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Geomatics-enabled Interdisciplinary Approach Based on Geospatial Data Processing for Hydrogeological Risk-analysis

Abstract: Hydrogeological risks that are associated with rivers have emerged as a significant concern worldwide, impacting both natural ecosystems and human settlements. This contribution presents an interdisciplinary project that leverages many technologies for data-acquisition and modeling to comprehensively analyze and manage risks in riverine environments. The project integrates geomatics, geological, and hydrological techniques to provide a holistic understanding of river dynamics and their associated hazards. As a central component of this project, geomatics plays a pivotal role in instrumental field surveying through the deployment of photogrammetry and LiDAR instruments. Remote-sensing data from satellite imagery further enriches the project's temporal analysis capabilities. By analyzing this data over time, researchers can monitor changes in river patterns, land use, and climate-related variables; this helps identify trends and potential triggers for hydrological events. To manage and integrate the vast amount of geospatial information that is generated, a geodatabase within a geographic information system (GIS) has been established. It enables efficient data storage, retrieval, and analysis, fostering collaboration among multidisciplinary researcher teams. This system offers tools for risk-assessment, modeling, and scenario planning; these allow for proactive measures for mitigating hydrological risks.

Keywords: geomatics, remote sensing, geoinformation, geodatabase, hydrogeological risk

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1. Introduction

Hydrogeological risks are among the most serious threats to human lives, properties, and ecosystems in many regions of the world. Floods, landslides, erosion, and sedimentation are some of the common hazards that result from the interaction between water and land [1]. Rivers are particularly prone to hydrogeological risks – especially in areas with high rainfall, steep slopes, or rapid urbanization [2]. Therefore, there is a need for effective methods to analyze and manage these risks in riverine environments.

According to the report on flood hazard conditions in Italy and the associated risk indicators that were published by ISPRA in 2021 [3, 4], Italy is exposed to various types of hydrogeological risks, such as floods, landslides, and coastal erosion (Fig. 1).

These risks are influenced by several factors, such as climate change, land use, geomorphology, and human activities. The report also presents those risk indicators that are related to the different elements at risk, such as populations, families, buildings, industries and services, and cultural heritage. One of the regions that is particularly vulnerable to flood risk is Marche, which is located in central-eastern Italy along the Adriatic coast. The flood risk in Marche was dramatically demonstrated by the catastrophic event that occurred on September 16, 2022, when torrential rain caused flash floods that swept through several towns in the provinces of Ancona and Pesaro-Urbino.

However, hydrogeological risk-analysis and -management is a complex and challenging task that requires a multidisciplinary approach. It involves the understanding of various physical processes that govern a river's dynamics, such as hydrology, geomorphology, geology, and geomatics. It also requires the collection and integration of large amounts of spatial and temporal data from different sources and scales.

To address these challenges, this paper presents an interdisciplinary project that leverages many technologies for data-acquisition and modeling to comprehensively analyze and manage hydrogeological risks in riverine environments. The project integrates geomatics, geological, and hydrological techniques to provide a holistic understanding of river dynamics and their associated hazards. As a central component of this project, geomatics plays a pivotal role in instrumental field surveying through the deployment of photogrammetry and LiDAR instruments. These are technologies that facilitate the precise collection of elevation data, river morphologies, and terrain characteristics. Such data is crucial for understanding a river's behavior and identifying any potential risk factors. Remote-sensing data from satellite imagery further enriches the project's temporal-analysis capabilities. By analyzing this data over time, researchers can monitor changes in river patterns, land use, and climate-related variables, helping to identify trends and potential triggers for hydrological events.

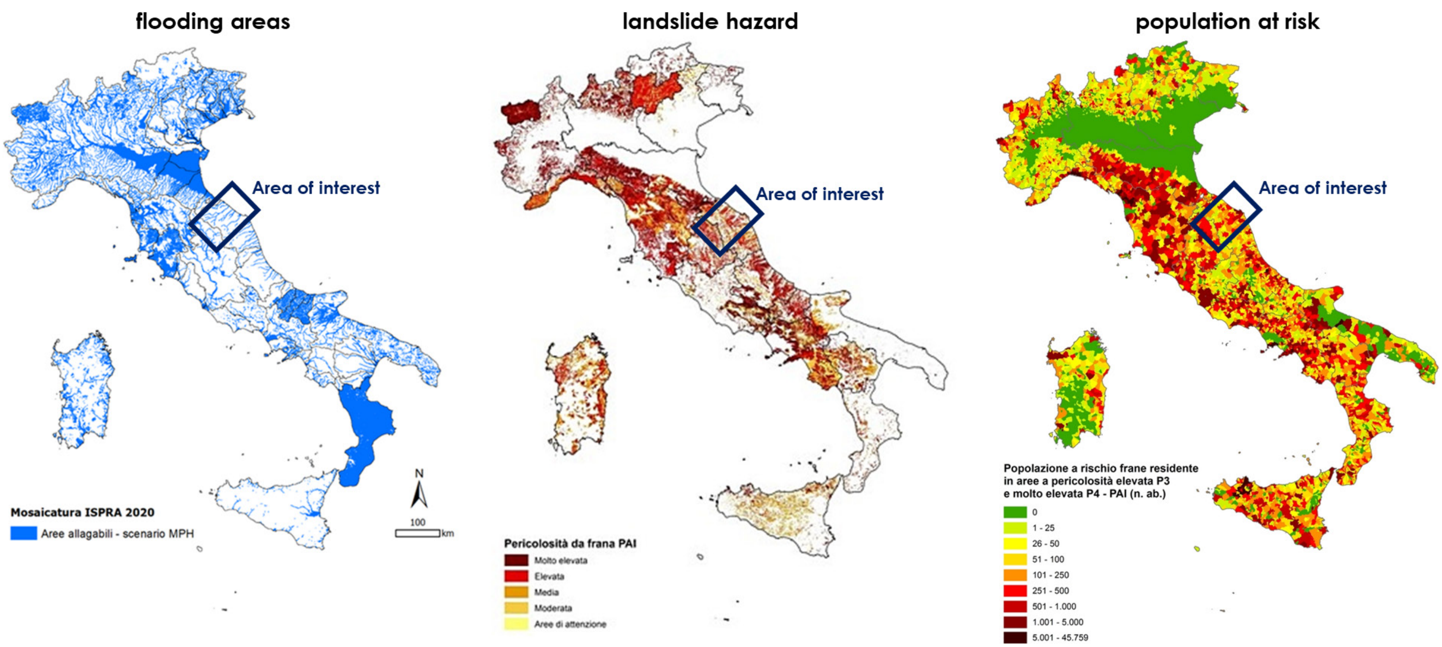

Fig. 1. Hydrogeological risks in Italy; blue box indicates area of interest under analysis for research activity

Source: according to [3, 4]

To manage and integrate the vast amount of geospatial information that is generated, a geodatabase within a geographic information system (GIS) has been established. This geodatabase acts as a central repository for all of the data that is acquired through geomatics and remote-sensing surveys. It enables efficient data storage, retrieval, and analysis, fostering collaboration among multidisciplinary researcher teams.

The paper is organized as follows: Section 2 provides the state-of-the-art of the literature regarding the research activities that are linked to geospatial data processing for hydrogeological risk-analysis; Section 3 describes the methods and technologies of geomatics that were used for the data-acquisition and modeling; Section 4 discusses the results of the risk-analysis and -management; and Section 5 concludes with some recommendations for future research.

2. State of the Art

Over the past decade (2012–2022), there has been a growing trend in the scientific literature that has been dedicated to the application of geomatics technologies for the analysis and management of hydrogeological risks (with a specific emphasis on riverine environments). This surge in scholarly attention reflects the recognition of the increasing complexities and vulnerabilities that are associated with water-related hazards, compelling researchers and practitioners to explore innovative approaches. Along with geomatics applications, incorporating such tools as geospatial technologies, remote sensing, and GIS have emerged as integral components in this paradigm shift.

Some recent hydrogeological literature has showcased the efficacy of geospatial techniques (including LiDAR and photogrammetry) in advancing the understanding and mitigation of hydrogeological risks; these are exemplified by studies that utilize high-resolution terrain data for the precise mapping and monitoring of subsurface processes. Costabile et al. [5] 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. [6] presented a case study on utilizing airborne LiDAR data to analyze flood disaster areas – specifically in the Sekarbela Subdistrict, Mataram. On the drone-mapping front, Saputra et al. [7] introduced a low-cost drone-mapping approach and participatory GIS for supporting urban flood modeling. Di Stefano et al. [8] provided a comprehensive literature review of mobile 3D scan LiDAR; its various fields of application include a wide-ranging look at laser-scanning technology that supports environmental monitoring and, in particular, landslides, flooding, and coastal erosion.

The use of remote sensing has proven to be useful for hydrogeological risk-assessment, as demonstrated by the numerous examples in the literature where satellite images have facilitated identification and monitoring. In the realm of remote-sensing applications, Ammirati et al. [9] utilized multispectral remote sensing for mapping flood-affected zones in the Brumadinho mining district, while Abdelkarim et al. [10] integrated remote sensing with hydrologic and hydraulic modeling to assess flood risk and mitigation in Al Lith (KSA). Zingaro et al. [11] explored new perspectives for earth surface remote detection in the hydro-geomorphological monitoring of rivers, while Samela et al. [12] employed satellite flood-detection by integrating hydrogeomorphic and spectral indexes. Tariq et al. [13] contributed to the field with a study on flash flood susceptibility assessment and zonation, integrating the analytic hierarchy process and frequency ratio model with diverse spatial data. Xue et al. [14] proposed flood monitoring through the integration of the flood indexes and probability distributions of water bodies. Phy et al. [15] provided a comprehensive review of flood-hazard and -management activities in Cambodia, identifying knowledge gaps and suggesting research directions. The use of spectral indexes on Sentinel-2 imagery has proven to be a powerful tool for detecting water features and monitoring land cover changes. NDWI (normalized difference water index) exploits the varying reflectance of water and other surfaces [16]. Negative NDVI (normalized difference vegetation index) values typically indicate the presence of water, while values close to zero are associated with bare soil, and positive values often represent vegetation [17, 18].

The implementation of GIS and a geodatabase system has significantly improved data-management capabilities, as demonstrated by those examples in the literature that have illustrated the storage, retrieval, and analysis of geospatial information for informed decision-making in risk-assessment and -mitigation strategies. Morelli et al. [19] examined the Arno River in Firenze, Italy, emphasizing the role of urban planning and geodatabases in mitigating flood risk and underscoring the practical implications for public policy. Giardino et al. [20] highlighted the proactive use of GIS and geomatics in disaster management, showcasing their contribution to emergency relief efforts in response to natural hazards. Balabanova et al. [21] employed a geodatabase to analyze past floods, providing essential support for preliminary flood-risk assessments. Additionally, Tomar et al. [22] conducted a GIS-based urban flood risk-assessment study in Delhi National Capital Territory, India, demonstrating the versatility of geodatabases in providing comprehensive frameworks for assessing and managing hydrogeological risks in urban environments. GIS is instrumental in the designation of flood-risk mapping from remote-sensing data, seamlessly integrating and analyzing geospatial information to provide accurate and actionable insights for effective flood-risk management [23–25].

3. Materials and Methods

Geomatics is a multidisciplinary discipline that integrates various technologies and methods for the acquisition, processing, analysis, and visualization of spatial data. In this study, we applied geomatics techniques to assess and manage the hydrogeological risk on the Metauro River in the Marche region. For this reason, the Ministry of Ecological Transition (MITE, Italian Government) promoted the "Autorita' Di Bacino Distrettuale Appennino Centrale (ABDAC)" project, which involved the universities of Marche region. Divided into different working groups, the research activities fall within the regional "Hydrogeological risk reduction interventions" plan, which is aimed at improving the knowledge and prevention of hydrogeological hazards in the region. The authors were involved in the working package (WP2) regarding the topographical leveling and LiDAR survey to support hydraulic- and solid-transport modeling. In the following paragraphs, the contribution of geomatics techniques for hydrogeological risk-analysis is described (Fig. 2).

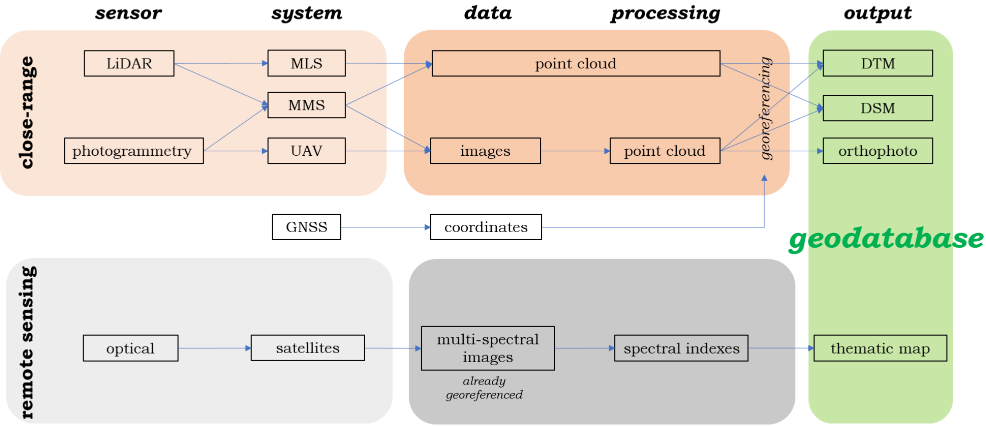

Fig. 2. Geomatics approach for hydrogeological risk-analysis

3.1. Close-range Surveys

To obtain high-resolution and accurate data of the river's morphology and dynamics, we employed two different data-acquisition technologies. The first one was based on RGB images from aerial photogrammetry, while the second one consisted of highly accurate 3D models that were obtained via mobile laser scanning (MLS) [8, 26, 27].

Aerial Photogrammetry

The RGB images from the UAV (unmanned aerial vehicle) were acquired using a DJI Mavic 3 Enterprise that was equipped with an RTK module that ensures centimeter-level accuracy when used with the Network RTK service (Table 1).

The GNSS RTK receiver was connected to the HxGN SmartNet permanent reference station network. The coordinates that were acquired by the drone's GNSS RTK were formatted in ETRF2000 (latitude, longitude, ellipsoidal height).

The flight missions were planned through the DJI PILOT 2 app. The primary flight altitude was set to 120 m above the ground, with a nadir image-acquisition axis, a ground sampling distance (GSD) of 3.09 cm/px, and a flight speed of 6 m/s. The lateral overlap was set to 80%, while the frontal overlap was set to 70% (with a 20-meter buffer at the edges).

Table 1. Technical specifications of DJI Mavic 3 Enterprise RTK

Maximum take-off weight	1050 g
Sizes	347.5 mm × 283.0 mm × 107.7 mm
Maximum flight speed	15 m/s (in absence of wind)
Sensor	4/3 CMOS, effective pixels: 20 MP

Source: DJI Mavic 3 https://www.dji.com/it/mavic-3/specs [access: 24.11.2023]

The images were processed in Agisoft Metashape Standard Edition software (Version 2.0.3) using the structure from motion (SfM) calculation method with the custom settings that are listed in Table 2.

Table 2. Agisoft Metashape settings used for image processing (example of stretch of river in exam)

Setting	Value
Photos	3294 images (4 flights)
Alignment photos	
Accuracy	Medium
Key point limit	40,000
Tie point limit	10,000
Optimize camera alignment	Fit all constants (f, cx, cy, k1–k4, p1–p2)
Point	5’430’987
Dense cloud	
Quality	Medium
Depth filtering	Aggressive
Point	196’657’193
Digital elevation model	
Coordinate system	WGS 84 / UTM Zone 33N (EPSG:32633)
Source data	Dense cloud
Interpolation	Enabled
Resolution	12.4 cm/px
Size	27,613 px × 25,622 px

Table 2. cont.

Setting	Value
Mesh	
Surface type	Height field
Orthomosaic	
Resolution	100 cm/px
Size	1992 px × 1573 px

The results of this workflow are shown in Figures 3 and 4.

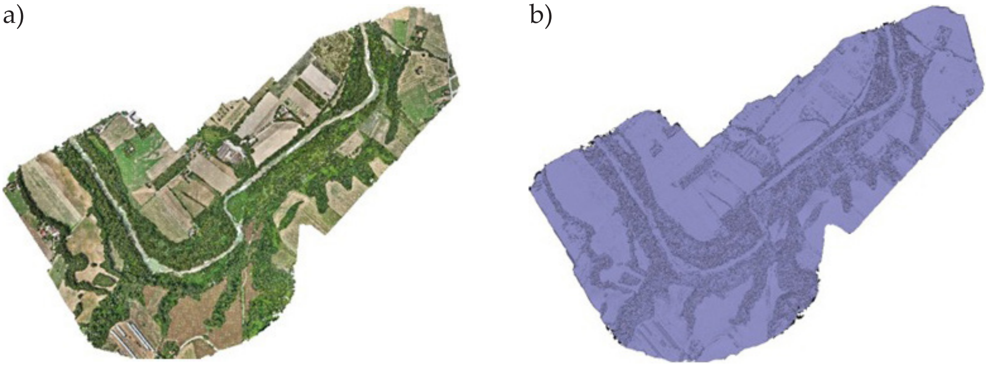

Fig. 3. Dense point cloud (a), and mesh (b)

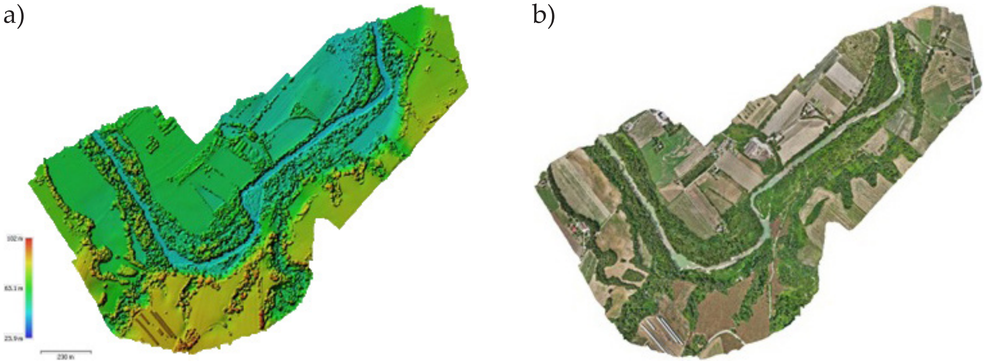

Fig. 4. DTM (a), and orthophoto (b)

Mobile Laser Scanning

MLS KAARTA Stencil 2-16 (Table 3) allowed us to scan the riverbanks or riverbed without water. A close-path trajectory in hand-held mode along the river resulted in a dense and homogeneous point cloud (Fig. 5).

Table 3. Technical specifications of MLS KAARTA Stencil 2-16

LiDAR	Velodyne VPL-16
Range	1 m [min] – 100 m [max]
FOV	360° × 30°
Accuracy	±30 mm
Speed	300,000 points/s
IMU	Internal MEMS-based IMU; Six DoF: X, Y, Z, Roll, Pitch, Yaw
Processor	Intel NUC 7i7 Quad Core
Feature tracker	640 px × 360 px resolution; black & white images
Weight	1730 g
Mounting platforms	hand-held; monopod; roadway vehicle, ATV, UAV

Source: KAARTA Stencil 2-16
https://www.kaarta.com/stencil-2-for-rapid-long-range-mobile-mapping-no-videos/ [access: 24.11.2023]

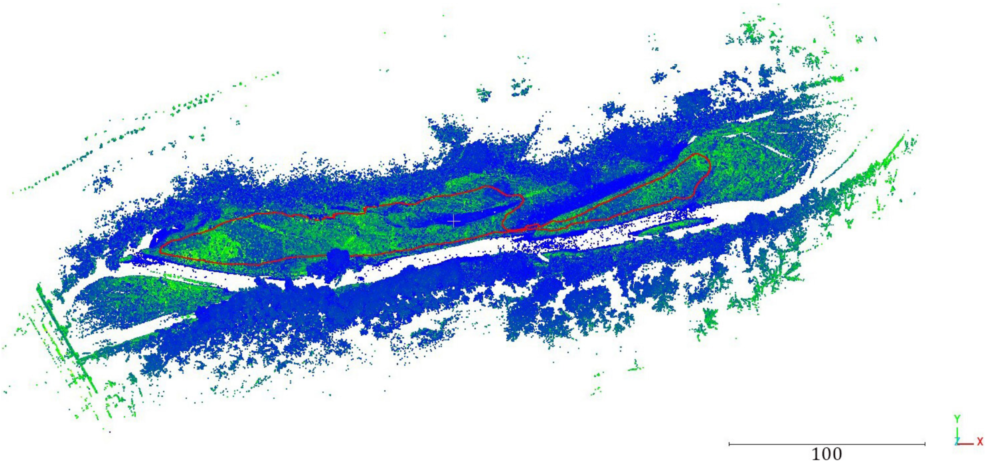

Fig. 5. Top view of point cloud acquired with MLS and trajectory (red line) made with it in hand-held mode

MLS creates highly detailed 3D representations (point clouds) of river environments, capturing the intricacies of river banks, bed morphologies, and surrounding vegetation. This cutting-edge device offers a fast and agile solution for capturing intricate details. In the realm of river environments, mobile laser scanners excel in rapidly mapping and monitoring topographical features. The ease of extracting specific river sections from the 3D point cloud that was obtained through the mobile laser scanner allowed for a graphic rendering of the river's cross-sectional profiles (Fig. 6).

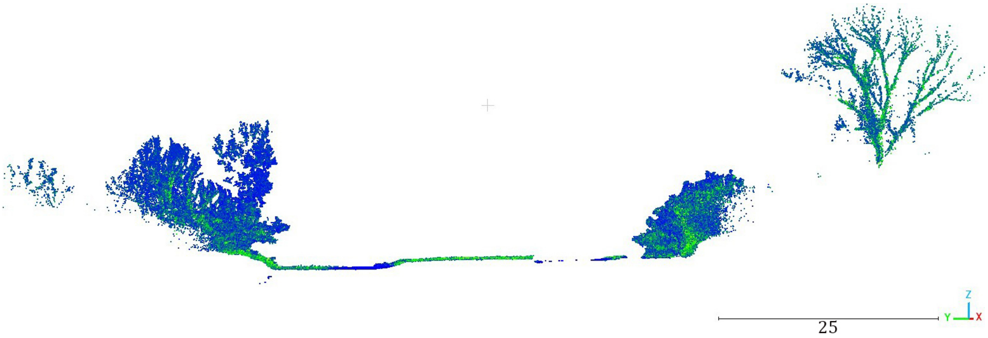

Fig. 6. Section of river extracted from LiDAR point cloud

Table 4 shows the salient specifications regarding the density, accuracy, and precision of the point cloud that was generated by Kaarta Stencil 2-16.

Table 4. Features of point cloud from MLS KAARTA STENCIL 2-16

Number of points	61,633,397
Area of project	52,288.00 m^2
Time surveying	721 s
Trajectory length	655.4 m
Voxel size	0.2 m
Error of registration	0.05 m

3.2. Remote-sensing Data

Remote sensing can provide valuable information for hydrogeological analysis, e.g., land cover, soil moisture, vegetation, water quality, and flood extent. In this study, remote-sensing data was obtained from the Sentinel-2 optical sensor constellation, which consists of two satellites (Sentinel-2A, and Sentinel-2B) that orbit the Earth every 6 days and capture multi-spectral images that are composed of 12 bands with a spatial resolution that ranges 10–60 m. The images can be downloaded from the Copernicus platform, which provides free and open access to Sentinel data (Fig. 7). One image for each season for each year from 2015 through 2022 (covering both satellites) was selected.

Then, the images were cropped to fit the area of interest along the river under exam. Normalized Difference Vegetation Index (NDVI) (1) and Normalized Difference Water Index (NDWI) (2) were used as spectral indexes to detect the water features.

$$\mathrm{NDVI} = \frac{\mathrm{NIR(Band08)} - \mathrm{Red(Band04)}}{\mathrm{NIR(Band08)} + \mathrm{Red(Band04)}} \tag{1}$$

$$\mathrm{NDWI} = \frac{\mathrm{Green(Band03)} - \mathrm{NIR(Band08)}}{\mathrm{Green(Band03)} + \mathrm{NIR(Band08)}} \tag{2}$$

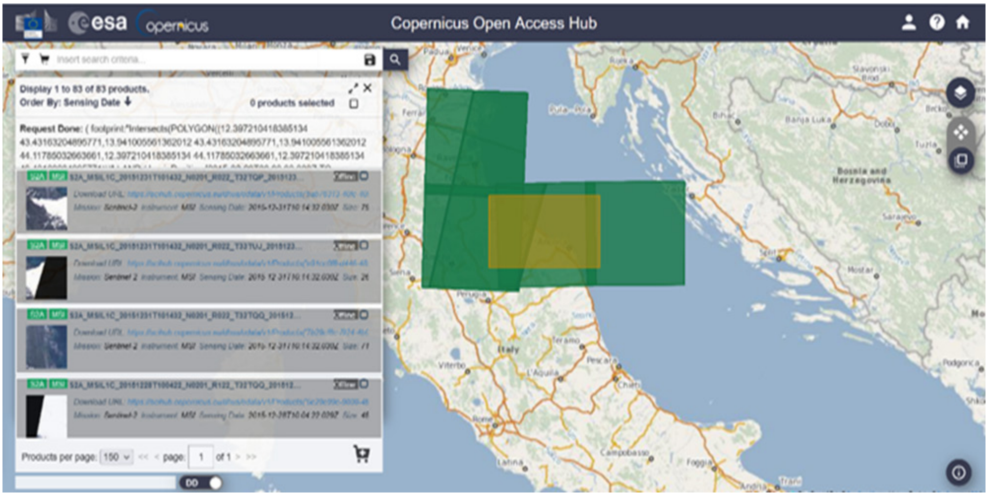

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Fig. 7. Copernicus platform for downloads of Sentinel-2 images

Bands 03, 04, and 08 have a spatial resolution of 10 m. The resulting NDVI values range from −1 to 1: higher values indicate greater amounts of healthy vegetation. The NDWI values range from −1 to 1: higher values indicate greater amounts of surface water. The temporal and spatial variations of these indexes were analyzed along the river (Figs. 8, 9) using GIS software.

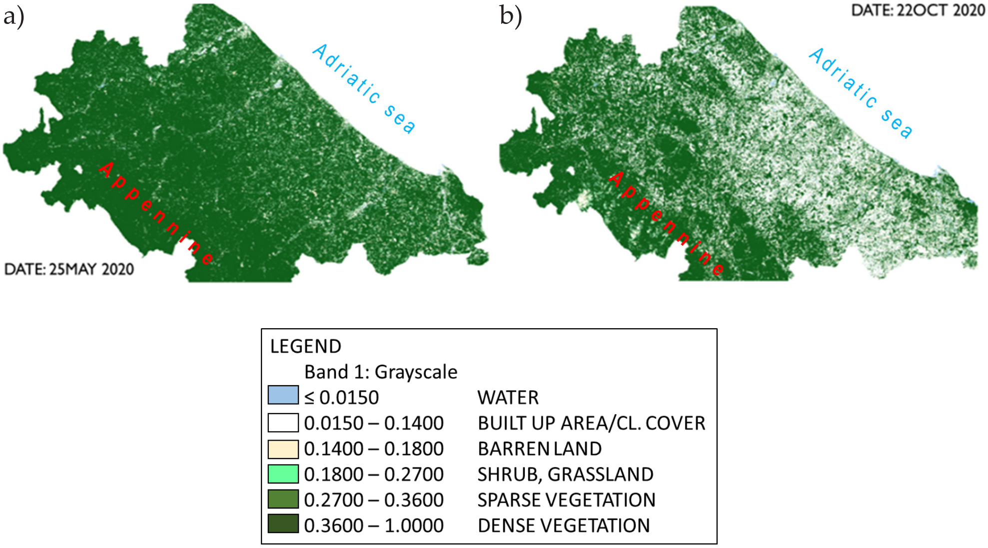


Fig. 8. NDVI analysis (2020): a) 25 May; b) 22 October

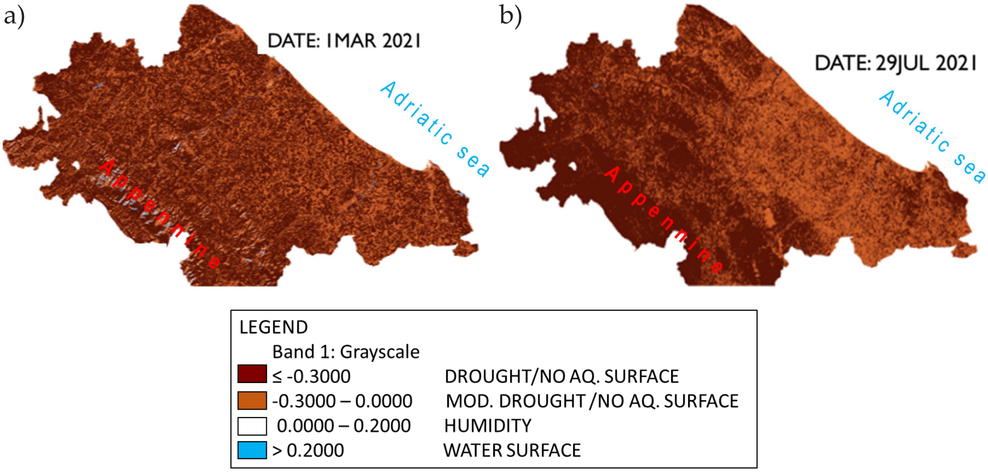
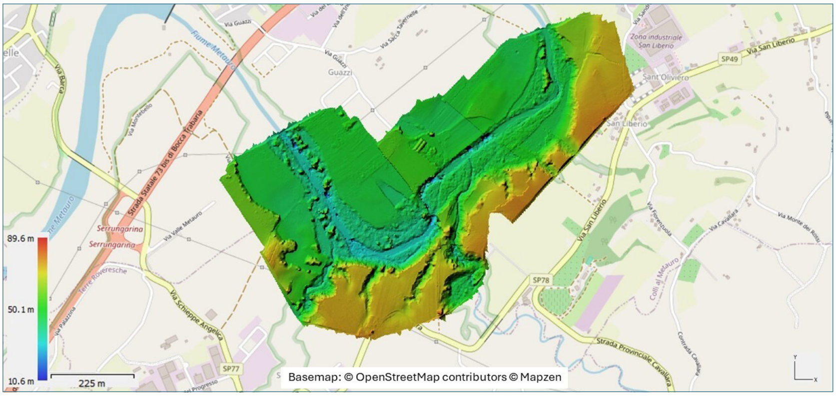


Fig. 9. NDWI analysis (2021): a) 1 March; b) 29 July

3.3. Geodatabase

In the development of a comprehensive geodatabase within GIS, a systematic approach was employed to collect the processed and modeled geospatial data got from the geomatics techniques [28–30]. QGIS 3.32 (Lima edition) was used as GIS software. The foundational layer of the river served as a reference element within the GIS framework. This layer was enriched by overlaying digital terrain models (DTM) (Fig. 10), digital surface models (DSM), and high-resolution orthophotos – all georeferenced and modeled through photogrammetry methodologies. It was also possible to integrate the cross-section drawings that were obtained by extracting the profiles of different sections of the river (as external files that were loaded into the attribute table). The integration of such detailed elevation and imagery data allowed for a comprehensive understanding of the terrain and its features.



Basemap: © OpenStreetMap contributors © Mapzen

Fig. 10. Geodatabase: DTM (1 m × 1 m) of area of river that was surveyed over map

Furthermore, the geodatabase was enhanced by incorporating the data that was derived from the remote-sensing technologies, including the NDVI and NDWI thematic maps as well as the Sentinel-2 satellite images with their footprints (Fig. 11); each served as an attribute layer that was intricately linked to the specific area of interest that was traversed by the river. This holistic approach to geodatabase creation ensured a robust foundation for a spatial analysis of the examined riverine environment.

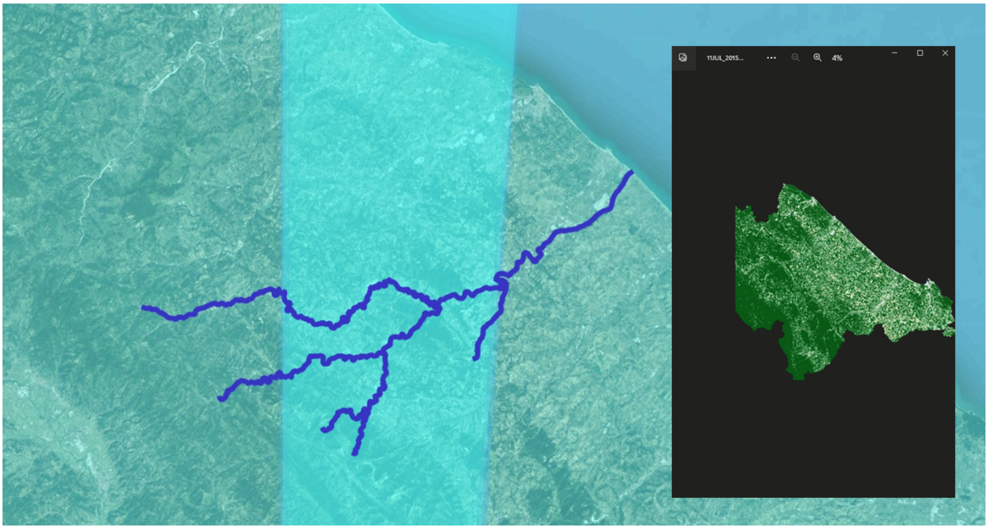


Fig. 11. Geodatabase. On the left, layer of Metauro River (blue) and footprints of Sentinel-2 images over area under examination. On the right, area indexed in NDVI attached in GIS

4. Discussion

The application of geomatics in hydrogeological risk-analysis specifically delves into the distinct attributes of close-range techniques (such as LiDAR and photogrammetry) and remote-sensing sensors. For close-range techniques, evaluating the data's accuracy becomes paramount, with considerations for the reliability of single surveys, the repeatability of the survey operations, and the ease of the data-processing operations. Although these techniques necessitate more time and costs for processing the software, they offer the advantage of conducting on-field surveys to capture temporal variations for local and punctual risk-analysis – particularly along riverbanks and buffer zones. On the other hand, remote-sensing sensors offer continuous and readily available data streams that are often obtainable at a low cost (or even free of charge). The data-processing for remote sensing involves complex operations but provides the benefit of large-scale geographical risk-analysis within a regional context. Additionally, a temporal analysis through time series and change-detection using spectral indexes allows for a comprehensive understanding of hydrogeological changes over time. To further enrich the temporal analysis of the hydrogeological risk, radar data (e.g., Sentinel-1) can be used; this can be merged with the optical data from the Sentinel-2 satellites. A noteworthy point is the potential synergy that can be achieved by integrating data from both close-range techniques and remote sensing in a GIS environment, thus providing a holistic approach to hydrogeological risk-assessment.

5. Conclusion

In conclusion, the comprehensive investigation into hydrogeological risk by focusing on understanding river dynamics and their associated hazards has been greatly enhanced through the integration of geomatics techniques. The utilization of laser scanning, photogrammetry, and remote sensing has proven to be instrumental in acquiring precise data for both geological and hydrological analyses. By leveraging these advanced technologies, a nuanced understanding of the complex interactions within river systems has been achieved, enabling the more accurate assessment of potential hazards. The creation of a geodatabase that consolidates data from diverse geomatics sensors serves as a pivotal step toward fostering an interdisciplinary approach. This not only facilitates accessibility and data-sharing but also ensures the seamless updating of information. The amalgamation of geomatics and the establishment of a geodatabase contribute significantly to advancing research in hydrogeological risk-analysis, offering a robust foundation for informed decision-making and sustainable management of river environments.

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CRediT Author Contribution

F. D. S.: conceptualization, methodology, software, investigation, resources, data curation, writing – original draft preparation, writing – review and editing.

S. C.: conceptualization, methodology, software, investigation, resources, data curation, writing – original draft preparation, writing – review and editing.

M. S.: conceptualization, methodology, software, investigation, resources, data curation, writing – original draft preparation, writing – review and editing.

R. P.: validation, formal analysis, investigation, writing – review and editing, visualization, supervision, project administration, funding acquisition.

E. S. M.: validation, formal analysis, investigation, writing – review and editing, visualization, supervision, project administration, funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Proprietary Data of the Ministry of Ecological Transition (MITE, Italian Government).

Use of Generative AI and AI-assisted Technologies

No generative AI or AI-assisted technologies were employed in the preparation of this manuscript.

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