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USE OF UAV IMAGERY FOR RAINWATER HARVESTING SYSTEMS AND SANITATION INFRASTRUCTURE IN A REMOTE VILLAGE OF MALI

Beatriz Macêdo Medeiros[1]; Luciana Sanches[2]; Camila Silva Franco[3]; Andréa Aparecida Ribeiro Corrêa[4], Milson Evaldo Serafim[5]; Marx Leandro Naves Silva[6]; Bernardo M. Cândido[7]; & João José Granate de Sá e Melo Marques[8]

Abstract: Remote areas with political instability and administrative limitations, such as those in Mali, are home to villages with poor sanitation conditions, making access and monitoring particularly challenging. Under these circumstances, the use of imagery obtained by unmanned aerial vehicles (UAVs) enables a more effective strategy for water supply and sanitation planning, as demonstrated in the case of the village of Bandiagara II, located in southern Mali, Africa, which is the focus of this study. Using a DJI Phantom 4 RTK drone, high-resolution images were captured, allowing the identification of roof types, spatial organization of buildings, and the location of sanitation structures and wells. Based on the image analysis, it was possible to assess the necessary infrastructure for implementing rainwater harvesting from building rooftops and to identify critical contamination areas due to the proximity between latrines and hand wells. The images supported the implementation of sanitation solutions and served as a basis for an inventory of hygiene structures. The results highlight that UAVs are practical tools for planning and monitoring in vulnerable regions, contributing to improved living conditions and water security.

Keywords – Unmanned aerial vehicles (UAVs); rainwater harvesting; rural sanitation; high-resolution imagery; water vulnerability; spatial planning; Sub-Saharan Africa

Resumo: Áreas remotas com instabilidade política e limitações administrativas, como no Mali, abrigam vilarejos com precárias condições de saneamento, tornando desafiadores o acesso e o monitoramento. Nessas condições, a aplicação de imagens obtidas por veículos aéreos não tripulados (VANTs) possibilita uma estratégia mais eficaz de planejamento de abastecimento de água e saneamento, como no caso da vila de Bandiagara II, localizada no sul do Mali, África, foco deste estudo. Por meio do uso de um drone DJI Phantom 4 RTK, foram capturadas imagens de alta resolução que permitiram identificar tipos de coberturas, organização espacial das edificações e

[1] Department of Soil Science, Federal University of Lavras, P.O. Box 3037, 37203-202, Lavras, Minas Gerais, Brazil. E-mail: bemacedom@gmail.com
[2] Department of Sanitary and Environmental Engineering, Federal University of Mato Grosso. Av. Fernando Correa da Costa, 2367, Cuiabá, Mato Grosso, Brazil. E-mail: luciana.sanches@ufmt.br
[3] Department of Environmental and Sanitary Engineering, Federal University of Lavras, Professor Edmir Sá Santos Roundabout, No. s/n, P.O. Box 3037, ZIP Code: 37203-202, Lavras, Minas Gerais, Brazil. E-mail: camila.sfranco@ufla.br
[4] Department of Engineering, Federal University of Lavras, Professor Edmir Sá Santos Roundabout, No. s/n, P.O. Box 3037, ZIP Code: 37203-202, Lavras, Minas Gerais, Brazil. E-mail: andrea.rcorrea@ufla.br
[5] Ministry of Agrarian Development and Family Farming, Senator Robert Kennedy Avenue, No. 601, São Torquato District, ZIP Code: 29114-300, Vila Velha, Espírito Santo, Brazil. E-mail: milsonserafim@gmail.com
[6] Department of Soil Science, Federal University of Lavras, P.O. Box 3037, ZIP Code: 37203-202, Lavras, Minas Gerais, Brazil. E-mail: marx@ufla.br
[7] Division of Plant Sciences and Technology, College of Agriculture, Food, and Natural Resources, University of Missouri, Columbia, MO 65211, United States. E-mail: bernardocandido@missouri.edu
[8] Department of Soil Science, Federal University of Lavras, Professor Edmir Sá Santos Roundabout, No. s/n, P.O. Box 3037, ZIP Code: 37203-202, Lavras, Minas Gerais, Brazil. E-mail: jmarques@ufla.br

localização de estruturas sanitárias e poços. Com base na análise das imagens, foi possível avaliar a infraestrutura necessária para a implementação da captação de água de chuva a partir das coberturas das edificações e identificar áreas críticas de contaminação devido à proximidade entre latrinas e poços. As imagens auxiliaram na implementação de soluções de saneamento, além de servirem como base para um inventário das estruturas de higiene. Os resultados evidenciam que os VANTs são ferramentas eficazes para o planejamento e monitoramento em regiões vulneráveis, contribuindo para a melhoria das condições de vida e da segurança hídrica.

Palavras-Chave – Veículos aéreos não tripulados (VANTs); aproveitamento de água de chuva; saneamento rural; imagens de alta resolução; vulnerabilidade hídrica; planejamento espacial; África Subsaariana.

INTRODUCTION

In the Global South, particularly in Southern Africa, water resources are unevenly distributed, and this situation is exacerbated by climate variability, especially the unpredictability of rainfall seasonality (Sibanda *et al.*, 2021). The quality and quantity of available water directly affect all water users, including smallholder crop irrigation. In this context, there is an urgent need to identify accurate and efficient methods for assessing surface water resources, especially in vulnerable regions.

Traditionally, the quantity and quality of water resources are assessed through in situ measurements, which, although precise, can often be time-consuming, costly, and logistically challenging, particularly in remote or politically unstable areas where personal security services are necessary (Gholizadeh *et al.*, 2016). These assessments require not only hydrological data but also a range of environmental parameters and field-based variables to achieve an accurate characterization of water availability and potential contamination sites at the local scale.

In response to these limitations, unmanned aerial vehicle systems (UAVs), also known as drones, have emerged as a promising alternative for mapping and monitoring water resources at local scales (Xiang *et al.*, 2019). UAVs offer flexibility, cost-effectiveness, and the capacity to capture high-resolution data at low altitudes, surpassing the spatial precision of satellite-based remote sensing. Their portability and ease of deployment make them ideal for monitoring inaccessible or hazardous regions. Advanced sensors and cameras onboard UAVs enable real-time detection of water stress, pest infestations, and other threats to crops, assisting farmers in optimizing irrigation and management practices (Reinecke *et al.*, 2017).

In addition to agricultural monitoring, UAVs play a strategic role in humanitarian and environmental applications. For instance, in the village of Bandiagara II, located in the Koutiala district of Mali, where water vulnerability and desertification present severe challenges, UAV-based imaging is crucial for identifying priority areas for rainwater harvesting and sustainable water storage interventions. This technology also enhances research safety, especially in regions marked by political instability and violence. According to Shurkin (2022), violent incidents in the Sahel region, particularly in Mali, Burkina Faso, and Niger, increased by 140% between 2020 and 2022, displacing more than 2.5 million people and resulting in thousands of deaths.

Despite their benefits, UAVs have limitations, such as restricted flight times due to battery constraints, which require careful planning and, in some cases, multiple flights to achieve full spatial coverage (Munghemezulu *et al.*, 2023). Nonetheless, their advantages in reducing researcher exposure, improving data quality, and enabling cost-effective monitoring position UAVs as a key technology for sustainable water management, especially in fragile and under-resourced contexts.

OBJECTIVE

This study aims to evaluate the application of unmanned aerial vehicle (UAV) imagery as a strategic tool for planning water supply and sanitation interventions in remote and vulnerable communities. Focusing on the village of Bandiagara II, in southern Mali, the research seeks to demonstrate how high-resolution aerial images can support the identification of rainwater harvesting potential, assess infrastructure needs, and locate critical points of contamination risk. The goal is to develop a replicable methodology for enhancing access to safe water and basic sanitation services in regions characterized by political instability, limited logistical capacity, and pronounced water vulnerability.

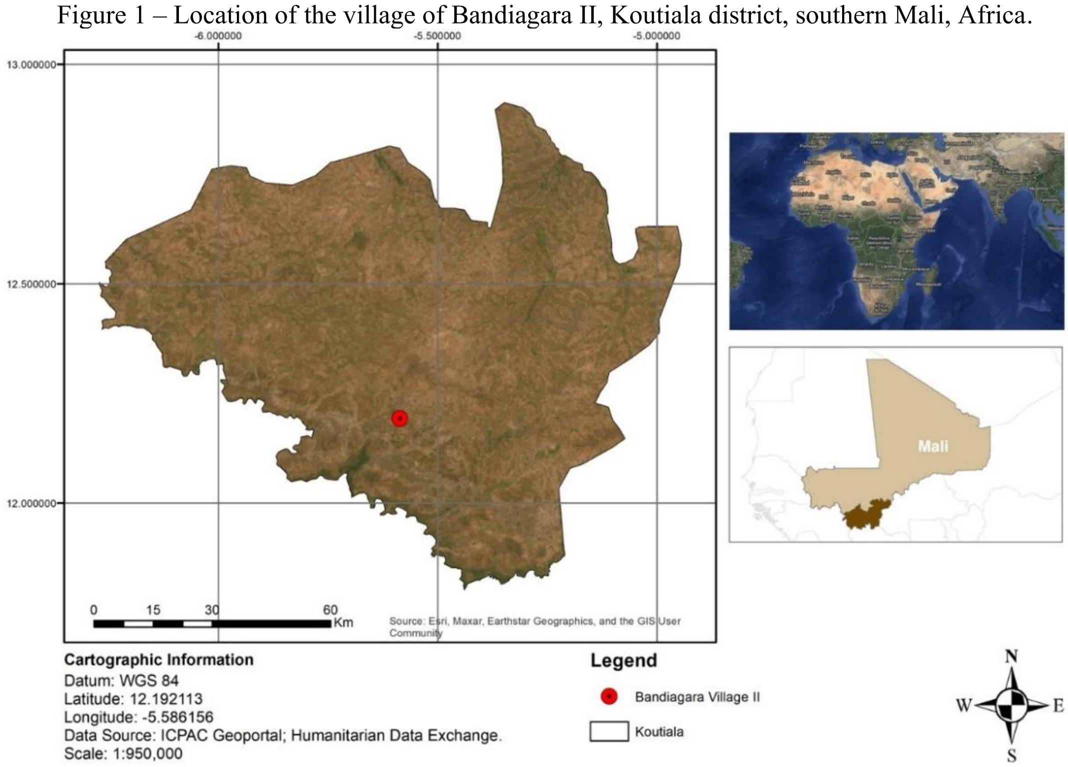
MATERIAL AND METHODS

Study area description

The study was conducted in the village of Bandiagara II, a small rural village located in the southern part of Mali, within the transition zone between the Sahel and the Sudanese Savanna. The village lies in a gently undulating plain at altitudes ranging from 250 to 400 meters above sea level, with predominantly flat terrain interspersed with small hills. These features facilitate agricultural practices but also expose the area to erosion risks, especially under intensive land use.

Village of Bandiagara II is geographically situated at approximately 12°11'30.06" N and 5°35'15.47" W and had an estimated population of 630 inhabitants in 2024 (based on informal local communication). The region has a semi-arid climate, marked by a rainy season from May to October and a dry season from November to April. Annual rainfall ranges between 600 and 900 mm, supporting primarily rainfed agriculture, with cotton as the main crop, followed by cereals and livestock.

Figure 1 – Location of the village of Bandiagara II, Koutiala district, southern Mali, Africa.



UAV data collection

In October 2018, high-resolution aerial images were obtained in the village of Bandiagara II, located in the Koutiala district of Mali, using a DJI Phantom 4 RTK unmanned aerial vehicle (UAV) equipped with a 20-megapixel RGB camera. Autonomous flights were conducted at an altitude of 120 meters with 70% image overlap, resulting in a spatial resolution of 3.4 cm/pixel. A total of 6,803 images were captured. The images were processed using Structure-from-Motion (SfM) photogrammetry with Agisoft Metashape software, generating 3D point clouds and digital elevation models (DEMs). These products enabled detailed terrain mapping to support analyses of sanitation conditions, water availability infrastructure, and local planning strategies.

RESULTS AND DISCUSSIONS

Roof typology and rainwater harvesting

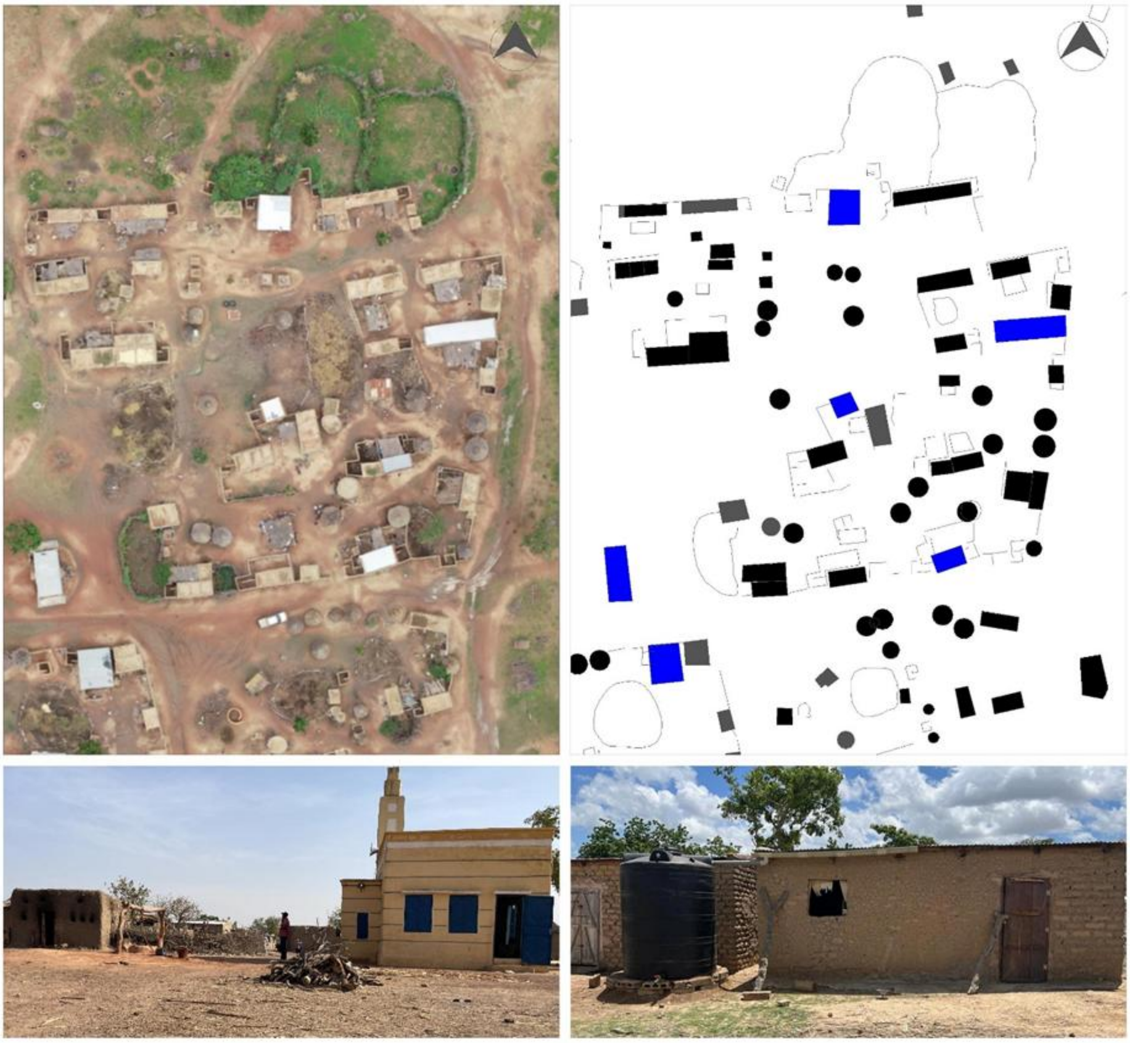
Figure 2 presents the UAV image, highlighting a dispersed pattern of constructions characteristic of Malian rural villages, where rectangular, circular, and other variations of dwellings can be observed, depending on the village's dynamics and displays a vector and schematic map in which thatched. Adobe roofs are identified in solid black, and metal roofs in solid blue. The surroundings of the buildings include green areas and dirt pathways connecting the structures. Identifying these characteristics is essential for infrastructure planning, ensuring that rainwater harvesting and storage systems are strategically positioned.

Given the architectural complexity and remoteness of the region, field validation of the information obtained from UAV imagery was made to ensure the accuracy and applicability of the data. Specifically, it is essential to verify whether the identified rooftops are structurally sound and suitable for rainwater harvesting. Figure 2 illustrates this need by presenting a variety of village structures, including traditional adobe dwellings and painted brick buildings, the latter of a mosque in this case. The implementation of rainwater collection systems, such as horizontal gutters attached to walls, requires careful on-site evaluation of critical factors, including material durability under high regional temperatures and the structural integrity of walls for secure gutter installation — all of which depend on local construction practices.

Rural buildings in this context present challenges due to two main factors: the absence of coordinated planning, which results in a disordered spatial layout, and the reliance on vernacular construction methods, often guided by the empirical knowledge of local craftsmen. This leads to a high diversity of roof types and building materials, further reinforcing the need for UAV-assisted analysis to inform infrastructure interventions (He *et al.*, 2019).

The UAV image of the village of Bandiagara II enabled the identification of flat roofs with the potential for rainwater harvesting. The images estimated the available roof area and the direction of surface water runoff (water flow). Additionally, the image enabled the localization of buildings within the village and family units, as well as the identification of their adjacent structures, facilitating the planning of water storage reservoir installations.

Figure 2 – UAV image of village of Bandiagara II (Top-left), vector schematic map with different types of roofs – thatched and adobe roofs in solid black and metal roofs in solid blue (Top-right), ground-level view of the village (Bottom-left), and rainwater harvesting system in a traditional adobe building with a metal roof (Bottom-right).



Installing gutters for water direction requires a specific approach in the case of adobe walls, a material with greater structural fragility. To ensure secure fixation, the wall must support the load of the harvesting system, using metal supports fixed to beams or wooden cross bars embedded in the wall structure, expansion anchors or chemical anchoring systems, and applying waterproof sealant around the fixations.

Buildings in Malian villages are deeply intertwined with traditional culture and national identity, especially in rural and vulnerable regions. However, the absence of detailed structural data in these areas significantly limits urban planning efforts and risk assessments. UAV imagery was a powerful tool to overcome these barriers by enabling the identification of roof typologies and supporting precise mapping and structural modeling.

In regions with precarious infrastructure, UAVs have been successfully applied in preventive maintenance and risk mitigation strategies (Alzarrad *et al.*, 2022). Their effectiveness is further enhanced by the integration of machine learning algorithms and neural networks, which allow for a more comprehensive analysis of structural conditions (Ölçer *et al.*, 2021). Artificial intelligence has also facilitated the automation of defect detection in rooftops, increasing both the speed and safety of inspections (Yudin *et al.*, 2018).

In environments where GPS signals are weak or unavailable, UAVs improve autonomous mapping capabilities and offer reliable data acquisition solutions (Kerle *et al.*, 2019). Moreover, in contexts where high-resolution satellite imagery is limited or logistically unfeasible, UAVs become indispensable. In traditional Chinese villages, for example, combining UAV imagery with dense point clouds has enabled the automatic extraction of roof feature lines, streamlining detailed structural analysis (Zhou *et al.*, 2024). Similarly, UAVs have proven highly effective in the inspection of sloped structures, offering a safe and precise alternative for monitoring and maintenance tasks (Bown and Miller, 2018).

In remote rural settings, such as isolated villages, these technical advancements not only support infrastructure planning and spatial organization but also contribute to significantly improving public health, safety, and the overall quality of life (Zhou *et al.*, 2024).

Sanitation infrastructure and WASH risks

UAV applications for water supply, hygiene, and sanitation (WASH) helped, firstly, to understand the village and family nuclei (FN) organization (13 people per FN, on average), where we can observe structures used for toilets, washrooms, and hand wells for water supply (Figure 3). Eighty-nine pit latrine unimproved toilets (UNICEF & WHO, 2023) (Figure 3) formats and twelve hand wells were identified by the structures in Figure 4 using the UVA. Their location guided the team on the field in diagnosing sanitation, water collection and quality to plan interventions and map possible contamination sources.

As a result, we detected the proximity of the latrines and solid waste to the hand wells along with the potential pathogen contamination, which was then confirmed by positive Escherichia coli analysis. Consequently, interventions focused on containing and treating human fecal excreta to avoid soil contact before microbial inactivation and improve water captions with a sand pre-filter and screed with concrete shackle, diminishing the perception of diarrhea cases among the residents.

UAV imagery enabled a comprehensive inventory of sanitation facilities, tracking the number and distribution of toilets over space and time to assess the expansion of installations. Additionally, this data will support ongoing monitoring efforts, evaluating the quality of construction materials used in sanitation infrastructure, and ensuring compliance with safety and durability standards. Furthermore, UAV-based assessments will facilitate the systematic evaluation of dry waste treatment processes, allowing for improvements in waste management strategies to enhance hygiene, reduce environmental contamination, and optimize resource recovery.

Figure 3 – Family organization with toilets, washrooms, and hand wells for water supply at village of Bandiagara II, Pit latrine unimproved toilets at Bandiagara II: UAV imagery (Top), and Field photo (Bottom).

Figure 4 – Handwells for water collection at village of Bandiagara II: UAV (Top), and Field photo (Bottom)

CONCLUSIONS

UAV-based imagery proved to be an effective solution for diagnosing, mapping, and planning sanitation and water supply interventions in the remote village of Bandiagara II. By enabling safe, high-resolution monitoring, even under political and logistical constraints, UAVs support the design of context-specific strategies that can be replicated in other vulnerable regions. Their integration into WASH initiatives enhances local resilience, improves public health outcomes, and advances sustainable development goals in under-resourced territories.

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