GeoPlanning
Journal of Geomatics and Planning
Geoplanning: Journal of Geomatics and Planning, Vol. 13, No. 1, 2026, 89 - 100

Received: 22 November 2025;
Revised: 26 May 2026;
Accepted: 01 June 2026;
Available Online: 15 June 2026;
Published: 25 June 2026.

Keywords:
Urban Wetland Monitoring, UAV Photogrammetry, Low-Cost Drone Protocol

*Corresponding author(s)
email: profecesar15@gmail.com

Original Research Open access

Low-Cost RPAS Photogrammetric Protocol for Multitemporal Monitoring of an Urban High-Andean Wetland: Application to Santa María del Lago, Bogotá

César Augusto Gutiérrez-Rodríguez[1]*

1. *Corporación Unificada Nacional de Educación Superior - CUN, Colombia*

DOI: 10.14710/geoplanning.13.1.89-100

Abstract

Urban wetlands require frequent high-resolution monitoring, yet costs and logistics hamper traditional approaches. This study designs and validates a low-cost photogrammetric protocol using remotely piloted aircraft systems (RPAS) to quantify short-term water-surface dynamics in an urban wetland. Ten fortnightly campaigns were conducted at Santa María del Lago (Bogotá) between 1 May and 4 September 2025 using nadir imagery with 80/75% overlap and a GSD of 2.8–3.2 cm/px. Without ground control points, internal geometric precision was assessed through sub-pixel reprojection error (~0.82 px) and relative scale consistency. Water extent was delineated using HSV thresholding and vectorization with a conservative positional threshold. Over 126 days, water-surface area decreased from 5.60 to 5.20 ha (−0.40 ha; −7.1%), with a median shoreline retreat of 1.1 m and a significant monotonic trend (Mann–Kendall $\tau = -1.00$, $p < 0.001$). Each campaign required 35–45 min of fieldwork and 2.0–3.5 h of processing, with direct costs of USD 25–40 per flight. The protocol produced reproducible multitemporal datasets with decimetric planimetric sensitivity while reducing time and direct costs relative to conventional monitoring. The protocol proved feasible for high-Andean urban wetlands and potentially transferable to similar environments following local adaptation and validation.

1. Introduction

Wetlands are ecosystems of global ecological and socio-economic importance because they regulate hydrological processes, improve water quality, store carbon and provide habitat for diverse species. Despite these functions, wetlands have experienced sustained degradation and loss worldwide due to land-use change, urban expansion, infrastructure development, pollution and hydrological alteration. At the global scale, it is estimated that more than 35% of wetlands have disappeared over the last five decades, reinforcing the need for frequent, comparable and spatially explicit monitoring tools to support evidence-based management decisions (Courouble et al., 2021; Davidson & Finlayson, 2018; Delle Grazie & Gill, 2022; Dronova et al., 2021).

In Colombia, wetlands are key components of environmental regulation and biodiversity conservation, particularly in areas where urbanization and land-use transformation have placed strong pressure on aquatic and transitional ecosystems. Colombian wetlands provide water regulation, pollutant filtering, carbon storage and habitat functions, but they are also exposed to agricultural expansion, waste disposal, infrastructure development and uncontrolled urban growth (Alikhani et al., 2021; Cuellar & Perez, 2023; Patino & Estupinan-Suarez, 2016). These pressures make systematic monitoring especially relevant for detecting changes in water extent, vegetation cover and ecosystem condition.

Within the Colombian Andes, high-Andean urban wetlands are particularly sensitive because they are embedded in dense urban matrices and operate under complex interactions between hydrological seasonality, built-up expansion, restricted hydraulic connectivity and intensive public use. In Bogotá D. C., wetlands function as ecological infrastructure for flood regulation, biodiversity conservation, environmental education and urban climate regulation. However, their small size, fragmented condition and exposure to surrounding urban pressures require monitoring approaches capable of detecting short-term and fine-scale spatial changes.

Santa María del Lago wetland exemplifies this situation. Historical management documentation indicates that the wetland has lost about 60.8 ha through urbanization and infilling, decreasing from approximately 71.6 ha to the current 10.8 ha. This transformation has resulted in a 27.33% reduction of open water and a 66.70% decrease in herbaceous vegetation between 1952 and 1990, with direct implications for hydrological regulation, habitat provision and the ecosystem services supplied to the city. The most recent update of the Environmental Management Plan provides the current institutional framework for conservation and restoration actions in the wetland (Observatorio Ambiental de Bogotá, 2023; Secretaría Distrital de Ambiente, 2010, 2023). In this context, access to monitoring series with fine spatial resolution and sufficient temporal frequency is critical to detect early changes and guide conservation and restoration measures.

Traditional wetland monitoring, based on sporadic field campaigns, manual shoreline delineation with handheld GNSS and analysis of aerial photographs or sub-metric to metric resolution satellite imagery, is often costly, logistically demanding and characterized by limited effective spatio-temporal coverage. As a result, its ability to represent periodic variability and capture micro-scale changes in water-surface boundaries is restricted. In contrast, emerging technologies such as remotely piloted aircraft systems (RPAS) and digital photogrammetry enable the acquisition of very high-resolution imagery from low-altitude flights, producing detailed cartographic products that are comparable over time at decreasing costs (Cvijanović et al., 2025; Dronova et al., 2021; Van Alphen et al., 2024). The present work adopts a low-cost approach based on consumer-grade platforms and open-source software, aimed at reducing acquisition and operating costs without compromising the geometric quality required for monitoring.

In response to this need, this article designs and validates a low-cost photogrammetric protocol for multitemporal monitoring of urban wetlands using RPAS, dispensing with ground control points and relying on georeferencing and scale derived from on-board Global Navigation Satellite System (GNSS) and rigorous block adjustment. The protocol is tailored to the geographical, ecological and regulatory conditions of high-Andean wetlands in Colombia and is validated at Santa María del Lago (Bogotá) through ten fortnightly campaigns between May and September 2025. Recent UAV-based wetland studies have demonstrated the value of very high-resolution imagery, multispectral–LiDAR fusion and machine learning classification for mapping habitat conditions, vegetation patterns and wetland change at fine spatial scales (Van Alphen et al., 2024; Zerrouk et al., 2025).

At the same time, recent guidance on drone remote sensing stresses the need to report mission parameters, georeferencing strategy, accuracy assessment and processing settings to ensure reproducibility and methodological transparency (Mathews et al., 2023). However, these advances have mainly focused on classification performance, multi-sensor fusion or general best-practice recommendations, while fewer studies translate them into low-cost, repeatable and site-level protocols for high-frequency monitoring of water-surface change in high-Andean urban wetlands. Two gaps therefore remain: first, the lack of operational protocols that specify mission parameters, quality-control criteria and change-detection thresholds for fortnightly RPAS series in these settings; and second, the limited quantitative evidence on the relative precision and practical sensitivity achievable when low cost is prioritized and ground control points are omitted.

This study aims to design and validate a low-cost RPAS-based photogrammetric protocol for fortnightly monitoring of water-surface dynamics in high-Andean urban wetlands, using consumer-grade equipment and open-source software, and to evaluate its geometric, operational and diagnostic performance through ten pilot campaigns at Santa María del Lago wetland in Bogotá. The central contribution does not lie in a new processing

DOI: 10.14710/geoplanning.13.1.89-100

algorithm, but in the formalization of an integrated operational protocol that combines mission parameters, processing workflow, quality-control criteria and change-detection thresholds under low-cost conditions and without ground control points. By documenting the relative precision and operational feasibility achieved in this context, the study provides a replicable monitoring scheme for wetlands with similar environmental and institutional conditions, subject to local adaptation and validation.

2. Data and Methods

2.1. Study Design and Site Characteristics

The study followed an applied quantitative, non-experimental, observational, longitudinal and prospective design with repeated measures at a single site. The protocol was validated at the urban wetland Santa María del Lago, located in the Engativá district of Bogotá D. C., within the Juan Amarillo (Salitre) river basin. The District Wetland Reserve covers 10.86 ha, of which the open water surface occupies approximately 5.64 ha. The system is a small urban lake surrounded by built-up matrix and major roads, with public access for passive recreation and environmental education.

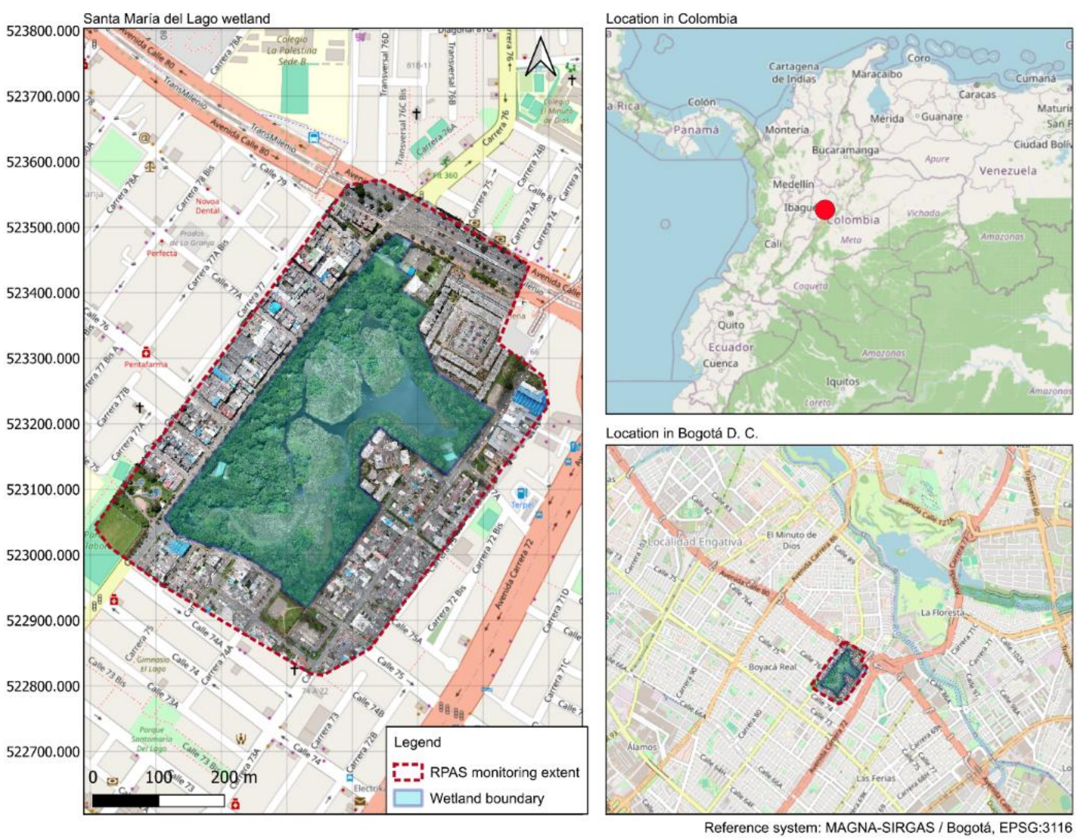


Figure 1. Location of Santa María del Lago wetland and RPAS monitoring area in Bogotá D. C., Colombia.

Figure 1 shows the study area boundary, the RPAS monitoring extent and the surrounding urban context. The map also includes insets indicating the location of Bogotá D. C. within Colombia and the position of Santa María del Lago wetland within the urban area. The spatial data are referenced to the MAGNA-SIRGAS / Bogotá coordinate reference system (EPSG:3116). The wetland is situated at a mean elevation of approximately 2550 m a.s.l., with a mean annual temperature of around 14 °C and frequent cloud cover. These high-Andean and urban environmental conditions influenced flight planning, the selection of suitable weather windows and the meteorological thresholds adopted for safe RPAS mission execution.

To improve methodological clarity and reproducibility, Figure 2 illustrates the complete workflow followed in the low-cost RPAS-based monitoring protocol, from mission planning and image acquisition to photogrammetric processing, quality control, water-surface delineation, multitemporal analysis and operational assessment.

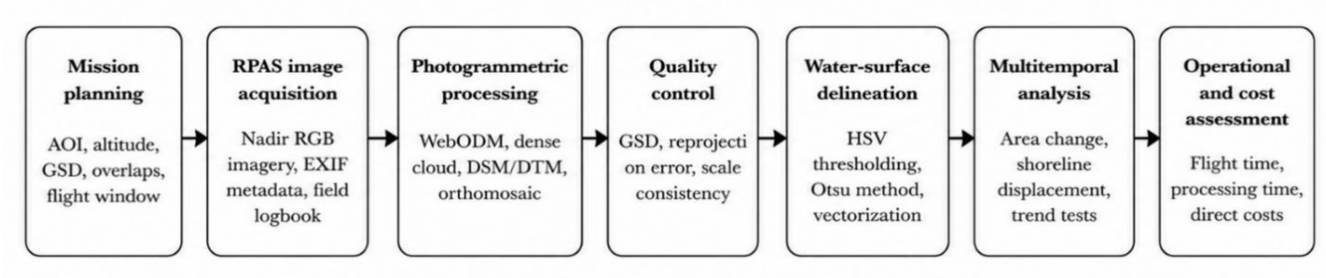


Figure 2. Workflow of the Low-Cost RPAS Monitoring Protocol

2.2. Design of the Low-Cost Photogrammetric Protocol

The low-cost photogrammetric protocol with RPAS was designed following established UAV photogrammetry principles and reporting recommendations for drone-based remote sensing, in order to ensure temporal comparability, geometric precision and technical traceability using accessible resources (Elkhrachy, 2015; Mathews et al., 2023; Salas López et al., 2022). Mission planning defines parallel flight lines with 80% forward overlap and 75% side overlap, a nadir-oriented sensor and a flight altitude calculated to achieve a ground sampling distance (GSD) between 2.8 and 3.2 cm/px. Where relief or homogeneous surfaces require it, a cross-block with perpendicular strips is added to reinforce block stability. Missions are scheduled in a mid-morning window under stable sky conditions to reduce radiometric variability, and an operational wind threshold of 6–8 m/s is adopted to ensure effective overlaps and image sharpness. The area of interest is delineated a priori and safety corridors, take-off zones and contingency areas are defined.

The capture configuration is set in manual mode, with fixed white balance, the lowest admissible ISO sensitivity given available light and shutter speed high enough to avoid platform motion blur. Focus is verified at an appropriate distance and kept constant during each campaign. The sensor is triggered at an interval that guarantees the planned overlap. The platform recorded the GNSS trajectory and exposure events. The lever arm between the GNSS antenna and the camera perspective center was measured and corrected during post-processing. Camera orientation is kept strictly nadir and automatic adjustments that could alter internal parameters in an uncontrolled manner are avoided.

2.3. Drone Data Acquisition

Data acquisition combined three types of information: (1) aerial photogrammetric surveys with a consumer-grade DJI Phantom 4 Pro V2.0 multirotor RPAS equipped with a 20 MP RGB sensor and mechanical shutter, nadir camera orientation and manual exposure, recording EXIF metadata and GNSS tags for each image; (2) a field logbook including local mid-morning time, weather conditions without rainfall, operational wind ≤8 m/s and homogeneous cloud cover, as well as safety incidents, operation times and contextual observations; and (3) cartographic registration in the MAGNA-SIRGAS / Bogotá reference system (EPSG:3116), using meters as units.

Ten fortnightly campaigns were conducted between 1 May and 4 September 2025, maintaining constant flight altitude, target GSD of 2.8–3.2 cm/px, 80% forward and 75% side overlap, and homogeneous exposure parameters. To preserve the low-cost character of the protocol, no ground control points were integrated into the bundle adjustment. In applications requiring verifiable absolute accuracy, external low-cost check points are envisioned as independent validation, without incorporating them into the adjustment.

2.4. Photogrammetric Processing and Quality Control

Photogrammetric processing was carried out in WebODM, an open-source platform for UAS image processing, and cartographic analysis was performed in QGIS, a free and open-source geographic information system widely used for spatial data management, analysis and visualization (Graser et al., 2025; Patel et al., 2024; QGIS Development Team, 2025; Toffanin, 2019).

Quality control comprised verification of effective overlaps, image sharpness, mosaic continuity and coherence between strips. Stable areas without apparent change were inspected to identify potential artifacts. Acceptance criteria were established for each campaign: GSD between 2.8 and 3.2 cm/px, median reprojection error <1.0 px and relative scale consistency ≤1.6%. When any criterion was not met, the cause was recorded and either flight repetition or reprocessing was scheduled as appropriate.

In this ten-campaign validation, Ground Control Points (GCP) were intentionally omitted to prioritize low cost and acquisition frequency. Absolute accuracy was not quantified against external topographic measurements; instead, multitemporal comparability relied on internal geometric precision (sub-pixel reprojection error and relative scale consistency ≤1.6%).

2.5. Water-Surface Delineation and Multitemporal Analysis

Multitemporal analysis was performed through co-registration of consecutive orthomosaics, keeping acquisition geometry and time window constant to reduce non-thematic differences between campaigns. Water-surface extent was delineated using thresholding in HSV color space with Otsu's method, an automatic thresholding approach widely used in image segmentation, followed by morphological filtering to remove noise and semi-automatic vectorization in QGIS (Benz et al., 2004; Johnson, 2011; Otsu, 1979).

To control positional significance, a conservative threshold was adopted whereby local variations ≤ 1–2 × GSD were considered indistinguishable from geometric uncertainty. Only coherent and persistent changes observed in at least two dates were reported. The time series was analyzed using linear regression (slope and 95% confidence interval) and the Mann–Kendall test to assess monotonic trends, following its common application in hydrological and environmental time-series analysis (Hamed & Rao, 1998; Yue et al., 2002).

2.6. Recording of Operational Times, Costs and Conditions

Operationally, planning time, field operation time and processing time per flight were recorded, along with direct costs per campaign and cost per monitored hectare, consolidating the information in a control table with date, local time, meteorological conditions, mission parameters and safety observations. All flights were conducted under visual line-of-sight (VLOS) conditions, with the pilot maintaining direct and continuous visual contact with the aircraft, observing its position, attitude and trajectory and monitoring the surroundings to avoid conflicts with people, obstacles and other aircraft. The operational planning considered the Colombian regulatory framework for unmanned aircraft systems, particularly RAC 100, which establishes the rules for UAS operations in the national territory (Unidad Administrativa Especial de Aeronáutica Civil, 2023).

3. Results and Discussion

3.1. Baseline Mapping and Initial Photogrammetric Product

Implementation of the low-cost photogrammetric protocol produced, for Flight 1 (1 May 2025), an RGB orthomosaic of Santa María del Lago with a target GSD of 2.8–3.2 cm/px and full coverage of the water surface and its immediate surroundings. Figure 3 presents the baseline orthomosaic used as the spatial reference for the multitemporal analysis of water-surface contraction and protocol performance. The orthomosaic displays the wetland water surface together with the surrounding urban environment, providing the spatial context for interpreting subsequent changes. The dataset is referenced to the MAGNA-SIRGAS / Bogotá coordinate reference system (EPSG:3116).

Source: Own elaboration based on RPAS surveys at Santa María del Lago, 2025

Figure 3. Baseline RPAS Orthomosaic of Santa María del Lago wetland from Flight 1, 1 May 2025

3.2. Temporal Evolution of Water-Surface Area (May–September 2025)

The multitemporal series of ten fortnightly campaigns showed a sustained contraction of the water surface over the 126-day observation period. Starting from the baseline (Flight 1), water-surface area decreased progressively, reaching an accumulated reduction of −7.1% by Flight 10. Typical fortnightly losses ranged between 0.03 and 0.06 ha per interval, consistent with the total contraction observed. To harmonize interpretation of changes, a conservative positional threshold of 2×GSD was adopted to distinguish real variations from oscillations attributable to geometric error. Water-surface areas were reported to two decimal places, with a conservative margin on the order of ±0.01 ha, consistent with sub-pixel reprojection error and the relative scale consistency achieved in the series.

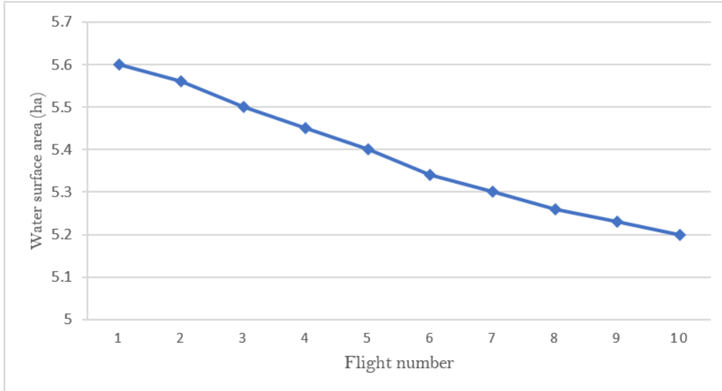
Table 1 summarizes the date, local time and water-surface area (ha) recorded during the ten flight campaigns conducted between May and September 2025. Flight 1 (1 May 2025) was used as the baseline, and subsequent changes are expressed as percentages relative to this baseline. Figure 4 presents the time series of water-surface area derived from the RPAS orthomosaics for each campaign, with area values (ha) shown by flight number and referenced to the baseline established in Flight 1. A linear fit to the series yielded a negative slope (area contraction per fortnight) with a high coefficient of determination (R^2 close to 1), while the Mann–Kendall test indicated a statistically significant monotonic decreasing trend ($p < 0.001$), reinforcing the consistency of the contraction observed over the analysis period.

Table 1. Schedule of Flight Campaigns and Time Series of Water-Surface Area (baseline = Flight 1)

Flight	Date	Local Time (hh:mm)	Water-Surface Area (ha)	Δ vs. Flight 1 (%)
1	01/05/2025	10:30	5.60	0.0
2	15/05/2025	10:30	5.56	−0.7
3	29/05/2025	10:45	5.50	−1.8
4	12/06/2025	10:45	5.45	−2.7
5	26/06/2025	10:45	5.40	−3.6
6	10/07/2025	11:00	5.34	−4.6
7	24/07/2025	11:05	5.30	−5.4
8	07/08/2025	11:15	5.26	−6.1
9	21/08/2025	11:15	5.23	−6.6
10	04/09/2025	11:00	5.20	−7.1

Source: Own elaboration based on RPAS surveys at Santa María del Lago, 2025

DOI: 10.14710/geoplanning.13.1.89-100



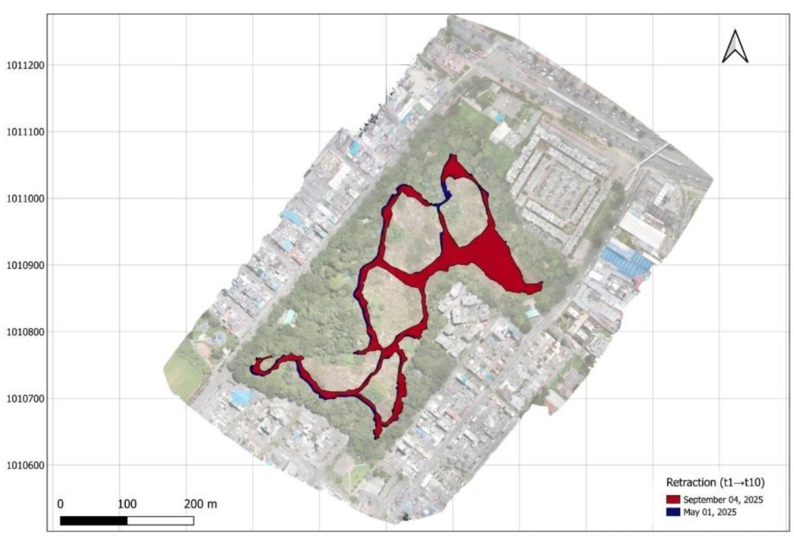
Source: Own elaboration from RPAS-derived water-surface area time series, 2025

Figure 4. Temporal Evolution of Water-Surface Area (ha) in Santa María del Lago Wetland during the Ten Flight Campaigns (May–September 2025)

The 7.1% contraction of water-surface area over 126 days should be interpreted as a short-term hydro-spatial response rather than as direct evidence of irreversible wetland degradation. In high-Andean urban wetlands, surface-water extent may respond rapidly to the combined influence of precipitation variability, evapotranspiration, restricted hydraulic connectivity, shallow marginal morphology and colonization by emergent vegetation. The concentration of retreat along shallow and irregular shoreline sectors supports this interpretation, since these areas are more sensitive to small water-level fluctuations and vegetation encroachment than deeper open-water zones. Therefore, the observed monotonic decrease is environmentally relevant because it identifies sectors and magnitudes of change that may require management attention, but it should be interpreted together with rainfall, water-level, inflow and outflow records in future monitoring cycles.

3.3. Spatial patterns of shoreline retreat and expansion

Beyond the global variation in area, spatial analysis of differences between consecutive campaigns allowed localized patterns of shoreline retreat and expansion to be identified. For each pair of consecutive orthomosaics, polygon differences were computed and changes were classified into three categories: retreat (loss of water surface), expansion (gain of water surface) and no change.



Source: Own elaboration based on RPAS orthomosaics of Santa María del Lago, 2025

Figure 5. Spatial Differences in the Water-Surface Boundary between the Baseline and Final RPAS Campaigns

A positional threshold of 2×GSD was used as the minimum criterion for mapping changes (equivalent to several decimeters on the ground), such that smaller variations were considered indistinguishable from geometric uncertainty and were not represented. Under this criterion, results showed that retreat concentrated along shallow shore sectors with colonization by emergent vegetation and more irregular edges, whereas localized expansions were associated with small incursions of water into adjacent depressions or marginal delineation adjustments in gently sloping sectors.

Figure 5 shows the spatial distribution of water-surface changes detected between the baseline and final campaigns. The map illustrates water-surface changes between 1 May and 4 September 2025 using a 2×GSD positional threshold. Retreat areas represent sectors where the water surface decreased beyond the positional uncertainty threshold, while the wetland boundary and the baseline and final water-surface limits are included to facilitate spatial interpretation. The spatial data are referenced to the MAGNA-SIRGAS / Bogotá coordinate reference system (EPSG:3116). In metric terms, median shoreline retreat was on the order of ~1.1 m, with interquartile ranges around 0.7–1.6 m, confirming that the protocol is capable of detecting shoreline displacements relevant to micro-scale management (tens of m^2) in high-Andean urban settings.

3.4. *Geometric and Operational Performance of the Protocol*

Geometric performance was evaluated from internal quality indicators of the photogrammetric adjustments: reprojection error and relative scale consistency between campaigns. Across the ten campaigns, reprojection error consistently remained in the ~0.8–0.9 px range, while relative scale consistency stayed at or below 1.6%. These results support the internal geometric stability of the series and the multitemporal comparability of the products generated in the absence of ground control points.

From a geometric standpoint, protocol performance is consistent with literature demonstrating the ability of RPAS and digital photogrammetry to achieve sub-pixel internal precision and very high-resolution products in environmental applications (Elkhrachy, 2015; Mathews et al., 2023; Salas López et al., 2022). In this study, reprojection errors on the order of 0.8–0.9 px and relative scale consistency ≤1.6% between campaigns support the assumption that a robust multitemporal comparability framework can be maintained without ground control points, provided that flight geometry and capture parameters remain constant. Recent studies on low-cost UAV photogrammetry, open-source photogrammetric processing and cost-effective wetland monitoring support the operational feasibility of using accessible RPAS workflows for relative environmental change detection (Cvijanović et al., 2025; Elkhrachy, 2015; Gbagir et al., 2023). In this context, the validated protocol indicates that omitting ground control points may be operationally acceptable for relative change detection when repeated flight geometry, stable acquisition parameters and conservative positional thresholds are maintained; however, it should not be interpreted as a substitute for external accuracy assessment when absolute positional accuracy is required.

A critical limitation of this validation is that the omission of ground control points prevents a direct assessment of absolute positional accuracy and may introduce systematic biases in the final orthomosaics. Therefore, the reported geometric performance should be interpreted as evidence of internal consistency and relative multitemporal comparability, not as proof of survey-grade absolute accuracy. This distinction is important for operational use: the protocol is suitable for detecting coherent shoreline changes and short-term water-surface dynamics within a repeated monitoring framework, but applications requiring legal boundary definition, engineering-grade measurements or integration with high-accuracy topographic datasets should incorporate independent check points or ground control points.

From an operational standpoint, each campaign required on average 1.0–1.5 h of planning, 35–45 min of field operations and 2.0–3.5 h of processing, with direct costs estimated between USD 25 and 40 per flight. Considering the baseline area of 5.60 ha, the cost per monitored hectare was approximately 4.5–7.2 USD/ha. This capture-to-product cycle of ~4.5–5.5 h per campaign made same-day outputs feasible. This is consistent with a low-cost approach designed to support institutional adoption and operational decision-making.

In operational terms, the documented times and costs (4.5–5.5 h per campaign and 4.5–7.2 USD/ha) are comparable to or lower than those reported in other studies implementing similar RPAS workflows in aquatic environments (Cvijanović et al., 2025; Dronova et al., 2021; Musungu et al., 2024). This supports the feasibility of low-cost approaches for local environmental agencies with budget constraints, provided that trained personnel and a clear protocol for planning, data capture, processing and quality control are available. Compared with extensive GNSS field campaigns, drone flights reduce staff exposure to unstable shorelines and enhance methodological traceability, in line with recent concerns regarding occupational safety and efficiency in environmental monitoring (Dronova et al., 2021; Mathews et al., 2023; Musungu et al., 2024).

The novelty of the protocol lies in its operational integration rather than in the isolated use of RPAS imagery or photogrammetric software. The proposed workflow combines low-cost equipment, open-source processing, repeated flight geometry, explicit quality-control thresholds and conservative change-detection criteria into a single monitoring scheme tailored to high-Andean urban wetlands. This is relevant because local environmental agencies often require rapid, repeatable and affordable information for site-level decisions, but lack the resources to implement frequent topographic surveys or commercial high-resolution monitoring programs. Under these conditions, the protocol provides a practical middle ground between regional satellite monitoring and labor-intensive field surveys, offering very high spatial detail and same-day operational outputs for wetland management.

3.5. Quantitative Comparison with Traditional Monitoring Methods

The time series generated by the low-cost photogrammetric protocol was used to quantitatively compare geometric and operational parameters against three traditional approaches to water-surface monitoring: (i) public orthophotography with 8 cm resolution, (ii) high- to medium-resolution satellite imagery and (iii) in situ shoreline delineation using handheld GNSS receivers. The comparison is based on the Santa María del Lago validation series and the operational characteristics discussed in this study. The RPAS results correspond to the ten-campaign monitoring protocol implemented between May and September 2025. To make the comparison more explicit, Table 2 summarizes the main geometric, temporal and operational differences between the low-cost RPAS protocol and three conventional monitoring approaches commonly used for water-surface delineation.

The drone-based protocol applied at Santa María del Lago produced orthomosaics with 2.8–3.2 cm/px GSD and a median internal reprojection error of ~0.82 px consistently across campaigns, with relative scale consistency ≤1.6%. This geometric quality enabled clear delineation of the water-surface boundary and derivation of stable planimetric metrics between consecutive dates. In contrast, available public orthophotography has 8 cm resolution, while commercial satellite images used in the region offer pixel sizes in the sub-metric to metric range, and handheld GNSS delineation is affected by measurement dispersion driven by environmental conditions (vegetation, multipath, satellite geometry) and operator behavior.

In terms of sensitivity to change, the RPAS protocol allowed detection of area variations from approximately 10 m², making it possible to identify localized retreats and expansions of the water surface even in the presence of emergent vegetation, shadow and sinuous shorelines. For traditional approaches, the practical detection threshold lies in higher ranges, on the order of ~100–900 m², due to both the effective resolution of the inputs and the variability of manual shoreline tracing in the field, which translates into a reduced ability to capture fine-scale changes between closely spaced campaigns.

Temporal comparability of the RPAS protocol was reflected in the stability of shorelines between consecutive dates, a necessary condition for spatial analysis of retreat and expansion and for assessing the persistence of changes. Public orthophotography typically provides only a single acquisition date; high-resolution satellite series are constrained by cloud cover, data availability and acquisition dates; and the repeatability of GNSS-based delineation depends on team discipline and physical accessibility of shore sectors.Regarding response time, the capture-to-product cycle of the RPAS protocol remained between 4.5 and 5.5 h per campaign (planning, field operations and processing), enabling delivery of maps and metrics on the same day as the flight. For traditional approaches, response times depend on the prior availability of orthophotos or satellite images (download, purchase and preprocessing) or, in the case of GNSS, on field days and travel required to walk the shoreline, which may be non-trivial in sectors with difficult access.

Table 2. Summary Comparison Between the Low-Cost RPAS Protocol and Traditional Water-Surface Monitoring Approaches

Comparison Criterion	Low-Cost RPAS Protocol	Public Orthophotography	Satellite Imagery	Handheld GNSS Survey
Spatial resolution or working scale	2.8–3.2 cm/px GSD	Approximately 8 cm resolution when available	Sub-metric to metric resolution, depending on sensor and product	Point-based delineation affected by receiver precision and field conditions
Geometric control	Median reprojection error around 0.82 px and relative scale consistency ≤1.6 %	Depends on source product and acquisition specifications	Depends on sensor, preprocessing level and georeferencing accuracy	Depends on satellite geometry, multipath, vegetation and operator path
Temporal comparability	Fortnightly campaigns with repeated flight geometry and acquisition window	Usually limited to available acquisition dates	Constrained by revisit time, cloud cover and image availability	Depends on field access, personnel availability and repeatability of manual tracing
Practical change-detection sensitivity	Approximately 10 m^2 for coherent changes beyond the 2×GSD threshold	Suitable for larger changes, limited for short-term micro-variations	More suitable for regional or medium-scale trends than fine shoreline displacement	Higher practical threshold due to manual tracing variability
Response time	Approximately 4.5–5.5 h from planning to final products	Depends on previous availability of orthophotos	Depends on image access, cloud-free acquisition and preprocessing	Usually requires field days and post-field processing
Direct cost	Approximately USD 25–40 per campaign or 4.5–7.2 USD/ha	May have no direct cost, but limited temporal availability	Variable licensing and processing costs	Low equipment cost, but higher field time and logistical costs
Main advantage	Very high spatial detail, repeatability and rapid site-level response	Useful as historical or reference cartography	Useful for regional context and long-term trends	Direct field verification of shoreline position
Main limitation	Absolute accuracy is not externally validated when GCPs are omitted	Limited temporal frequency	Cloud cover and pixel size limit fine-scale interpretation	Lower repeatability in vegetated or inaccessible sectors

Source: Own elaboration based on RPAS validation results at Santa María del Lago, operational records from the monitoring campaigns, and comparative criteria for traditional water-surface monitoring approaches, 2025

Direct costs of the RPAS protocol ranged between USD 25 and 40 per campaign, which, taking 5.60 ha as baseline, corresponds to approximately 4.5–7.2 USD/ha monitored. Public orthophotography may entail no direct cost but usually lacks temporal series; satellite imagery involves variable costs associated with licensing and processing; and handheld GNSS has low equipment costs but higher opportunity costs related to field time and logistics and lower shoreline precision, especially in dense vegetation and multipath conditions.

Comparison with traditional approaches reinforces these findings. The literature shows that medium-resolution satellite imagery and conventional orthophotos characterize regional trends and large-magnitude changes but are limited in capturing micro-variations in water edges and water–vegetation transitions. (Cvijanović et al., 2025; Dronova et al., 2021; Van Alphen et al., 2024). Consistent with this, the drone-based protocol operating at 2.8–3.2 cm GSD enabled detection of planimetric changes on the order of tens of square meters and shoreline retreats exceeding 2×GSD, whereas the typical working scales of satellite imagery or handheld GNSS delineation shift the practical detection threshold towards larger magnitudes. These findings support studies highlighting the value of RPAS and UAV photogrammetry for fine-scale wetland monitoring, particularly where changes are rapid, spatially heterogeneous, or difficult to capture through conventional surveys (Cvijanović et al., 2025; Dronova et al., 2021; Musungu et al., 2024).

At the same time, the results confirm that the protocol does not replace traditional methods but complements them at a different level of detail. While satellite time series and public orthophotos remain essential for assessing historical wetland loss and regional landscape configuration (Ramsar Convention

Secretariat, 2022; Van Alphen et al., 2024), fortnightly RPAS campaigns add a layer of very high-resolution information useful for site-level operational management: identifying sectors with accelerated retreat, tracking the expansion of emergent vegetation and supporting maintenance and public-use decisions. This cross-scale complementarity is consistent with recent approaches that frame urban wetlands and nature-based solutions as multifunctional systems for urban sustainability, resilience, biodiversity support and ecosystem-service provision (Alikhani et al., 2021; Cook et al., 2025; Davidson & Finlayson, 2018).

4. Conclusions

This study designed and validated a low-cost RPAS-based photogrammetric protocol for multitemporal monitoring of water-surface dynamics in a high-Andean urban wetland. Applied to Santa María del Lago through ten fortnightly campaigns over 126 days, the protocol produced very high-resolution orthomosaics with 2.8–3.2 cm/px GSD and internally consistent products that allowed detection of a 7.1% reduction in water-surface area, from 5.60 to 5.20 ha, and a median shoreline retreat of approximately 1.1 m. These results confirm that short-term water-surface changes can be detected using repeated flight geometry, standardized processing, and conservative change-detection thresholds. The study establishes an operational monitoring protocol integrating consumer-grade RPAS, open-source photogrammetric processing, quality-control criteria, and cost-sensitive field procedures. The protocol does not replace satellite imagery, public orthophotography or GNSS-based surveys, but complements them by providing very high spatial detail, rapid response times and operational costs compatible with local environmental monitoring. Its novelty lies in demonstrating that a low-cost, no-GCP configuration can support relative multitemporal comparability and shoreline-change detection, provided that its use is restricted to relative monitoring and not interpreted as survey-grade absolute positioning. Future work should extend the monitoring series to at least one full hydrological year and integrate precipitation, water-level, inflow and outflow records to distinguish seasonal variability from structural wetland change. Additional validation using independent low-cost check points would strengthen the assessment of absolute accuracy without substantially increasing operational costs. Replicating the protocol in wetlands with contrasting morphologies, hydrological regimes and urban pressures would also help evaluate its transferability and refine the parameters required for broader institutional adoption.

5. Acknowledgments

This work was supported by Corporación Unificada Nacional de Educación Superior - CUN through its research fund under project INV-IS-BOG-GR02-PROY2024-32.

6. References

Alikhani, S., Nummi, P., & Ojala, A. (2021). Urban Wetlands: A Review on Ecological and Cultural Values. *Water*, *13*(22), 3301. [Crossref]

Benz, U. C., Hofmann, P., Willhauck, G., Lingenfelder, I., & Heynen, M. (2004). Multi-Resolution, Object-Oriented Fuzzy Analysis of Remote Sensing Data for GIS-Ready Information. *ISPRS Journal of Photogrammetry and Remote Sensing*, *58*(3–4), 239–258. [Crossref]

Cook, E. M., Kim, Y., Grimm, N. B., McPhearson, T., Anderson, P., Bulkeley, H., Collier, M. J., Diep, L., Morató, J., & Zhou, W. (2025). Nature-Based Solutions for Urban Sustainability. *Proceedings of the National Academy of Sciences*, *122*(29). [Crossref]

Courouble, M., Davidson, N., Dinesen, L., Fennessy, S., Galewski, T., Guelmami, A., Kumar, R., McInnes, R., Perennou, C., Rebelo, L.-M., Robertson, H., Segura-Champagnon, L., Simpson, M., & Stroud, D. (2021). *Global Wetland Outlook: Special edition 2021* (N. Dudley (ed.)). [Crossref]

Cuellar, Y., & Perez, L. (2023). Multitemporal Modeling and Simulation of the Complex Dynamics in Urban Wetlands: The Case of Bogota, Colombia. *Scientific Reports*, *13*(1), 9374. [Crossref]

Cvijanović, D., Novković, M., Milošević, D., Stojković Piperac, M., Galambos, L., Čerba, D., Stamenković, O., Damnjanović, B., Mesaroš, M., Pavić, D., Simić, V., Trbojević, I., Anđelković, A., Drešković, N., Stammel, B., Cyffka, B., & Radulović, S. (2025). Conservation and Ecological Screening of Small Water Bodies in Temperate Riverine Wetlands Using UAV Photogrammetry (Middle Danube). *Nature Conservation*, *58*, 61–82. [Crossref]

Davidson, N. C., & Finlayson, C. M. (2018). Extent, Regional Distribution and Changes in Area of Different Classes of Wetland. *Marine and Freshwater Research*, *69*(10), 1525–1533. [Crossref]

Delle Grazie, F. M., & Gill, L. W. (2022). Review of the Ecosystem Services of Temperate Wetlands and Their Valuation Tools. *Water*, *14*(9), 1345.[Crossref]

Dronova, I., Kislik, C., Dinh, Z., & Kelly, M. (2021). A Review of Unoccupied Aerial Vehicle Use in Wetland Applications: Emerging Opportunities in Approach, Technology, and Data. *Drones*, *5*(2), 45. [Crossref]

Elkhrachy, I. (2015). Flash Flood Hazard Mapping Using Satellite Images and GIS Tools: A case study of Najran City, Kingdom of Saudi Arabia (KSA). *The Egyptian Journal of Remote Sensing and Space Science*, *18*(2), 261–278. [Crossref]

Gbagir, A.-M. G., Ek, K., & Colpaert, A. (2023). OpenDroneMap: Multi-Platform Performance Analysis. *Geographies*, *3*(3), 446–458. [Crossref]

Graser, A., Sutton, T., & Bernasocchi, M. (2025). The QGIS Project: Spatial without Compromise. *Patterns*, *6*(7), 101265. [Crossref]

Hamed, K. H., & Rao, A. R. (1998). A Modified Mann-Kendall Trend Test for Autocorrelated Data. *Journal of Hydrology*, *204*(1–4), 182–196. [Crossref]

Johnson, P. (2011). Topographies of Urbanization: Survey in and around Pompeiopolis. *Pompeipolis I, Içinde*, 195–245.

Mathews, A. J., Singh, K. K., Cummings, A. R., & Rogers, S. R. (2023). Fundamental Practices for Drone Remote Sensing Research Across Disciplines. *Drone Systems and Applications*, *11*, 1–22. [Crossref]

Musungu, K., Dube, T., Smit, J., & Shoko, M. (2024). Using UAV Multispectral Photography to Discriminate Plant Species in a Seep Wetland of the Fynbos Biome. *Wetlands Ecology and Management*, *32*(2), 207–227. [Crossref]

Observatorio Ambiental de Bogotá. (2023). *Plan de Manejo Ambiental: Humedal Santa María del Lago*. https://oab.ambientebogota.gov.co/?p=15068&post_type=dlm_download

Otsu, N. (1979). A Threshold Selection Method from Gray-Level Histograms. *IEEE Transactions on Systems, Man, and Cybernetics*, *9*(1), 62–66. [Crossref]

Patel, S., Chintanadilok, J., Hall-Scharf, B., Zhuang, Y., Strickland, J., & Singh, A. (2024). *WebODM: An Open-Source Alternative to Commercial Image Stitching Software for Uncrewed Aerial Systems (AE593)* (Issue AE593).

Patino, J. E., & Estupinan-Suarez, L. M. (2016). Hotspots of Wetland Area Loss in Colombia. *Wetlands*, *36*(5), 935–943. [Crossref]

QGIS Development Team. (2025). *QGIS Geographic Information System*. QGIS Association. https://qgis.org

Ramsar Convention Secretariat. (2022). *Global Wetland Outlook: Special Edition 2021 -- The Value of Wetlands and the Threats They Face*. Ramsar Convention on Wetlands.

Salas López, R., Terrones Murga, R. E., Silva-López, J. O., Rojas-Briceño, N. B., Gómez Fernández, D., Oliva-Cruz, M., & Taddia, Y. (2022). Accuracy Assessment of Direct Georeferencing for Photogrammetric Applications Based on UAS-GNSS for High Andean Urban Environments. *Drones*, *6*(12), 388. [Crossref]

Secretaría Distrital de Ambiente. (2010b). *Resolución 7773 de 2010: Por la cual se ajusta y aprueba el Plan de Manejo Ambiental del Humedal Santa María del Lago y se adoptan otras determinaciones*. https://www.alcaldiabogota.gov.co/sisjur/normas/Norma1.jsp?i=41090

Secretaría Distrital de Ambiente. (2023). *Resolución 2026 de 2023: Por la Cual se Adopta la Actualización del Plan de Manejo Ambiental de la RDH Santa María del Lago*. https://www.alcaldiabogota.gov.co/sisjur/normas/Norma1.jsp?i=152521

Toffanin, P. (2019). *OpenDroneMap: The Missing Guide. A Practical Guide to Drone Mapping Using Free and Open-Source Software*. MasseranoLabs LLC.

Unidad Administrativa Especial de Aeronáutica Civil. (2023). Resolución 1983 de 2023: Por medio de la cual se incorpora la norma RAC 100 -- Operación de sistemas de aeronaves no tripuladas UAS a los Reglamentos Aeronáuticos de Colombia. https://www.suin-juriscol.gov.co/viewDocument.asp?id=30050174

Van Alphen, R., Rains, K. C., Rodgers, M., Malservisi, R., & Dixon, T. H. (2024). UAV-Based Wetland Monitoring: Multispectral and Lidar Fusion with Random Forest Classification. *Drones*, *8*(3), 113. [Crossref]

Yue, S., Pilon, P., Phinney, B., & Cavadias, G. (2002). The Influence of Autocorrelation on the Ability to Detect Trend in Hydrological Series. *Hydrological Processes*, *16*(9), 1807–1829. [Crossref]

Zerrouk, M., Ait El Kadi, K., Sebari, I., & Fellahi, S. (2025). Machine and Deep Learning for Wetland Mapping and Bird-Habitat Monitoring: A Systematic Review of Remote-Sensing Applications (2015–April 2025). *Remote Sensing*, *17*(21), 3605. [Crossref]