data and to accelerate spatial interpretation, thereby strengthening evidence-based decision-making in spatial planning practices.

AUTHOR CONTRIBUTIONS

Conceptualization: ET, ES. Methodology: ET, LSP. Data collection and field survey: LSP, ES, AB. UAV operation and technical data acquisition: LSP. Data processing and spatial analysis: AB, ET. Visualization: AB. Writing (original draft preparation): ET. Writing (review and editing): ES, AB. Supervision: ES. All authors have read and agreed to the published version of the manuscript.

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