High-Resolution TLS Applications for Civil Infrastructure Inspection in Urban Rivers of Nuevo León, México

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Abstract

Light Detection and Ranging (LiDAR) has become a powerful technology for acquiring dense 3D point clouds with high spatial accuracy, enabling volumetric analysis and topographic characterization at multiple scales. Terrestrial Laser Scanner (TLS), here after LiDAR, have expanded their use from natural resource management to the structural health monitoring (SHM) of critical civil infrastructure in dynamic and hazard-prone environments. This study focused on inspecting and documenting infrastructure conditions along the three main rivers of the Monterrey Metropolitan Area: Pesquería, La Silla, and Santa Catarina. The objective was to assess structural integrity and identify elements requiring preventive maintenance or removal. Photographic datasets were compared with Google Street View and Google Earth Pro imagery to geolocate and detect visible changes. Based on this initial analysis, 5 to 6 structures per river were selected for detailed surveys using TLS equipment. TLS data were processed to create detailed plans and 3D models of each structure. Technical files were completed to document structural characteristics, condition assessments, repair proposals, and risk and accessibility analyses. This study demonstrates an effective methodology for SHM of riverine infrastructure. It also emphasizes the need for multidisciplinary expertise—including engineering, geospatial analysis, and urban planning—to support evidence-based public policy. The resulting datasets can inform hydrological and hydraulic modeling, enhance resilience assessments, and guide urban planning, construction strategies, and civil protection efforts in one of Mexico's most vulnerable metropolitan regions.

1. Introduction

Every year there is an increment on the frequency and intensity for the environmental catastrophes (such as landslides, floods, storm surges, forest fires, etc.) and this a consequence of the climate change effect, but also due to the exacerbation of socioeconomic vulnerabilities (Charak et al. 2024). Faive et al. (2018) recognized that there are well-established connections between disaster risk reduction and the impact to the environment. As for this Yépez et al. (2013) indicated that prevention and mitigation are the most effective ways to reduce the negative consequences in countries like México.

Sustainable cities and safer communities are a global goal that has been pursued in the hopes of reducing disaster impacts and constructing more resilient and strengthening communities (Shafik, 2025; Hao et al., 2023; Lee & Ellingwood, 2017). Back in the 90´s the Yokohama Strategy was the first intent made by the United Nations to address an international disaster risk policy (Balgos, 2013). The Yokohama Strategy marked the beginning of a new thinking on international cooperation and decisions focused on disaster risk reduction (DRR) by providing guidelines for prevention and mitigation (Basher, 2013). Then in 2005 the focus was shifted to managing capacities and risk preparedness interventions by the Hyogo Framework for Action (Beco, 2024). And the most recently created Sendai Framework for Disaster Risk Reduction 2015–2030 (SFDRR) enhances activities to disasters and allows for resilience measurements assessing the integration to the Sustainable Development Goals and the Paris Agreement (Mpiere et al., 2025; Mandirola, et al., 2022).

The primary objective of this document was to evaluate structural integrity and determine which elements require preventive maintenance or removal through terrestrial LiDAR scanning, while incorporating Google capacities throughout the Google Earth and Google Street View to obtain a comprehensive understanding of the territorial infrastructure.

1.1 The role of laser scanning in disaster risk reduction and infrastructure monitoring

Intensity and frequency of the climate-related catastrophes have heightened the need for advanced technologies to support prevention and mitigation strategies (Wei et al., 2021). According to Lin et al., (2021) scour around bridge pears are the leading cause of structural failures (and the major reason for bridge collapses in the United States a fact declared initially by Smith in 1976 cited by Cook, 2014), underline the importance of real-time monitoring systems in managing disaster risks. Remote sensing technologies, particularly Terrestrial Laser Scanning (TLS), offer valuable tools for enhancing disaster resilience and infrastructure risk assessment.

Remote sensing plays complementary roles in modern disaster risk management frameworks like the Sendai Framework and (Shafian and Hu, 2024), and supporting efforts to enhance resilience and reduce vulnerability (Kerle, 2024). When integrated effectively, LiDAR technologies can significantly strengthen the ability of communities and engineers to anticipate, prepare for, and mitigate the impacts of natural hazards (Necsoiu and Hooper, 2009) or for reconstruction such as the ability of TLS excelling precision and localized monitoring (e.g., for early signs of bridge scour). As Table 1 displays these particularities are very well delimited and can be part of the analysis.

	TLS (Terrestrial Laser Scanning)	ALS (Airborne Laser Scanning)
Advantages	• Produces elaborated and precise point clouds. • Provides better control over point clouds, reducing redundant data during processing. • Easier to operate, no need for GPS/IMU integration.	• More automated, less manual handling. • Can scan from different heights, capturing more points in less time. • Covers larger areas than TLS. • Effective for scanning large or hard-to-reach places.
Disadvantages	• Requires manual setup and repositioning. • Limited mobility, risk of incomplete or obstructed scans. • Large point clouds take longer to acquire. • Hard to access remote or difficult areas.	• Needs pre-planned flight paths to avoid excess data. • Strongly affected by weather conditions. • Generates heavy point clouds, requiring more complex and time-consuming processing.

Table 1. Advantages and disadvantages of Terrestrial Laser Scanners (based on Kaartinen et al., 2022).

1.2 Bridges and structural health monitoring

Bridges are key elements of transportation infrastructure (Gonzalez et al., 2020) and are particularly vulnerable to the impacts of climate-induced hazards such as floods, storm surges, and scour (Shaw et al., 2025). As these events become more frequent and severe, the need for effective Structural Health Monitoring (SHM) systems is essential to ensure safety and resilience. LiDAR (Light Detection and Ranging) technologies—specifically Terrestrial Laser Scanning (TLS) and Airborne Laser Scanning (ALS)—offer advanced capabilities for capturing high-resolution, three-dimensional data of bridge structures and their surrounding environments. These technologies enable accurate monitoring of structural deformations, erosion, and scour, facilitating early detection of potential failures. By integrating LiDAR into SHM strategies, engineers can enhance bridge maintenance, improve risk assessment, and support disaster mitigation efforts (Figure 1).

Bridge infrastructure had been studied by Yu and Yu (2011) determining structural failures, related to hydrometeorological phenomena as the main cause (NCHRP, 2003 and Shirole and Holt, 1991). Structural health monitoring systems of bridges are reported by engineers around the world (Limongelli et al., 2024; Comisu et al., 2017) and have the task to develop real time bridge scour monitoring systems to evaluate risk management (Yépez et al., 2013).

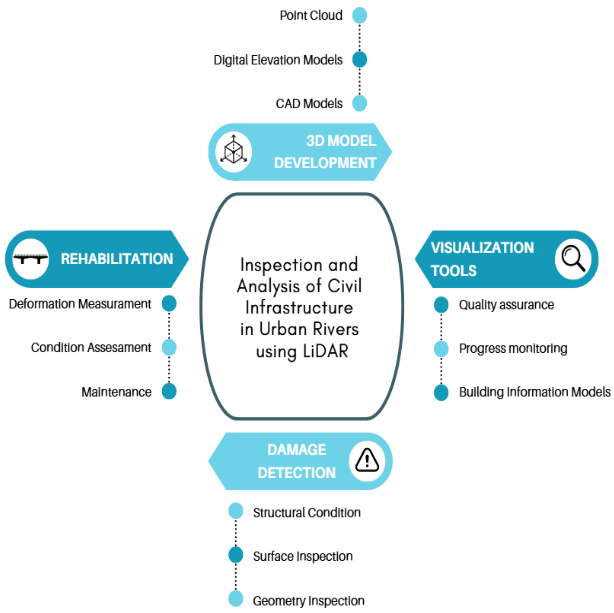


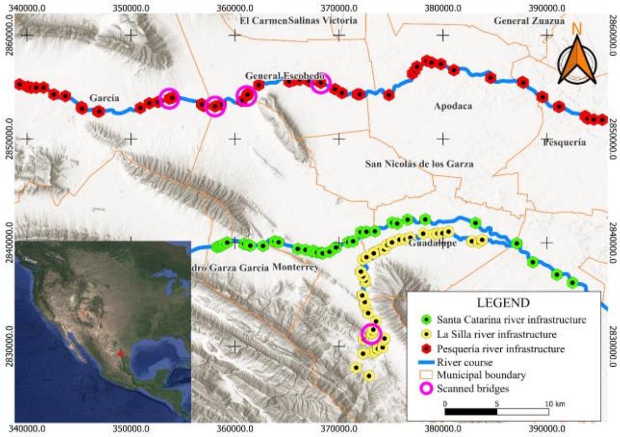
Figure 1. Applications of LIDAR for SHM (modified from Kaartinen et al., 2022).

1.3 Bridges historical and current conditions

Among the six bridges studied in the Monterrey Metropolitan Area, the Gonzalitos Bridge stands out due to its significant historical changes (Figure 2), particularly following the impact of Hurricane Alex. he 2010 event inflicted catastrophic losses in Nuevo León, with reported damages exceeding 21.5 billion pesos, of which over 7.4 billion pesos were allocated to communications and transportation infrastructure (Mercado-García, 2025). The hurricane caused substantial damage to the bridge, prompting a major reconstruction effort with a considerable budget allocation aimed at restoring its structural integrity and functionality.

However, despite the scale of investment, the reconstruction of Gonzalitos Bridge reflects a missed opportunity: there is little evidence that the redesign incorporated hydrological requirements or lessons learned from previous disaster events. The current condition of the bridge shows substantial modifications compared to its original state, yet these changes appear to lack consideration of the river’s dynamic behavior and flood risks that contributed to the initial damage.

This case underscores a critical challenge in urban river infrastructure management—the need for integrating scientific disaster risk knowledge into reconstruction and planning processes. Without this integration, costly interventions may fail to enhance long-term resilience, leaving bridges vulnerable to future hydrometeorological hazards.



A

B

|C

Figure 2. The infrastructure of bridges in the Monterrey Metropolitan Area consisted of: (A) scanned elements, (B) changes to the Gonzalitos bridge between 2006 and (C) 2025 images, all obtained from Google Earth.

1.4 Critical points for urban river bridges using LiDAR-based SHM

1.4.1 Monitoring Scour and Riverbed Erosion

Urban river bridges are especially vulnerable to scour—erosion of soil around bridge foundations—due to fluctuating flow rates, sediment transport, and flood events. ALS provides a topographic and bathymetric context of the riverbed, while TLS can inspect individual piers and abutments (Reil et al., 2018). Together, they enable detection of changes in riverbed geometry that threaten structural stability.

1.4.2 Flood risk and hydraulic modeling

In cities, riverbeds are often constrained by engineered banks, built-up infrastructure, and modified flow paths. LiDAR data (from ALS and TLS) can define accurate terrain and channel geometries, enabling hydraulic models to simulate flood discharges and water surface elevations. These simulations help in planning mitigation, e.g., retrofitting bridge openings or raising abutments to reduce the risk of overtopping.

Urban bridges endure not only hydraulic forces but also traffic loads, pollutant exposure, and sometimes limited maintenance access. TLS allows high-resolution scanning of structural members (piers, beams, decks) to detect small deformations, cracks, or corrosion. Early identification in an urban context is crucial to avoid disruptions to services and ensure safety.

Bridges over urban rivers often serve as key transportation lifelines. LiDAR-based monitoring produces datasets that inform not only bridge maintenance but also broader urban planning: emergency response routes, resilience zoning, land use adjacency, and investment priorities. Having up-to-date structural health information helps city planners, civil protection agencies, and infrastructure managers make decisions that safeguard mobility, economy, and public safety.

2. Methodology

2.1 Bridges LiDAR data acquisition

For this research, five bridges out of a total of 142 located in the Monterrey Metropolitan Area (MMA), Northeast Mexico, were selected for detailed structural assessment. 41% of the bridges belong to the Pesquería river, 28% to Santa Catarina, and 31% to the La Silla river. These bridges were chosen based on their exposure to riverine hazards, structural typology, and accessibility for detailed inspection.

Each of the selected bridges represents a typical reinforced concrete structure and serves as a key component of the urban transportation network. Data collection involved creating an attribute table in QGIS using freely available sources, including Google Earth Pro, Google Maps, and Google Street View. This included the first and most recent recorded satellite images of the infrastructure, street-level views, the number of lanes or presence of pedestrian crossings, and the current status of the structure (e.g., cracks, potholes, vandalism, or horizontal signage).

In the second stage, a standardized inspection format was applied to evaluate the structural condition of each bridge (Walbridge, 2022). This technical sheet, developed by the Department of Structural Engineering and adapted from FEMA-based methodologies, had general information (bridge name, location, typology, and material), documentation of observed damages, proposed repair actions, accessibility and environmental risks, and terrestrial laser scanning (TLS) survey records.

The integration of field inspection and TLS provided a comprehensive dataset that linked visual assessments with high-resolution three-dimensional measurements, particularly relevant for bridges located on the Pesquería and La Silla rivers, where hydrometeorological hazards such as scour and erosion directly affect structural performance. This combined assessment enabled systematic structural inspections, documentation of condition, and vulnerability analysis, contributing to a broader understanding of the resilience of civil infrastructure in hazard-prone urban river corridors.

2.2 Technical information for the bridges

The American Association of State Highway and Transportation Officials (AASHTO) recognize some of the common structural types are typically recognized in urban river infrastructure (Figure 3).

2.2.1 Arch Bridge: This type of bridge transfers loads through compression along a curved structure, typically supported at both ends by abutments. Their shape allows them to efficiently resist gravitational and hydrodynamic forces, making them suitable for spanning moderate distances over rivers (Troitsky, 1994).

2.2.2 Cable-Stayed Bridge: Cable-stayed bridges support the deck with straight cables connected directly to towers. They offer a balance between structural efficiency and aesthetics and are increasingly used in modern urban infrastructure. Monitoring focuses on cable tension, deck deflection, and tower integrity (Gimsing & Georgakis, 2012).

2.2.3 Suspension Bridge: Suspension bridges carry loads via vertical suspenders connected to main cables, which are anchored at both ends and supported by towers. These bridges are ideal for long spans and flexible to dynamic loading but demand advanced SHM systems due to their sensitivity to wind and vibration (Comanducci, 2015).

2.2.4 Beam Bridge: This type of bridge is among the simplest and most common types, consisting of horizontal beams supported by piers. They are typically used for short spans and urban settings. Despite their simplicity, beam bridges are highly susceptible to scour around piers and therefore require close SHM attention (Antonopoulos, 2025).

2.2.5 Cantilever Bridge: Cantilever bridges use projecting arms anchored at only one end. These structures are effective for medium spans and are often used in areas where it is difficult to install temporary supports, such as deep or fast-flowing rivers. Their structural behavior requires detailed monitoring, especially at joints and anchor points (Petroski, 2018).

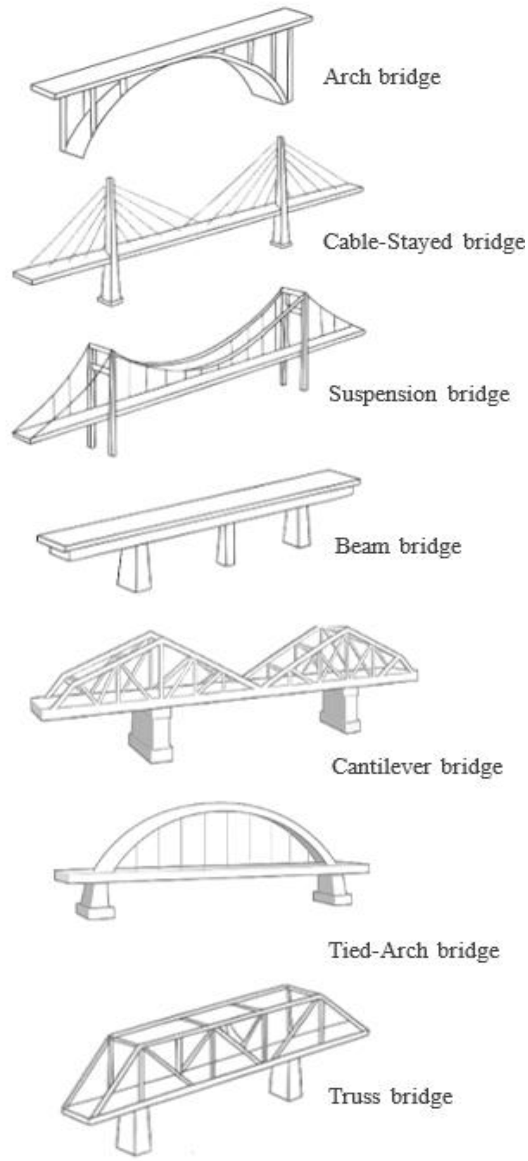


Figure 3. Scheme of bridge types (based on AASHTO).

2.2.6 Tied-Arch Bridge: This type of bridge incorporates a horizontal tie between the arch ends, absorbing outward thrust and allowing construction on weaker foundations or over wide spans. This makes them particularly effective for urban rivers where space constraints or soft soils limit traditional abutments (Melbourne, 2008; Finke, 2016).

2.2.7 Truss Bridge: Truss bridges use a triangulated framework of elements in tension and compression, offering strong weight distribution and stability. Common in older urban areas or for railway crossings, truss bridges benefit from SHM due to their numerous joints and potential for fatigue (Lin & Yoda, 2017).

In this study, bridge typology is addressed as one of several descriptors recorded in the inspection sheets, complementing other classifications such as construction material, observed deterioration, and proposed interventions, to provide a comprehensive understanding of bridge resilience in hazard-prone urban river corridors.

2.3 Information collected

In the general data collection, the identification name of each structure was recorded, as well as the municipality in which it is located and the classification according to the type of element: bridges, dams, and others (facilities/roads). In addition, an analysis of the infrastructure development for each bridge was conducted using satellite image history, comparing the earliest available image with the most recent, to identify possible changes in the infrastructure and its surroundings (Figure 4).

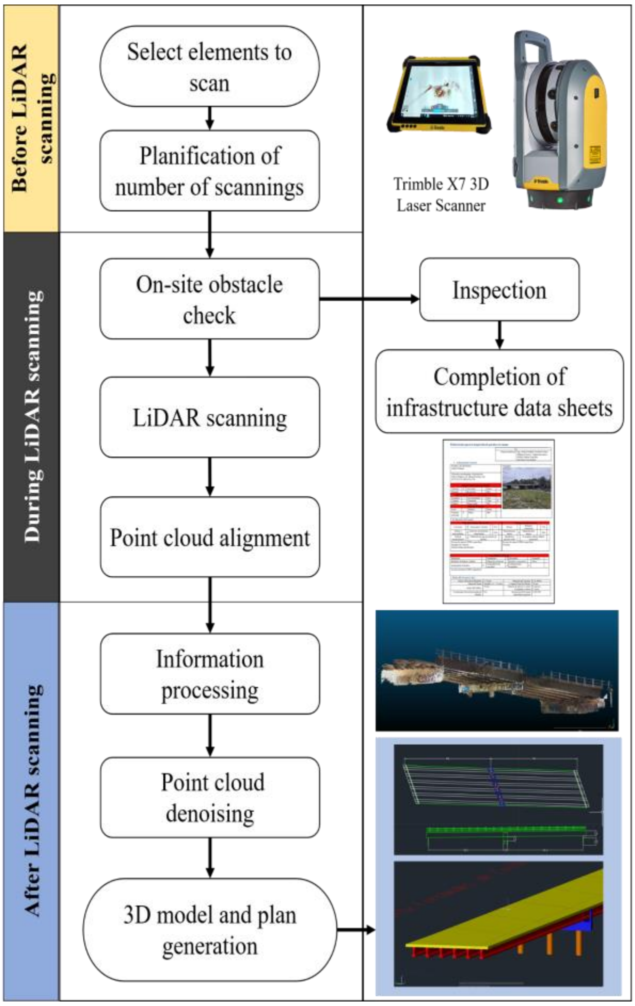


Figure 4. Workflow for 3D mapping, indicating the type of sensor and process.

2.3.1 Terrestrial Laser Scanner (TLS) Trimble X7

The Trimble X7 terrestrial laser scanner is a high-precision instrument designed for structural and topographic documentation. It features a Class 1 eye-safe laser operating at a wavelength of 1,550 nm, which is non-visible and safe for use in populated environments.

The device achieves a point acquisition rate of up to 500,000 points per second, enabling rapid and detailed 3D data capture. For this study, the scanning range was set to 80 meters, with a laser spot size of approximately 16 mm at 100 meters, ensuring accurate geometry modeling at mid-range distances.

Parameters	Characteristics
Scanning EDM Laser Class	Laser class 1, eye safe in accordance with IEC EN60825-1
Scanning Speed	Up to 500kHz
Scan Duration	Fastest 1 min 34 sec without images, 2 min 34 sec with images
Range Principle	High speed, digital time-of-flight distance measurement
Range	0.6 m - 80 m
Range Accuracy	2 mm
Range Noise	<3 mm @ 60 m on 80% albedo
Imaging	
Imaging Sensors	3 coaxial, calibrated 10MP cameras
Raw Image Capture	Fast 1 minute - 15 images - 158MP Quality 2 minutes - 30 images - 316MP
Automatic Level Compensation	
Range	± 5°
Accuracy	< 3" = 0.3 mm @ 20 m
Environmental	
Operating Temperature	–20 °C to 50 °C (–4 °F to 122 °F)

Table 2. Technical specifications for the Trimble X7.

The X7 also integrates an internal camera capturing high-resolution RGB imagery (10 megapixels), which is automatically aligned with the point cloud to enhance visual interpretation. In addition to spatial coordinates, the scanner records intensity values, supporting material differentiation and surface condition assessment (Table 2).

The topographic survey (Figure 5) required careful parameter configuration based on the project's environmental conditions and specific objectives. For this Project, a medium point density (6.3 mm at a 10-meter distance) was selected to achieve a balance between detail and efficiency. General accuracy over the scans was ±3mm.

In addition, real-color capture was enabled to produce a point cloud with rich visual information, which is crucial for detailed analysis. Each scan station took approximately seven minutes, though the duration varied slightly depending on the environmental complexity and the specific equipment settings.

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Figure 5. Fieldwork scanning the rivers in the riverbed. (A) Preparing the scanner (B and C) Bridge conditions.

2.4 Data processing and point cloud denoising

Upon collection, the raw data was processed using CloudCompare (V2). This software was used to remove noise and extraneous data, a critical step to ensure the accuracy and reliability of the final deliverables. The average registration accuracy achieved was ±3mm. The point cloud was meticulously cleaned to prevent any errors or inconsistencies from affecting the subsequent generation of engineering drawings. Using TBC software were applied thresholds to remove the noise and vegetation points.

2.5 Plan generation and modeling

To create the final plans, various views of the processed point cloud—including plan, profile, and section views—were captured. These captures were then imported into Autocad (2024) to generate the final 2D and 3D drawings, and the creation of precise and detailed models of the bridge, ensuring the accuracy required for all project specifications.

3. Results

3.1 Infrastructure characteristics using images from Google Street View and Earth Pro

Of the infrastructure attribute tables generated, the quantity of each type of infrastructure for the three rivers was obtained. Figure 6 represents the total quantity for the three rivers, showing that vehicular bridges are the most common, constituting 65% of the total.

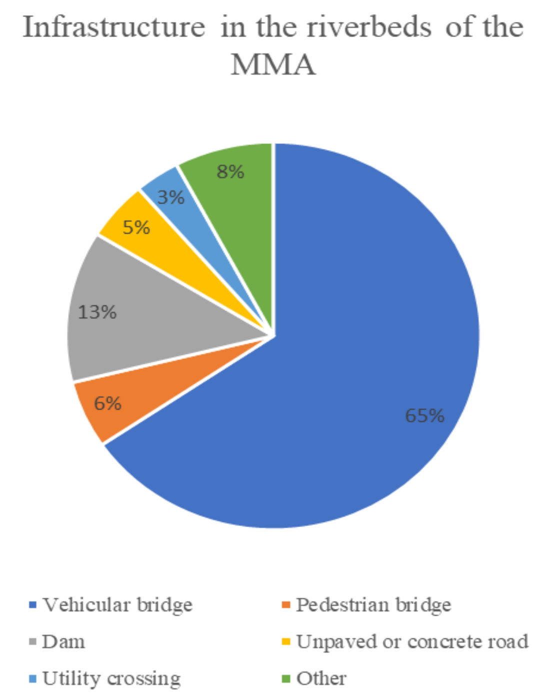

Figure 6. Bridge statistics.

3.2 Detection and location of points

Within the Monterrey Metropolitan Area, each structure on the Santa Catarina, La Silla, and Pesquería rivers was identified. This was done using Google Earth Pro and Google Maps to locate the study points to analyses infrastructure development over time and assess its current status. A total of 143 structures were identified along the rivers, of which 40 correspond to the Santa Catarina River, 44 to the La Silla River, and 59 to the Pesquería River. This distribution allows for scaling the number of elements to be evaluated and prioritized in each of the rivers.

3.3 Collected information characteristics

The analysis revealed that most bridges had undergone widening, adding lanes due to increased vehicular traffic demand. To determine the characteristics of the structures, a Street View survey was conducted. The bridges were divided into three categories: vehicular, pedestrian, or mixed-use. In addition, the number of lanes and the direction of travel were recorded for each bridge. Several aspects were considered in assessing the current condition of the bridge to determine whether the structure required maintenance. Among these factors was the presence of cracks and potholes in the road surface, the level of damage being measured by number, width, and depth. Good road markings promote better traffic flow, so it was also necessary to detect wear or lack thereof. The achieved mean registration accuracy was 2.8mm and an overall point cloud precision was 5.2 (RMSE). These results can easily determine the deformations exceeding 1cm from the structures. These are quantitative results that confirm the reliability of this method, and the accurate documentation and inspection of bridges in urban river environments.

The urban image also influences the condition of the bridge. In cases of vandalism, graffiti, garbage accumulation, or damage to bridge elements are detected. Based on the analysis, the percentage of structures requiring maintenance was determined along the three rivers evaluated. The Pesquería River represents the highest priority, with 96% of structures in poor condition. The Santa Catarina River is in second place, with 56%, and finally the La Silla River, with 40%.

3.4 Structural damage identification via visual inspection

The inspection and laser scanning results from the 5 bridges inspected revealed different levels of vulnerability. All of the inspected bridges corresponded to reinforced concrete beam-type structures (Figure 3). Bridges located on the Pesquería River exhibited severe structural deterioration, including corrosion and cracking in 66.7% of the cases, as well as concrete spalling, loss of parapets, deterioration of abutments, and exposure of reinforcement (each reported in 33.3% of the cases).

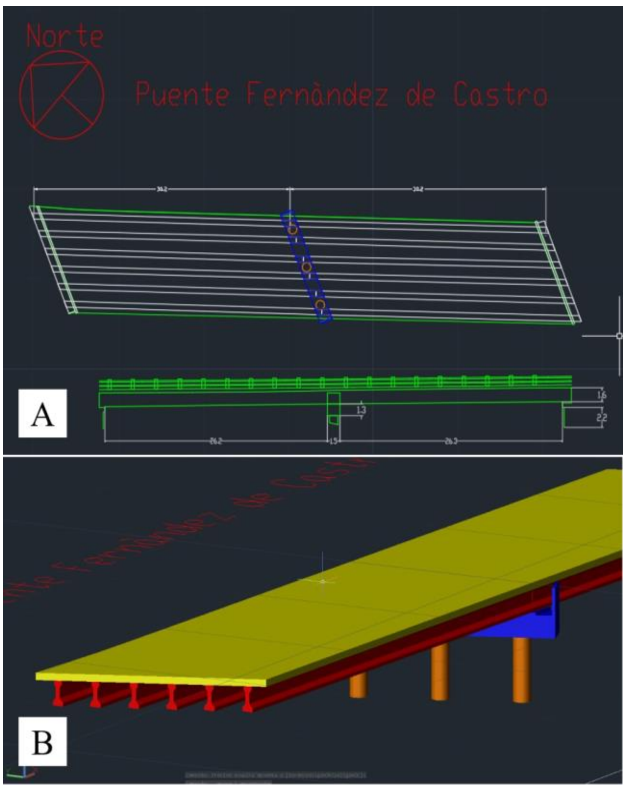

Figure 7. Products generated from LiDAR point clouds, A) Plan and B) 3D models.

These findings suggest an urgent need for major maintenance and structural reinforcement. In contrast, the bridge inspected on the La Silla River did not display significant structural failures; rather, deficiencies were related to maintenance and environmental conditions, such as invasive vegetation, accumulation of debris, and vandalism. These results highlight the varying nature of risks between rivers and underscore the value of TLS for documenting both structural and environmental factors.

3.5 Plans and 3D modeling

From LiDAR point clouds, detailed plans and 3D models were generated for each of the selected bridges (Figure 7). These products will be used to understand their current conditions and assess whether the infrastructure continues to fulfill its design requirements. The 3D models will also serve as input for hydrological modeling, to determine if the bridges can withstand potential flood events and how they interact with the surrounding river environment.

4. Conclusions

The integration of standardized inspection formats with TLS data acquisition and open-source geospatial tools proved effective for assessing the current condition of urban river bridges in the Monterrey Metropolitan Area. From the 5 bridges evaluated, the results indicate that bridges over the Pesquería River require priority interventions due to the severity of structural damage, while the bridge on the La Silla River demands preventive maintenance actions. Although this study did not rely on comprehensive geospatial datasets to quantify all existing bridges per river, the field-based inspections combined with laser scanning provide a replicable methodology for evaluating vulnerability and supporting disaster risk reduction strategies.

The use of Google Earth Pro, Google Maps, and Street View provided a valuable baseline for preliminary assessment and historical analysis, allowing for the efficient selection of inspection targets based on typology, accessibility, and visible deterioration. The attribute table developed in QGIS enabled structured data collection, while the technical inspection sheets ensured consistency in recording structural conditions and associated risks.

LiDAR-derived 3D models allowed for a detailed geometric simulation of each bridge and contributed to the identification of scour-prone zones and structural vulnerabilities. These high-resolution datasets are suitable for integration into a risk atlas, offering a spatial decision-support tool for civil protection and urban planning authorities.

The findings underscore the importance of multidisciplinary collaboration, combining civil engineering, geospatial science, and public policy to address infrastructure resilience in the face of climate-related and hydrological hazards.

The methodology proposed here can serve as a model for other metropolitan areas seeking to enhance their infrastructure monitoring frameworks using accessible technologies and remote sensing data.

Overall, this research contributes to the development of a more proactive and evidence-based approach to infrastructure management, supporting long-term urban resilience in one of Mexico's most vulnerable regions.

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