UAV for flooding risk assessment in a new Dam Construction in Northeast Mexico

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Abstract

Dam construction in flood-prone regions requires accurate terrain and hydrological assessment to mitigate potential risks. In Mexico, a full environmental assessment known as the Environmental Impact Manifestation (Manifestación de Impacto Ambiental, or MIA) must be submitted to the Secretariat of the Environment and Natural Resources (SEMARNAT) for approval. The MIA describes the possible environmental effects of a dam project, including those resulting from construction and operation. Traditionally, these assessments rely on ground-based topographic surveys and limited hydrological data, which—although they fulfill legal requirements—often lack spatial detail and rapid update capabilities. In contrast, UAVs (Unmanned Aerial Vehicles) provide high-resolution, up-to-date geospatial data over large and complex terrains, improving both risk modeling and environmental monitoring. In Northeast Mexico, where increasing rainfall variability and extreme weather events demand robust flood modeling, this study applies UAV-based LiDAR and imagery to assess flood risk and support dam planning. The analysis incorporates return period scenarios and includes the spatial quantification of affected trees and infrastructure, highlighting the operational and ecological implications of dam implementation.

1. Introduction

Reservoirs represent critical infrastructure, specifically for ensuring water supply in regions characterized by variable hydrological conditions (Temizel et al., 2025). The planning and construction of new reservoirs requires the integration of advanced monitoring technologies to enhance operational safety and efficiency. In the case of large-scale dams—especially those located in semi-arid regions— comprehensive planning strategies must be implemented to account for potential flood inundation zones and mitigate associated environmental and socio-economic risks. According to Ahmad, (2024), although dams are essential for meeting basic human needs, their impact on ecosystems and water resources calls for rigorous evaluation of both existing and proposed dam structures.

The flood inundation area within the dam basin is of critical importance due to the potential submergence of vegetation and rural residential infrastructure. These areas often contain significant tree cover and human settlements, both of which are vulnerable to degradation and loss upon inundation. Moreover, the environmental impact is substantial, as flooding can lead to the destruction of local flora and fauna. Therefore, conducting detailed tree and infrastructure inventories to ecological assessments is essential to inform mitigation strategies and guide sustainable reservoir planning.

Floodplains are of critical concern not only for the areas that will be submerged within the dam basin upon water impoundment, but also for downstream regions. These downstream zones remain vulnerable to flood events triggered by extreme weather, controlled floodgate discharges due to reservoir overflow, or structural failure.

One of the primary limitations in large-scale project areas is the lack of up-to-date spatial information, which may not accurately reflect recent topographical modifications or land-use changes (Krüger et al.,2013). A viable alternative for acquiring such data is the use of Unmanned Aerial Vehicles (UAVs). UAVs offer a cost-effective means of surveying extensive areas while collecting high-resolution, multispectral, and topographic data suitable for diverse applications. This technology has been increasingly employed in ecological, environmental, and hydrological research (Acharya et al., 2021; Manfreda et al., 2018).

In hydrological studies, the use of UAVs for generating Digital Elevation Models (DEMs) via LiDAR has proven particularly valuable for mapping flood-prone areas, including river floodplains, lake basins, and potential dam breach zones (Li et al., 2021). However, most existing UAV-based flood mapping efforts have been conducted post-infrastructure intervention (Karamuz et al., 2020; Miro et al., 2018) or in response to extreme climatological events (Kishanlal et al., 2024). UAVs have been generally used in the development of tree inventories for both forest management and urban green space monitoring (Corte et al. 2022; van der Sluijs et al., 2024;). The integration of LiDAR and hyperspectral data with deep learning algorithms has proven effective in the classification, quantification, and identification of tree species. However, the application of these technologies in semi-arid regions and areas dominated by scrub vegetation remains underexplored. For instance, Temuulen T. Sankey et al. (2016) demonstrated the potential of UAVs for vegetation classification in arid and semi-arid grassland and woodland ecosystems in the southwestern United States.

Given the growing demand for water supply in northeastern Mexico, the construction of new reservoirs presents an ideal opportunity to demonstrate the beneficial applications of UAVs. Since many existing reservoirs were built over two decades ago, upcoming dam projects offer a valuable context for integrating UAV technology into environmental monitoring and management. UAVs can be effectively employed before, during, and after dam construction to support comprehensive environmental assessments, including the development of mitigation programs for the conservation of local flora and fauna, flood risk evaluation, and ongoing infrastructure supervision.

This research recognizes the following critical points related to dam construction and its environmental consequences:

- Building a dam can cause water levels to rise, flooding nearby land unexpectedly.
- Vegetation in these areas often isn't adapted to constant water exposure and may die off.
- Trees that aren't water-tolerant can rot or be permanently damaged.
- This flooding disrupts the natural ecosystem, affecting plants and animals alike.
- Communities near the reservoir may experience displacement and loss of assets.
- Farmland may be submerged, threatening local food production..
- Long-term environmental damage may be irreversible, even if the dam operation ceases.

1.1 Background

The water supply for the population in Monterrey Metropolitan Area (5.9 million) is carried out through three dams: Rodrigo Gómez “La Boca”, José López Portillo “Cerro Prieto” and Solidaridad “El Cuchillo”. Aside from these reservoirs, a fourth dam has been erected to assist in the increased demand in the water supply for the Monterrey Metropolitan Area and the Montemorelos and Linares municipalities.

“La Libertad” dam site is located at 25°0’ N and 99°17’ W between the Montemorelos and Linares municipalities in the Northeast of Mexico (Figure 1). The reservoir basin is located in a warm sub-humid climate zone, likely classified as Cw under the Köppen climate system (INEGI, 2021). The area is predominantly characterized by scrubland, pasture, and irrigated agriculture (INEGI, 2018) and is situated at approximately 350 meters above sea level.

The project is operated by Water and Sewer Services of Monterrey with the goal of guaranteeing the ecological flow established by the National Water Commission (CONAGUA) and to ensure water supply for human consumption and the economic activities of the population settled downstream.

The reservoir has a conservation capacity at the ordinary maximum water level (NAMO) of 221.83 million m^3 and a total capacity at the extraordinary maximum water level (NAME by its acronym in Spanish) of 307.73 million m^3.

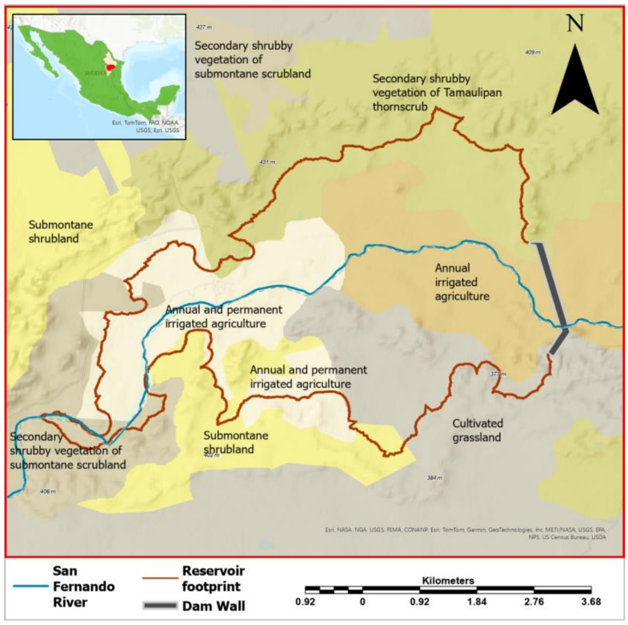

Figure 1. La Libertad Dam study area

2. Methodology

2.1 UAV-based LiDAR data acquisition

To generate high-resolution digital elevation models, a UAV-mounted LiDAR system was deployed over the projected reservoir site and the downstream river segment. The survey was conducted during the dry season (July–August 2024) to ensure optimal ground point returns. Data acquisition was performed using a DJI Matrice 350 RTK multirotor UAV equipped with a Zenmuse L2 LiDAR sensor.

The UAV followed pre-programmed flight paths at a constant altitude of 100 meters above ground level (AGL), maintaining a 70% overlap between adjacent flight swaths to guarantee full coverage and data redundancy. The surveyed area covered approximately 2000 hectares, including the reservoir footprint and adjacent hydrologically relevant zones. Ground control points (GCPs) were established using real-time kinematic (RTK) GPS to improve the spatial accuracy during post-processing.

Processing workflow enabled the generation of high-resolution orthomosaics and classified point clouds, segmented by intensity, elevation, and ground surface, using DJI Terra software. To ensure complete coverage of the study area, a total of 16 UAV flights were carried out, each with an approximate duration of 35 minutes. The resulting orthophoto mosaic had a ground sampling distance (GSD) of 3.08 centimeters per pixel and was exported in GeoTIFF format using the WGS 84 / UTM Zone 14N coordinate reference system.

LiDAR sensor operated at a peak acquisition rate of 240,000 points per second and supported up to five returns per pulse, enabling detailed vertical structure characterization, particularly in densely vegetated areas. The resulting point clouds were processed, classified, and filtered to produce both a Digital Surface Model (DSM) and a bare-earth Digital Terrain Model (DTM), derived entirely from LiDAR data, with a spatial resolution of 5 cm. These high-resolution topographic datasets allowed for the accurate delineation of terrain features, identification of vegetated and built-up zones, and flood-prone area assessment (Zhang et al., 2019; Wang et al., 2021).

Figure 2 illustrates the complete methodological workflow implemented in this study, starting from UAV-based data acquisition and continuing through point cloud processing, building footprint digitization, topographic profile extraction, and flood risk analysis. This schematic provides a comprehensive overview of the sequential steps and the tools used at each stage, enabling replication and understanding of the integrated geospatial approach adopted for dam impact assessment.

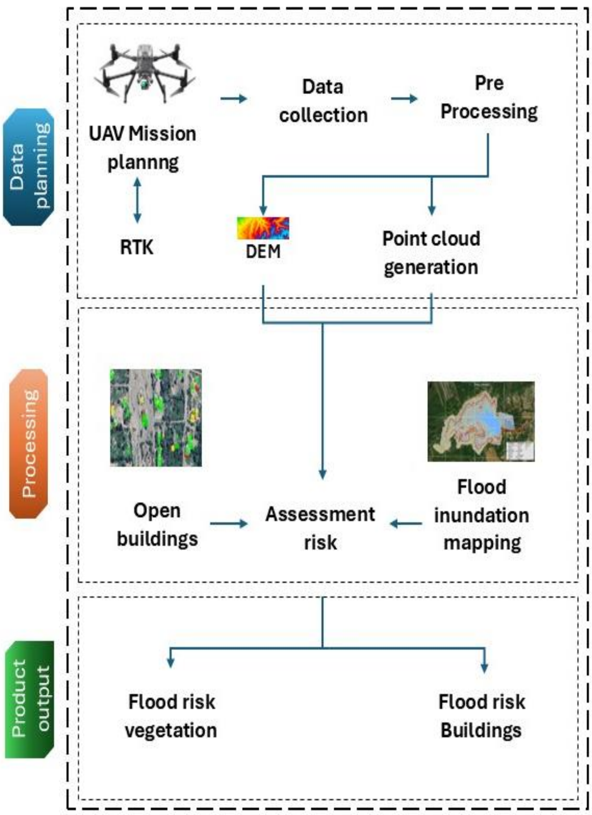

Figure 2. Methodology workflow

2.2 Buildings footprints digitalization

A detailed digitization of residential structures was conducted to identify buildings potentially affected by inundation under different return period scenarios. Two complementary geospatial datasets were used:

First, the Open Buildings deep learning model (developed by Google) was applied via the Google Earth Engine platform to automatically detect building footprints using high-resolution (1 m) satellite imagery. These footprints served as a first approximation of built-up areas across the study zone.

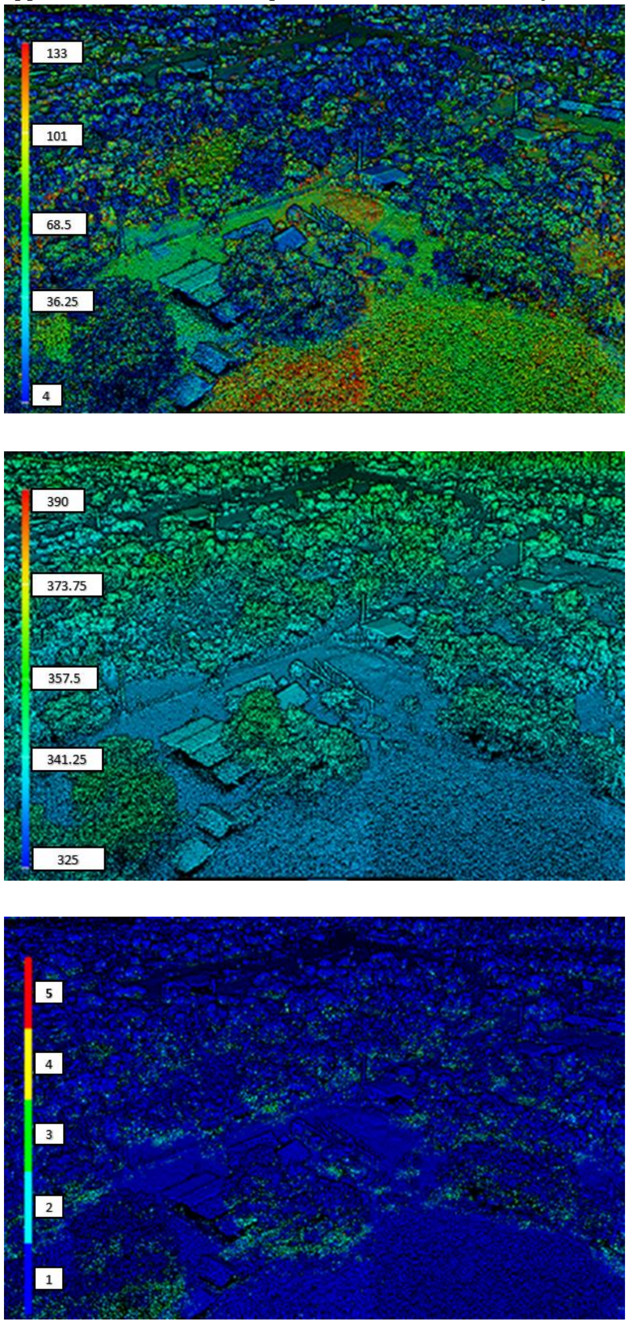

Figure 3. Reflectivity, heights and the number of returns.

Second, LiDAR-derived point clouds were used to refine this information by verifying the presence, location, and height of buildings within the floodable zone. Point clouds were processed in DJI Terra to extract geometric (XYZ), spectral (RGB), and structural attributes (height, reflectivity, number of returns) (Figure. 3). This enabled the validation and correction of building outlines identified from satellite data, particularly in areas where vegetation cover or image resolution introduced uncertainties.

While the DSM and DTM were generated exclusively from LiDAR data, the integration of satellite-based building footprints improved the spatial completeness and initial detection of structures, which were subsequently validated and enriched using the LiDAR dataset.

2.3 Topographic profile extraction

The LiDAR point clouds enabled highly detailed analysis of terrain and man-made structures across the study area. One of the most relevant applications of this data was the generation of topographic profiles, which provided critical insights into house elevations within and around the reservoir zone.

These profiles, derived from transects across the point cloud, offer a two-dimensional representation of terrain elevation and built structures. This technique enabled high-precision visualization and quantification of structural heights relative to ground level and the anticipated flood elevation threshold. The profiles contributed to the accurate estimation of volumes subject to submersion and supported the planning of infrastructure removal or protection measures.

2.4 Hydrological modeling and return period analysis

To evaluate downstream flood risk, a hydrological model was developed using historical precipitation data and regional Intensity-Duration-Frequency (IDF) curves. A synthetic design storm with a 100-year return period was generated as input for the hydrodynamic simulation.

The HEC-HMS software was used to estimate inflow hydrographs, while HEC-RAS 2D facilitated flow routing through the downstream channel network. Model calibration was performed using historical flood data and peak discharge records obtained from nearby hydrometric stations. The resulting floodplain maps enabled the spatial visualization of areas affected under the 100-year event scenario, with particular attention to urban zones and critical infrastructure exposure.

3. Results

3.1 Topographic profile of flooded zones

The elevation data obtained from topographic profiles—derived from digitized surface models—provided a robust basis for estimating the heights of various types of structures present within the study area (Figure 4). This step was essential for accurately determining the volume of material that would need to be removed or relocated prior to reservoir impoundment. These profiles also supported planning for mitigation operations and informed risk management strategies as water levels are expected to rise.

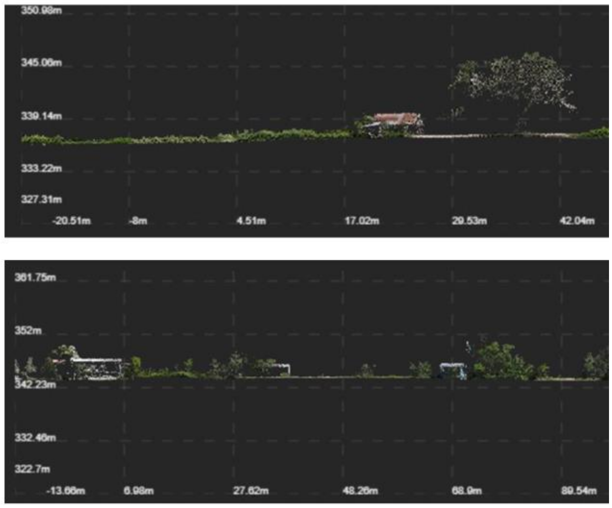

Figure 4. Topographic profile of houses near the river.

These topographic profiles, extracted from the point cloud, provide a two-dimensional representation of terrain elevation and built structures along specific transects within the area of interest. This technique enables high-precision visualization and quantification of the height of houses and other constructions relative to ground level and the predicted flood elevation. The resulting elevation information also facilitates the identification of areas that require elevation adjustments or protective measures to minimize inundation impacts. Additionally, the profiles allow for the detection of terrain anomalies and potential flow paths, supporting more effective emergency planning.

To validate the accuracy and added value of the UAV-derived elevation data, a comparative analysis was performed against the official topographic profiles available from INEGI at a 1:50,000 scale. This comparison revealed notable discrepancies in elevation measurements, particularly in areas with abrupt slopes and complex terrain near residential zones. In several transects, differences of up to 1.7 meters were observed, highlighting the underestimation of terrain variation in coarse-resolution datasets. The higher precision of the UAV-LiDAR data not only improved the reliability of structural height assessments but also enhanced the delineation of potential inundation zones, supporting more robust planning for risk mitigation and infrastructure management (Figure 5).

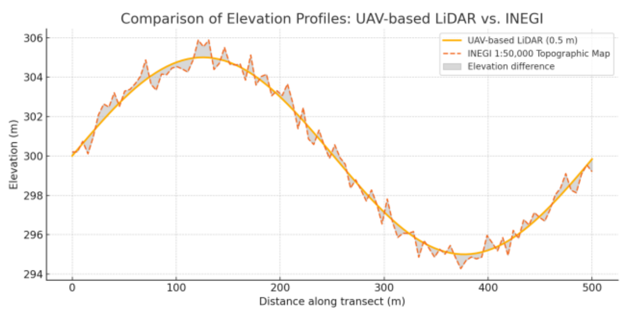

Figure 5. Comparison between traditional topographic profile (INEGI 1:50,000) and UAV-LiDAR-derived profile.

3.2 Flood risk assessment

The assessment of flood risk for a 100-year return period scenario was enabled through high-resolution UAV-derived terrain data. DEMs and DSMs were generated for the reservoir basin and a 3 km downstream segment, allowing for accurate hydrological and hydraulic modeling (Figure 6).

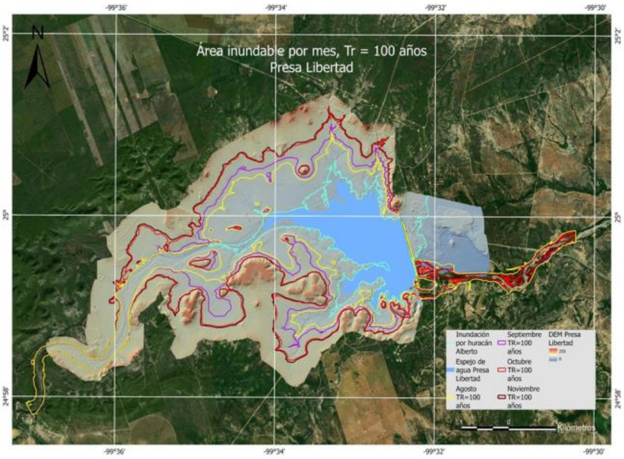

Figure 6. Floodable surfaces with return periods of 100 years.

These datasets were essential for identifying specific areas with high exposure to flooding, including homes, roads, and other infrastructure located within the reservoir zone. The analysis revealed a progressive increase in flood-prone areas throughout the year, particularly between August and November, allowing for a temporal differentiation of risk levels. These models allow for the prediction of extreme flood scenarios, which is crucial for making decisions about the need to relocate at-risk populations and remove residential infrastructure located within the dam basin.

By considering 100-year return periods, human safety can be prioritized, minimizing exposure to catastrophic events, while ensuring the integrity of the dam and optimizing its function. Furthermore, the long-term removal of homes and infrastructure from flood-prone areas not only mitigates the risks of human and property losses but also helps preserve the reservoir's capacity and water quality to fulfill its operational purpose without endangering nearby communities (Figure 7).

Figure 7. La Libertad dam and some vegetated areas flooded.

Following the initial detection, ArcGIS Pro was used to perform precise vectorization of each building's footprint, allowing for accurate measurements of their surface areas. This methodology enabled the spatial delineation of households potentially exposed to inundation, based on projected water levels for different return periods. The results serve as a critical input for flood risk assessment and the planning of mitigation strategies (Figure 8).

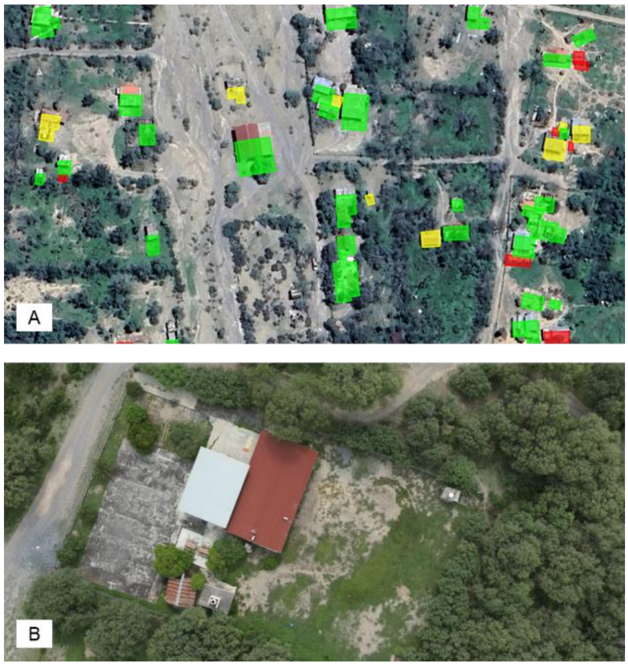

Figure 8. Buildings footprints

As shown in Table 1, 126 homes were identified at risk in August, affecting a surface area of 6.43 km². This number rose to 171 homes in September (8.10 km²), 258 in October (13.46 km²), and finally 265 in November (13.73 km²). October showed the most significant increase in exposure, with a 66.17% rise compared to September. These monthly variations reflect seasonal rainfall patterns and underscore the importance of assessing flood scenarios with a dynamic, time-sensitive approach.

Temporality	Number of dwellings	Surface Area (Km^2)	Increase (%)
August 100T	126	6.43	-
September 100T	171	8.1	25.97
October 100T	258	13.46	66.17
November 100T	265	13.73	2

Table 1. Flood exposure analysis of residential structures

Additionally, the vegetation expected to be impacted under the different return periods was analyzed. Table 2 presents the area (in km²) of each vegetation type that will be affected according to the different return periods. In the 50-year return period, which corresponds to the water surface of the La Libertad Dam, two main types of vegetation were identified: submontane scrub with 0.084 km² of coverage and riparian forest with an extent of 0.614 km². This vegetated area was calculated after Tropical Storm Alberto; therefore, considering the extent of the flooded area (2.59 km²), the area of affected vegetation is larger.

Return period (km²)	Soil (km²)	LTS (km²)	TTS (km²)	SS (km²)	RF (km²)	TF (km²)	Non-vegetal (km²)	Field crops (km²)
50 years				0.614	0.084			
100 years (August)	1.927	1.434	1.238	4.677	0.705	0.663	0.058	0.109
100 years (September)	2.368	1.839	1.666	5.663	0.810	0.771	0.059	0.142
100 years (October)	3.252	2.641	2.538	7.625	1.063	0.934	0.052	0.160
100 years (November)	3.351	2.727	2.631	7.877	1.114	0.963	0.028	0.166

Table 2. Areas of vegetation types according to return periods.

The texture of the orthomosaics allows us to identify the riverbed, bodies of water such as ponds, and the area flooded by the unexpected Tropical Storm Alberto. A close-up of one of the orthomosaics shows an area flooded with vegetation and the varying depths depending on each return period (Figure 9).

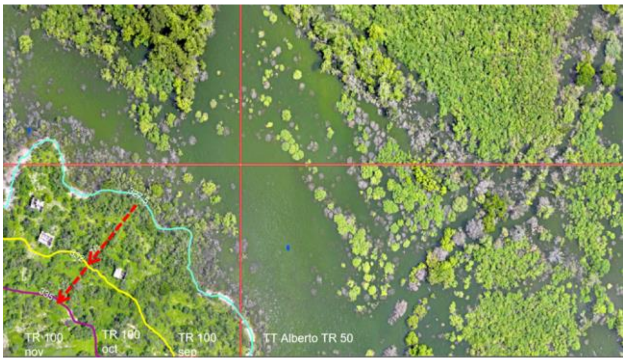

Figure 9 . Details of the different return periods exemplify the vegetation cover that will be flooded.

The vegetative cover impacted by the water accumulated from Hurricane Alberto represents 2.26% of the total vegetated area within the dam reservoir. The inundation of vegetated areas not only leads to a reduction in biodiversity but also disrupts ecosystem dynamics. Vegetation types such as riparian forest and submontane scrub are not typically adapted to prolonged flooding, and their degradation may lead to habitat loss for various species. Moreover, the environmental disturbance extends to nearby human communities, who may experience displacement or the loss of agricultural and residential land. Even if dam operations are halted in the future, the ecological damage—particularly in terms of flora regeneration and soil recovery—can be difficult to reverse.

3.3 Downstream community exposure: the case of "El Canelo"

○ The downstream section of the river, extending 3.2 km from the La Libertad dam wall to the rural community of El Canelo, was surveyed using the same UAV-based methodologies applied to the reservoir basin. A buffer of 300 meters on each side of the main river channel was considered for detailed topographic analysis. This segment belongs to the RH25D Hydrological Region: San Fernando – Soto La Marina.

Figure 10 presents the Digital Elevation Model (DEM) for this area. The main channel of the Potosí River follows a meandering course and is depicted in blue tones, indicating relatively lower elevations compared to the surrounding terrain. Elevated areas adjacent to the channel appear in green gradients, transitioning into browns, which denote abrupt slopes or prominent topographic features. The average slope in this section is 0.27%, and the river maintains a Strahler order of 7, reflecting its geomorphological maturity and hydraulic significance.

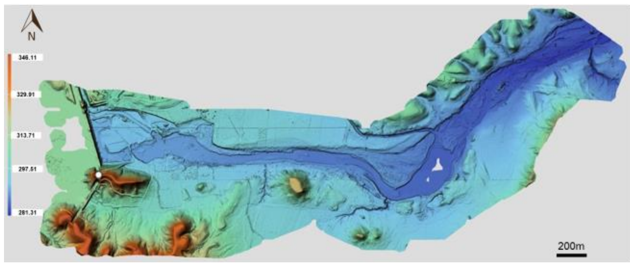

Figure 10. Digital elevation model for the Potosí River downstream of La Libertad Dam.

The ordinary flood events have shaped the floodplain visibly, defining a channel influence width of approximately 100 meters. Figure 11 shows an overlaid Digital Surface Model (DSM) using a color-coded scale to represent height variations. Purple and pink areas correspond to the lowest elevations—primarily the riverbed and adjacent floodplain—while greens and blues denote mid-level elevations and gentle slopes.

Along the riverbanks, riparian vegetation stands out clearly due to its greater height and irregular patterns in texture and tone. These taller formations—comprising trees and shrubs—contribute significantly to bank stabilization, sediment retention, and flood impact mitigation during high-flow events. The visual contrast between riparian vegetation and surrounding arid or altered landscapes marks a distinct ecological transition.

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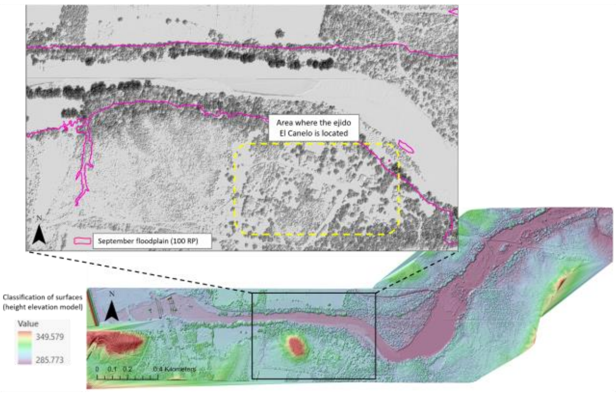

Figure 11. Classification of surfaces based on the height elevation model.

Such vegetated zones located in the floodplain or at slightly elevated margins act as natural barriers, protecting the adjacent terrain and providing habitat for local fauna. This structural and ecological information is valuable for hydraulic modeling and flood risk analysis, as it supports the identification of active floodplains and the extent of influence of extreme hydrological events.

The community of El Canelo is located on the right bank of the river at an elevation of 297 meters, whereas the currently modeled floodplain—under a 100-year return period scenario, such as that caused by Hurricane Alberto—reaches up to the 293-meter contour line. Based on this elevation difference, the residents of El Canelo are not exposed to immediate flood risk under standard extreme event conditions.

However, while current models suggest a low risk, the growing intensity and unpredictability of extreme weather events due to climate variability could increase the exposure of El Canelo in the future. The community's proximity to the river and its lack of formal resettlement call for continuous monitoring, emergency preparedness, and the possible implementation of early warning systems.

By incorporating downstream settlements such as El Canelo into reservoir impact assessments, planning authorities can strengthen resilience, protect vulnerable populations, and promote the sustainable and inclusive management of new dam infrastructure

3.4 Usefulness of UAV data for decision-making

The implementation of unmanned aerial vehicles (UAVs) during the flood risk assessment stage proved to be a highly effective tool for generating precise, up-to-date, and high-resolution geospatial data. The information collected enabled the development of Digital Elevation Models (DEM) and Digital Surface Models (DSM), which were essential for the hydraulic simulation of water behavior both within the reservoir basin and downstream.

One of the main advantages was the ability to accurately delineate the areas to be occupied by the reservoir during filling, as well as to precisely identify existing houses and structures within the inundation zone. This information is critical for planning resettlements, defining buffer zones, and assessing social impacts.

Additionally, the data enabled the modeling of flood risk scenarios with different return periods, such as the 100-year event considered in this study. The identification of a village located along the river downstream and the confirmation of its safety under an extreme event scenario represent valuable input for hydrometeorological risk management and for decision-making regarding mitigation or early warning measures.

Overall, UAV technology helps reduce the time and cost required to collect detailed topographic data, facilitating more informed, accurate, and proactive planning in hydraulic infrastructure projects. Moreover, its integration during early design and evaluation stages of dams contributes to strengthening safety and sustainability components in regional development.

3.5 Implications of flooded vegetation on water quality

The submersion of significant amounts of vegetation—particularly riparian forest and submontane scrub—within the reservoir basin introduces a critical concern regarding future water quality. When large masses of biomass decompose under anaerobic conditions, as typically occurs in flooded areas, the breakdown process releases high concentrations of dissolved organic carbon (DOC), nitrogen compounds (e.g., ammonia and nitrates), and phosphorus (Deemer et al., 2016). This can result in eutrophication, oxygen depletion, and the release of greenhouse gases such as methane (CH_4), especially in warm climates .

Given that the water stored in La Libertad reservoir is intended for human consumption and agricultural use, these impacts present considerable treatment challenges. Elevated levels of organic matter and nutrients can overburden conventional water treatment facilities, increasing operational costs and potentially compromising water safety if not properly addressed. Moreover, the degradation of organic material may promote the formation of disinfection by-products (DBPs) during chlorination, further complicating water quality management.

This highlights the critical need to carry out early vegetation quantification and biomass removal before reservoir filling. The data obtained in this study through UAV-based LiDAR and remote sensing can serve as a baseline to design and implement such preemptive measures. Including this stage in environmental assessments could substantially reduce future treatment costs and ensure safer water delivery.

4. Conclusions

This study demonstrated that the use of Unmanned Aerial Vehicles (UAVs) is a highly effective tool for flood risk assessment in the context of new dam construction, specifically in the northeastern region of Mexico. The deployment of UAV-mounted LiDAR systems enabled the generation of high-resolution Digital Elevation Models (DEMs) and Digital Surface Models (DSMs), allowing for the precise identification of flood-prone areas both within the reservoir and downstream.

Through the integration of UAV data and hydrological modeling, this study identified vulnerable households and infrastructure under a 100-year return period scenario. A temporal analysis showed a significant increase in flood exposure from August to November, highlighting the importance of including seasonality in risk assessments. The capacity to map and quantify infrastructure at risk with high spatial detail supports informed planning for relocation, compensation, and disaster preparedness.

In addition to structural exposure, this work assessed the amount and type of vegetation that will be submerged within the reservoir basin. The presence of submontane scrub and riparian forest—ecosystems not adapted to prolonged inundation—raises major environmental and operational concerns. The anaerobic decomposition of this biomass is expected to deteriorate water quality by increasing concentrations of organic matter and nutrients, posing serious challenges for water treatment facilities intended to serve the local population. These impacts not only represent ecological degradation but also translate into significant economic costs.

Therefore, the integration of UAV technology in early stages of environmental impact assessments is strongly recommended, especially for future dam projects in ecologically sensitive and densely vegetated areas. UAV-based data can support pre-emptive measures such as vegetation removal, improve flood risk modeling, and facilitate adaptive management strategies aimed at reducing long-term environmental and economic impacts. Incorporating these technologies systematically into reservoir planning will enhance infrastructure resilience, protect public health, and ensure the sustainability of water resources in the face of climate variability.

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