

Article

Assessing the Capabilities of UAV-Based Observation for Marginalized Communities: A Case Study of Roma Settlements in Slovakia

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Highlights

What are the main findings?

- A UAV-based methodological framework enables multi-scalar analysis of marginalized settlements by integrating high-resolution imagery, field observations, and stakeholder engagement.
- UAV-derived data effectively detect settlement morphology, infrastructure deficiencies, environmental hazards, and thermal inequalities at centimeter-level spatial resolution.

What are the implications of the main findings?

- The framework supports evidence-based planning and targeted interventions to improve living conditions in marginalized settlements.
- Integrating ethical considerations, community engagement, and regulatory awareness demonstrates a responsible approach to UAV-based.

Abstract

This study assesses the capabilities of UAV-based Earth observation for analyzing marginalized communities, using Roma settlements in southeastern Slovakia as a case study. Marginalized populations are often underrepresented in official spatial datasets, resulting in a limited understanding of their living conditions, infrastructure needs, and environmental risks. To address this gap, we propose a multi-scalar, UAV-based observational approach that bridges the limitations of coarse satellite imagery and logistically constrained ground surveys. High-resolution RGB and thermal imagery were acquired across three settlements with varying spatial characteristics and processed using photogrammetric workflows to generate detailed orthophotos and spatial products. The results demonstrate that UAV data with centimeter-level spatial resolution enable precise mapping of settlement morphology, infrastructure, waste distribution, and thermal inequalities. Furthermore, UAV observations enable change detection and environmental risk assessment at scales that are not achievable with conventional remote sensing. However, the study also highlights critical operational and ethical challenges, including regulatory constraints, privacy concerns, and the need for community engagement. By integrating technical evaluation with socially



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sensitive research practices, this work proposes a methodological framework for responsible UAV deployment in marginalized contexts. The findings underscore the potential of UAV-based observation to improve spatial visibility and support evidence-based planning while emphasizing the importance of ethical implementation.

Keywords: Unmanned Aerial Vehicles; marginalized communities; Roma settlements; data fusion; ethical geospatial research; community engagement

1. Introduction

The use of Unmanned Aerial Vehicles (UAVs) in environmental and social research has expanded significantly in recent years, offering new opportunities for collecting high-resolution spatial data in areas where traditional surveying methods are limited or impractical [1,2]. Among the population groups that can particularly benefit from these advancements are marginalized and underserved populations, including Roma people. These communities often reside in informal or rapidly evolving environments and in concentrated settlements at the outskirts of villages, where they are isolated from the majority population by natural barriers such as forests and rivers, or by man-made structures such as fences, train tracks, waste collection sites, and factories [3]. Also, they are often not reached by municipal drinking water, sanitation, waste management, and health-promoting services, which leads to increased exposure to pathogens and resulting disease exposure [4]. In these regions, official spatial data is outdated, incomplete, or entirely unavailable. As a result, the lack of comprehensive, high-quality spatial data on marginalized populations makes it difficult to document their living conditions, infrastructure needs, and environmental vulnerabilities, leaving these factors poorly understood and insufficiently documented [5]. This gap hinders effective planning, resource allocation, and policy development.

UAVs provide a flexible, cost-effective, and minimally intrusive means of capturing detailed spatial information at scales relevant to community-level analysis. High-resolution aerial imagery and 3D models generated from UAV flights can provide valuable insights into settlement structure, housing conditions, public service accessibility, environmental health risks, and land-use changes [6,7]. When combined with participatory approaches and ground-based socio-economic data, UAV-based observations can support evidence-based decision-making and more targeted interventions [8]. However, the use of UAVs in marginalized contexts also raises important considerations regarding privacy, representation, consent, and engagement. Responsible implementation, therefore, requires collaboration with communities, transparency of purpose, and sensitivity to local social dynamics to ensure that technology contributes to empowerment rather than surveillance or further exclusion.

Despite the rapidly expanding capabilities of UAV technologies in environmental monitoring and spatial analysis, their application in research on marginalized populations and infrastructure needs remains comparatively underexplored [9]. In particular, there is a limited systematic assessment of how UAV-derived spatial data can be responsibly integrated into community-focused research, planning, and policy processes. While UAVs have demonstrated considerable value in fields such as disaster response, environmental monitoring, and informal settlement mapping, their potential to support the documentation and analysis of marginalized communities in Europe has received little scholarly attention.

This paper conducts a comprehensive capability assessment of UAV-based observation for studying marginalized populations, using Roma settlements as a case study, while extending UAV applications beyond conventional environmental and engineering domains

into socially sensitive contexts. Using centimeter-resolution RGB and thermal imagery acquired across three Roma settlements, the analysis identified 149 individual buildings, documented settlement expansion of approximately 5–15% between 2017 and 2024, detected 64 unmanaged waste accumulation sites, and revealed pronounced microscale thermal variability associated with housing and environmental vulnerability. Beyond demonstrating these capabilities, the study seeks to answer three research questions:

RQ1: To what extent can UAV-derived RGB, thermal, and elevation data provide detailed information on the physical, environmental, and infrastructural characteristics of marginalized settlements beyond what is achievable using conventional Earth observation data?

RQ2: Which settlement characteristics—including housing morphology, settlement expansion, waste accumulation, and thermal variability—can be systematically identified through UAV-derived observations to support environmental and public health assessments?

RQ3: What are the practical, operational, and ethical considerations that influence the responsible use of UAVs for research and evidence-based planning in marginalized communities?

2. Literature Review

2.1. Overview of Roma Studies (*Demographics, Marginalization, Spatial Dynamics*)

The Roma, often described as Europe's largest ethnic minority, are a heterogeneous group originating in Northern India, who migrated westwards from around the 11th century [10], entering Europe in Bulgaria, and settling there, in Romania, Hungary, Slovakia, and Serbia [11,12]. The Roma number about 11 million, or 1.35% of the total population of Europe, with the majority of Roma still residing in these countries of primary settlement in the southeastern part of Europe. The term Roma encompasses diverse groups, including Roma, Gypsies, Travellers, Manouches, Ashkali, Sinti and Boyash [4,13]. Estimates vary widely due to underreporting and contested census practices [13]. Despite their presence across multiple states, the Roma have long been subjected to structural exclusion, anti-Gypsyism, and discriminatory policies that manifest in limited access to education, healthcare, employment, and adequate housing [4].

A significant strand of Roma studies has explored the spatial dimensions of exclusion. Roma communities are often geographically segregated, residing in informal settlements on urban peripheries or in rural enclaves with limited infrastructural integration [14,15]. This spatial marginality is both a result and a reinforcement of socio-political exclusion. The physical invisibility of many Roma settlements on official maps contributes to their neglect in urban planning, infrastructure development, and public policy.

Research in this area has emphasized the need for alternative methodologies that can both map and make the lived realities of Roma communities visible. However, current approaches remain constrained by outdated or incomplete data, often collected through extractive or top-down methodologies. A new generation of research must therefore consider innovative tools—such as UAVs—that can ethically document spatial configurations and environmental conditions while engaging Roma voices in knowledge production.

A recent systematic scoping review capturing the state of the art of water and health insecurity assessment in Roma communities in Europe [5] found that existing studies fail to unlock the full potential of geoinformation to, e.g., carry out spatial analysis of risks, but rather use geodata only to describe the study area [16,17]. While geospatial tools, data, and analyses could help better understand environmental and health challenges in marginalized communities, e.g., by detecting waste collection sites or hazardous waterways that are not fully exhausted, this entails a missed opportunity to benefit assessments.

2.2. UAVs in Social Science and Spatial Studies

UAVs, or drones, have become increasingly prevalent in human geography, anthropology, and development studies due to their ability to capture high-resolution spatial data quickly and cost-effectively. Initially used primarily in environmental science and military applications, UAVs have since been adopted by social scientists to conduct participatory mapping, disaster assessment, and spatial ethnography [18].

UAVs offer several advantages in spatial research: they allow for flexible, fine-grained data collection over large or difficult-to-access areas; they can produce both quantitative and visual data (e.g., orthophotos, 3D models); and they facilitate novel forms of community engagement when integrated into participatory research designs [19]. These tools are particularly promising in contexts where marginalized communities live in unregistered or informal settlements that are excluded from conventional GIS databases.

Nevertheless, UAV research remains unevenly applied in the social sciences, particularly in the study of marginalized ethnic groups in Europe. Roma, despite their spatial vulnerability, have not yet been the focus of any known UAV-based academic research—a gap this paper aims to begin addressing.

Case Studies Using UAVs for Marginalized Communities

Existing case studies of UAV deployment in marginalized contexts offer instructive insights. For instance, UAVs have been used to document environmental hazards in indigenous territories in the Amazon basin [20], to map water points in rural Malawi [9], and to assess post-disaster recovery in refugee camps in the Middle East [21]. In each of these contexts, UAVs have improved data accuracy, enabled more responsive humanitarian interventions, and provided marginalized communities with new tools for self-representation.

These examples suggest that UAV deployment must be embedded within locally grounded, ethically reflexive research frameworks—a lesson highly relevant for work with Roma populations, who have historically been the subject of top-down surveillance and intervention.

2.3. UAV Applications in Urban Anthropology and Human Geography

Urban anthropology and human geography have increasingly adopted UAVs to study dynamic spatial phenomena—from gentrification and land use change to environmental degradation and infrastructural inequality. Scholars have used UAVs to examine the spatial distribution of informal housing, urban agriculture, waste systems, and micro-ecologies, particularly in Global South contexts [19,20]. These disciplines emphasize the interplay among space, power, and lived experience, making UAVs a compelling tool for supplementing ethnographic methods or community-based research.

Yet, in European contexts, UAVs have rarely been applied in studies of ethnic or socioeconomically marginalized communities and have not been used in environmental (health) risk assessment. There is a substantial gap in integrating UAV data with qualitative, ethnographic understandings of place—a methodological innovation that would be especially useful in researching the Roma, whose spatial environments are closely tied to political marginality, cultural identity, and strategies of resistance—and where the potential to use the resulting evidence to develop and improve targeted interventions, e.g., for health promotion and social justice, is tremendous.

2.4. Methodological Innovations and Gaps

Despite growing interest in UAVs, few studies have integrated these technologies into participatory, community-driven research paradigms. Many UAV-based studies remain technocratic in design, prioritizing efficiency over inclusion and often lacking sustained en-

agement with the people whose spaces are being mapped. This is particularly problematic in research on marginalized groups, where the power asymmetries between researchers and participants are already significant—and where information on place could be used in ways that harm them (un)intentionally.

Moreover, while UAVs have been widely used for environmental or structural assessments, their integration into social studies, everyday practices, and cultural landscapes remains underdeveloped. There is also a methodological gap in combining UAV-generated spatial data with ground-level ethnographic insights, such as oral histories, kinship networks, or spatial narratives.

This paper proposes a hybrid methodology that addresses these gaps—utilizing UAVs not only as mapping tools, but also as instruments of participatory visibility, designed in dialogue with Roma community members and contextualized within broader anthropological inquiry.

2.5. Ethical and Legal Considerations in UAV Research

Ethical considerations are central to UAV-based research, particularly when involving vulnerable or historically marginalized populations. Key concerns include informed consent, data ownership, privacy, and the potential for unintended exposure or misuse of collected imagery [18,22]. In many jurisdictions, UAV operations over residential areas require specific permissions, and the collection of identifiable data must comply with regulations such as the EU's General Data Protection Regulation (GDPR).

These challenges are especially pronounced in the context of Roma communities, given their long history of marginalization, discrimination, and limited institutional support. The use of aerial imagery—even for research purposes—may be perceived as intrusive, making transparency, cultural sensitivity, and trust-building essential. Ethical UAV deployment therefore requires not only legal compliance but also clear protocols for data anonymization, community consultation, and responsible dissemination.

Beyond minimizing harm, ethical research should aim to empower communities by promoting data sharing, supporting local advocacy, and involving participants throughout the research process. This perspective aligns with broader calls for more inclusive and reflexive research practices that prioritize long-term engagement and reciprocity [23].

To address these considerations, this study followed a strict ethical protocol. Ethical approval was obtained from the Geo-Ethics Committee at the Faculty of Geo-information Science and Earth Observation, University of Twente (#230039; 9 September 2024), and from the Ethical Commission of the Košice Self-governing Region (#10239/2024/ODDZ-45091; 24 September 2024).

3. Methodological Framework and Capability Assessment

This study adopts a multi-scalar and ethically grounded research design to evaluate the potential of UAV-based Earth observation for analyzing marginalized Roma settlements. The methodological framework (Figure 1) integrates high-resolution aerial RGB and thermal data acquisition, spatial analysis, and community-informed field practices to bridge the gap between coarse spaceborne observations and logistically complex ground surveys. Three settlements in southeastern Slovakia were selected to represent varying degrees of spatial centrality and living conditions, allowing comparative analysis across different urban morphologies. The research design combines technical rigor—through standardized mission planning, data collection, and photogrammetric processing—with context-sensitive engagement involving municipal authorities, social workers, and Roma community representatives. This approach ensures that data collection is analytically

robust while remaining socially responsible, minimizing disruption, and aligning research practices with the lived realities of the communities studied.

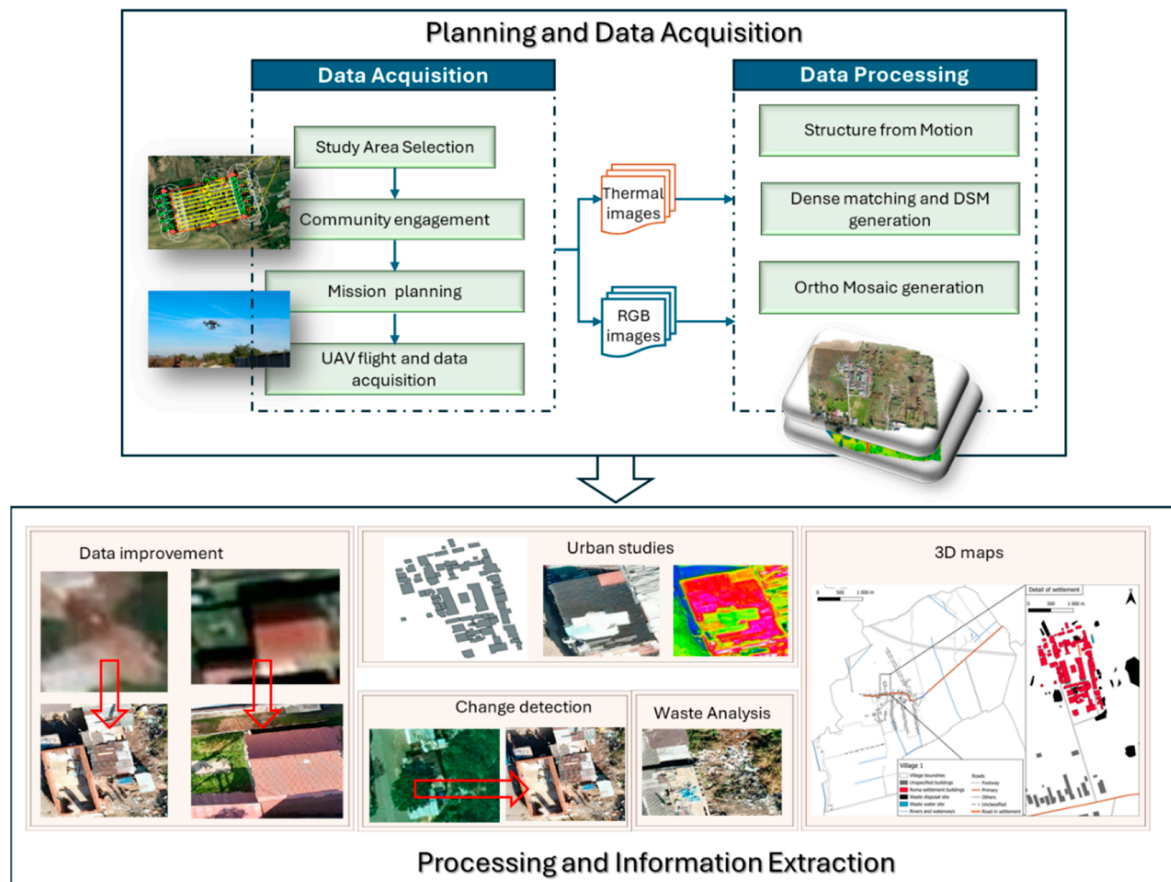


Figure 1. Designed Methodological workflow.

3.1. Research Design and Rationale

This research is designed to address a critical gap in existing Earth observation strategies for studying marginalized communities. Space-based observations, while valuable at regional and global scales, are often too coarse in spatial resolution and insufficient in temporal frequency to capture fine-grained settlement patterns and rapid local dynamics. Conversely, ground-based measurements, although detailed, are frequently costly, logistically challenging, and, in many cases, impractical or intrusive due to the physical complexity, informal structures, and social vulnerability of marginalized settlements. To bridge this gap, the study adopts a UAV-based observational approach that enables high-resolution, flexibility, and repeatable data collection while minimizing on-site disruption. The research is conducted in Eastern Europe and focuses on three marginalized villages with significant Roma populations. Study sites were selected through a combination of peer studies, consultations with municipal authorities (including mayors), and long-standing collaborations with researchers experienced in working with Roma and similarly marginalized communities. Site selection and fieldwork design were further informed by local consultations with Roma representatives and social workers to ensure contextual understanding and ethical sensitivity. Throughout the research design, particular emphasis was placed on maximizing analytical value while minimizing social disruption, ensuring that data collection methods are respectful, non-extractive, and aligned with the lived realities of the communities involved.

3.2. UAV System and Technical Specifications

For aerial data acquisition, we employed the DJI Matrice 300 RTK platform equipped with RGB and thermal imaging sensors (Figure 2). The Matrice 300 RTK is an industrial-grade UAV designed for high-spatial inspection by DJI company originated in China, monitoring, and mapping applications. The platform offers high flight stability, extended endurance, and advanced navigation capabilities, making it well-suited for remote sensing missions and autonomous data collection. In addition, the drone is equipped with a Real-Time Kinematic positioning system, which enables centimeter-level positioning accuracy and improves the georeferencing potential of the acquired imagery. In our project, the drone was used to capture RGB and thermal imagery at different flight altitudes and viewpoints, yielding accurately georeferenced multimodal datasets for subsequent analysis and processing.



Feature	Description
Maximum flight time	Up to 55 min (without payload)
Maximum take-off weight	9 kg
Maximum payload capacity	2.7 kg
RTK positioning accuracy	1 cm + 1 ppm (horizontal), 1.5 cm + 1 ppm (vertical)

Figure 2. DJI Matrice 300 RTK specifications.

3.3. Study Area Selection (e.g., Urban vs. Rural Roma Settlements)

For this study, three final locations in southeastern Slovakia were selected through a multi-step process designed to ensure both the practical feasibility of the research and differences in settlement characteristics. Southeastern Slovakia was chosen because the region currently faces persistent economic challenges, including a relatively high unemployment rate of approximately 9.5%. The region also contains some of the highest shares of the Roma population in the country [24]. In these districts, the combination of economic stagnation and demographic structures contributes to a range of interconnected issues, including insufficient infrastructure, reduced access to quality education and healthcare, and underinvestment in local development. Municipalities were first screened using satellite imagery (mapy.cz) to confirm the presence of at least one Roma settlement and to verify that the area was located outside restricted no-fly zones. This was a crucial step toward the unrestricted use of UAV systems. Next, to obtain the necessary research approvals in villages, we conducted in-person consultations with mayors of several potential candidate villages, who either approved fieldwork within their municipalities or denied it. These consultations also helped define the flight plans and identify safe take-off and landing locations. The final selection included three settlements representing distinct levels of centrality and living conditions; village 1 with a peripheral settlement located outside the

main built-up area with the poorest living conditions; village 2 with a settlement situated on the edge or partly within the village with moderately better conditions; and village 3 with a settlement located at the village edge with the most favorable living conditions, as documented in the Atlas of Roma Communities.

The selection of the three study sites was guided not only by their differing settlement characteristics but also by practical considerations, including the availability of flight permissions, municipal approval, accessibility, and the feasibility of conducting ethically responsible UAV surveys. Consequently, this study should be regarded as an exploratory capability assessment and case study. While the proposed methodological framework demonstrates the potential of UAV-based observations for characterizing marginalized settlements, the findings are not intended to be statistically representative of all Roma settlements or directly generalizable to other marginalized communities without further validation across a broader range of contexts.

3.4. Community Engagement and Mission Planning

Community involvement was essential for the successful implementation of this part of the research. Local social workers serving Roma community members, and Roma “community police” (Miestna občianska a preventívna služba” (MOaPS)), Roma police officers, and Mayors responsible for the villages that Roma settlements belonged to provided critical support, drawing on their knowledge of local dynamics, movement patterns, and sensitive areas to identify suitable take-off and landing sites and ensure operations were conducted safely. Their presence during fieldwork facilitated smooth coordination and served as a valuable point of contact for residents with questions about the research activities. Beyond the necessary logistical support, their engagement helped build trust with community members, foster openness to our presence, and maintain a calm, cooperative atmosphere in the study areas.

For this study, we received ethical approval from the Ethics Committee of the Košice Self-Governing Region (EC of KSGR) in Slovakia. The preparation of our study protocol, which was submitted for ethical clearance, built on extensive previous collaboration and research with similarly vulnerable and marginalised population groups in the research area, Slovakia as a whole, and other countries in Europe. While we took into account our previous learning and reflections on research in complex and vulnerable settings, we acknowledge that involving community representatives in preparing the ethics application could have facilitated closer alignment with local expectations. In preparation of our fieldwork, settlement residents were informed about research activities, and particularly, that UAV-based environmental monitoring would take place in the village, in multiple ways: The purpose of the flights was communicated through the municipal loudspeaker system (common in smaller villages in Slovakia), and moreover, residents were directly and approached on site by staff from the local social centre (e.g., through social workers), the Roma community police or the research team, in Romani language, Slovak or English. The activity was accepted overall without concerns. In the few instances where residents expressed discomfort or concerns about privacy and their unfamiliarity with UAV technology, the Roma community police provided additional clarification. Community involvement proved essential to maintaining trust and ensuring respectful conduct during fieldwork.

3.5. Data Collection Procedures

3.5.1. Mission Planning and Aerial Mapping

Mission planning was conducted to ensure consistent, safe, and context-sensitive data acquisition across the three study villages. For each village, two distinct UAV flight missions were designed: one to acquire high-resolution RGB imagery and a second to

collect thermal imagery. This separation enabled optimization of flight parameters based on sensor characteristics and data requirements. Detailed flight plan specifications, including altitude, overlap, speed, and ground sampling distance, are summarized in Table 1. While a standardized planning framework was applied across sites, mission designs were adapted to local constraints. In the second village, flight duration and spatial coverage were reduced from the original plan due to proximity to restricted (red zone) areas, requiring compliance with safety and regulatory limitations. In the third village, the planned thermal imaging mission was intentionally shortened in response to emerging environmental concerns observed during field operations, prioritizing minimal disturbance while still ensuring sufficient data coverage for analysis. Overall, mission planning balanced methodological rigor with regulatory compliance, environmental sensitivity, and ethical considerations specific to the study context.

Table 1. Summary of the flight plan parameters.

	Village 1		Village 2		Village 3	
Area	49,892 m ²		53,120 m ²		31,995 m ²	
Flight height	100 m		80 m		80 m	
Flight Speed	3.8 m/s		4.0 m/s		4.8 m/s	
Camera	RGB	Thermal	RGB	Thermal	RGB	Thermal
Mean GSD	3.5 cm/pixel	8.9 cm/pixel	2.4 cm/pixel	6.2 cm/pixel	2.8 cm/pixel	7.1 cm/pixel
End/Side lap	70/75%		70/80%		70/80%	
Images	118	311	156	754	178	406

Field data collection commenced at approximately 09:00 in the first village and continued throughout the day. Careful consideration was given to the selection of take-off and landing locations, balancing operational safety, visibility requirements, and local sensitivities. The setup locations were strategically chosen to ensure that the UAV crew maintained a continuous visual line of sight while minimizing disturbance. These decisions were made in consultation with municipal authorities and local representatives. In each village, RGB data acquisition was conducted first, followed by thermal imaging to optimize mission efficiency and sensor performance. In total, six UAV flights were completed across the three sites, resulting in the capture of 452 RGB images and 1471 thermal images.

3.5.2. Environmental and Spatial Observations

In parallel with UAV data acquisition, systematic environmental and spatial observations were conducted to document contextual features not fully captured through aerial imagery alone. These observations included notes on terrain conditions, slope and drainage patterns, proximity to infrastructure (roads, utilities, waste disposal areas), vegetation cover, and visible signs of environmental stress such as standing water, informal waste accumulation, or erosion. Particular attention was given to settlement boundaries, access routes, building materials visible from ground level, and the spatial relationships between Roma settlements and the municipalities' main built-up areas. Field notes were georeferenced where possible and later cross-referenced with orthophoto outputs to support the interpretation of morphological patterns and thermal anomalies. These observations provided qualitative validation of remotely sensed indicators and ensured that subsequent spatial analyses were grounded in locally observed realities.

3.5.3. Community Consultations and Participatory Approaches

The research and associated field activities were carried out in close coordination with municipal authorities, social workers, and members of the MOaPS, a local civil and preventive service employing residents from the settlements themselves. These collaborations were established through a series of preliminary meetings held prior to data collection. During these consultations, available municipal base maps were jointly reviewed with mayors to support study design, including the delineation of flight areas, selection of UAV crew staging points, and discussion of local concerns and expectations. In parallel, existing aerial and satellite imagery were used to refine mission planning and ensure contextual awareness. Engagements with local stakeholders also informed adjustments to data collection tools and helped clarify relationships between municipalities and Roma settlements. Given the high sensitivity of research involving marginalized communities and aerial data collection, continuous communication and strong collaboration among all involved parties were essential to ensure ethical conduct, local acceptance, and methodological robustness. Data collection was conducted iteratively across multiple project phases rather than as a single linear process.

3.6. Photogrammetry Processing and Product Generation

Processing of the acquired UAV imagery was conducted following a standardized photogrammetric workflow consisting of three primary stages: (1) Structure from Motion (SfM), (2) digital surface model (DSM) generation, and (3) ortho-mosaic generation. This workflow was applied consistently to all datasets, covering the three study villages and both RGB and thermal flight missions. Following image acquisition, photogrammetric processing was used to generate georeferenced point clouds and ortho-photos for each site, enabling spatially explicit analysis of settlement characteristics. Representative outputs of the processing chain are presented in Figure 3.

In the first stage, Structure from Motion algorithms were employed to reconstruct the three-dimensional scene geometry and estimate camera exterior orientation parameters from overlapping two-dimensional images. Feature detection and matching were performed using the Scale-Invariant Feature Transform (SIFT) algorithm, which identifies and matches tie points across image sequences. These matched features serve as input to the SfM process, enabling simultaneous estimation of camera positions and relative orientations, and the generation of an initial sparse point cloud representing the scene. Camera calibration parameters were solved internally within the SfM optimization process.

The second stage involved generating a dense point cloud through multi-view stereo (MVS) reconstruction of the oriented imagery. This step densifies the sparse point cloud by leveraging pixel-level radiometric information across multiple viewing angles, yielding a high-resolution three-dimensional representation of surface features for each study area.

Image processing was based on the RTK positioning data recorded during the flights. No Ground Control Points (GCPs) or independent checkpoints were established, as the study focused on evaluating the observational capabilities of the UAV-derived products rather than conducting a formal geometric accuracy assessment.

In the final stage, orthomosaics were produced by combining the meshed surface derived from the dense point clouds with the original UAV imagery. The ortho-mosaic generation procedure follows established photogrammetric principles, as in traditional aerial photography. However, due to the use of non-metric sensors and variable radiometric properties typical of UAV platforms, higher forward and side image overlaps were applied during data acquisition to ensure sufficient geometric accuracy and radiometric consistency in the final products.

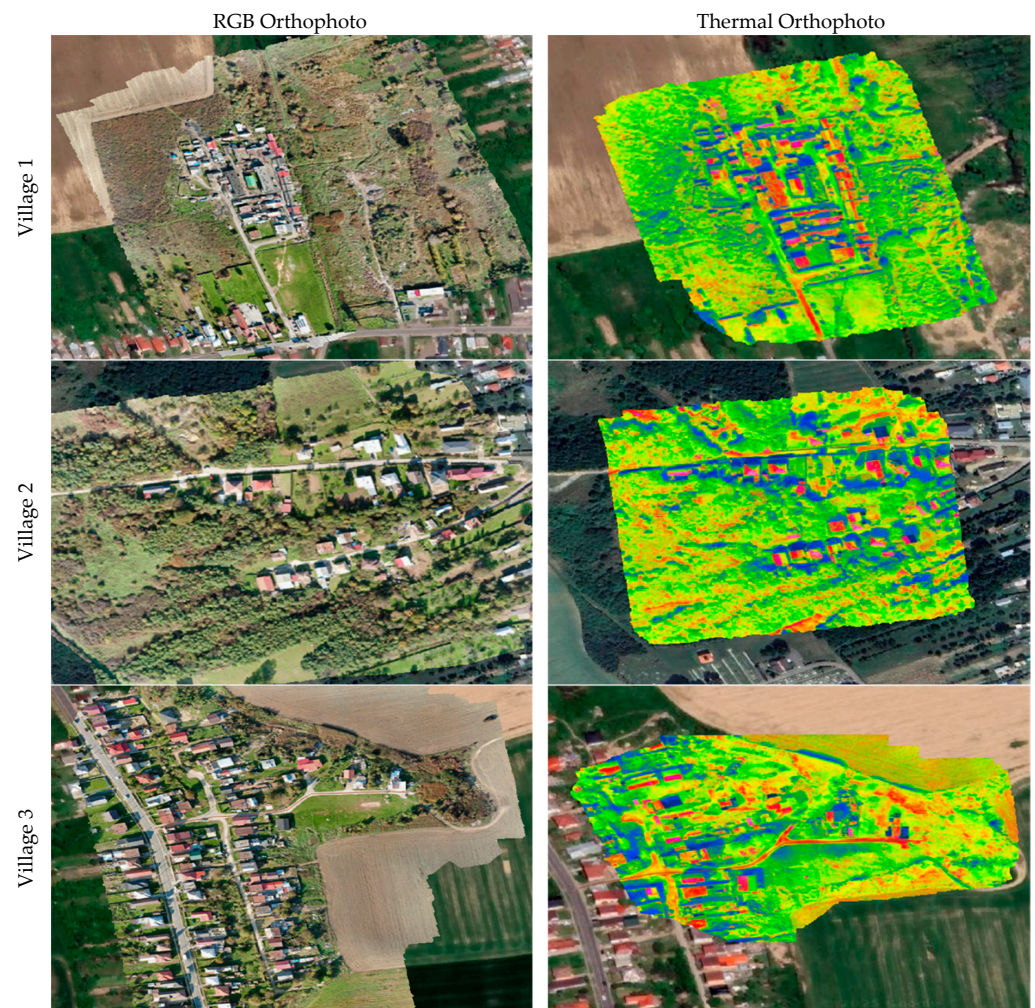


Figure 3. UAV-derived RGB (left) and thermal (right) orthophotos for the three study villages, illustrating fine-scale spatial detail and temperature variability within the settlements; here cooler surfaces are shown in blue/purple, moderate temperatures in green/yellow, and warmer surfaces in red.

Following photogrammetric processing, the generated orthomosaics, digital surface models (DSMs), and thermal maps were interpreted through manual visual analysis within a GIS environment. Settlement features, including housing structures, road networks, waste accumulation sites, vegetation, surface water, and infrastructure elements, were identified through expert interpretation, supported by field observations and local contextual knowledge gained during community engagement activities. No automated feature extraction, object-based image analysis (OBIA), or machine learning algorithms were employed, as the primary objective of this study was to evaluate the capabilities of UAV-derived imagery to support the observation and assessment of marginalized settlements, rather than to develop an automated mapping methodology.

3.7. Data Analysis and Information Extraction

3.7.1. Better Spatial Resolution

One of the primary advantages of UAV-based observation is its substantially higher spatial resolution than satellite imagery, conventional aerial photographs, and national mapping products. While open-access satellite data typically provide spatial resolutions in the range of 10–30 m and commercial satellites reach approximately 0.3–0.5 m, national orthophotos and manned aerial surveys generally achieve 5–25 cm ground sampling distance (GSD). In contrast, UAV imagery collected in this study achieved a mean GSD of

2–5 cm, enabling detection of fine-grained settlement features, including small dwellings (<20 m²), narrow access paths, roof-material heterogeneity, informal extensions, and micro-scale environmental conditions. This enhanced spatial detail is critical in the context of Roma settlements, where morphological complexity, incremental construction, and high structural density require sub-decimeter resolution for accurate mapping and analysis. Figure 4 summarizes the comparative spatial resolution characteristics of the different data sources.

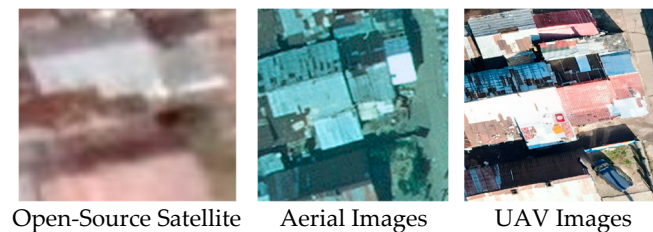


Figure 4. Spatial resolution comparison of Satellite, Aerial, and UAV-based data.

3.7.2. Accurate Large-Scale Maps

The UAV-derived datasets enabled the production of high-detail, large-scale thematic maps for each of the three study villages, integrating orthophoto backdrops with vectorized building footprints, infrastructure networks, environmental features, and field-based observations. As illustrated in Figure 5, the final cartographic outputs combine UAV-extracted settlement buildings (including differentiated Roma settlement structures), classified unspecified buildings, road hierarchies, footpaths, waterways, waste disposal sites, and georeferenced environmental sampling locations within the framework of official village boundaries. The high geometric accuracy and centimeter-level spatial detail of the UAV imagery allowed precise delineation of informal structures and internal circulation networks that are typically generalized or absent in national mapping products. By overlaying newly captured UAV data with existing regional datasets, the resulting maps provide a comprehensive and analytically robust spatial representation suitable for micro-scale settlement analysis, environmental risk assessment, and local planning interventions.

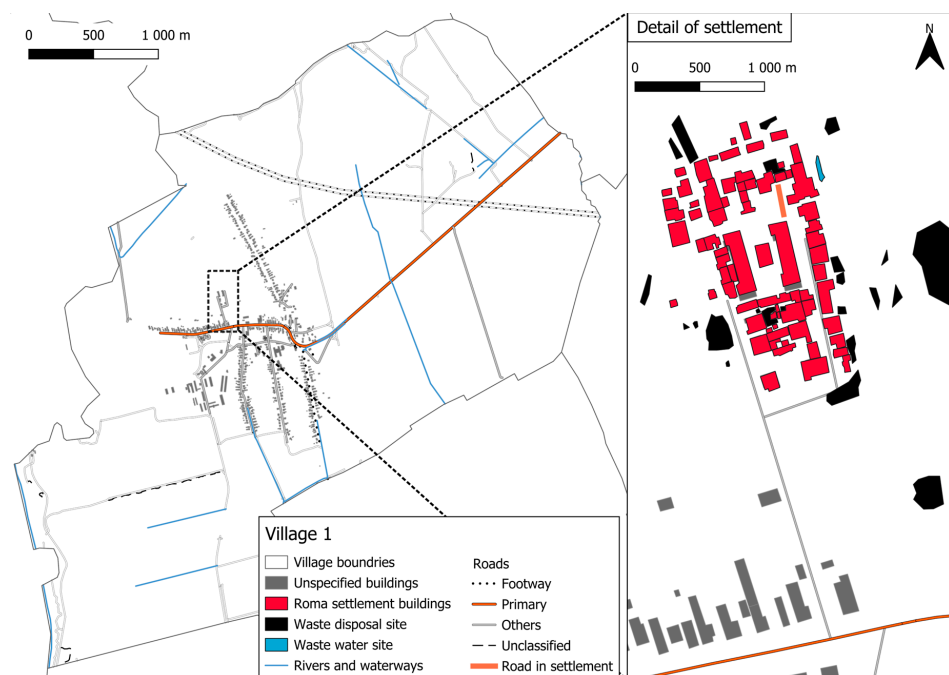


Figure 5. Cont.

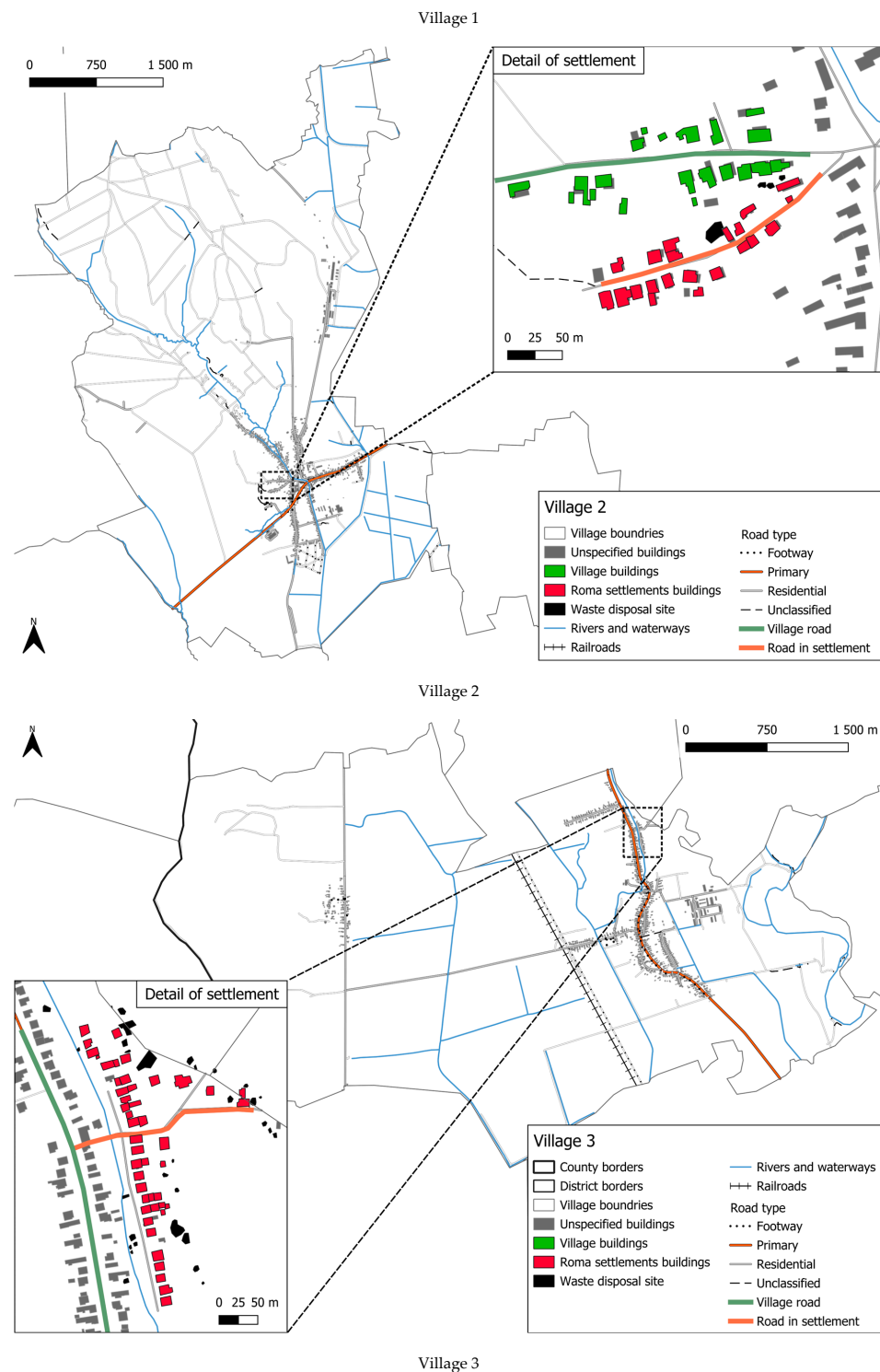


Figure 5. Large-scale maps were generated and combined with available national base maps for each of villages.

3.7.3. Change Detection

Settlement Dynamics & Growth: Change detection analysis indicates that settlement growth occurs through both incremental infill within existing clusters and outward expansion into adjacent peripheral land. Infill processes intensify density and overcrowding, while edge expansion often reflects insecure land tenure and occupation of marginal or environmentally constrained areas. Between 2017 and 2024, the settlements expanded by approximately 5–15%, with the greatest increase observed in Village 1 and the smallest in

Village 2. This growth was primarily associated with the construction of new dwellings at the settlement periphery and the densification of existing built-up areas. These spatial dynamics illustrate patterns of containment, in which growth remains physically constrained by infrastructural barriers, agricultural land, or administrative limits. Interpreted through the lens of urban marginality theory, such development trajectories reflect ongoing peripheralization and spatial exclusion, whereby Roma communities are structurally confined to the urban fringe and excluded from formal planning, serviced land markets, and secure tenure systems. Figure 6 presents examples of settlement expansion between the historical imagery (2017–2022, depending on data availability) and the UAV orthomosaics acquired in 2024.



Figure 6. Samples of temporal changes in constructions that have happened within the last 10 years.

To assess settlement dynamics, the 2024 UAV-derived orthomosaics were visually compared with historical high-resolution satellite imagery available through <https://mapy.tuzvo.sk/> accessed on 25 May 2026. Historical images acquired between 2017 and 2022 (depending on data availability for each study village) served as the baseline for evaluating settlement changes. Change detection was performed through manual visual interpretation by comparing settlement boundaries, building footprints, and newly developed structures between the two datasets. The objective was to identify and quantify general patterns of settlement expansion and densification rather than to perform automated image differencing.

3.7.4. Waste Analysis

UAV-based RGB and thermal imagery enabled detailed identification and spatial assessment of informal waste accumulation within and around the settlements. As illustrated in Figure 7, waste deposits are clearly detectable in high-resolution RGB imagery through texture, color heterogeneity, and irregular surface patterns, while thermal imagery further enhances their visibility by revealing distinct temperature anomalies compared to surrounding soil and built surfaces. The analysis indicates that waste is not confined to minor dumping zones but is widely distributed across the settlements, in some cases located in immediate proximity to residential structures and adjacent to children's play areas. This spatial pattern highlights potential environmental and public health risks, including exposure to contaminants, fire hazards, and increased vulnerability to vector-borne diseases. The extracted waste locations were digitized and incorporated into the integrated large-scale maps presented in Section 3.7, thereby enabling a comprehensive spatial overview of waste distribution relative to housing density, access routes, waterways, and community spaces. This multi-layered analysis demonstrates the capacity of UAV data to support fine-scale environmental risk assessment in marginalized settlement contexts.

Waste accumulation sites were identified through manual visual interpretation of the UAV-derived orthomosaics within a GIS environment. Identification was based on the presence of irregular clusters of discarded materials exhibiting heterogeneous textures, mixed surface colors, and non-natural spatial patterns that were clearly distinguishable from surrounding vegetation, bare soil, or built structures. Thermal imagery was used as complementary information to identify localized surface temperature anomalies where these coincided with visually identified waste deposits. The interpreted waste accumulation sites were subsequently verified through field observations and local knowledge obtained from social workers and community representatives familiar with the study areas.

Following identification, each waste accumulation site was manually delineated in the GIS to quantify its extent. A total of 26 waste accumulation sites were identified in Village 1, ranging in size from 7 to 2300 m². In Village 2, 4 sites were identified, with areas ranging from 18 to 24 m², while 34 sites were mapped in Village 3, ranging from 10 to 350 m². These quantitative statistics complement the qualitative assessment by providing an objective characterization of waste distribution across the study areas.

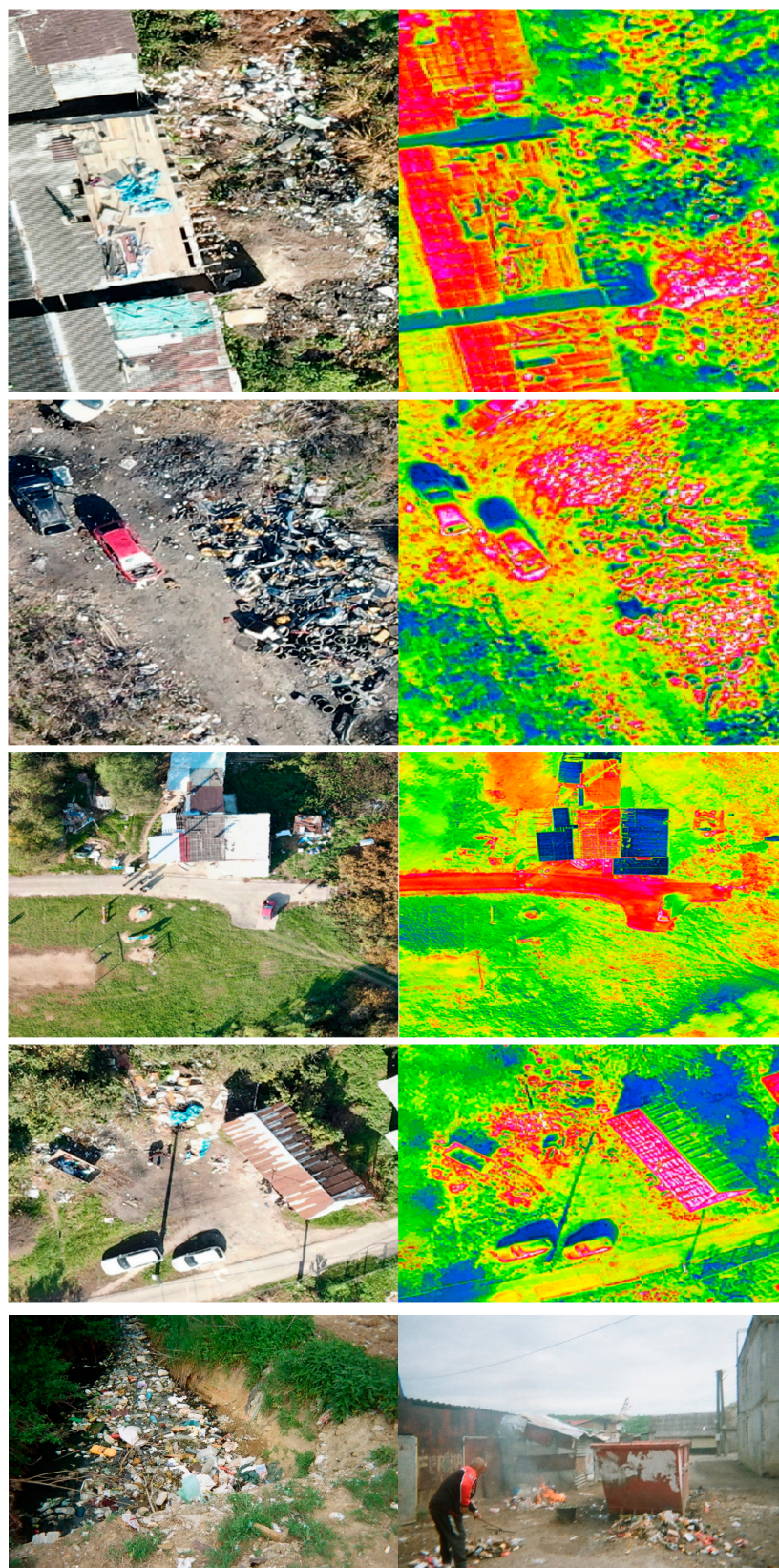


Figure 7. UAV-derived RGB (**left**) and thermal (**right**) imagery illustrating the detection of waste accumulation within the study sites, with some photos taken by Roma settlement residents to document the waste-related challenges faced; here **cooler surfaces are shown in blue/purple, moderate temperatures in green/yellow, and warmer surfaces in red.**

3.7.5. Urban Studies

Settlement Morphology, Building Density, & Urban Structure:

Roma settlements represent distinct forms of informal urban morphology, characterized by self-built structures, incremental construction, and irregular spatial layouts that differ markedly from formally planned urban areas. Typically located in peri-urban or environmentally constrained spaces, these settlements reflect broader processes of socio-spatial marginalization and limited integration into formal infrastructure and housing systems. Their heterogeneous building sizes, irregular arrangement, and dense spatial configuration make them difficult to analyze using conventional medium-resolution satellite imagery.

The UAV-derived orthomosaics enabled detailed extraction and characterization of individual building footprints, demonstrating the value of centimeter-resolution imagery for fine-scale settlement analysis (Figure 8). A total of 75 buildings were identified in Village 1, 28 in Village 2, and 46 in Village 3. Building footprints ranged from 10 to 500 m² (total footprint area: 7500 m²) in Village 1, 28 to 200 m² (total 2200 m²) in Village 2, and 16 to 280 m² (total 5200 m²) in Village 3 (Figure 8). These results illustrate considerable variation in dwelling size and settlement morphology both within and among the study areas, highlighting the ability of UAV imagery to capture spatial details beyond the resolution of conventional satellite observations.



Figure 8. Buildings vector map extracted based on overlays of RGB and thermal imageries.

The extracted building footprints also reveal a compact and irregular urban fabric characterized by closely spaced structures and limited open space, indicating localized overcrowding. Such spatial configurations have important implications for public health and urban resilience, including reduced natural ventilation, increased exposure to heat stress, greater risk of communicable disease transmission, restricted emergency access, and increased pressure on basic infrastructure such as water supply, sanitation, drainage, and road connectivity. Compared with nearby formally planned settlements, which typically exhibit larger plots, regulated setbacks, and organized street networks, the observed morphology highlights pronounced spatial inequalities. These findings demonstrate that UAV-based mapping provides not only a detailed representation of settlement structure but also valuable spatial evidence for assessing housing conditions, environmental vulnerability, and planning priorities in marginalized communities.

Thermal Inequality & Environmental Justice: Thermal orthophoto analysis revealed significant microscale temperature variability within the settlements, highlighting localized heat accumulation patterns consistent with a micro-urban heat island effect. Relative rooftop surface temperature differences of up to approximately 25 °C were observed within individual thermal orthomosaics, demonstrating substantial thermal heterogeneity across the settlements. Because the thermal imagery was primarily acquired for comparative spatial analysis rather than radiometric temperature measurements, these values should be interpreted as relative surface temperature variations rather than absolute temperatures. Elevated rooftop temperatures, particularly in smaller and densely clustered dwellings, sug-

gest reduced building thermal performance associated with limited insulation or thermally inefficient construction materials (Figure 9), consistent with previous studies demonstrating the value of thermal remote sensing for assessing building thermal performance and surface heat dynamics [25,26].

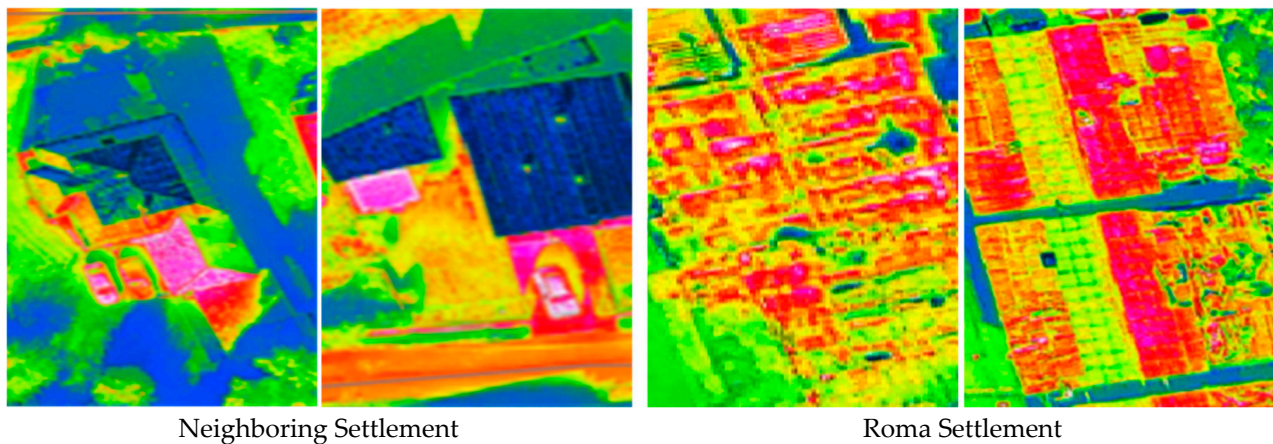


Figure 9. Comparison of Roma (right) and a neighboring settlement (left), considering the height inequality; here cooler surfaces are shown in blue/purple, moderate temperatures in green/yellow, and warmer surfaces in red.

Although rooftop temperature alone cannot directly measure energy poverty, relative thermal anomalies can serve as spatial screening indicators of housing and energy vulnerability [27,28]. The concentration of warmer rooftops within already marginalized areas highlights potential inequalities in climate exposure and heat stress. Consequently, UAV-derived thermal imagery can support environmental justice assessments by identifying areas warranting further investigation, while recognizing that confirmation of energy poverty requires complementary socioeconomic information, building condition assessments, or indoor environmental measurements.

From an urban studies perspective, UAV imagery provides the spatial detail necessary to interpret the material and infrastructural characteristics of informal settlements (Figure 10). The high-resolution RGB orthophotos enable differentiation of roof materials, revealing patterns of incremental construction, material reuse, and structural heterogeneity that reflect socio-economic conditions. In addition, the imagery supports the precise mapping of narrow transportation pathways, informal access routes, and circulation networks that are typically absent from official maps. These micro-scale observations enable quantification of settlement compactness, accessibility constraints, and internal spatial organization. In contrast, medium-resolution satellite imagery cannot resolve such fine-grained material and infrastructural features, while even commercial satellite data often lacks the clarity required to systematically capture informal transport networks. This reinforces the value of UAV data for urban morphological analysis in marginalized contexts.



Figure 10. Comparison of Roma (right) and a neighboring settlement (left), considering the building materials examples.

4. Discussion

To place the proposed UAV-based framework into the broader context of Earth observation approaches, Table 2 summarizes the strengths and limitations of commonly used data sources for analyzing marginalized settlements.

Table 2. Comparison of available data sources for studying Roma settlements.

Criteria	Open Satellite	Commercial Satellite	National Orthophoto	Manned Aerial	UAV	Field Survey
Spatial Resolution (GSD)	10–30 m	0.3–0.5 m	0.1–0.25 m	0.05–0.2 m	2–5 cm	N/A
Temporal Resolution/Revisit	5–16 days	On tasking	1–3 years	On tasking	On demand	Episodic
Detect Small Dwellings (<20 m²)	Very Low	Moderate	High	High	Very High	Very High
Detect Roof Materials/Building Quality	No	Limited	Limited	Moderate	High	High
Settlement Boundary Delineation Accuracy	Low	Moderate	High	High	Very High	Very High
Cloud Sensitivity	High	High	Moderate	Low	Low	None
Operational Flexibility	Low	Moderate	Low	Moderate	Very High	High
Cost Level	Free	High	Public-funded	High	Moderate	High labor
Regulatory Constraints	Minimal	Minimal	Minimal	Aviation permits	UAV airspace rules	Access permissions
Ethical/Privacy Risk	Low	Moderate	Moderate	High	High (identifiable imagery)	High
Community Engagement Potential	None	None	None	Limited	High (participatory UAV mapping possible)	Very High
Scalability	National–Global	National–Regional	National	Regional	Local–Regional	Local
Data Processing Complexity	Low	Moderate	Moderate	High	Moderate	Moderate
Overall Suitability for Fine-Scale Roma Settlement (1–5)	1	3	4	4	5	5

Note: Ground Sampling Distance (GSD) is not applicable to field surveys, as information is collected through direct on-site observations rather than image pixels.

The comparison of Earth observation and field-based data sources (Table 2) demonstrates that no single approach is sufficient to comprehensively characterize marginalized settlements. While open and commercial satellite imagery provide valuable regional context and enable large-scale monitoring, their spatial resolution remains insufficient to reliably detect fine-scale settlement characteristics, such as small dwellings, roofing materials, or localized environmental hazards. Similar limitations have been reported in studies of informal settlements, where sub-meter imagery is often required to capture settlement heterogeneity and infrastructure deficiencies [29].

Our findings indicate that UAVs bridge this spatial information gap by combining centimeter-level spatial resolution with flexible, on-demand data acquisition. Unlike conventional aerial or satellite platforms, UAVs enable detailed assessment of settlement morphology, infrastructure quality, waste accumulation, vegetation, and thermal conditions within a single survey. This confirms previous studies demonstrating the value of UAVs for high-resolution urban and humanitarian mapping, while extending their application to assessing marginalized Roma communities by integrating RGB, thermal, and elevation data.

Despite these advantages, UAVs should not be viewed as a replacement for field surveys. Community engagement remains essential for interpreting remotely sensed ob-

servations, validating detected features, and ensuring ethical data collection in socially sensitive environments. Rather, our results support an integrated observation framework in which satellite imagery provides regional context, UAVs deliver detailed spatial information, and field surveys contribute local knowledge and socioeconomic insights. Such complementary approaches can provide a more robust evidence base for public health interventions, environmental justice assessments, and evidence-based planning in marginalized settlements.

The identified settlement characteristics should therefore be interpreted as spatial indicators of potential environmental and social vulnerability rather than direct measures of socioeconomic conditions. While high-resolution UAV observations provide valuable evidence on settlement morphology, waste accumulation, and relative thermal anomalies, confirmation of issues such as energy poverty, residential overcrowding, or public health outcomes requires complementary household surveys, infrastructure assessments, and socioeconomic data. In the present study, field observations, consultations with local social workers, Roma community police, and community representatives were used to contextualize the interpretation of the UAV-derived products and support the visual analysis. Nevertheless, establishing direct causal relationships between remotely sensed spatial characteristics and socioeconomic conditions was beyond the scope of this capability assessment.

4.1. Further Anticipated Applications and Benefits

Beyond the analyses presented in this study, UAV-based observations offer additional applications and benefits for research on marginalized communities, particularly Roma settlements. The ability to collect high-resolution, temporally flexible data enables improved assessment of settlement structure, infrastructure access, and environmental conditions, which are often insufficiently captured in conventional spatial datasets.

From an environmental and public health perspective, UAV-derived data can support the identification of localized risk factors, including exposure to hazards, informal waste sites, flood susceptibility, and heat stress. When combined with ground-based measurements and social indicators, repeated UAV observations enable monitoring of temporal changes and evaluation of policy interventions or community-driven improvements.

UAV-based approaches also provide practical advantages by reducing logistical constraints and the need for intrusive fieldwork in complex or hard-to-access settlements. When embedded within participatory and consultative research frameworks, UAV data can complement qualitative methods and support more inclusive, evidence-based decision-making. Ultimately, such approaches can help bridge existing data gaps and improve the visibility of Roma communities within planning and policy processes.

4.2. Challenges and Limitations

Operational limitations: One practical challenge involved securing an experienced, licensed pilot for the DJI Matrice 300 RTK platform together with all permits and documentation required to conduct the missions legally and safely. This challenge was addressed through collaboration with the Technical University of Košice, which provided both the UAV platform and a qualified pilot.

Weather conditions also represented an important operational constraint. Because the field campaign was conducted in autumn, flight missions had to be scheduled during periods without frost, as low temperatures reduced battery efficiency and frost accumulation on the propellers could compromise flight safety. Morning fog, increased humidity, and low-to-medium cloud cover, which are common during autumn in southeastern Slovakia, further constrained mission planning by reducing visibility and affecting sensor perfor-

mance. Furthermore, higher ground-surface temperatures reduce thermal contrast, making it more difficult to distinguish people, animals, and built structures in thermal imagery.

A further limitation is that data collection was conducted during a single field campaign and in only one season. Consequently, the observations do not capture seasonal variability, such as snow cover during winter or vegetation growth during summer, nor do they represent longer-term settlement dynamics or temporal changes in human activities.

Ethical and community-related considerations: The presence of municipal representatives and Roma community police was both an advantage and a limitation. Their involvement was essential for ensuring the safety of the research team and equipment, facilitating access to the settlements, and supporting communication with residents. However, because some participants were approached through these intermediaries, their willingness to participate may have been influenced by the presence of local authorities.

Ethical approval for the Slovak component of the study was granted by the Ethics Committee of the Košice Self-Governing Region (EC of KSGR). Although community representatives were not involved in the ethics application, residents were informed about the UAV surveys in advance through the municipal loudspeaker system. During fieldwork, the purpose of the flights was explained by the research team, Roma community police, or local social centre staff whenever needed. The surveys were generally well accepted, with only occasional privacy-related questions that were successfully addressed through communication with trusted local intermediaries. These experiences highlight the importance of transparent communication and local stakeholder involvement for the responsible use of UAVs in marginalized communities.

Methodological limitations: The findings presented in this study should be interpreted within the scope of a capability assessment rather than a quantitative validation study. The identified settlement characteristics therefore represent **spatial indicators** of potential environmental and social vulnerability rather than direct measures of socioeconomic conditions. While high-resolution UAV observations provide valuable evidence on settlement morphology, waste accumulation, and relative thermal anomalies, confirmation of issues such as energy poverty, residential overcrowding, or public health outcomes requires complementary household surveys, infrastructure assessments, and socioeconomic data. In the present study, field observations, together with consultations with local social workers, Roma community police, and community representatives, were used to contextualize the interpretation of the UAV-derived products and to support the visual analysis. Nevertheless, establishing direct causal relationships between remotely sensed spatial characteristics and socioeconomic conditions was beyond the scope of this capability assessment.

Furthermore, this study focused on evaluating the observational capabilities of UAV-derived imagery rather than the quantitative accuracy of the generated products. Settlement characteristics were identified through manual visual interpretation, supported by field observations and local contextual knowledge, rather than by automated classification algorithms. UAV image processing relied on the RTK positioning system integrated into the DJI Matrice 300 platform, and no independent Ground Control Points (GCPs) or checkpoints were collected during the field campaigns. Consequently, quantitative positional accuracy metrics such as RMSE could not be determined. Likewise, conventional performance metrics such as precision, recall, F1-score, and Intersection over Union (IoU), commonly used to evaluate automated extraction methods, were not applicable. In addition, the thermal imagery was interpreted comparatively to identify relative thermal anomalies rather than absolute radiometric temperatures, and no radiometric calibration was performed. Future research should complement this capability assessment with independent validation of orthophoto positional accuracy, quantitative evaluation of extracted settlement features using

appropriate reference datasets, and radiometrically calibrated thermal surveys supported by ground-based measurements.

5. Conclusions

This study demonstrates that UAV-based observation provides a powerful and flexible approach for capturing fine-scale spatial information in marginalized Roma settlements, addressing critical limitations of conventional Earth observation methods. The high spatial resolution and operational flexibility of UAVs enable detailed analysis of settlement morphology, infrastructure accessibility, environmental risks, and thermal inequalities, offering insights that are otherwise unattainable through satellite imagery or traditional mapping products. By integrating UAV-derived data with field observations and stakeholder engagement, the study highlights the potential for more comprehensive, context-sensitive analysis of marginalized environments.

At the same time, the research underscores that technical capability alone is insufficient. Ethical considerations, including privacy, informed consent, and community trust, are central to responsible UAV deployment, particularly in socially sensitive contexts. Operational challenges such as regulatory requirements, environmental conditions, and logistical constraints further shape the feasibility of UAV applications.

Overall, this work contributes to the development of a hybrid methodological framework that combines high-resolution spatial data with participatory and ethically grounded research practices. Future research should focus on multi-temporal data collection, deeper integration with socio-economic datasets, and co-designed approaches with communities to ensure that UAV-based observations not only improve spatial understanding but also contribute to more inclusive and equitable planning and policy processes.

Although the methodological framework presented here demonstrates considerable potential to support research and planning in marginalized settlements, the findings should be interpreted in the context of the three case-study sites investigated in southeastern Slovakia. Future research should evaluate the transferability of the proposed approach across a wider range of settlement types, geographic regions, and marginalized communities to assess its broader applicability and generalizability.

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