Analysis of socio-environmental problems in the La Silla River, Monterrey, México: An approach with UAV geospatial data (LiDAR and RGB)

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Abstract.
This study examines socio-environmental issues in the La Silla River, situated in the Metropolitan Area of Monterrey (MAM), Nuevo León, Mexico, utilizing advanced technologies such as unmanned aerial vehicles (UAVs) as platforms with onboard sensors, elevation profiles, and a population analysis based on a national database. Like other urban rivers, the La Silla River faces significant challenges, including illegal dumpsites, wastewater discharges, irregular settlements, and solid waste accumulation, all of which are exacerbated by accelerated urban growth. To document these issues, UAVs equipped with an RGB camera and a LiDAR sensor captured high-resolution data, enabling the generation of orthophotos and point clouds, which were then processed for detailed spatial analysis. This information enabled the photo-interpretation mapping of pollution sources and the study of their spatial distribution. Ground-based observations were also collected to compare the effectiveness of field-level data with that of UAV-acquired imagery. A population analysis is presented to understand the social context of the residents living in the river basin, many of whom are vulnerable. This integrated approach strengthens the link between technology and society, offering a valuable and replicable tool for environmental monitoring in urban areas.

1. Introduction

Urban rivers are increasingly affected by ecological pressures, primarily driven by rapid urban development. The La Silla River, situated in the MAM, faces significant socio-environmental challenges, including the accumulation of solid waste, construction debris, and irregular settlements. In addition to the river's environmental condition, vulnerable populations reside within its basin, making the La Silla River a resilient example of a waterway facing socio-environmental challenges that demand urgent and practical solutions.

The La Silla River originates within the Cumbres de Monterrey National Park, in the municipalities of Santa Catarina and San Pedro Garza García. It is part of the Administrative Hydrological Region VI Río Bravo, within the Río Bravo–San Juan Basin, and is considered one of the few "living rivers" in the MAM (Ceballos *et al*., 2009).

Throughout its course, the La Silla River passes through two Protected Natural Areas (PNA) (Bonilla *et al*., 2023). In 2009, the "Nuevo Parque Ecológico La Pastora" Protected Natural Area was established, covering a 7.4 km section of the river in the municipality of Guadalupe which represents 67% of its total length. Later, on June 5, 2023, the La Silla River was officially recognized as a Municipal Protected Natural Area (ANPM) in Monterrey, under the category of Riparian Biological Corridor (Gobierno de Monterrey, 2021; Gobierno de Monterrey, 2022), covering the first 16.4 km of the river.

Although the efforts to promote protected natural areas have been significant and show evident progress in fostering sustainable development along the La Silla River, this study presents an updated inventory of the socio-environmental problems that continue to affect this ecosystem.

The identification and monitoring of socio-environmental problems in urban rivers continues to represent a significant methodological challenge, as access to these water bodies is often limited by various factors such as gated communities, river channelization, debris accumulation, constructions within the riverbed, or the proliferation of riparian vegetation. In this context, the case of the

La Silla River stands out for presenting such restrictive conditions, which would make a comprehensive analysis difficult if it were based solely on fieldwork. The incorporation of advanced technologies, such as unmanned aerial vehicles (UAVs), has proven essential to overcoming these limitations (Mohsan *et al*., 2023). These tools enable a comprehensive view of the river channel, access to difficult-to-reach areas, continuous monitoring, and precise measurements.

The comparison between the problems identified through ground-level imagery and those detected via photo-interpretation of orthomosaics generated with UAVs revealed significant differences, demonstrating the potential of these technologies for urban river analysis and their application in environmental monitoring.

This study presents the results of a research project that utilizes UAVs to identify and spatially analyze socio-environmental problems affecting the La Silla River, including the development of a georeferenced inventory of these issues. It also examines the relationship between environmental degradation and vulnerable populations living in the basin.

The contribution of this research is as follows:

1. High-resolution mapping of socio-environmental problem areas through photointerpretation of UAV-derived imagery and photogrammetry.
2. Creation of a georeferenced inventory of socio-environmental problems along La Silla River.
3. Development of a replicable model that integrates geospatial technology and citizen-based analysis for urban river monitoring.

2. Study area

The study area corresponds to the La Silla River, an urban river located in northeastern Mexico (Fig. 1). This river basin passes through several municipalities, including San Pedro Garza García, Monterrey, Guadalupe, and Juárez, within the MAM.

The river has a total length of 35.6 km and is primarily fed by surface runoff from Cerro de la Silla, a prominent mountain in the region (Bonilla *et al.*, 2023).
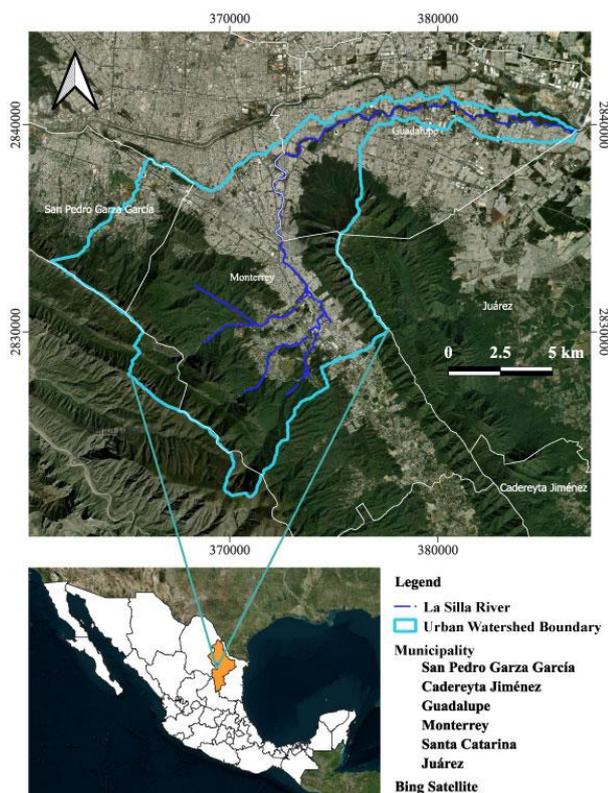

Fig. 1. Location of the La Silla River in the northeast of Mexico. Coordinates in WGS 84 / UTM Zone 14N, units in meters.

3. Methodology

3.1 Data collection

Figure 2 illustrates the information acquisition workflow using a UAV. Data acquisition was performed using a DJI Matrice 350 RTK UAV, equipped with an integrated LiDAR L2 sensor. The UAV mission covered an area of approximately 1596.36 Ha, including the river channel and adjacent buffer zones.

The flight was executed at an average altitude of 97.2 meters above ground level and a consistent cruising speed of 9.43 m/s.

The LiDAR sensor operated in a repetitive scan mode with a 70° × 3° field of view, a pulse repetition rate of 240 kHz, and a scan rate of 1200 kHz. This configuration provided high-density point cloud data (124 points/m^2) with a ground beam footprint of approximately 117 mm × 39 mm.
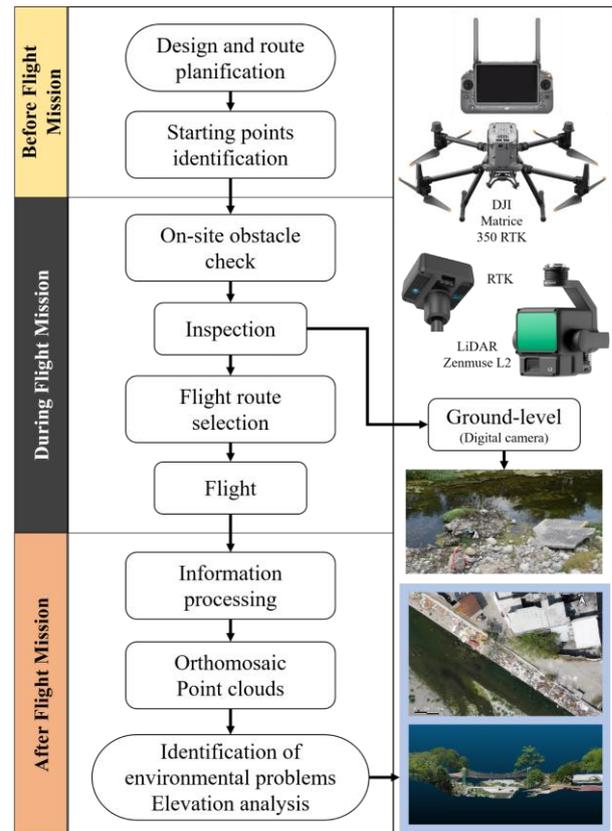

Figure 2. Workflow.

Furthermore, Real-Time Kinematic (RTK) correction was enabled through a custom base station, achieving 99.49% FIX status throughout the trajectory. RGB imagery was simultaneously collected to support colorization and the generation of orthomosaics, using the camera integrated into the LiDAR L2 sensor. This camera features a 4/3-inch CMOS sensor with an effective resolution of 20 MP. The effective range of the LiDAR sensor was configured between 0.5 and 300 meters, ensuring comprehensive coverage of both vertical and horizontal aspects of the study area.

Complementing the UAV flights, a ground-level inspection was performed with digital cameras to collect evidence from specific points of interest in the field.

3.2 Data Processing

Processing was conducted using the DJI Terra platform (version 4.5.0), which was configured to automatically optimize and classify point cloud returns. Advanced parameters were applied for ground classification, including a smooth slope model and an iteration distance of 0.5 m. As a result, a Digital Elevation Model (DEM) was generated at a 1:500 scale with a spatial resolution of 0.25 m.

Total processing covering point cloud optimization, colorization, classification, and export in both LAS and PNTS formats. A fixed

POS status was maintained in 95.37% of the data, and root mean square errors (RMSE) for the X, Y, and Z components were below 2 cm, validating the spatial accuracy of the derived model. The LiDAR point clouds have a spatial resolution of approximately 1 point/cm².

RGB imagery acquired concurrently with the UAV mission was processed to generate a true color 2D orthomosaic. Image alignment and mosaicking were performed using high-precision photogrammetric workflows, resulting in a raster product with a ground sampling distance (GSD) of 3.08 cm per pixel. Orthomosaics were georeferenced to the WGS 84 / UTM Zone 14N coordinate reference system.

3.3 Image Analysis

The orthomosaics were analyzed using QGIS software. Each orthomosaic was examined individually to identify and spatially record the areas affected by various issues. The result was the creation of a database that details the location, classification of the issue, and the associated municipality.

3.4 Elevation Analysis by Point Clouds

From the point clouds generated by the LiDAR sensor mounted on a UAV, sections of the river with various issues were identified. The point clouds were sectioned into profiles in these areas to obtain the elevation differences of the riverbanks and existing infrastructure, such as houses, dams, bridges, and avenues.

3.5 Population Analysis

The thematic population analysis maps were developed using ArcGIS Pro software. Three block-level maps were generated to represent different aspects of vulnerability among the population living in the La Silla River basin. Shapefiles from the population and housing census, provided by the National Institute of Statistics and Geography (INEGI), were used.

4. Results

4.1 Socio-environmental problems identified with ground-level inspection

The socio-environmental issues identified through fieldwork were primarily concentrated in the municipalities of Monterrey and Guadalupe, where a total of 24 affected sites were recorded (Fig. 3).

Among these, five locations exhibited evidence of wastewater discharge, while four sites corresponded to informal settlements, apparently situated within the river's floodplain.

Additional issues included the presence of invasive plant species and fire incidents, mainly associated with the burning of solid waste. The most frequent problem observed in both municipalities was the accumulation of solid waste, documented at nine sites, many of which were linked to irregular dumping activities (Fig. 4).
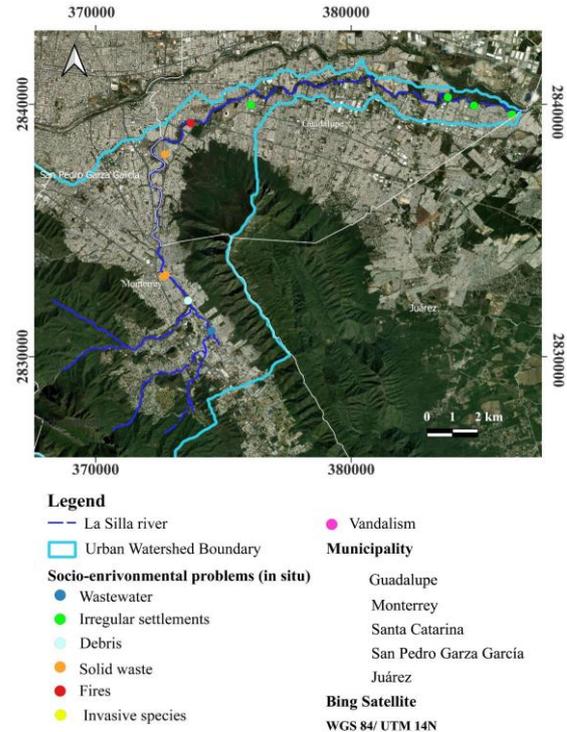

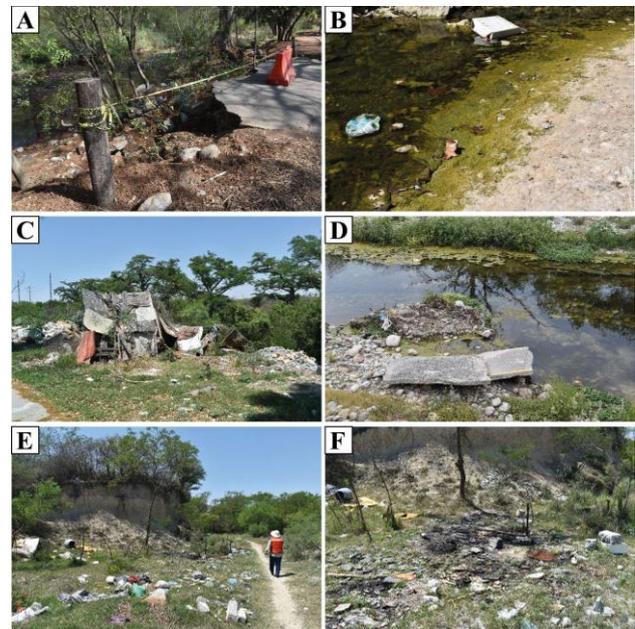Fig. 3. Map of socio-environmental problems of the La Silla River recognized by field work (in situ).

Fig. 4. A) Debris from a former road that used to cross the riverbed. Although the area is cordoned off, it lacks proper signage, posing a risk. B) Solid waste, mainly plastics and household appliances, within the river. C) Irregular settlements can be seen along the riverbank. These structures are uninhabited and exhibit signs of having been exposed to water flow, as evidenced by their partial destruction. D) Debris from what used to be a road along the riverbank is visible. E) Depicts scattered solid waste on the riverbank, including plastic bottles and bags, as well as appliance debris. F) Burned solid waste is shown,

indicating that this might be a clandestine dump site where waste is incinerated.

4.2 Socio-environmental problems identified with UAV

This geodatabase was generated by interpreting images obtained from the UAV, providing an aerial perspective of various socio-environmental issues affecting the La Silla River.

The analysis focused primarily on the municipalities of Monterrey (32.0453 km) and Guadalupe (22.6956 km), along with a smaller section of Juárez (4.7381 km).

The main issues identified were: wastewater discharge, informal settlements, animal husbandry, debris, fires, infrastructure built within the river, and solid waste, the latter being the most persistent problem along the river's course (Table 1 and Fig. 5).

In the municipality of Monterrey, the primary socio-environmental issues include poorly managed solid waste in the riverbed, with 35 identified sites, as well as irregular settlements, with 4 identified sites, and debris dumps, with 9 registered sites. To a lesser extent, wastewater, animal husbandry, fires, and infrastructure damage were reported within the riverbed.

In the municipality of Guadalupe, at least 60 sites near or within the riverbed where solid waste is located, 11 sites containing debris, and seven sites containing irregular settlements have been identified. Animal husbandry, fires, and infrastructure within the riverbed were also identified.

Although a smaller area was analyzed in Juárez than in Monterrey and Guadalupe, seven sites containing solid waste and two sites containing irregular settlements were detected.

The following table compiles the socio-environmental problems identified by drones in the municipalities of Monterrey, Guadalupe, and Juárez. Adding up to a total of 148 points with the register of socio-environmental issues.

Table 1. Counting of environmental problems identified with drone imagery at the municipal level in the La Silla River.

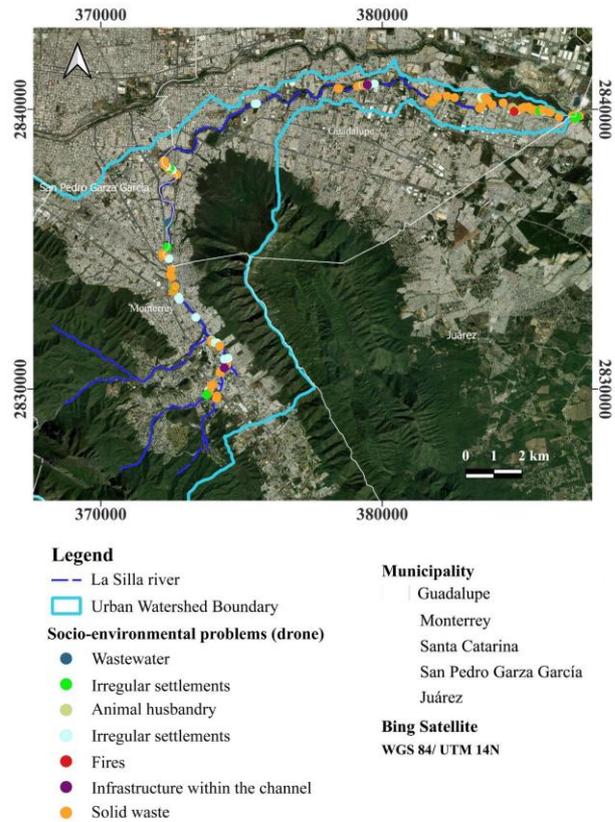| Municipality	Socio-environmental problems	Total number of records
Monterrey	Wastewater (2)	54
	Irregular settlements (4)	
	Animal husbandry (1)	
	Debris (9)	
	Fires (2)	
	Infrastructure within the channel (1)	
	Solid waste (35)	
Guadalupe	Irregular settlements (7)	85
	Animal husbandry, (4)	
	Debris (11)	
	Fires (2)	
	Infrastructure within the channel (1)	
	Solid waste (60)	
Juárez	Solid waste (7)	9
	Irregular settlements (2)	

Figure 5. Map of socio-environmental problems of the La Silla River recognized by drones (UAVs) imagery.

Figures 6–8 illustrate socio-environmental issues identified using UAVs. Data resolution is transcendental to locate and analyze these types of problems in urban rivers.
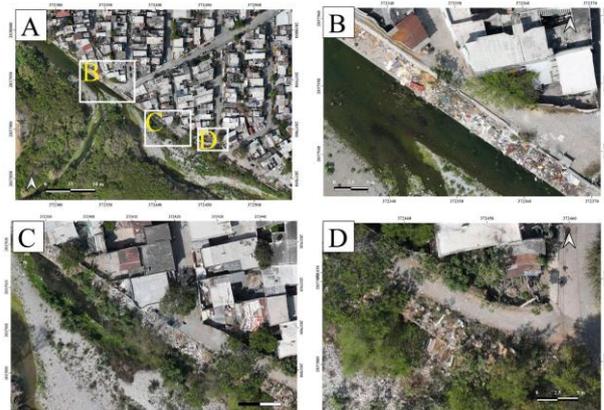

Fig. 6. A) shows approximately 300 meters of the La Silla River channel. In this specific transect, the river separates the populated area to the north from the riparian vegetation to the south. The riverbank adjacent to the populated area is affected by solid waste. Panels B), C) and D) provide detailed views of the solid waste in this transect.

Fig. 7. A) Solid waste directly in the river. Panel B) highlights waste composed mainly of tires and furniture. C) Accumulation of tires in what appears to be a dump or recycling center located on the riverbank. Panel D) provides a close-up of this issue, revealing that the solid waste includes not only tires but also various plastic waste and furniture
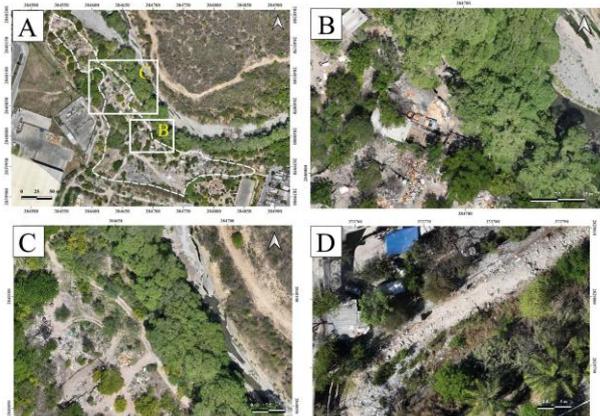

Fig. 8. A) The area, approximately 0.025 km², is being used as a dumping site and is located next to the river (outlined with a white dashed line). Panels B) and C) show close-ups of panel A, revealing settlements and solid waste in the area. D) Shows informal settlements along the riverbank, as well as solid waste scattered throughout the riverbed.

4.3 LiDAR point cloud analysis

The La Silla River shows few cases of solid waste accumulation, although areas with various types of infrastructure are found along its course.

Figure 9 shows the profile and top view of a section of the river located in Monterrey. Here, the left bank of the river was channeled, and a 4-meter-high retaining wall was placed on the right bank. Warehouses and debris disposal sites are observed very close to the sides.

This river is widely used as a recreational and community area, with parks and sports zones along its banks, such as Parque Río La Silla, Parque Canoas, Paseo Río La Silla Unidad Pipo, and Parque Tolteca.

Figure 10 illustrates Parque Canoas in the municipality of Monterrey, which currently features a pedestrian bridge, playgrounds, and a community center. Image C shows the park in 2009 before the arrival of Hurricane Alex, where the infrastructure was more extensive, including swimming pools, courts, and outdoor theaters, among others, which were swept away by the river. Image D is a present (2025) satellite image.

Fig. 9. Section of the La Silla River in the municipality of Monterrey. A) Profile view and B) Top view. Elevations expressed in meters above sea level (MASL).
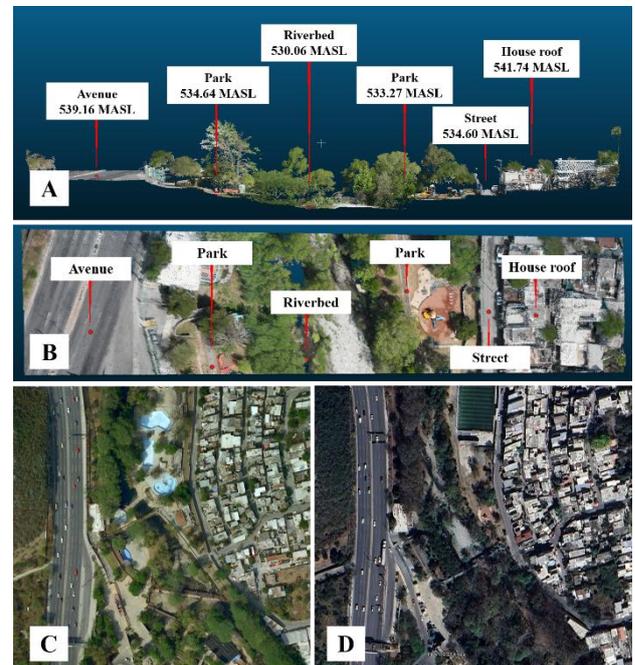

Fig. 10. Section of the La Silla River located in "Parque Canoas," Monterrey. A) Profile view, B) Top view, C) Satellite image from April 23, 2009, and D) Satellite image from February 23, 2025. Elevations expressed in meters above sea level (MASL).

Figure 11 presents the case of "Paseo Río La Silla Unidad Pipo", which has a park with recreational areas on the right bank of the river and a dam approximately 2 meters high over the riverbed.
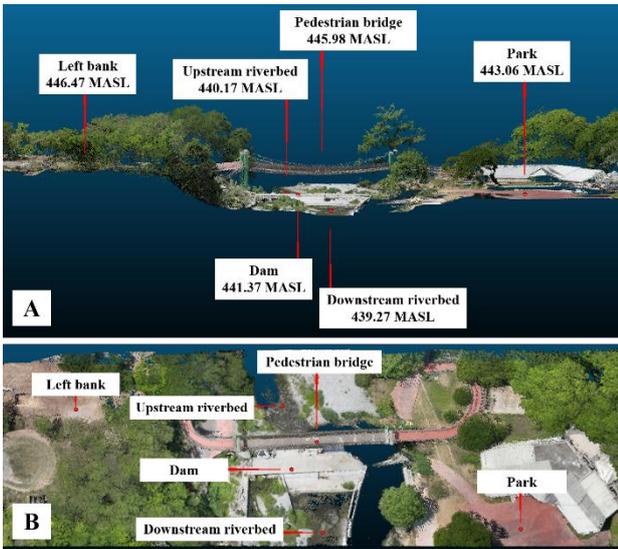
Fig. 11. Section of the La Silla River located in "Paseo Río La Silla Unidad Pipo," Guadalupe. A) Profile view and B) Top view. Elevations expressed in meters above sea level (MASL).
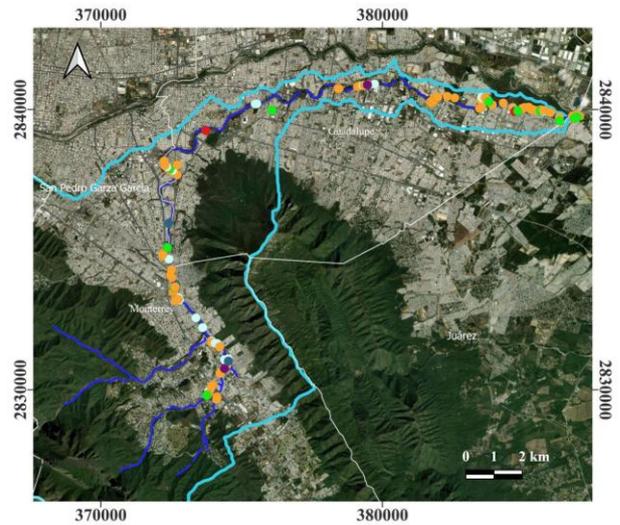
4.4 Inventory of socio-environmental problems in the La Silla River

Based on the analysis conducted along the La Silla River using UAVs' orthomosaics and fieldwork, 172 sites with socio-environmental issues were identified (Table 2 and Fig. 12).

Table 2. Counting of environmental problems identified at the municipal level in the La Silla River.

Municipality	Socio-environmental problems	Total number of records
Monterrey	Wastewater (4)	60
	Irregular settlements (4)	
	Animal husbandry (1)	
	Debris (10)	
	Fires (2)	
	Infrastructure within the channel (1)	
	Solid waste (38)	
Guadalupe	Wastewater (3)	103
	Irregular settlements (11)	
	Animal husbandry, (4)	
	Debris (12)	
	Invasive species (1)	
	Fires (4)	
	Infrastructure within the channel (1)	
	Solid waste (66)	
	Vandalism (1)	
Juárez	Solid waste (7)	11
	Irregular settlements (2)	

6% of the issues were located in the section within the municipality of Juárez (4.7381 km), 35% in Monterrey (32.0453 km), and 59% in Guadalupe (22.6956 km) (Fig. 13).

Fig. 12. Map of the socio-environmental problems identified along the Río La Silla floodplain in the Monterrey metropolitan area, Nuevo León, Mexico. The map displays different issues such as solid waste, wastewater, decline in fauna, and irregular settlements, among others.
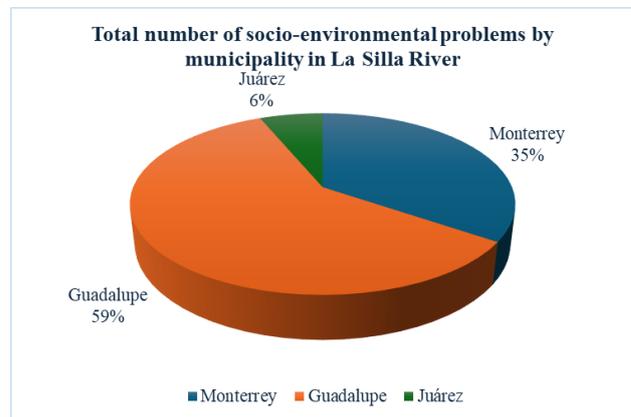

Fig. 13. Percentage diagram of the total number of socio-environmental problems identified by municipality.

The highest percentage of socio-environmental issues along the La Silla River corresponds to solid waste, accounting for 64%, followed by 13% related to construction debris dumping, and 10% to irregular settlements (Fig. 14).
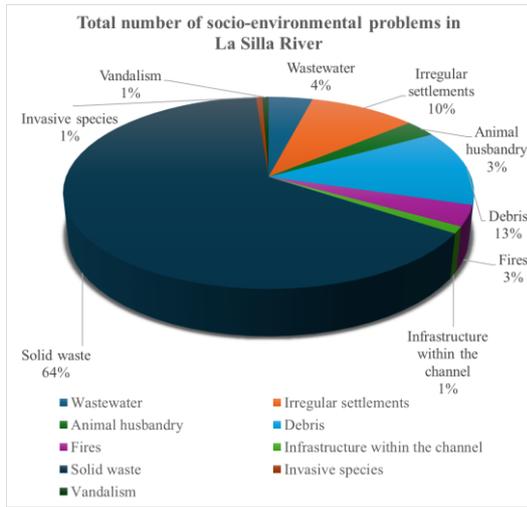
Fig. 14. Percentage diagram of the total number of socio-environmental problems identified along the La Silla River.

8.5 Population analysis in the Urban Watershed of the La Silla River

To identify areas of greater social vulnerability within the study area, a spatial analysis of key demographic variables was conducted in the urban watershed of the La Silla River. Three sociodemographic indicators were evaluated: the proportion of vulnerable population (children and older adults), individuals with disabilities or physical limitations, and households lacking basic infrastructure.

The results allow for the examination of the spatial distribution of these conditions across the three municipalities that comprise the watershed: Monterrey, Guadalupe, and San Pedro Garza García.
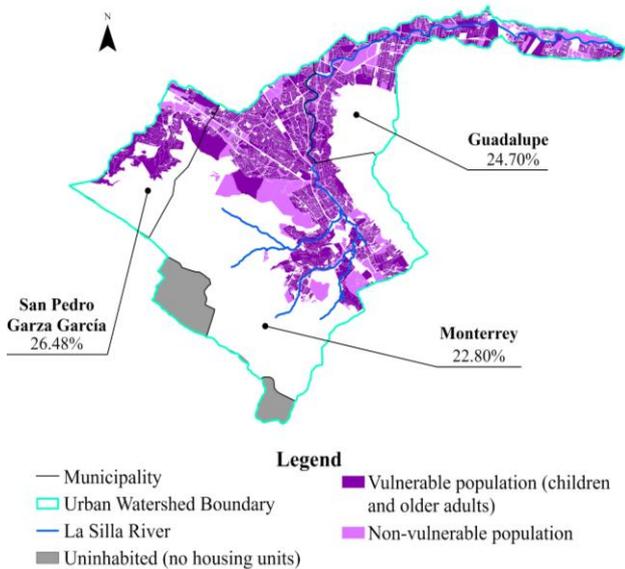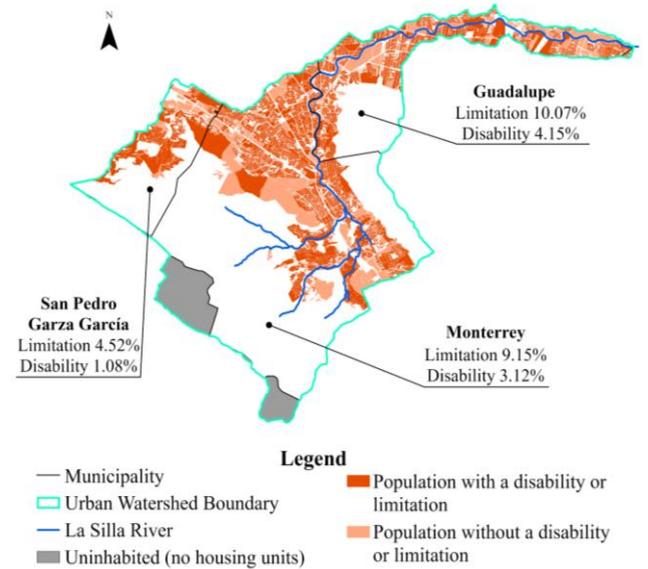

Note: The percentage represents the proportion of vulnerable population (children and older adults) with respect to the total population

Fig. 15. Map of vulnerable population (children and older adults) within the urban basin of the La Silla River.

Figure 15 illustrates the proportion of the population considered vulnerable due to age. Significant concentrations of vulnerable individuals were identified along the main course of the La Silla River. This spatial distribution is particularly relevant for defining priority areas in terms of civil protection and risk-sensitive urban planning.

Figure 16 shows the proportion of the population with some form of disability or limitation in performing daily activities. Guadalupe exhibits the highest values for both limitations (10.07%) and disabilities (4.15%), followed by Monterrey and San Pedro Garza García.

The concentration of these populations in densely populated urban areas highlights the increased need for accessible infrastructure and inclusive response strategies in the context of environmental emergencies or evacuation scenarios.
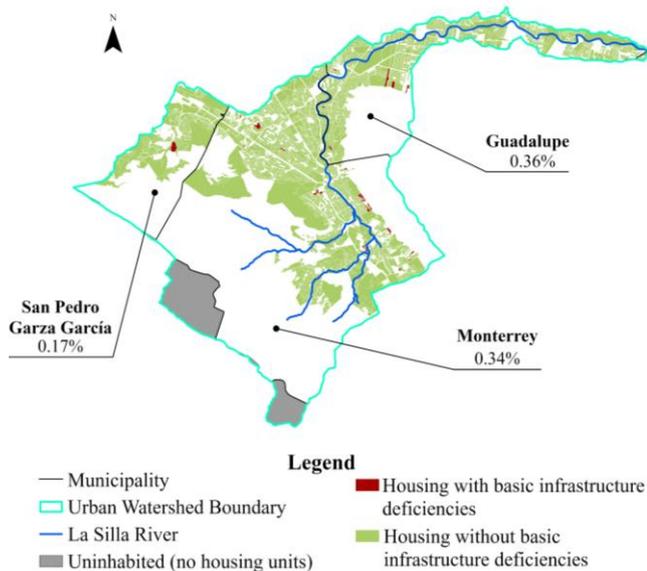

Note: The percentage represents the proportion of population with a disability or limitation relative to the total population

Fig. 16. Map of population with a disability or limitation within the urban basin of the La Silla River.

Figure 17 shows the distribution of homes lacking basic services. Although the percentages are low at the municipal level (San Pedro Garza García: 0.17%, Guadalupe: 0.36%, Monterrey: 0.34%), specific areas within the basin are concentrated, mainly in the north and northwest.

These areas represent critical points of structural vulnerability, as the lack of basic infrastructure increases the risk of extreme events such as flooding or service network failures

The joint analysis of the three indicators reveals spatial patterns that enable the identification of areas of high socio-environmental vulnerability, where sensitive demographic factors and precarious material conditions intersect. These areas require priority attention in the formulation of public policies, urban design, and risk mitigation strategies.

Legend

— Municipality

☐ Urban Watershed Boundary

— La Silla River

■ Uninhabited (no housing units)

■ Housing with basic infrastructure deficiencies

■ Housing without basic infrastructure deficiencies

Note: The percentage represents the proportion of households with deficiencies in their basic infrastructure

Fig. 17. Map of households with deficiencies in their basic infrastructure .

5. Conclusions

Using a combination of UAV-derived RGB and Lidar data, field inspections, and population analysis, a total of 172 critical sites were identified along the river. These included solid waste accumulation, construction debris, and irregular settlements, with the municipalities of Guadalupe and Monterrey being the most affected.

The use of UAVs equipped with high-resolution sensors, combined with photogrammetric or LiDAR technologies and analyzed using geospatial analysis techniques, enabled the precise mapping of pollution points and elevation profiles. The comparison between UAV-based data and ground-level observations revealed clear advantages in aerial monitoring, especially in detecting hidden or inaccessible problem areas.

Through direct fieldwork, a total of 24 socio-environmental problem sites were identified, primarily in areas with reasonable accessibility. In contrast, 148 sites were detected using UAV-derived orthomosaics and photointerpretation, covering a much broader section of the La Silla River.

The La Silla River features various types of infrastructure along its banks, clearly visible in LiDAR point clouds. This infrastructure serves as a recreational area for the community. Currently, it is in good condition, situated between 3 and 4 meters above the riverbed. However, during extraordinary events such as hurricanes or severe storms, this entire infrastructure could be swept away by the current. This has occurred in previous years, notably in 2010.

Based on geospatial information from INEGI's Geo-statistical Framework, thematic maps were developed to identify areas with the highest concentration of vulnerable populations along the La Silla River. These maps enabled the correlation of sociodemographic variables such as income level, population density, and access to basic services with critical sites identified through UAV surveys and fieldwork. Spatial analysis revealed a substantial overlap between areas of environmental risk and communities facing the most significant social disadvantages, particularly in the municipalities of Guadalupe and Monterrey. This correlation underscores the pressing need to implement integrated territorial management strategies that account for both ecological and social dimensions in urban planning and river conservation.

The georeferenced inventory developed in this study serves as a baseline tool for environmental monitoring, offering actionable insights for local governments and community organizations.

This work also aligns with several United Nations Sustainable Development Goals (SDGs), including Goal 6 (Clean Water and Sanitation), Goal 11 (Sustainable Cities and Communities), Goal 13 (Climate Action), and Goal 15 (Life on Land).

5. Acknowledgements

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