LiDAR-driven Topographic Surveys for Floodplain Management

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Abstract

LiDAR technology has become an essential tool for hydrological monitoring, offering high-resolution topographic data for river basin management. This study presents LiDAR-based topographic surveys conducted on the Metauro and Cesano river basins in Central Italy to improve flood risk assessment and regional planning. Airborne LiDAR and ground-based GNSS techniques have been integrated to generate accurate DTMs and DSMs, enabling precise floodplain mapping and man-made structures analysis. The data processing involved automated classification and manual corrections to differentiate between terrain, vegetation, and built structures. The results provided detailed cross-sectional altimetric profiles, revealing geomorphological changes such as sediment deposition and erosion. Additionally, Airborne LiDAR-derived datasets supported flood modeling, infrastructure assessment, and long-term environmental monitoring. The study highlights the effectiveness of LiDAR data collection in hydrological management, enhancing flood risk mitigation, urban planning, and ecological restoration. Future research should focus on expanding survey coverage, integrating real-time flood forecasting, and leveraging AI-driven techniques for automated data processing. This work contributes to improved geospatial knowledge, providing decision-makers with advanced tools for sustainable surface water resource management.

1. Introduction

Hydrological risks that are associated with rivers have emerged as a significant concern worldwide, impacting both natural ecosystems and human settlements (Busico et al., 2020). As a central component of this project, geomatics is a key component in surveying through the deployment of LiDAR (Light Detection and Ranging) instruments. By analyzing this data over time, researchers can monitor changes in river patterns, land use, and climate variables; this helps identify trends and potential triggers for hydrological events.
According to the report on flood hazard conditions in Italy and associated risk indicators, published by ISPRA[1] in 2021, Italy is exposed to various types of hydrogeological risks, such as floods, landslides, and coastal erosion. The report also presents indicators related to different risk elements, such as population, buildings, industries and services, and cultural heritage (Di Stefano et al., 2024). One of the Italian regions particularly vulnerable to flood risk is the Marche Region, located in Central-eastern Italy along the Adriatic coast. The flood risk in the Marche Region was dramatically demonstrated by the catastrophic event that occurred on September 16, 2022 (Fronzi et al., 2024; EMSR 634, Copernicus Emergency Management)[2], when torrential rains caused flash floods that swept through several localities in the provinces of Ancona and Pesaro-Urbino. However, the analysis and management of hydrogeological risk is a complex and challenging task that requires a multidisciplinary approach. It includes understanding various physical processes that govern river dynamics, that involve the disciplines of geomatics, hydrology and geomorphology.

[1] https://www.isprambiente.gov.it/it/pubblicazioni/rapporti/rapporto-sulle-condizioni-di-pericolosita-da-alluvione-in-italia-e-indicatori-di-rischio-associati

[2] https://mapping.emergency.copernicus.eu/activations/EMSR634/

The Hydrogeological Structure Plan (PAI) of the basins of the Marche Region identifies, on a historical-morphological base and hazard zones associated with a 200-year return period, the areas potentially affected by river flooding.
This methodological choice, although perfectly in line with the regulatory provisions in force at the time of the Plan's drafting, after two decades is no longer in line with the regulatory changes that have occurred in the meantime (Italian regulations: Leg. D. 152/2006, Dir. 2007/60/EC, Leg. D. 49/2010) and therefore requires a significant upgrade aimed, as a priority, at identifying multiple hydraulic hazard zones characterized by different return periods and thus able to allow the activation of risk management policies required by EU-level regulations.
With reference to the regional territorial scope, the Central Apennine District Basin Authority (AUBAC) has initiated campaigns of topographic surveys and hydraulic modeling on some watercourses in the Marche Region to provide suitable products for updating the floodplain management planning. The update of the territorial knowledge framework involved surveying the watercourses of interest, Metauro and Cesano rivers, their tributaries, and their pertinent areas using appropriate techniques and instrumentation. The activities carried out involved detailed surveys using suitable technologies such as Airborne LiDAR and GNSS tools. The goal has been to obtain information regarding the configuration of the terrain and infrastructure, in order to use the results of these surveys in subsequent phases and also make comparisons with previous information (previous surveys carried out in 2001-2002).

2. Related works

As evidenced by the literature, LiDAR technology has become an essential and consolidated tool in hydrological monitoring and forecasting, offering high-resolution topographic data essential for accurate floodplain mapping and risk assessment

(Di Stefano et al., 2021; Kumar et al., 2023; Kubendiran & Ramaiah, 2024). Airborne LiDAR's capability to produce detailed elevation models are crucial for understanding flood risks and informing land-use planning (Kiaghadi et al, 2020). The efficacy of geospatial techniques in advancing the understanding and mitigation of hydrogeological risks is exemplified by studies that utilize high-resolution terrain data for the precise mapping and monitoring of subsurface processes. Costabile et al. (2021) emphasized the potential of terrestrial and airborne laser scanning coupled with 2D modeling in generating detailed 3D flood-hazard maps for urban areas. Hariyono et al. (2020) presented a case study on utilizing Airborne LiDAR data to analyze flood disaster areas specifically in the Sekarbela Subdistrict, Mataram (Indonesia). In riverine environments, Topo-Bathymetric LiDAR has advanced the monitoring of river morpho-dynamics and habitat mapping. Mandlburger et al. (2015) highlight that Airborne LiDAR Bathymetry (ALB) enables high-resolution mapping of fluvial topography, capturing both aquatic and riparian zones with remarkable accuracy. The integration of LiDAR-derived Digital Elevation Models (DEMs) into the hydraulic models enhance the precision of flood simulations. Srinivas et al. (2022) demonstrate that high-resolution LiDAR DEMs improve surface water flow modeling and aid in identifying optimal locations for conservation practices in agricultural watersheds.
Furthermore, the fusion of LiDAR data with deep learning techniques has opened new avenues for flood monitoring. Feng et al. (2022) presents a method for extracting building facade openings from LiDAR data using deep learning, which assists in creating flood risk maps by comparing detected openings' heights with predicted water levels. The application of LiDAR extends to urban flood modeling as well. Bhatnagar et al. (2021) discuss the use of UAV-based LiDAR to drive high-resolution flood propagation and modeling, addressing the challenge of collecting fine-grained terrain data, crucial for accurate flood assessments.
This study details the topographic surveys on Metauro and Cesano river basins (Central Italy), designed to support hydrogeological monitoring, forecasting, and regional planning. By integrating LiDAR technology with traditional ground-based techniques (Di Stefano et al., 2020), this study provides an enhanced geospatial knowledge framework essential for managing hydrogeological risks and improving territorial planning. The objectives and outcomes of this study include:

1. Provide updated geospatial datasets for Metauro and Cesano river basins.
2. Develop high-resolution Digital Terrain Models (DTMs) and Digital Surface Models (DSMs) underlining infrastructural features.
3. Generate floodplain modeling and validate cross-sections on the rivers, natural and adjacent infrastructures.

3. Methodology

Figure 1 summarize the main steps of the methodology workflow which is described in the following paragraphs.

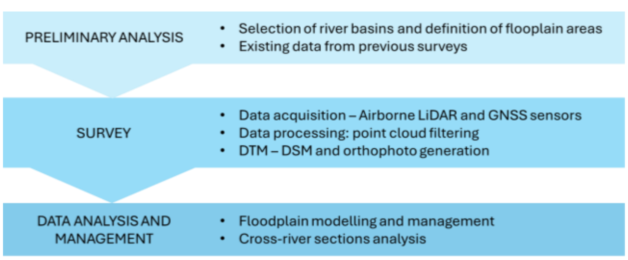


Figure 1. Methodology workflow.

3.1 Preliminary Analysis

For this study and analysis, the Metauro and Cesano river basins have been identified, and the floodplain areas have been defined to delimit flood risk zones (Figure 2). The Marche Region had previously conducted a survey campaign between 2001 and 2002, and, as stated in the Introduction, an update of the territorial knowledge framework is now necessary. In the past, surveys were based on the use of total stations and referred to the national trigonometric network. However, after approximately 25 years, technological advancements in the field of geomatics now allow for the acquisition of a significantly larger amount of data in much shorter timeframes. Thanks to the use of Airborne LiDAR technologies, it is possible to obtain a detailed and comprehensive representation of the surveyed area, enhancing the accuracy of territorial analyses.

Figure 2. Map of Metauro (blue) and Cesano (red) river basins and their floodplain areas.

3.2 Survey

3.2.1. Data Acquisition – Airborne survey. The survey employed a combination of Airborne LiDAR technology and ground-based GNSS techniques, ensuring the highest levels of accuracy and consistency. First, the surveys covered a total area of 175 kmq within Metauro basin and 33 kmq within Cesano basin using a RIEGL VQ780ii LiDAR sensor (Table 1) mounted on a P68 Observer2 aircraft. This sensor has been chosen for its high-frequency pulse capability and ability to capture multi-echo returns, essential for distinguishing between terrain, vegetation, and built structures.
Additionally, to complement the Airborne LiDAR sensor, the onboard instruments used during the aerial surveys included: an Applanix AP60+ inertial system paired with the LiDAR sensor; a 16-channel GPS system (L1/L2/L2C GLONASS L1/L2) with a reception frequency of 5 Hz; and a PhaseOne iXM 100MP medium-format digital photogrammetric camera, configured with settings to ensure an orthophoto GSD of 5 cm.
Table 2 presents the Airborne LiDAR survey activities carried out on the two river basins. Additional flight missions have been conducted to compensate for cloud cover. Using the MTA (Multiple Time Around) technology developed by RIEGL, the system allows for the planning of flight strips (Figure 3) over terrain with altitude variations. The missions have been carried out once the necessary permits (ENAC regulations)[3] for the survey activities have been obtained and only under favourable weather conditions, to avoid issues of reflection between the LiDAR and any suspended water particles. Flight planning ensured optimal overlap between scan lines, achieving a minimum point density of 19 points/m², which increased to 23 points/m² after overlapping.

[3]https://www.enac.gov.it/la-normativa/normativa-enac

https://doi.org/10.5194/isprs-archives-XLVIII-G-2025-1035-2025 |

Range Measurement Performance	
Laser Pulse Repetition Rate	2000 kHz
Max. Measuring Range - natural target ρ ≥ 20% - natural target ρ ≥ 60%	 1500 m 2450 m
Min. Measuring Range	100 m
Number of Laser Pulse	4
Accuracy	20 mm
Precision	20 mm
Laser Wavelength	near infrared
Laser Beam Divergence	≤ 0.18 mrad @ 1/e
Laser Class	3B (acc. to IEC60825-1:2014)
Scanner Performance	
Scanning Mechanism	rotating polygon mirror
Scan Pattern	parallel scan lines
Scan Angle Range	± 30°-60°
Total Scan Rate	300 lines/sec
Angle Resolution	0.001°

Table 1. Technical specs of RIEGL VQ780ii LiDAR sensor

River basin	Days	Scan lines	Altitude
Metauro	7	171	2139 ft (652 m) AGL
Cesano	2	52	1680 ft (512 m) AGL

Table 2. Flight mission data

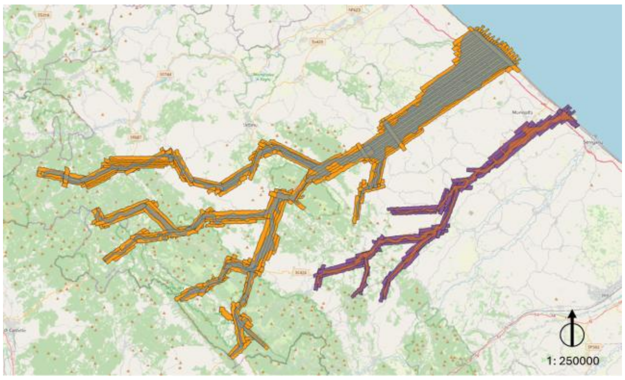


Figure 3. Map of the flight scan lines performed on the two areas covered by the river basins.

After the system installation, a calibration procedure has been carried out to determine the geometric acquisition properties of the Airborne LiDAR, specifically the boresight angles (Roll, Pitch, Heading) between the IMU and the scanner. Since these parameters may vary over time, corrections are necessary to prevent errors in the final data. The calibration flight has been conducted over a test area with 4 crossed flight strips in both flight directions. The report showed minimal deviations (2–3 cm RMS) and optimal graph trends, confirming the successful calibration. Following the aerial survey, trajectory calculation has been performed using POSPac[4] software (Applanix), utilizing permanent GPS ground stations from the global correction service. The compensation has been carried out using either single-base or multi-base methods, depending on the coverage flown for each mission and the location of the bases.
During the pre-processing phase, both a relative adjustment between the scan lines, to reduce any misalignments between adjacent and intersecting scan lines, and an absolute adjustment have been performed to verify and, if necessary, correct any planimetric and altimetric errors.

[4]https://applanix.trimble.com/en/software/applanix-pospac-uav

3.2.2. Data Acquisition – Ground-based survey. GNSS-RTK systems have been employed for ground surveys: 22 natural river cross-sections (only in Metauro river basin) and 44 GCP (in total in both river basins) to georeference the data (orthophotos).
The cross sections consist of two reference points, positioned at the section's extremities, and intermediate points surveyed along the same line. For each section, two iron stakes were placed at the ends, with a taut wire stretched between them to indicate the direction to follow. Subsequently, the intermediate points were acquired. The surveys conducted ensure centimetric accuracy.

3.2.3. Data Processing. Airborne LiDAR data processing has been carried out using the RiWorld software application, which generates a georeferenced point cloud based on selected echoes and the compensated sensor trajectory. All calculations have been performed in a geocentric system and then converted to the geodetic system EPSG:7792 - RDN2008 / UTM zone 33N.
The first quality control process involves examining the quality of overlaps between parallel scan lines, as well as overlaps of cross scan lines, to ensure overall homogeneity. A global trajectory compensation was performed, which allowed, through statistical and point-by-point analysis tools, to reduce the observed discrepancies between strips.
Once the geometric quality of the data has been verified, filtering and classification of the raw point cloud have been carried out. The raw data obtained directly as the final product of pre-processing contains all spatial, temporal, intensity, and echo information not directly usable to produce DTM and DSM. A subsequent step, called post-processing, has been necessary, in which the laser measurement set data have been classified to divide them into classes of belonging:
- First pulse (return echoes from elements such as vegetation);
- Only (return echoes on uniquely determined surfaces);
- Intermediate (return echoes typical of vegetated areas);
- Last pulse (return echoes typically under vegetation).

For the successful creation of products from Airborne LiDAR data, points designated as outliers have been removed from the classification. These are points with macroscopically incorrect elevations due to false returns measured by the sensor or other interfering elements (e.g., birds). Point clouds have been thus processed using TerraScan[5] (Terrasolid suite), enabling efficient classification in LAS file into "ground" (last pulse) and "overground" (first, only and intermediate pulses) categories. Automated workflow, as supervised classifications, with CANUPO plug-in[6] (CloudCompare software) (Mammoliti et al., 2022) ensured the correct removal of vegetation (Table 3).
For the DTM, only points previously classified as "ground" and corrected during the editing phase have been used.
The DSM First and Last models have been obtained using first echoes and only echoes for the First models, and intermediate echoes and last echoes for the Last models, respectively.
The DTMs and DSMs have been created with a grid mesh with a single step of 1 m x 1m.
For easy data management and organization, portions of all models created have been saved in ASCII format with a 1km x 1km grid, corresponding to an elementary unit defined as a tile (Figures 4 and 5).
Colorized point clouds, enriched with high-resolution RGB orthophotos, provided an enhanced visualization of land use. Additionally, intensity maps have been utilized to characterize material properties, aiding in the identification of surface types and potential flood-prone areas.

[5]https://terrasolid.com/products/terrascan/
[6]https://www.cloudcompare.org/doc/wiki/index.php/CANUPO_(plugin)

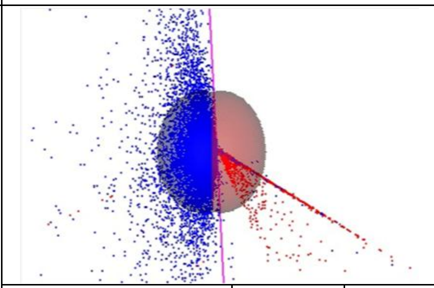
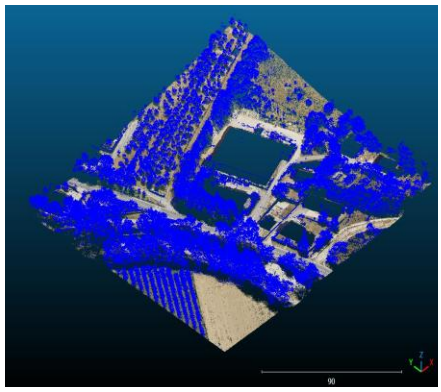
<table>
<tr><th>Dataset</th><th colspan="3">Statistics</th><th>Result</th></tr>
<tr><td rowspan="5"></td><td colspan="3"></td><td rowspan="7"></td></tr>
<tr><td>Class</td><td>vegetation</td><td>built</td></tr>
<tr><td>Total (points)</td><td>20000</td><td>20000</td></tr>
<tr><td>Truly classified (points)</td><td>18990</td><td>19524</td></tr>
<tr><td>Falsely classified (points)</td><td>1010</td><td>476</td></tr>
<tr><td>vegetation</td><td>Balanced Accuracy</td><td colspan="2">0,9641 (96%)</td></tr>
<tr><td>built</td><td>Fisher Discriminant Ratio</td><td colspan="2">0.2607</td></tr>
<tr><td></td><td colspan="3"></td><td>vegetation</td></tr>
</table>

Table 3. Procedure for vegetation removal using the CANUPO plugin (CloudCompare).

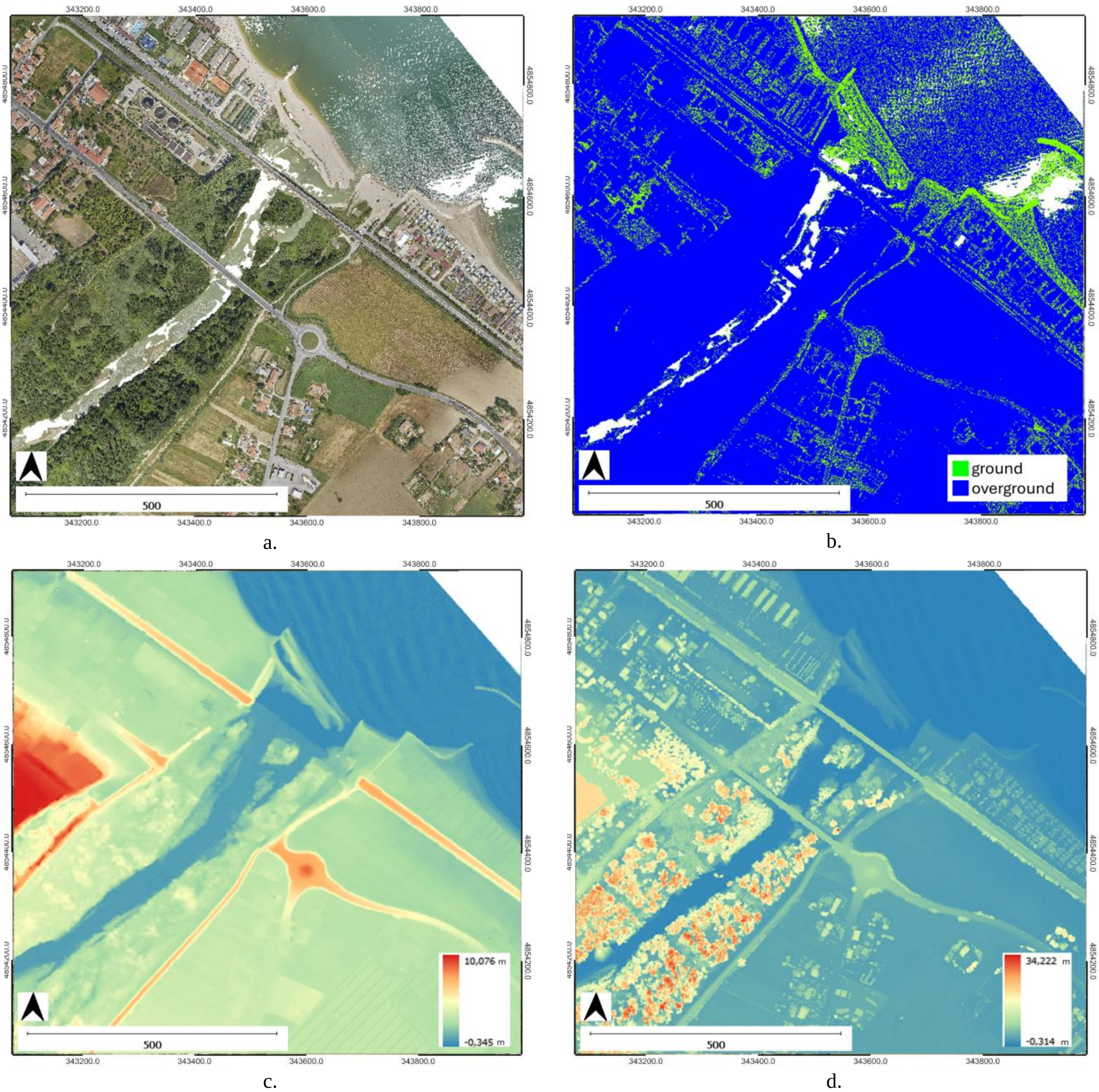


Figure 4. Example of same tile of the products of the acquisition and processing phases. a. Airborne LiDAR point cloud in RGB scale; b. classified Airborne LiDAR point cloud; c. DTM; and d. DSM Last pulse.

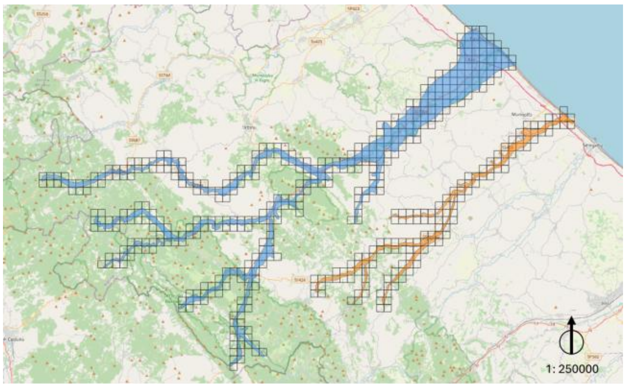


Figure 5. Map of the tiles over the two river basins.

4. Results

4.1 Floodplain modeling

The floodplain modeling has been conducted using the Hydrologic Engineering Center – River Analysis System (HEC-RAS), a widely utilized tool developed by the U.S. Army Corps of Engineers for simulating and analyzing water flow in natural and constructed channels (Hydrologic Engineering Center, 2021). This software provides essential capabilities for floodplain management, dam safety analysis, and river engineering.

In this study, hydraulic modeling has been preceded by hydrological modeling of the examined basins using the Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS), which simulates the complete hydrologic processes of watersheds. The hydraulic model has been developed based on reference hydrological data processed for the basins and ground data acquired by means of Airborne LiDAR surveys. Specifically, DTMs and DSMs have been utilized to extract natural river cross-sections for integration into HEC-RAS, as well as to derive the geometries of hydraulic structures interfering with surface flow, including bridges, weirs, and crossings. Additionally, DTMs have been employed to delineate 2D flood-prone areas.

To assess flood hazard, three flood scenarios have been simulated in accordance with EU-regulatory policies, corresponding to return periods of 50, 200, and 500 years (Figure 6). Although still in a preliminary phase, the hydraulic model has been structured by subdividing the entire basin into multiple sub-basins, each simulated with a distinct hydraulic model incorporating specific hydrological input data.

This approach ensured both computational efficiency and the adoption of a precautionary scenario in terms of hydraulic hazard assessment for each analyzed basin.

4.2 River cross-sections analysis

For the purposes of the AUBAC project, 22 cross-sections of watercourses (Metauro river and its tributaries) have been selected to operate cross-check validation. The activity carried out provided geometric information on the morphology of riverbeds through the survey of cross-sections using the GNSS-RTK sensor. Finally, the processed data have been cataloged in appropriate monographs (Figure 7).

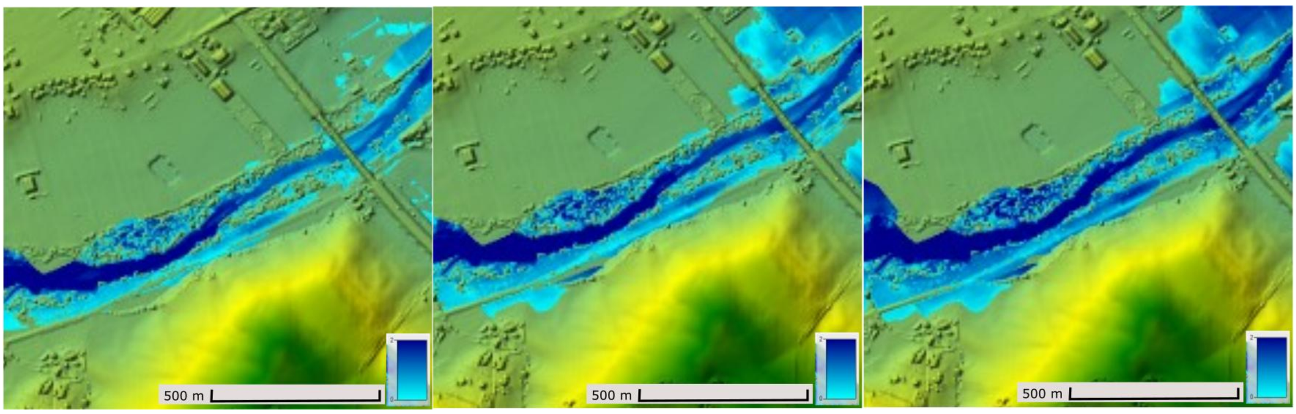
As part of the AUBAC project, 20 hydraulic infrastructures considered at risk have been identified in the Metauro river basin. These include 17 bridges (both road and railway), one weir, one dam, and one check dam. The objective has been to evaluate the evolution of river morphology and the impact of these structures on the watercourse (Figure 8).

To carry out this assessment, a detailed comparison has been conducted between historical data from 2001-2002 and more recent data obtained through Airborne LiDAR survey in 2024. This approach allowed for the analysis of changes that occurred over a span of more than two decades.

The historical data, provided in DWG format, included planimetric and altimetric profiles of various sections, based on the Gauss-Boaga reference system (EPSG 3004) with geoidal heights. In contrast, the 2024 data, in LAS format, uses the more recent RDN 2008 reference system (EPSG 7792), also with geoidal heights. This comparative study not only offers a detailed view of the riverbed's evolution over time but also provides crucial information for hydrogeological risk management and planning of future interventions in the Metauro river basin. Altimetric profiles of natural river cross-sections revealed geomorphological changes, including sediment deposit and erosion, while mapping key hydraulic structures such as bridges and embankments supported assessments of structural integrity under hydrogeological stress.

4.3 Orthophotos

Enhanced land-use visualization has been achieved through colorized point clouds combined with high-resolution RGB orthophotos, allowing for a more detailed analysis of terrain characteristics and infrastructure (Figure 9). To ensure high geospatial accuracy, GCPs served as reference points for georeferencing the orthophotos, reducing positional errors and improving the alignment of the dataset with real-world coordinates.



a. b. c.

Figure 6. Example of 2D flooded area maps obtained by the HEC-RAS simulation corresponding to return periods of a. 50, b. 200, and c. 500 years.

Section name	**07-232M**	
Reference points	07-232M_A	07-232M_B
WGS84 – UTM 33N (ellipsoidal height)	N 4838525.541 E 310287.744 q 198.613	N 4838498.880 E 310301.964 q 191.013

General Overview

Cross-river section

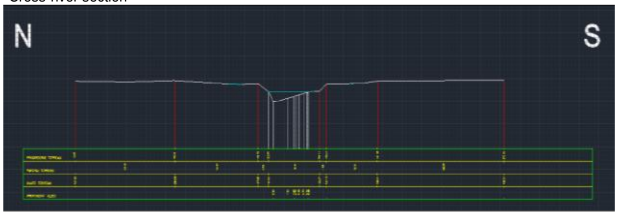
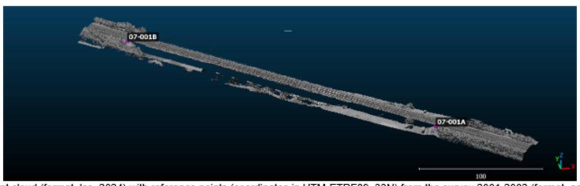


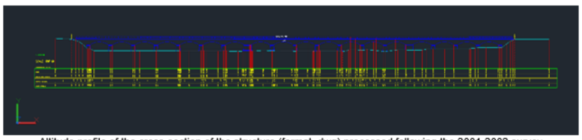
Figure 7. An example of monograph of a cross section of Metauro river.

bridge	OPT-1760	07-001M

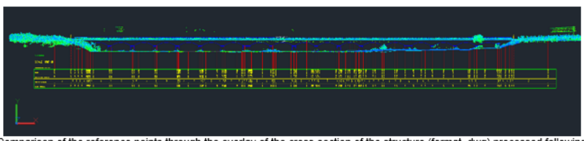
Reference points	07-001M_A	07-001M_B
Gauss-Boaga - EPSG 3004 (previous survey 2001-2002)	N 4854572.730 E 2363683.471 q 7.37	N 4854738.545 E 2363464.527 q 7.36
UTM-ETRF89_33N (conversion with ConveRgo software)	X 343676.289 Y 4854555.972 q 7.37	X 343457.361 Y 4854721.785 q 7.36
dz variation [m]	+ 0.005	- 0.010



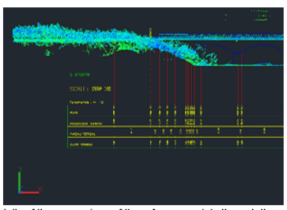
Point cloud (format .las, 2024) with reference points (coordinates in UTM-ETRF89_33N) from the survey 2001-2002 (format .ascii)

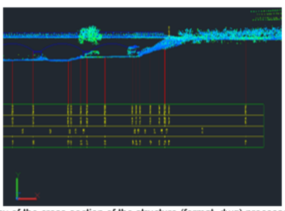


Altitude profile of the cross-section of the structure (format .dwg) processed following the 2001-2002 survey



Comparison of the reference points through the overlay of the cross-section of the structure (format .dwg) processed following the 2001-2002 survey with the section extracted from the point cloud of the 2024 survey (format .rcp)





Details of the comparison of the reference points through the overlay of the cross-section of the structure (format .dwg) processed following the 2001-2002 survey with the section extracted from the point cloud of the 2024 survey (format .rcp)

Figure 8. An example of monograph of a hydraulic infrastructure located in the riverbed of Metauro river.

Figure 9. Extract of orthophoto on Metauro river basin

Furthermore, an output control report has been generated to evaluate the vertical accuracy, specifically analysing the dz variations between the processed dataset and the reference points (Tables 4 and 5). This validation step was crucial in assessing elevation discrepancies and ensuring the reliability of the data for flood modeling, risk assessment, and mitigation planning.

No. GCPs	30
Average dz [m]	-0.010
Minimum dz [m]	-0.065
Maximum dz [m]	+0.059
Average magnitude [m]	0.028
RMS [m]	0.035
Std deviation [m]	0.035

Table 4. Output control report of the orthophoto georeferencing on Metauro river**.**

No. GCPs	14
Average dz [m]	+0.017
Minimum dz [m]	-0.117
Maximum dz [m]	+0.103
Average magnitude [m]	0.045
RMS [m]	0.055
Std deviation [m]	0.055

Table. 5. Output control report of the orthophoto georeferencing on Cesano river.

5. Discussion

The methodologies employed in this survey demonstrate the utility of integrating LiDAR technology with traditional surveying techniques for large-scale hydrogeological studies.
Although LiDAR technology has long been established in environmental monitoring, particularly for river systems, recent technological advancements have significantly enhanced its efficiency and applicability. These improvements allow for faster and more extensive monitoring and territorial updates, especially in natural areas requiring constant analysis to mitigate risks associated with extreme events such as floods, landslides, and erosion.

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The evolution of LiDAR systems has been multifaceted, encompassing improvements in sensor technology, data capture rates, and resolution. Modern LiDAR sensors can now capture millions of points per second, providing unprecedented detail in topographic mapping. This high-density data acquisition is particularly valuable in complex terrains and urban environments where subtle changes in elevation can have significant impacts on flood modeling and risk assessment.

In this context, LiDAR represents a cutting-edge solution, keeping pace with modern demands by integrating AI-driven algorithms for data acquisition and processing. Machine learning techniques are now being employed to automatically classify LiDAR point clouds, distinguishing between ground, vegetation, built environment with remarkable accuracy. This automation significantly reduces processing time and enhances the overall efficiency of data analysis.

The synergy between advanced LiDAR technology and sophisticated data processing techniques ensures high-precision results, making LiDAR an essential tool for advanced environmental risk assessment and management. Its ability to provide accurate, up-to-date, and detailed 3D representations of landscapes is invaluable for urban planning, disaster preparedness, and ecological conservation efforts.

As climate change continues to alter environmental dynamics, the role of LiDAR in monitoring and predicting these changes becomes even more critical. Its capacity to detect subtle changes in terrain over time makes it an indispensable tool for tracking hydrogeological change detection. More in general, to obtain accurate results in modeling, updated DTM and DSM are required for flood-prone areas, properly filtered to remove vegetation. Additionally, ground-based cross-sections are essential for accurately simulating flow dynamics within the river channel. However, since the morphological conditions within the riverbeds can change after each significant flood event, regular monitoring is crucial to ensure the continued validity of the survey data within the modelled areas.

In this case the surveys generated high-resolution datasets with critical implications for hydraulic modeling and hydrogeological management. DTMs provided precise ground-level features, including riverbanks and floodplains, while DSMs offered detailed surface-level data, capturing vegetation, buildings, and other infrastructure.

A 1-meter resolution Digital Terrain Model (DTM) is a highly detailed dataset for hydrogeological flood risk analysis. This level of resolution captures fine-scale topographic variations, such as minor elevation changes, riverbanks, and floodplain features, which are crucial for accurate hydrodynamic modeling. The DTM generated from LiDAR data with a 1-meter resolution offers significantly higher precision compared to the 20-meter resolution DTM provided by the Marche Region[7]. This enhanced accuracy allows for capturing finer topographic details, crucial for local hydrology, and more accurately representing areas of hydrogeological interest such as riverbanks, flood zones, and landslide-prone slopes. The 1-meter resolution greatly improves hydraulic modeling, especially in complex urban and river contexts, enabling more accurate predictions of flow paths and potentially floodable areas. Furthermore, it facilitates the identification of artificial structures, allows for more precise volume calculations, and integrates better with other high-resolution geospatial data. This level of detail is essential for in-depth hydrogeological analysis, detailed urban planning, and more effective management of hydrogeological risk at the local scale.

[7] https://datitest.regione.marche.it/it/dataset/dtm-della-regione-marche

Long-term monitoring is bolstered by integrating historical and contemporary data, providing insights into climate change impacts and sediment transport dynamics. Infrastructure maintenance and ecological restoration, such as reforestation and habitat reconstruction, benefit from the spatial precision of the data. Finally, the datasets empower regional planning and policymaking, offering tools to prioritize investments, enforce zoning, and implement sustainable development strategies, addressing current and future hydrogeological challenges effectively.

6. Conclusion

This study highlights the effectiveness of LiDAR-driven topographic surveys for hydrogeological monitoring and risk assessment in river basins. By integrating airborne LiDAR with ground-based GNSS techniques, we generated high-resolution DTMs and DSMs, enabling precise floodplain mapping and structural assessments. The results demonstrate the critical role of LiDAR in detecting geomorphological changes, supporting flood modeling, and enhancing regional planning. The integration of AI-driven data processing further optimizes accuracy and efficiency, making LiDAR a key tool for sustainable water resource management. Future research should focus on expanding survey coverage, incorporating real-time flood forecasting, and leveraging machine learning for automated data processing to enhance hydrogeological risk mitigation.

Future work should explore:

1. Expanding the survey coverage to other river basins, particularly those with high hydrogeological risk, to establish a more comprehensive dataset for regional and national flood management strategies. This would enable comparative studies across diverse hydrological contexts, improving predictive models and adaptive planning.
2. Utilizing the datasets for real-time flood forecasting systems by integrating LiDAR-derived terrain models with meteorological and hydrogeological data streams. This would enhance early warning capabilities, providing more accurate flood predictions and supporting proactive disaster response measures. The combination of high-resolution topographic data with real-time hydrological monitoring would significantly improve flood risk assessment and emergency planning.
3. Investigating the potential for machine learning techniques to automate data classification and enhance processing workflows. AI-driven algorithms could refine the differentiation between terrain, vegetation, and built structures, reducing manual processing time and improving the precision of digital elevation models. Additionally, deep learning models could be trained to detect and predict morphological changes in river basins, further strengthening long-term monitoring capabilities.

Furthermore, the integration of LiDAR with other remote sensing technologies, such as multispectral and hyperspectral imaging, is opening new avenues for comprehensive environmental assessment. This fusion of data sources allows for a more holistic understanding of ecosystem dynamics, land use changes, and their potential impacts on hydrogeological systems. By combining LiDAR's precise elevation data with spectral information from other sensors, researchers can better assess vegetation health, soil moisture levels, and sediment transport processes. This multi-sensor approach can enhance the detection of early signs of environmental degradation, contributing to more effective conservation efforts and sustainable water resource management.

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