Geomorphometric analysis of urban fluvial terraces using UAV LiDAR: A case study from the La Silla River, Mexico

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ABSTRACT:

This study presents a high-resolution geomorphological analysis of river terraces along the urban corridor of the La Silla River (Monterrey Metropolitan Area, Mexico) using UAV-based LiDAR and photogrammetry, with a DJI Matrice 350 RTK equipped with a Zenmuse L2 sensor, generating dense point clouds, Digital Elevation Models (DEMs), and orthomosaics. These products allowed for the precise identification of three terrace levels (T1-T3), their geomorphometric attributes, and their lithological composition. The results reveal contrasting degrees of anthropogenic modification: while terrace 1 retains its natural morphology, terraces 2 and 3 show substantial alterations due to residential expansion, public infrastructure, and road construction, which alter the original geomorphological surfaces. Temporal satellite images also show the sensitivity of terrace geomorphology to extreme hydrometeorological phenomena, with cyclones such as Hanna (2020) and Alberto (2024) causing vegetation loss, surface restructuring, and local modification of terraces. Overall, UAV-LiDAR proved to be very effective for mapping terraces in restricted urban environments, providing essential details for monitoring, risk assessment, and sustainable management of urban rivers.

1. INTRODUCTION

Urban rivers provide valuable records of geomorphological evolution through their fluvial terraces, which preserve evidence of past hydrological regimes, sedimentation cycles, and tectonic or anthropogenic influences (Pederson et al., 2006; Delchiaro et al., 2024). However, in highly urbanized environments, these features are often hidden or modified by infrastructure, channeling, and changes in land use. Currently, detailed morphometric analysis using unmanned aerial vehicle (UAV)-based light detection and measurement (LiDAR) allows for high-resolution characterization of terrace systems (Tlapáková et al., 2012; Li et al., 2019), supporting both geomorphological interpretation and environmental management.

In the Monterrey Metropolitan Area (MMA), in northern Mexico, several rivers such as Santa Catarina, Pesquería and La Silla drain the surrounding mountainous terrain of the Sierra Madre Oriental (SMO). Although the geomorphological evolution of the Santa Catarina River has been partially documented (Martínez-Quiroga et al., 2021), the La Silla River remains understudied despite being an essential urban hydrological system. For that purpose, we present new evidence of terrace environments in an environment based on a high-resolution UAV-LiDAR dataset. The specific objectives of this study are (i) to identify the spatial extent of the fluvial terraces, (ii) to determine the morphometric characteristics of the fluvial deposits, and (iii) to evaluate the effects of anthropogenic influence on the current geomorphology of the La Silla River.

1.1 Study Site

The La Silla River is a tributary located in the southeastern part of the MMA, in the state of Nuevo León, Mexico, which extends through the municipalities of Monterrey and Guadalupe (Figure 1). The La Silla River originates at about 1812 meters above sea level (m a.s.l.) within the mountainous sector of the Monterrey Curvature, which in turn is part of the Sierra Madre Oriental, which flows from southeast to northeast, bordering the Cerro de La Silla, until it joins the Santa Catarina River.

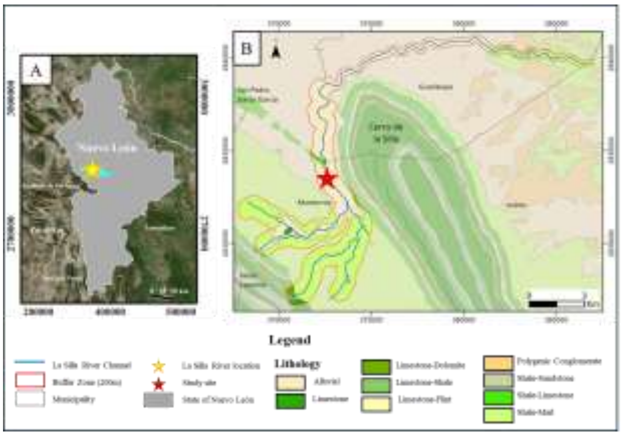

Figure 1. Location map. (A) Nuevo León, México. (B) Lithological map with Study site.

The geology of the La Silla River is mainly made up of alluvial sedimentary material composed of gravel, sands and silts of Tertiary and Quaternary age (66 million years to the present) that overlie a stratified package made up of shales and limestones (Méndez and San Felipe formations) that, on occasion, outcrops within the course of the La Silla River. These strata represent the youngest age of the Mesozoic sequence (90 to 66 Ma) that extends to the Upper Jurassic (162 Ma) with a total thickness of 3000 m, which due to tectonic events rise to form the mountains that are located along the valley of the MMA, which are part of the SMO (Padilla and Sánchez, 2007).

The climate is semi-arid to subhumid subtropical, with marked seasonality and concentrated rainfall during the summer months (Aguilar Barajas and Ramírez Orozco, 2021). Episodes of intense rainfall, frequently associated with tropical cyclones such as Hanna (2020) and Alberto (2024), have promoted episodes of flooding, channel incisions, and terrace reactivation, with an average annual rainfall of 650.2 mm (Comisión Nacional del Agua, CONAGUA, 2024). The land use along the study section is predominantly urban and recreational, including parks, trails, and flood control structures that have partially modified the natural morphology of the river.

2. METHODOLOGY

2.1 UAV Platform and Data Acquisition

Between May and June 2025, aerial surveys were conducted using a DJI Matrice 350 RTK platform (Table 1). For data collection, the UAV was equipped with a Zenmuse L2 sensor (Table 1), which combines a LiDAR scanner, an integrated inertial measurement unit (IMU) and an RGB imaging system, which allows high-density three-dimensional point clouds to be captured together with high-resolution optical images in a single flight. Under a favorable satellite geometry and Global Navigation Satellite System (GNSS) reception, the system maintained positional accuracies of the order of 5 cm horizontally and 4 cm vertically, with a distance measurement error of approximately 2 cm. The RGB component produced images with a mean ground sampling distance (GSD) of 3 cm, providing detailed surface information suitable for discrimination of geomorphological features and terrace morphology.

DJI MATRICE 350 RTK			
Max. Flight Time	Max. Transmission Distance	Hovering Accuracy (with moderate or no wind)	RTK Accuracy
Approx. 55 min (under no-wind conditions)	8 km (with unobstructed, free of interference)	±0.1 m (horizontal) ±0.1 m (vertical), with RTK positioning	1 cm + 1 ppm (horizontal) 1.5 cm + 1 ppm (vertical)

Table 1. Key technical specifications of the DJI Matrice 350 RTK used in this study.

The flights were conducted with 60% forward and 70% side overlap to ensure adequate point density and complete surface coverage. Operations were performed at an average speed of 7.64 m/s, with each mission lasting roughly 23 minutes, enabling completion within a single battery cycle. All spatial datasets were projected onto the WGS84 / UTM Zone 14N coordinate system (EPSG: 32614).

Figure 2. Equipment used in the field: (A) RTK positioning system, (B) RTK positioning system and DJI Matrice 350 with the Zenmuse L2 sensor.

All processing was performed on a computational environment equipped with an AMD Ryzen 7 5800H processor (16 cores), 32 GB of RAM, and an NVIDIA RTX 4070 GPU, enabling efficient optimization and classification times while maintaining reproducibility and stability of results. This workflow produced high-precision deliverables including dense point clouds, high-resolution DEMs, and georeferenced orthomosaics that adhere to international quality standards and are suitable for advanced scientific analysis and high-accuracy terrain modeling

ZENMUSE L2 SENSOR			
Pulse frequency (kHz)	Sampling rate (Hz)	Horizontal FOV (°)	Max returns
240	200	±70	5

Table 2. Key technical specifications of the Zenmuse L2 LiDAR sensor used in this study.

2.2 Data Processing

The data processing workflow was carried out using a DJI Zenmuse L2 LiDAR sensor mounted on a multirotor aerial platform, following a dual-flight strategy designed to ensure optimal geometric coverage of the study area. Initial processing included the integration of GNSS and IMU data through POS computation, yielding a trajectory with 95.37% fixed-solution epochs and mean positional errors below 0.014 m in horizontal axes and 0.017 m vertically. Trajectory refinement was performed using GNSS–IMU fusion, achieving roll, pitch, and yaw errors on the order of 10^{-4} radians. This high-precision trajectory provided the geometric foundation necessary for reliable point-cloud reconstruction.

The LiDAR and RGB datasets were processed in DJI Terra 4.5.0 using a workflow aimed at maximizing geometric accuracy and point-cloud integrity. The software performed automated alignment, RTK-based georeferencing, noise removal, and precision refinement to ensure a smooth and reliable surface reconstruction. Processed outputs were then exported in multiple standardized formats PNTS and LAS for point clouds, B3DM/PLY/OBJ for 3D modeling, and GeoTIFF for DEM generation providing full compatibility with GIS, photogrammetry, and 3D analysis platforms.

2.3 Orthomosaic Analysis

An RGB orthomosaic was generated from the aerial imagery captured during the same UAV flights using the integrated photogrammetric sensor of the Zenmuse L2. The images were processed in DJI Terra, where sequential steps of image alignment, georeferencing, and mosaic stitching were performed. The flights were conducted at mean altitudes of 97.2 m and 102.8 m and average ground speeds of 9.43 m/s and 6.91 m/s, respectively. The sensor operated in repetitive-scan mode with a pulse repetition frequency of 240 kHz and a scan rate of 1200 kHz, providing a uniform distribution of laser returns and adequate overlap for accurate three-dimensional reconstruction.

The resulting orthomosaic had a spatial resolution of approximately 3-4 cm per pixel, enabling detailed visualization of surface features. This orthomosaic served as a valuable reference for the visual interpretation of land surface characteristics, including vegetation cover, terrace boundaries, erosional features, and anthropogenic modifications.

The RGB-derived products and LiDAR-derived DEMs were used in a complementary manner. While LiDAR data provided high-accuracy elevation information for terrain modeling and terrace delineation, RGB orthomosaics supported visual interpretation of surface features such as vegetation, infrastructure, and geomorphological boundaries. The integration of both datasets improved the reliability of terrace identification and geomorphological interpretation.

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2.4 Elevation Analysis by Point Clouds

From the classified point cloud, a DEM was generated using a scale-based interpolation approach at a nominal 1:500 scale, corresponding to a 0.25-m grid cell size. The DEM showed a low percentage of non-conforming cells (3.11%), consistent with the high point density of the dataset. Additional DEM representations at 0.5-m and 1-m resolutions were also produced, maintaining comparable densities and non-conformance percentages below 2%, demonstrating the dataset's robustness across spatial scales.

Complementary RGB imagery employed in the colorization process was also used to generate geometrically corrected orthomosaics aligned to the WGS84 / UTM Zone 14N coordinate system, ensuring spatial coherence among all derived products.

The LiDAR system operated with a pulse repetition frequency of approximately 200,000 points per second.

2.5 Geomorphological and Lithological Analysis of the Fluvial Terraces

The fluvial terraces were identified, characterized, and delimited by interpreting orthomosaics, point clouds, digital elevation models (DEM), and contour lines obtained through photogrammetric surveys and drone LiDAR. These interpretations were validated through fieldwork, where traditional surveys were conducted to delimit river terraces at strategic points along the riverbed. Spatial analysis was performed using ArcGIS Pro software.

2.6 Identification of Socio-Environmental Factors

Demographic information and complementary cartographic elements were obtained from the G14C26 topographic data (INEGI, 2021). These data supported the contextual characterization of the urban surroundings in the study area. The total surface area of each terrace was calculated using the polygon geometry. Subsequently, the areas occupied by residential blocks, public spaces, and other forms of infrastructure were extracted by intersecting these features with each terrace polygon. The mapped features and quantitative results were integrated to evaluate the degree of anthropogenic modification across terrace levels. This interpretation was used to assess how urban growth within the Monterrey Metropolitan Area has transformed the original geomorphology of the fluvial terraces.

A visual interpretation key was followed to ensure consistency during the identification, based on tone, texture, shape, pattern, and spatial association (Table 3), additional to ground level observations. The orthomosaic was carefully photo interpreted allowing to georeference areas directly in QGIS.

Category	Visual indicators	Interpretation criteria
Solid waste	Irregular patches of multicolored debris, near or within the river	Heterogeneous textures with no vegetation
Debris	Angular objects near or within the river	Coarse, near roads or exposed ground, grey

Table 3. Visual interpretation key for socio-environmental factors.

3. RESULTS AND DISCUSSIONS

3.1 Photogrammetry and Point Cloud Post-processing

By processing high-density point clouds using DJI Terra, we were able to visualize the terrain in its natural state with vegetation present (Figures 3A and 3B), as well as after filtering out vegetation (Figure 3C), which facilitated the identification and delimitation of river terraces. The tool for switching between the two visualizations made it possible to identify and highlight geomorphological features that were originally hidden. This more accurate interpretation of the terrain model contributes to a more robust assessment of areas at risk of erosion and other processes that could affect the population and ecosystems.

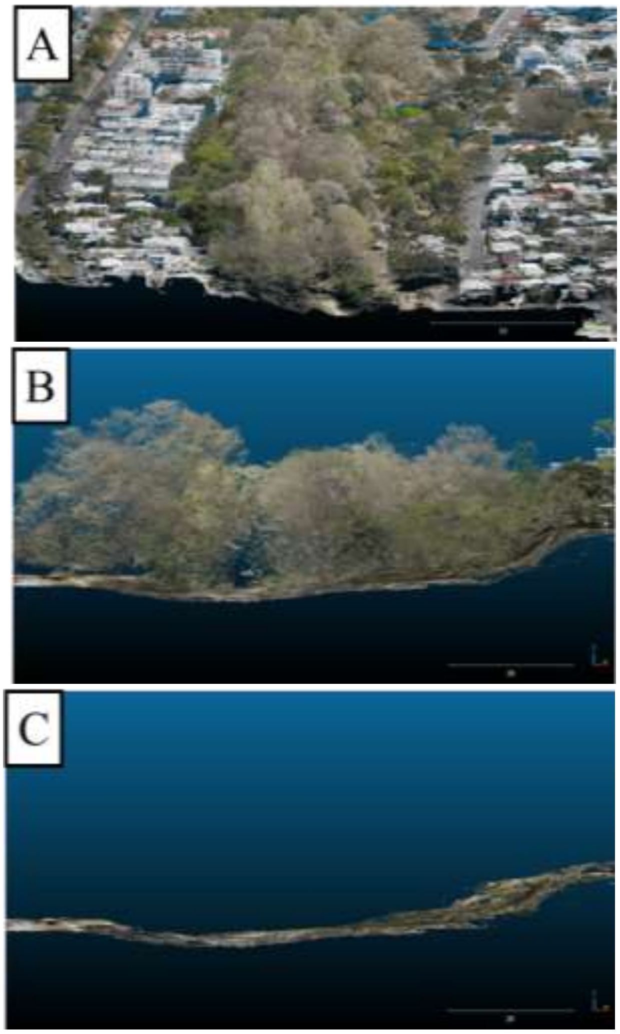

Figure 3. Visualization of processed point clouds for geomorphological analysis. (a) Top view with vegetation cover; (b) profile view with vegetation cover; and (c) profile view of bare terrain obtained by filtering vegetation.

3.2. Geomorphological and Lithological Characterization of the Fluvial Terraces of the La Silla River

A study was conducted on the lithology and geomorphology of the river terraces of the La Silla River, with the aim of understanding the geomorphological evolution of the riverbed and the areas at risk from flooding events. Geomorphological analysis helps to identify former flood levels and areas susceptible to erosion or accumulation, while the lithological study provides information on the composition of river sediments. Together, these aspects provide a basis for assessing flood risk and locating areas potentially affected by urban

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settlements and anthropogenic activities, thus contributing to safer and more sustainable management of the river environment.

Three levels of river terraces were identified, as detailed below:

3.2.1. Fluvial Terrace 1

The T1 river terrace is the youngest unit in the system and represents the current floodplain of the La Silla River. It is located at the lowest elevation above the riverbed, or "water mirror," and is the surface that the river alters most frequently during flood events. Its main composition is gravel and boulders with a sandy matrix, indicating a fluvial deposit environment dominated by coarse materials. The clasts are subrounded to rounded in shape, evidence of prolonged fluvial transport and intense weathering processes.

The boulders are the result of the erosion of sedimentary rocks, mainly limestone, which are exposed in the middle-upper parts of Cerro de la Silla and its surroundings (≈ 1,500 - 900 m above sea level). These rocks contain fossiliferous limestone, in which marine fossils (rudists) (figure 4) characteristic of Cretaceous formations such as the Cupido and Aurora formations have been identified.

Due to its high proportion of gravel and boulders, T1 has very high porosity and permeability, favoring water infiltration and recharge of the local aquifer. However, it is the most unstable surface of the terrace system, subject to continuous processes of erosion, transport, and deposition during river floods, making it an area of high geomorphological and hydrogeological dynamism.

Figure 4. River Terrace 1 (T1) identified in the field.

3.2.2. Fluvial Terrace 2

The T2 terrace features a heterogeneous alluvial deposit composed of gravel, sand, and silt ranging in color from dark brown to gray. The lithology indicates a recent fluvial sedimentation environment with poorly consolidated materials, notably rounded limestone gravel and clasts of varying sizes, evidence of transport by a medium-energy current. At the base of the slope, the presence of exposed roots of the sabino trees and the accumulation of organic matter reflect processes of lateral erosion of the riverbed (Figure 5).

Figure 5. Overview of the River Terrace (T2) of the La Silla River.

3.2.3. Fluvial Terrace 3

Terrace 3 is covered by asphalt, as it is located above roads and subdivisions. According to the Mexican Geological Service (SGM), lithologically it is composed of Quaternary alluvial deposits consisting of calcareous gravel and sand with silty intercalations, resting on shales and marly limestones of the Méndez Formation (Upper Cretaceous) (SGM, 2008).

Below is a representative section of the river terraces of the La Silla River, where three levels (T1, T2, and T3) were identified (Figure 6). The map shows the spatial distribution of these geomorphological units based on a terrain elevation model obtained by drone surveying and field validation.

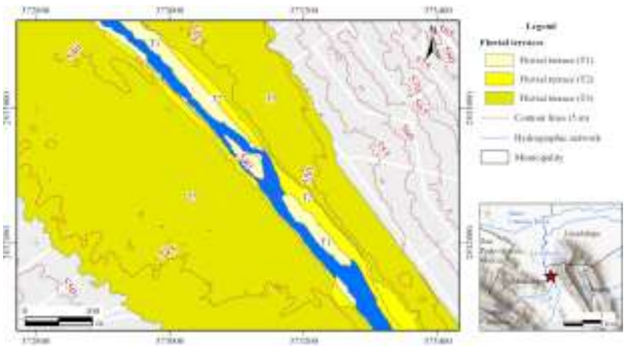

Figure 6. Spatial distribution of river terraces and their relationship with the river channel.

3.2.4. Spatial Distribution of Terraces and Urban Features

The spatial arrangement of geomorphological and urban units within the La Silla River shows a clear pattern of transformation driven by the rapid expansion of the Monterrey Metropolitan Area (AMM). As documented in previous works, urban growth has become one of the most significant challenges for the region (Veloquio, 2017; INEGI, 2021), progressively altering the morphology of the fluvial terraces. In many sectors, these terraces are now partially or completely buried beneath residential blocks, public infrastructure, and transportation networks.

The map (Figure 7) reveals three main terrace levels (T1, T2, and T3), each displaying different degrees of anthropogenic modification. Terrace 1 (T1) remains the least affected landform, preserving a greater proportion of its original morphology. In contrast, Terrace 2 (T2) and Terrace 3 (T3) show substantial alterations associated with residential expansion, public spaces, and road networks.

Terrace 2 covers a total area of approximately 1.60 ha. Of this surface, 39.32% has been transformed into residential blocks, while 22.35% corresponds to public spaces, primarily parks, green areas, and boulevards. These modifications indicate moderate urban pressure, although parts of the terrace morphology remain recognizable.

Terrace 3 is the most extensive and the most heavily altered unit, with an approximate area of 24 ha. Within this terrace, 72.23% of the surface is occupied by residential blocks, and 12.20% corresponds to public spaces. The remaining percentage is distributed mainly among streets, roadways, and other infrastructure. This pattern reflects a high level of anthropogenic impact, making T3 the terrace most affected by urban development.
Overall, the spatial distribution of urban features over the fluvial terraces illustrates a progressive and asymmetric pattern of landscape transformation. The upper terraces (T2 and T3) have been significantly reshaped by urbanization, while T1 still retains a comparatively lower degree of disturbance.

Figure 7. Spatial distribution of fluvial terraces (T1–T3), urban layout, and socio-environmental challenges within the La Silla River. The map shows the orthomosaic base, the delineation of fluvial terraces, urban blocks, public spaces, and key infrastructure (benchmark, pumping station, cultural building, schools, roadways, and aqueduct), as well as identified socio-environmental issues such as debris and solid waste.

3.3 Summary of Tropical Cyclones that Have Impacted the La Silla River

The geomorphological configuration and current state of the fluvial terraces along the La Silla River must be understood within the broader hydrometeorological dynamics of the region. Several tropical cyclones and associated rainfall events have been documented by the National Oceanic and Atmospheric Administration (NOAA; 2025), as well as by local monitoring systems (Bravo-Lujano, 2024), including the La Huastequita meteorological station (SMN, 2025) (Table 4). These events have historically contributed to channel incision, terrace formation, and periodic reactivation of fluvial processes (Figure. 8).

Date	Precipitation (mm)	Maximum temperature (°C)	Minimum temperature (°C)	Event
09/04/2019	220	29	17.5	Tropical Depression Fernand*
07/26/2020	200.8	28	20	Tropical Depression Hanna*
09/18/2020	54	31	13.5	No name
06/19/2024	600	-	-	Tropical Storm Alberto*

Table 4. Main precipitation and meteorological events of recent years recorded at the *La Huastequita* station (SMN, 2025). Data on tropical storms and cyclone trajectories obtained from NOAA (2025). Information of the tropical storm Alberto by Bravo-Lujano (2024).

In Figure 8, the 2020 satellite images illustrate a before and after scenario associated with the impact of Tropical Depression Hanna. The image dated 05/17/2020 represents the pre-event conditions, where Terrace 2 appears in its original configuration. Following the passage of Hanna, the image dated 10/18/2020 shows noticeable geomorphic changes, particularly the displacement and reworking of Terrace 2. This modification visually reduces the apparent extent of Terrace 1. This observation highlights the sensitivity of terrace morphology and surface cover to high-intensity hydrometeorological events.

The images dated 04/30/2023 (Figure 8) do not correspond to a specific major tropical cyclone; however, they provide insight into the temporal evolution of the terraces. The 2023 image shows a noticeable proliferation of vegetation, partially obscuring the surface expression of the terrace levels.

The image dated 04/04/2024 (Figure 8) represents the conditions prior to Tropical Storm Alberto. Compared with the post-event image from 08/16/2025, it is evident that the vegetated surface decreased significantly after the storm's passage. Despite the ~16 month gap between images, the contrast clearly illustrates how the rainfall and runoff associated with Tropical Storm Alberto stripped and displaced vegetation, leaving the fluvial terrace surfaces more exposed.

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Figure 8. Main tropical cyclones that have affected the region in recent years, accompanied by a gallery of satellite images retrieved from Google Earth Pro and regional news reports documenting each event. The La Silla River Natural Park is used as a geographic reference in all images.

5. LIMITATIONS

Despite the high accuracy of UAV-LiDAR data, this study presents some limitations. First, data acquisition was limited to specific time periods, which restricts the analysis of temporal variability in terrace morphology. Second, although LiDAR effectively penetrates vegetation, dense vegetation cover may still introduce minor uncertainties in ground point classification. Third, the integration of RGB and LiDAR data was primarily used for visual and geomorphological interpretation, and a more rigorous quantitative fusion of both datasets could further improve the analysis. Finally, access restrictions in urban areas may have limited the spatial coverage of certain sectors of the river.

6. CONCLUSIONS

This research demonstrates the value of integrating UAV-based LiDAR and photogrammetry for high-resolution geomorphometric characterization of river terraces in an urbanized environment. The combined use of DEM, point clouds, orthomosaics, and validation with fieldwork allowed us to identify three terrace levels (T1-T3) along the La Silla River, as well as to characterize their geomorphology and lithological composition in detail.

Specifically, the lower terrace (T1) shows the most recent fluvial activity and a mostly natural morphology, while terraces T2 and T3 show significant anthropogenic alteration.

Temporal analysis of satellite images revealed the influence of extreme hydrometeorological phenomena, especially tropical cyclones such as Hanna and Alberto, which produced notable changes in the extent of the terraces, vegetation cover, and sediment redistribution, reaffirming the dynamic nature of the system and the importance of continuous monitoring in the areas surrounding the La Silla River.

UAV-LiDAR proved particularly effective in detecting subtle changes in elevation and overcoming observation limitations imposed by vegetation or infrastructure. Its centimeter accuracy makes it a suitable tool for risk assessment and geomorphological research in rivers with dense vegetation.

Based on the results, we recommend: (1) incorporating UAV - LiDAR as a standard technique for monitoring urban rivers in northern Mexico, (2) integrating socio-environmental diagnostics prior to flight planning to anticipate visual obstructions or access restrictions, and (3) using multi-temporal UAV datasets to track terrace reactivation after extreme weather events.

Finally, this work contributes to a better understanding of the geomorphological evolution of the La Silla River and supports sustainable urban planning in line with the United Nations Sustainable Development Goals on clean water (Goal 6), sustainable cities (Goal 11), climate action (Goal 13), and terrestrial ecosystems (Goal 15).

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8. REFERENCES

Aguilar Barajas, I., Ramírez Orozco, A.I., 2021: *Agua para Monterrey Logros, retos y oportunidades para Nuevo León y México*. Segunda Edición. Instituto Tecnológico y de Estudios Superiores de Monterrey. https://hdl.handle.net/11285/642843

Comisión Nacional del Agua (CONAGUA)., 2024: Precipitación (mm) por entidad federativa y nacional. https://smn.conagua.gob.mx/es/climatologia/temperaturas-y-lluvias/resumenes-mensuales-de-temperaturas-y-lluvias

Delchiaro, M., Iacobucci, G., Della Seta, M., Gribenski, N., Piacentini, D., Ruscitto, V., Zocchi, M., Troiani, F., 2024: A fluvial record of late Quaternary climate changes and tectonic uplift along the Marche Piedmont Zone of the Apennines: New insights from the Tesino River (Italy). *Geomorphology*, 445, 108971. https://doi.org/10.1016/j.geomorph.2023.108971

Mexican Geological Service (SGM)., 2008: Geological-Mining Map Monterrey G14-7. Second Edition. https://mapserver.sgm.gob.mx/Cartas_Online/geologia/72_G14-7_GM.pdf

Instituto Nacional de Estadística y Geografía (INEGI)., 2021: En Nuevo León somos 5 784 442 habitantes: Censo de población y vivienda 2020 [Comunicado de prensa No. 40/21].

Instituto Nacional de Estadística y Geografía (INEGI)., (2021): Carta Topográfica escala 1:20 000 G14C26 [Conjunto de datos]. INEGI.

Li, H., Chen, L., Wang, Z., Yu., 2019: Mapping of River Terraces with Low-Cost UAS Based Structure-from-Motion Photogrammetry in a Complex Terrain Setting**.** *Remote Sensing*, 11(4), 464. https://doi.org/10.3390/rs11040464

Martínez-Quiroga, G.E., De León-Gómez, H., Yépez-Rincón, Y.D., López-Saavedra, S., Cardona Benavides, A., Cruz-López, A., 2021: Alluvial terraces and contaminant sources of the Santa Catarina River in the Monterrey Metropolitan Area, México. *Journal of Maps*, 17(2), 247-256. https://doi.org/10.1080/17445647.2021.1898483.

N+., (2024, junio 20): *En alerta, vecinos en Guadalupe, NL, por desbordamiento de Río La Silla* [Imagen/noticia]. N+.

National Oceanic and Atmospheric Administration (NOAA)., 2005: Historical hurricane tracks (Interactive map). National Oceanic and Atmospheric Administration. https://coast.noaa.gov/hurricanes/

Servicio Meteorológico Nacional (SMN)., 2025: Normales climatológicas diarias: Estación 19096 "La Huastequita". Comisión Nacional del Agua.

Padilla and Sánchez, R. J., 2007: Geological evolution of southeastern Mexico from the Mesozoic to the present in the regional context of the Gulf of Mexico. *Bulletin of the Mexican Geological Society*, 59(1), 19-42.

Pederson, J.L., Anders, M.D., Rittenhour, T.M., Sharp, W.D., Gosse, J.C., Karlstrom, K.E., 2006: Using fill terraces to understand incision rates and evolution of the Colorado River in eastern Grand Canyon, Arizona. *Journal of Geophysical Research: Earth Surface*, 11(52). https://doi.org/10.1029/2004JF000201

Tlapáková, L., Pánek, T., Horácková, S., 2021: Holocene fluvial terraces reveal landscape changes in the headwater streams of the Moravskoslezské Beskydy Mountains, Czechia. *Geomorphology*, 337, 107589. https://doi.org/10.1016/j.geomorph.2020.107589

Veloquio, G. G., 2017: Índice de densidad de población y su aplicación en el área metropolitana de Monterrey. *Realidades: Revista de la Facultad de Trabajo Social y Desarrollo Humano*, 3(2), 53–62.