

Combined Photogrammetric and Laser Scanning Survey to Support Fluvial Sediment Transport Analyses

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Abstract. This paper presents the contribution of digital surveying techniques for the estimation of fluvial sediment transport. The aim is to create predictive models able to minimize or reduce the hydrogeological hazard, especially before or during critical meteorological events. The case study is the Caldone stream, a watercourse located in the municipality of Lecco (Italy). Structure-from-Motion photogrammetry and terrestrial laser scanning techniques were used to collect metric data about the morphology of the riverbed. Data acquisition was carried out to create a digital model of visible and submerged parts of the riverbed. Then, a second area with a sedimentation pool was selected to monitor the variation of the depth induced by progressive accumulation of sediments. As the pool is constantly covered by water, a low-cost bathymetric drone was used coupling the measured depth values with total station measurements to track the drone. Finally, the paper describes the implementation of an on-line data delivery platform able to facilitate retrieval of heterogeneous geospatial data, which are used in the developed numerical model for sediment transport. This service aims at providing simplified access to specific map layers without requiring knowledge about data formats and reference systems.

Keywords: Geosciences · Hydrogeology · River monitoring · Remote sensing · Structure-from-Motion · Terrestrial laser scanning

1 Introduction

1.1 General Project Framework

The activities described in this paper have been carried out within "SMART-SED: Sustainable Management of sediment transpoRT in responSE to climate change conDitions", an interdisciplinary research project that involved different research groups from Politecnico di Milano, Italy (Applied Geology, Surveying, Geophysics, Hydraulic

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engineering, Mathematics, Hydrology) and the Municipality of Lecco, a city located in northern Italy. Fondazione Cariplo funded the project.

The main aim of SMART-SED project was to address severe issues and hazards related to critical events due to hydrogeological instability, which is a major concern for a large part of the Italian territory. Indeed, some of the most critical events are often localized in mountain or hilly areas, acting as an effective threat for local populations, economical activities, and the built environment.

The project objective is mainly related to the transportation of solid sediment by rivers and streams. During acute meteorological events, the overall amount of solid sediment moved by the water flow can reach critical limits: this phenomenon dramatically increases its effects in areas characterized by hydrogeological instability.

The additional challenges introduced by climate change require urgent answers and interventions. For instance, rainfalls bring higher quantities of water into the hydrogeological basins in short periods, resulting in increased hydraulic energy able to displace high volumes of sediments.

The SMART-SED project aims at creating a feasible tool for erosion prediction within a certain hydrogeological basin. The hydraulic processes of the watercourses are analyzed and compared with data belonging to regional and national databases. Here, the morphology of the involved riverbed is one of the main data sources to be included within the final mathematical model for predictions of future hazardous events.

Nowadays, different Geomatics instruments and techniques can be used to reconstruct the geometry of rivers and streams [7, 10, 27]. Global Navigation Satellite Systems (GNSS [4]), total stations (TS) [15, 16, 19], and terrestrial laser scanning (TLS) [17, 20, 25, 26, 28] measurements are common solutions able to create accurate geometric models. Remote sensing [29] is also one of the most common tools, especially in combination with echo sounding and photogrammetry [6, 11]. The application of photogrammetry was already proposed in early research work, such as [5]. Recently some effective solutions based on digital Structure-from-Motion/photogrammetry [31, 32] were presented [9, 24]. Data from UAVs [23] were used in [12]. Echo-sounding methods were also used by several authors [7, 10].

At a different scale, airborne bathymetric laser scanners [8, 13] and Light Detection and Ranging (LiDAR) technology were also tested [14, 18, 30]. An updated review of remote sensing methods applied to watercourse surveying is presented in [29].

1.2 The Local Framework of the Project

The case study of the project is the Caldone stream in Lecco (Fig. 1). Lecco is a town in northern Italy that directly fronts onto the Lario lake. It is included within the Prealpine area, close to the first relieves belonging to the Prealps mountain range. The presence of the lake, its main emissary (the Adda river), and many minor streams made the Caldone water body an ideal case study for the analysis required in the project.

The selected observation period lasted two years. Caldone is a watercourse that springs from different minor river channels mount and ends up into the Lario lake. It is one of the three main watercourses crossing the town of Lecco along with Gerenzone and Bione. The first portion of the riverbed is mostly located in a natural environment, while the last section flows closer to the urbanized area and passes through it.

Here, the stream was highly exploited during the industrialization phases of this area during the 19th–20th Centuries to provide water energy to several mills and industries that were built along its course. The original natural banks in this area were completely transformed and substituted by artificial barriers.

During the 60s and 70s of the 20th Century, the final part of the stream was completely covered. These interventions dramatically modified the stream. In the 19th century, the deviation of the water has been already proposed for urban development of the town, reducing the risk related to sediments. The covering has increased the issues related to critical meteorological events because the water is forced into an underground culvert; as a direct consequence, floods of the Caldone are not rare events.

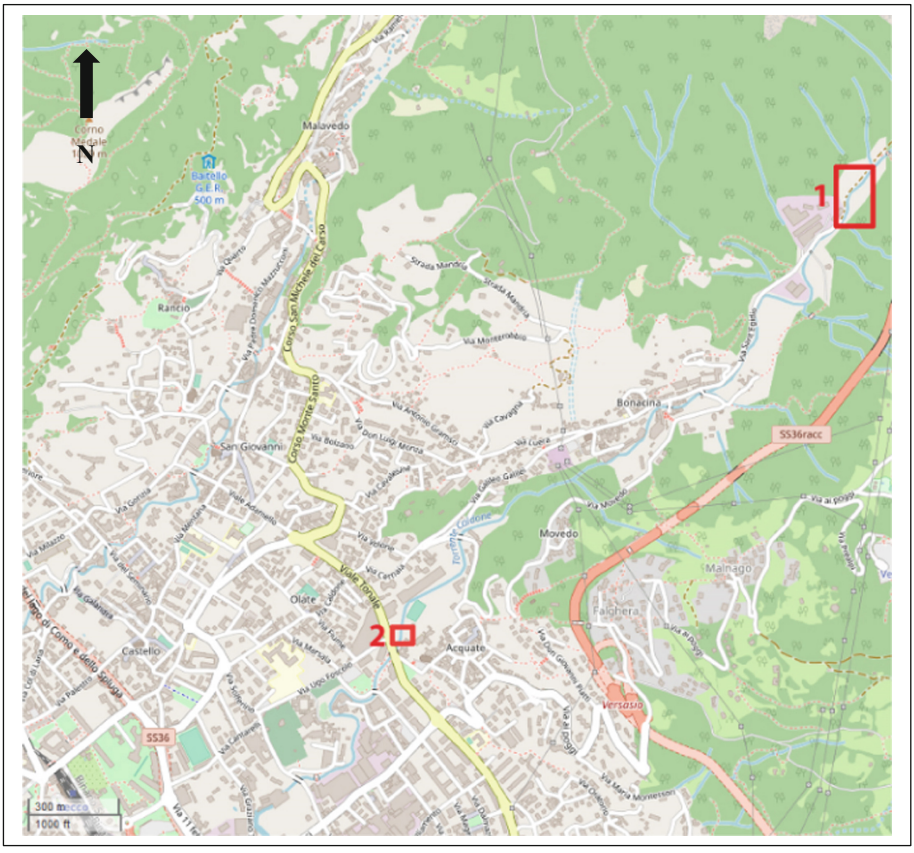


Fig. 1. Localization of selected areas 1 and 2 (red rectangles) of Caldone stream in the territory of the town of Lecco, Italy. (Color figure online)

2 Surveying Activity

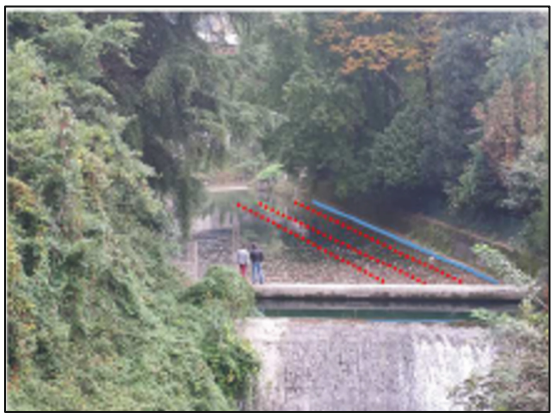
2.1 Overview

The surveying activity was focused on the data acquisition of two data sets along the Caldone stream riverbed within the administrative region of the Municipality of Lecco, Italy (see Fig. 1). These areas (see Fig. 2) feature different characteristics:

- Area 1 is close to the mountain and within a quasi-natural environment included in the Bonacina district; and
- Area 2 is close to downtown, where a sedimentation pool and a weir helps to control the water flow.



(a)



(b)

Fig. 2. Views of both selected areas reported in Fig. 1: Area 1 is located in a non-urbanized environment (a); Area 2 is a sedimentation pool (b).

The main goal of the investigation carried out in Area 1 was to record the morphology of the stream during a period of shallow water. The acquired data will be successively processed and imported into the mathematic model used for erosion prediction developed in the project.

The same area had already been used for previous tests aimed to analyze different aspects of sediment transport. Several pebbles in this section of the riverbed were equipped with an RFID transponder and painted to allow for a quick recovery. The position and movements of pebbles were recorded after every rain event to assess the displacement of sediments. At the same time, selected areas within the riverbed were painted in red: the amount of displaced sediment after each rainfall was performed by comparing multitemporal information [2, 3, 21].

A section 120 m long was surveyed with an approach based on multiple geodetic instruments and techniques. Four permanent benchmarks were positioned and measured in the stream proximity with RTK-GNSS instruments to establish a reference system based on the WGS84-UTM 32N (ETRF2000) datum. These benchmarks will allow all subsequent measurements to be geo-referenced in the mapping grid. To transform the ellipsoidal elevation obtained from GNSS measurements, the mean geoid undulation in the area was derived from the national geoid model distributed by the IGMI (Istituto Geografico Militare Italiano/Italian Military Geographic Institute).

The main surveying activity was carried out with a terrestrial laser scanner (TLS) Faro Focus HDR 130 (Fig. 3). TLS instrument can measure several million points, recording not only the morphology of the stream but also the close surroundings with very high detail. 21 scans were acquired on the field, some of which directly inside the riverbed. To register single scans, checkerboard and sphere targets were also located along the riverbed. Checkerboard targets were previously measured with a total station georeferenced using GNSS benchmarks. An open traverse was established to cover the entire length of the considered section of the stream. The scans were successively registered with a precision of about ± 4 mm, resulting in a single georeferenced point cloud.

Several total station stand-points were also established in the same area, from which a large number of points were measured inside the riverbed, both on dry and wet sections (475 points in submerged parts). The location of these measurements was scattered according to a random acquisition sequence, depending also on the depth of the water level. A user manually placed a pole inside the river, which is sufficiently shallow to allow operators to enter directly in the water (Fig. 3a).

The aim was to gather data sufficient to recreate a digital model of the riverbed also in those parts covered by water. Laser scanning technology cannot provide information on those areas unless a bathymetric instrument is adopted [33]. Although quite slow, manual measurements taken with the total station (Fig. 3b) were the only solution to measure the riverbed permanently covered by water. A series of measurements located along sequences of stripes perpendicular to the river flow was taken to obtain multiple sections of the bottom of the stream.

Finally, a UAV flight (Fig. 3c) has been also planned throughout the stream to integrate TLS point clouds within a photogrammetric block. A series of ground control points (GCPs) measured with both a total station and an RTK-GNSS were also measured along the course of the stream.

The flight was carried out at a fixed height of 50 m, due to the presence of trees all over the area. A total number of 115 images were acquired using a DJI Spark drone, equipped with an on-board 1280×960 pixel camera. Drone and laser scanning surveys were simultaneously executed on a working day.

Figure 3 depicts the point cloud obtained from drone-photogrammetry, as described in successive sections.



Fig. 3. Some images of 3D surveying by terrestrial laser scanning (a), total station (b), and the point cloud obtained from Structure-from-Motion photogrammetry based on UAV images (c).

2.2 Fieldwork in Area 2

Area 2 is closer to the urbanized downtown of the town of Lecco, where an artificial sedimentation pool helps to control the sediment transport. In this case, the natural course of the stream is "blocked" by a deep pool of water approximately 45 m long and 15 m wide, which is cyclically filled up by solid sediments. The aim was to estimate

the volume of submerged sediments that are constantly covered by water and to monitor it over a given period to understand the process.

This task requested a different approach because the bottom of the pool was never visible. Thus, the riverbed can not be reached, even with the help of extendable poles.

Three GNSS benchmarks were measured to establish a reference system as already described in the previous sections. A floating device specifically designed for this purpose was equipped with a commercial depth sensor that could be remotely controlled. The sedimentation pool was divided into different stripes corresponding to the different areas to be covered by the sensor, moving the floating device manually along this path.

To correlate depth measurements and spatial positioning of the sensor, a total station (TS) was set up in the middle of the riverbed in correspondence of one of GNSS benchmarks. A 360° topographic reflector was fixed on the top of the floating device, to guarantee full and constant visibility from any direction between the device and the TS during measurement operations. A fully automated approach was used, i.e., automatic detection of the prism, followed by automatic tracking and automatic measuring at a rate of one second. Such a measuring rate was enough to assure redundant data that could be successively decimated. An overall number of more than 2,500 points was measured with this method (Fig. 4).

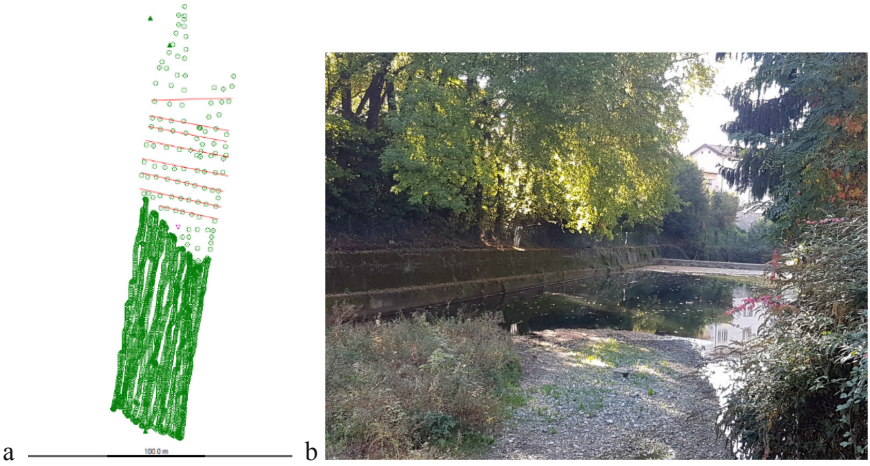


Fig. 4. Spatial distribution (a) of measured points on the riverbed in Area 2 (b): the lower part corresponds to the sedimentation pool. Red lines show hydraulic sections. (Color figure online)

Measurements by the floating device were integrated with a series of standard hydraulic sections as previously presented. This approach was applied in the sector where the riverbed can be reached with an extendable pole. An overall number of 8 hydraulic sections was recorded in addition to other single measurements of the bottom of the riverbed.

TLS was also used to record the surrounding environment and the banks; point clouds were then registered together using checkerboard targets previously measured with the TS.

3 Data Processing

3.1 Area 1

One of the aims was to generate a digital elevation model (DEM) of the selected part of the riverbed. To reach this goal, data from TLS scans were used for the area not covered by water. The UAV images were processed using Agisoft Metashape® (ver. 1.4.0) photogrammetric software, obtaining a point cloud to be integrated with laser scanning data. GCPs were also measured with a GNSS receiver to define the reference system of the project.

Besides, an orthophoto of the area covered by the UAV flight was generated. The ground sampling distance of the image was set to 15 mm, which is much higher than the resolution of the available cartographic data in the same area.

Points measured with TS instrument were used to reconstruct the profile of the submerged riverbed, whereas TLS and image-based points were used for areas above the water level instead. In the case of laser scanning measurements, a manual selection was necessary to decimate the final point cloud substantially. A subset of points was extracted to guarantee a uniform distribution in space, which is for DEM generation through interpolation. Points were selected and picked using Faro Scene® (ver. 2019.0.1.1653) software, obtaining text files of 3D coordinates that could be merged to those coordinates from TS measurements. An example showing the homogenous distribution of the selected points is shown in the left part of Fig. 5.

The set of 3D coordinates were then processed using Surfer® (ver. 14), a software for DEM generation from scattered data. Main challenges were found in the complex and irregular morphology of the riverbed, mostly due to the presence of several medium-size boulders in it, causing numerous and sudden changes in elevation compared to the relatively regular bottom of the stream made up of small pebbles.

A DEM able to describe the morphology of the stream without many details that could prevent its use within the final hydrogeological model was the main priority.

During the creation of DEM, the nearest neighborhood method was selected as the more appropriate interpolation. Indeed, other interpolation methods provided a smoothing effect of the riverbed, while we planned to preserve the typical roughness of the topographic surface.

The DEM was also superimposed to the orthoimage to check the correct georeferencing and to provide a graphic output (Fig. 5 on the right side).

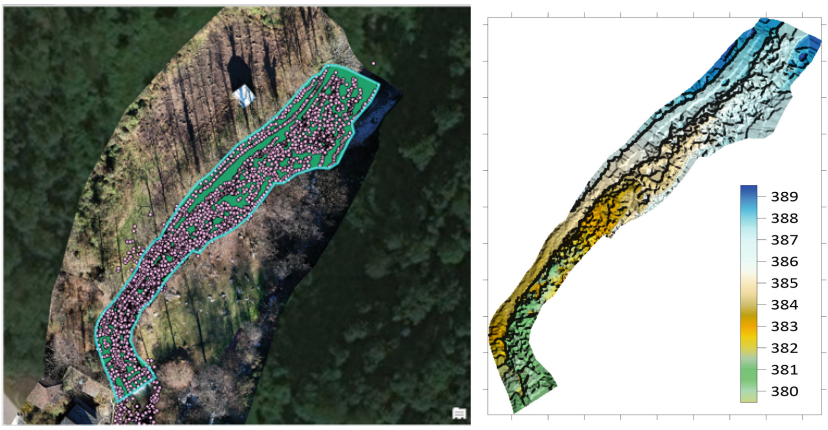


Fig. 5. Reconstruction of a digital elevation model (DEM) of Area 1: spatial distribution of points selected from TLS, drone-photogrammetry, and TS for DEM generation (a); and the final DEM (b).

3.2 Area 2

TS measurements georeferenced using GNSS points are the data used in area 2. A successive decimation and selection of data were necessary: the position of the floating device carrying the depth sensor had been measured every second, resulting in thousands of points.

The calculation of the depth value at a certain location of the sedimentation pool requires both data coming from the bathymetric sensor and the spatial coordinates measured with the TS. This approach provided the average profile of the bottom at a certain time; if repeated constantly, this approach will allow monitoring the amount of solid sediment transported by the stream at different epochs.

4 Data Sharing Platform

The availability of cartographic data is a fundamental aspect of Geosciences. Although many different institutions, such as geographic and geological institutes, public administrations, collaborative communities, and web companies, make available many open data, the availability of specific reference data for fluvial sediment transport analysis is still limited. For this reason, the authors decided to develop a novel platform to share the main data source for sediment transport evaluation in the case of the Caldone stream. The platform can be intended as a data-hub where two sets of information can be downloaded:

- novel data produced in the framework of the project; and
- existing data sets (especially open-source data) that can be retrieved from various repositories. In such a case, data harmonization procedures may be necessary to generate uniform products in terms of formats and reference systems.

In particular, the developed platform shares the DTM of a 120 m long portion of the Caldone stream, obtained by combining laser scanning and UAV data, and the orthophoto derived from UAV photogrammetry.

Other existing data can be added in the future, such as cartographic layers (both vector and raster formats) or land use data sets that need to be recovered from various services.

The developed platform represents a unique data hub where the data needed for sediment transport analysis can be retrieved, overcoming limitations related to uneven formats and reference systems. This concept could be then extended to other areas to facilitate the creation of a cartographic repository for fluvial sediment transport analysis.

Two key elements when dealing with data repository and creation of data-sharing platforms are as follow:

- user-friendly data search and retrieval; and
- data interoperability.

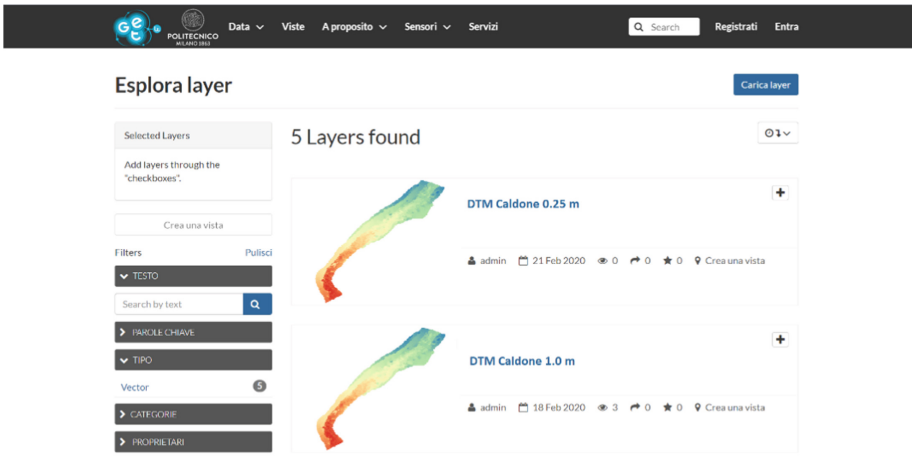
The implemented online data delivery platform is based on the software GET-IT (http://www.get-it.it/), which is particularly suitable for the deployment of Spatial Data Infrastructures (SDI) (see [1, 23] for more details). In particular, the platform allows for visualization, sharing, and management of different heterogeneous data types of geographic data: digital images, vector data, processed maps, data acquired by sensors (observations), or text documents.

Besides, different data formats are supported. For example, raster products can be delivered as TIFF, NetCDF, EUMETSAT archive, etc. The supported front-end for data-source access includes not only the initial data format but also OGC standard services (e.g., WMS, WFS, WCS), providing standardized access to the published data sets.

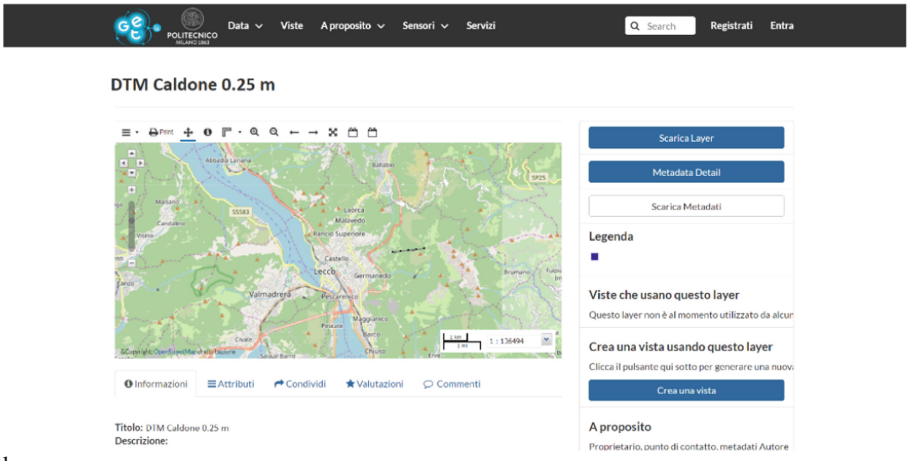
One of the most important characteristics of the platform is the possibility to act as a working environment (EDI) for the guided creation of metadata, improving search and discovery of the data and its reuse. Indeed, it is possible to create metadata compliant with the INSPIRE directive through a guided procedure. This is a fundamental aspect of data retrieval since it allows one to link the developed infrastructure to existing brokering services [22, 23].

The availability of a semantic broker automatically looks for synonyms and provides multi-language support. In this way, an automatic search can be performed in a specific language, and the broker allows to retrieve results published in a different language. For instance, after inserting the Italian word “sedimenti”, the broker allows one to identify results published in another language, like the keyword “sediments” in English. Search expansion is carried out by using a set of aligned semantic instruments, which are typically controlled vocabularies, thesauri, gazetteers, and ontologies.

Figure 6 shows an example of an automatic search for the word “Caldone”. The idea is to extend (in future work) the approach developed for the Caldone stream to other areas in which such data are available through various data sources.



a



b

Fig. 6. The graphic interface of the developed fluvial sediment data-sharing platform: (a) results for the query with the keyword "Caldone" and (b) metadata page for the product "DTM Caldone 0.25 m")

5 Conclusions

This paper presented the work aimed at generating 3D metric products in the framework of the estimation of solid sediments in mountain rivers and streams. The knowledge of riverbed geometry is a fundamental requirement for both basic and advanced analyses.

Structure-from-Motion photogrammetry and terrestrial laser scanning were used to capture the complex and irregular geometry of a river. The integration of total station

measurements was needed to survey those parts permanently covered by water (e.g., the riverbed), where the previous solutions were not able to provide any information.

The integration of data acquired with several instruments allowed one to overcome the limitations of single techniques, obtaining several final deliverables based on orthoimages, point clouds, and digital elevation models.

For what concerns the surveying of the first area, data gathered during on-field measurements were successfully used to produce numeric outputs. About the second area, the method was able to determine the depth of the sedimentation pool and it will be repeated at different epochs to understand the accumulation of materials inside the pool.

A surveying approach based on the combination of different methods (TS, TLS, UAV, and bathymetric sensor) was necessary to produce accurate metric data that will be used for the mitigation of hydrogeological hazards. Finally, the development of a data-sharing platform allowed us to publish the obtained results as Open Data allowing an easy search and discovery of data for further analysis on this topic. The inclusion of geospatial data in other sites can extend the proposed approach to national and international level, facilitating the work of operators involved in numerical simulation for hydrogeological risk assessment and mitigation.

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