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Published
DOI:10.1016/j.catena.2023.107599

Catena 235 (2024) 107599

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Multi-temporal analysis to support the management of torrent control structures

Sara Cucchiaro [a,*], Lorenzo Martini [b], Eleonora Maset [c], Giacomo Pellegrini [b], Maria Eliana Poli [a], Alberto Beinat [c], Federico Cazorzi [a], Lorenzo Picco [b]

[a] *University of Udine, Department of Agricultural, Food, Environmental and Animal Sciences, Udine, Italy*
[b] *University of Padova, Department of Land, Environment, Agriculture and Forestry, Legnaro, Italy*
[c] *University of Udine, Polytechnic Department of Engineering and Architecture, Udine, Italy*

ARTICLE INFO

Keywords:
Torrent control structures
Maintenance Priority index
Multi-temporal analysis
Sediment morphology dynamics
Hydro-geomorphic risk

ABSTRACT

In the last decade with increasing frequency of extreme weather events, an accurate, sustainable, and effective planning of torrent control structures has become essential to reduce hydro-geomorphic risk. Quite often in planning interventions, there is a lack of information on the effectiveness of existing structures, the evolution of the ongoing hydro-geomorphic process, and a priori in-depth study to analyze the sediment morphology dynamics and the interaction with possible existing torrent control structures.

Nowadays, High-Resolution Topography data (HRT) greatly simplifies the monitoring of sediment morphology dynamics and the understanding of the interaction with torrent control structures over time. Therefore, thanks to repeated HRT surveys, it is possible to derive multi-temporal Digital Terrain Models (DTMs), and DTMs of Difference (DoDs) to quantify the morphological changes and study continuously the catchment morphodynamics. This information can be very valuable to support watershed management plans if combined with up-to-date field surveys that identify the existing torrent control structures, and asses their current status and functionality.

The present work aims at introducing a methodological approach based on the integration of the sediment morphology dynamics data over large time spans (e.g., from 2003 to 2022), obtained by multi-temporal DoDs (realized from three DTMs at 1 m resolution), with an updating cadastre of torrent control structures enriched by a very simple, quick, and user-friendly Maintenance Priority index (*MPi*). The proposed workflow proved to be very useful in the test basins analysed, providing more complete data on torrent control structures and sediment dynamics evidence to stakeholders compared to the past. Moreover, it served as a proxy to assess the long-term effectiveness of the management interventions. The approach also helped to constantly identify the areas most prone to hazards, improve the intervention planning, and find more appropriate solutions or direct the maintenance works.

Finally, the suggested workflow could be the starting point to outline up-to-date guidelines to be used in other catchments equipped with torrent control structures, emphasizing possible intervention priorities on where decision-makers could better invest resources. By providing current information and accurate tools to realize a more complete decision-making chain, which is often neglected, it is certainly possible to support more sustainable and effective risk management decisions.

1. Introduction

In steep territories such as the Alps, accurate and effective planning of torrent control structures has become essential to reduce hydro-geomorphic risk (Conesa-Garcìa and Lenzi, 2010; Comiti, 2012; Piton et al., 2017), especially in the last decade, due to the increasing

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Abbreviations: ALS, Airborne Laser Scanning; DoD, DTM of Difference; DTM, Digital Terrain Model; FIS, Fuzzy Inference Systems; FVG, Friuli Venezia Giulia; GCD, Geomorphic Change Detection; GPS, Global Positioning System; GNSS, Global Navigation Satellite System; HRT, High-Resolution Topography; ICP, Iterative Closest Point; LiDAR, Light Detection And Ranging; *minLoD*, minimum Level of Detection; *MPi*, Maintenance Priority index; TIN, Triangulated Irregular Networks.

* Corresponding author.

E-mail address: sara.cucchiaro@uniud.it (S. Cucchiaro).

https://doi.org/10.1016/j.catena.2023.107599
Received 26 May 2023; Received in revised form 10 October 2023; Accepted 12 October 2023

frequency of extreme weather events (Seneviratne et al., 2012; Jia et al., 2019). Check dams are one of the most common hydraulic structures (Lucas-Borja et al., 2021), built transversally across the morphologically active stream in mountain regions for over 150 years (Jaeggi and Pellandini, 1997; Piton and Recking, 2017).

In several cases, the planning of torrent control structures proves only partially effective because of the uncertainties related to flow and solid transport dynamics, the approximations of the hydrological and hydraulic models applied, and the limits in identifying the most correct location or geometry of some structures. Among others, Tacnet et al., (2014) highlighted how risk management decisions are based sometimes on incomplete technical and scientific knowledge. There is a lack of information on the long-term sediment dynamics in catchments, on the structure damages incurred during their lifecycle as a result of the process that they are meant to mitigate (Dell'Agnese et al., 2013; Mazzorana et al., 2008), and on the cost/benefit of implementing these types of interventions in basins where extreme events are frequent and of high magnitude (Cucchiaro et al., 2019a).

The effectiveness (i.e., an estimation of the beneficial effects of the structures, compared to what could be expected from them; Piton et al., 2017) of torrent control structures is highly dependent on several factors, e.g. size, number, and position (Osti and Egashira, 2008; Abbasi et al., 2019), catchment characteristics, and the recurrence of extreme events (Mazzorana et al., 2018). Indeed, each basin has its specific characteristics and there is often a lack of in-depth a priori studies to analyze the sediment dynamics (starting from the sediment source areas up to the debris yield), to define the basin activity and the most critical areas, but also to study the interaction with possible existing torrent control structures. Moreover, it is well-established that these torrent control structures have long-term efficiency only if maintained regularly, but maintenance interventions are often not carried out due to high costs (Ballesteros Cánovas et al., 2016; Marchi et al., 2019) or not considered in the work design. In addition to the gradual loss of effectiveness, lack of maintenance may result in the collapse of the structure with the sudden release of large sediment volumes, increasing, in turn, downstream hazards and compromising the whole risk management plan (Cucchiaro et al., 2019b; Mazzorana et al., 2018; Baggio and D'Agostino, 2022). Therefore, risk management in mountain basins must also consider these aspects when planning interventions, but up-to-date information on existing structures and constant monitoring to understand the evolution of the ongoing hydro-geomorphic process is often lacking.

Nowadays, the growing capability of producing High-Resolution Topography data (HRT) greatly simplifies the analysis of geomorphological changes at multiple spatial and temporal scales and enables the development of innovative approaches to monitor sediment morphology dynamics and understand the interaction with torrent control structures (Carrivick et al., 2016; Vericat et al., 2017; Cucchiaro et al., 2019b). Among the techniques that permit collecting multi-temporal HRT, Airborne Laser Scanning (ALS) is the most suitable and exploited to acquire HRT data over large spatial scales (Cavalli and Marchi, 2008; Scheidl et al., 2008; Willi et al., 2015; Victoriano et al., 2018), and in catchment areas covered by vegetation, thanks to the use of the Light Detection and Ranging (LiDAR) technology.

Thanks to repeated HRT surveys, it is possible to derive accurate multi-temporal Digital Terrain Models (DTMs) and reliable DTMs of Difference (DoDs) useful to quantify the morphological changes and the evolution of erosion and deposition patterns, as demonstrated by several studies conducted in Alpine basins (Bezak et al., 2017; Cavalli et al., 2017; Oss Cazzador et al., 2021; Rainato et al., 2021; Scorpio et al., 2022). Furthermore, a continuous study of the catchments morphodynamics based on HRT data can support decisions in channel management practice as highlighted in Wohl et al. (2018). Other research showed how DoDs may improve the understanding of the impact of torrent control structures on sediment dynamics, thus recognizing the effectiveness of the interventions (Cucchiaro et al., 2019a; 2019b), prioritizing the maintenance and future management of the check dams (Victoriano et al., 2018), and helping the prediction of future trajectories for the risk management system (Simoni et al., 2017; Veyrat-Charvillon and Memier, 2006).

Once the information on channel morphology dynamics has been collected, it is important to understand how this interacts with the present torrent control structures or what effects implementing additional interventions in the catchment can cause. For this reason, it is fundamental to locate and identify the torrent control structures and assess their current status (i.e., structural condition: deterioration, damage) and functionality (i.e., the aim for which the intervention was made). The research of Dell'Agnese et al. (2013), tested a damage index of several structures in 18 mountain streams of South Tyrol (Northern Italy), highlighting how the check dam conditions are more important than event intensity. Therefore, a constant updating of torrent control structures cadasters with indications of the condition of the structures, combined with data obtained from DoDs, could provide useful and innovative supporting information to prioritize the maintenance intervention and evaluate the effectiveness of the implemented torrent control works over time, normally poorly considered or developed.

Therefore, the present work aims at introducing a methodological approach based on the integration of sediment morphology dynamics data over large time spans with a *Maintenance Priority index (MPi)* of existing structures. The information provided by sediment morphology dynamics coupled with an *MPi* indicator, obtained through an analysis of the physical status and functionality of torrent control structures, could help to support the development of watershed management strategies, assess the effectiveness of existing interventions, and foster a more complete decision-making chain. Exploiting multi-temporal HRT surveys and the field monitoring of the torrent control structures in some test watersheds, allowed the creation of a simple and user-friendly methodology that could be exported to other basins. The general proposed approach could provide important clues to decision-makers on the evolution of mountain catchments and identify the most critical areas for intervention planning. Moreover, to guarantee an accurate torrent control structures database and comparable multi-temporal HRT data, the development of robust workflows and guidelines, often lacking in this context, is set as the objective of this research. All this information can be used effectively and sustainably to detect potential deficiencies in the risk management system.

2. Study areas

To test the proposed methodology, four catchments were selected and investigated, with a focus on specific reaches that are particularly interesting and representative of the basin dynamics for this work. They are located in the Friuli Venezia Giulia Region (FVG, Italy), and their main morphological features are presented in Table 1. These basins were chosen because they were represented by a historical topographic database, several torrent control structures were built along their main channel network, and they have shown very active sediment morphology dynamics over time. Moreover, the geological characteristics of the mountain area (i.e., diffusion of rocks with poor mechanical quality such as gypsum, marls, and cataclastic rocks, a complex tectonic history, and high seismicity), strongly conditioned the behaviors of the materials and the morphological evolution of the landscape. The climatic conditions are typical of the easternmost part of the Italian Alps: cold winters and mild summers with abundant precipitation throughout the year, ranging from about 1800 to 2500 mm.

The Vegliato Torrent (Fig. 1A) is located in the Julian Prealps, in the municipality of Gemona del Friuli (UD). The stream is ephemeral and dry during most of the year, showing water and sediment transport in the form of debris flow and debris flood in the upper part, and hyperconcentrated and bedload in the lower part only during intense summer storms or prolongated rainfall events that characterize the spring and autumn seasons. A large oversized alluvial fan, on which Gemona

Table 1
Main morphological characteristics of the four study catchments, including the Melton index (Melton, 1965).

Catchment	Area (km^2)	Average slope (°)	Elevation (m a.s.l.)	Channel network length (km)	Average channel network slope (°)	Melton index
Vegliato	4.40	35	355–1739	8.6	17.9	0.660
Agozza	5.87	31	922–2512	10.1	16.6	0.656
Miozza	10.67	33	486–2125	12.1	16.0	0.502
Uccelli	10.56	38	620–2042	13.7	14.0	0.438

del Friuli stands, develops at the base of the reliefs. The valley axis coincides with an E-W striking, S-verging reverse fault of regional importance called Periadriatic Thrust (Barcis-Staro Selo in Carulli, 2006; Gemona-Kobarid in Zanferrari et al., 2013), which overlaps the Upper Triassic Dolomia Principale Fm. on the turbiditic facies of the Eocene Flysch and the Jurassic to Cretaceous limestones. As secondary effects of the destructive 1976 Friuli earthquakes (Mw6.5 on 6th May and Mw6.1 on 15th September), numerous landslides (generally rock-falls) affected a widespread area of the FVG Region (Govi and Sarzana, 1977). In particular, the southern slope of M. Deneal (Crete Porie) was affected by large rock-fall phenomena, which generated a large amount of chaotic sediments, progressively reactivated as debris flows due to intense and short-lived rainfalls. After the 1976 earthquakes, the torrent underwent a deep alteration of the discharge regime, increasing its erosive capacity in the steep slope areas, scouring the channel, and damaging many existing hydraulic control works (Coccolo and Sgobino, 1996). Moreover, the check dams and bed sill built after 1976 in the lower part of the basin (Fig. 1A) greatly modified the natural channel slope leading to sediment deposition processes in this area.

The Agozza (Fig. 1B) and Miozza (Fig. 1C) catchments are located in the Carnic Alps and their outlets are located in the municipalities of Forni di Sopra (UD) and Ovaro (UD), respectively. The Miozza catchment is mainly divided into two tributaries, the Miozza Torrent and the D'Archia Stream (Fig. 1C), and both are characterized by intense sediment transport in the form of debris flows and flash floods with large sediment discharge in summer (Tarolli and Dalla Fontana, 2009). Particularly, debris flow processes are constantly fueled by large (ca. 2.5 % of the catchment) and active landslides located at the head of the basin. These instabilities result from the aggregation of many landslides and are triggered by different events including intense and short-lived rainfalls, low-intensity long-duration rainfalls, and snow melt. Tarolli and Tarboton (2006) classified these landslides as shallow translational ones and highlighted how these phenomena generated several debris flows in a few years. From a geological point of view, many factors cause slope instability along the Miozza Creek: the basin is carved on erodible lithologies such as marly limestones, sandstones and shales, and vuggy carbonates of the Werfen Fm. (Lower Triassic) and dolostones with laminate gypsum of the Bellerophon Fm. (Permian). Along the Miozza stream a reverse fault, belonging to the Sauris thrust-system, overlaps the Bellerophon Fm. on the Werfen Fm. causing intensive rock deformation and a very common thick cataclastic belt. The Quaternary covers (melted glacial and slope deposits) are widespread.

The Agozza Torrent flows North to South (Fig. 1B), collecting water and sediment from the upper and wide part of the catchment, in which erosional processes are dominant. In the central and lower part of the basin, the channel narrows due to the confinement of vertical rocky walls. The sediments, also mobilized in the form of debris flows, are almost completely deposited in the alluvial fan close to the confluence with the Tagliamento River. The Agozza Torrent is carved on the carbonate platform succession and the mostly terrigenous basin sequences of the Lower-Middle Triassic (Pisa, 1974). In particular, the eastern slope is made up of dolomitic-limestones (Dolomia del Tiarfin) extensively interested in karstic phenomena, while the western one is mainly carved on the terrigenous-carbonatic sequences of Wengen and San Cassiano Fms showing alternations of marls, sandstone muds, red limestone with Ammonites, marly limestones, arenaceous limestones and frequently basaltic volcanic bodies and volcanoclastic layers. The high erodibility of the rock-substratum gives rise to widespread and thick slopes and colluvial deposits.

Lastly, the Uccelli Torrent catchment, which lies within the Pontebba municipality (UD), features an upper part, where sediment is produced along the hillslopes, and a downstream part in which the stream flows more confined (Fig. 1D). The rocky substratum of the catchment consists mainly of massive dolomites and dolomitic limestones (Dolomia dello Sciliar in Venturini, 1990). Restricted outcroppings of terrigenous sediments (arenites, pelites, limestones, and breccias) characterize the medium portion of the Uccelli catchment. The main geomorphological feature of the basin is a huge accumulation of chaotic material present on the right side of the upper portion of the valley. It probably represents the deposit of an ancient rock landslide and is the main source of sediment for solid transport in the lower part of the channel (Dini and Selloroni, 2005). Indeed, massive sediment transport processes are present in the upper part of the basin. These debris flows, triggered alongside tributaries of the stream, however, stop at a weakly sloping depositional zone located upstream of the landslide body.

3. Material and methods

Multi-temporal topographic data were used to understand the effectiveness of torrent control structures in the four catchments. The study was carried out through the generation of multi-temporal DTMs, derived from ALS surveys acquired at different epochs, which allowed the analysis of morphological change due to different events. Moreover, an update of the old torrent control structures cadastre was used to obtain useful information about the status and functionality of interventions. A detailed methodological workflow was followed to combine the use of older and newer data characterized by different quality and accuracy (Fig. 2).

3.1. Inventory of torrent control structures

In the four studied catchments, several torrent control structures were built over time (from the 1920 s to the present), hence it is possible to assess their interaction with sediment dynamics during a long period (e.g., in this study from 2003 to 2022). Among the several torrent control structures, numerous check dams (i.e., structural defense measure transversally built across the stream and above the bed level, even several meters), bed sills (differently from a check dam, these structures are built at the bed level and not above it), and open check dams (dams with slot openings in their bodies) have been realized. Exploiting as a starting point the Regional Cadastre of torrent control structures realized by Friuli Venezia Giulia Region (IRDAT, 2023), an updated inventory of all the interventions located within the four study catchments was carried out in the summer of 2022 by field surveys. The Regional Cadastre reported all the structure's characteristics (e.g., dimensions, typology, building material), year of construction, location, and functional states at the survey time (Step *i.* in Fig. 2). However, it was necessary to geolocate the torrent control structures more accurately, to check whether they still exist, and to update and improve the assessment of the status and functionality of each structure. To achieve the latter goal, a procedure was implemented according to:

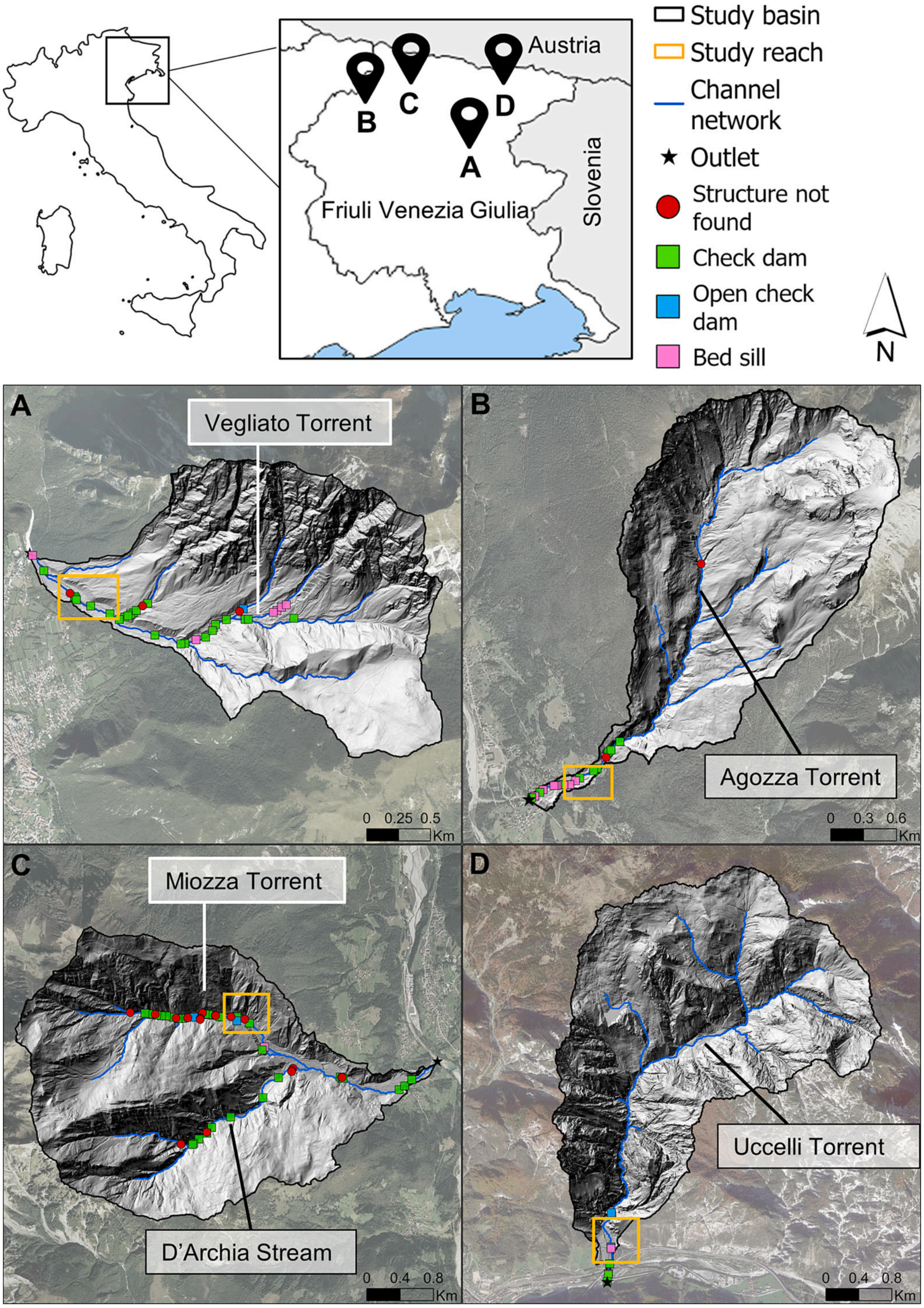

Fig. 1. Location of the study basins in the Friuli Venezia Giulia Region (Italy). The Vegliato Torrent (A), Gemona del Friuli municipality (UD); the Agozza Torrent (B), Forni di Sopra municipality (UD); the Miozza Torrent (C), Ovaro municipality (UD); the Uccelli Torrent (D), Pontebba municipality (UD). The check dams and bed sills analysed in the present work are shown in the maps alongside the structures that were not found in the last survey (i.e., summer 2022). One study reach per basin was identified to further discuss the interaction between structures and sediment dynamics.

- the classification of the torrent control structure present in the case studies analyzed, according to the existing literature.
- the identification (when possible) or assumption of the general objectives for which the torrent control systems were built, based on their construction characteristics and the hydro-geomorphic risk within catchments.
- the setting-up of customized tables (i.e., considered only the types of structures found in the case studies analyzed; Step *ii.* in Fig. 2; Table 2 and 3), starting from the existing bibliography (e.g., Carladous et al., 2016; Piton et al., 2017), to relate the different types of torrent control structures with their primary function and structural status. To produce a simple and practical index, a single primary function, and its expected effects (at full functionality) were identified for each torrent control structure, aware of the multiple purposes for which an intervention may be built. Moreover, to assess issues related to structural status and current functionality, simple markers

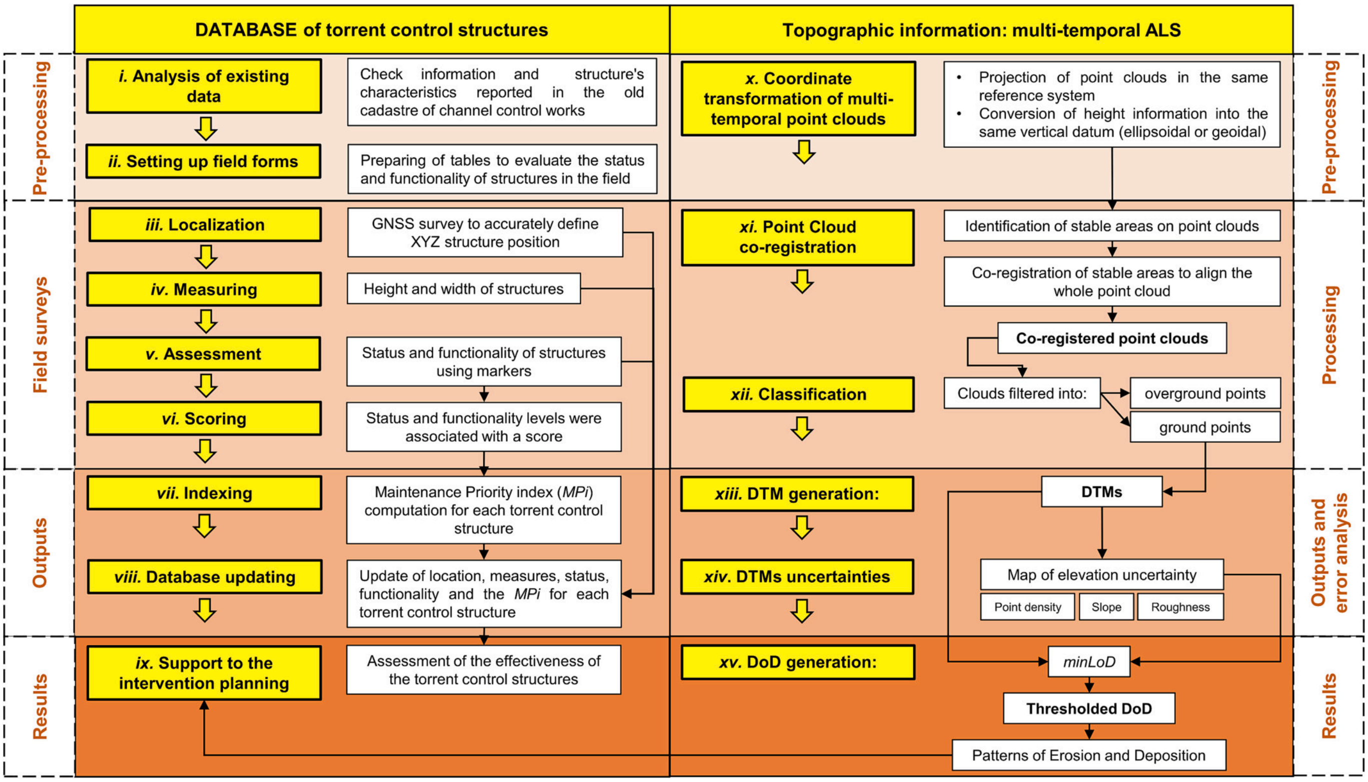

Fig. 2. General workflow of the analysis developed in this study. Two main branches are outlined concerning the inventory of torrent control structures and the multi-temporal processing of ALS data and. Within the branches, progressive steps were followed and grouped into four main sections for each branch.

(to be observed during field surveys), were identified in Tables 2 and 3.

Therefore, during the field surveys: *i*) the torrent control structures location was mapped using a Leica Zeno 20 Global Navigation Satellite System (GNSS) in Relative Stop&Go post-processed mode and referenced in the Italian ETRS89 (RDN2008) UTM 33 official coordinate system (Step *iii.* in Fig. 2); *ii*) the height and width were measured with a TruPulse 200 laser range finder from the center of the spillway to the correspondent orthogonal point on the downstream bottom (Step *iv.* in Fig. 2); *iii*) status and functionality problems were qualitatively assessed by visual inspections, considering the markers in Table 2 and 3. (Step *v.* in Fig. 2). The markers related to observed issues (Tables 2 and 3) were used to assign a corresponding score (3 levels) to each torrent control structure in terms of functional and structural status (Step *vi.* in Fig. 2).

Exploiting the scores of structural state and functionality, the Maintenance Priority index (*MPi*), defined by **Eq. (1)**, was developed (Step *vii.* in Fig. 2). The *MPi* values (Table 4) were added to the database as an attribute of each structure together with other updated information (Step *viii.* in Fig. 2). The torrent control structures are identified by a unique code with the initial letter of the basins in which they are located (i.e., "V" means Vegliato, "M" = Miozza, "A" = Agozza, "U" = Uccelli), a progressive number, and only for the Miozza a suffix for either the main Miozza Torrent (i.e., "S" = main stream) or the D'Archia tributary (i.e., "D") is attached.

$$MPi = 1 - \left(Score_{status} \times \left(\frac{Score_{status} + Score_{functionality}}{2} \right) \right) \tag{1}$$

The *MPi* (Eq. **(1)** was then grouped into four classes, visualized according to four colour ranks: red ($MPi = 1$), orange ($0.63 \leq MPi \leq 0.88$), blue ($0.25 \leq MPi \leq 0.50$) and green ($MPi = 0$) as shown in Table 4. The colour association was provided not only to give a visual and impactful indication of the priority of maintenance interventions, but also to give a key to reading the index (see **Section 4.1**). Indeed, the red-rank structures are torrent control works completely destroyed so that they cannot have any level of functionality. The interventions on this rank should have the highest priority. Orange-ranked structures are characterized by remarkable structural damages, hence interventions should address the long-lasting durability of the structure itself. The torrent control structures characterized by blue-rank show good structural condition but poor functionality, therefore indicating that a careful review of the planning process should be carried out. Among this rank, it is possible to find structures recently built, hence showing high structural integrity, but low functionality. Finally, torrent control structures with high functionality and physical status belong to the green rank, which indicates the lowest priority of interventions.

The information derived from the *MPi* added with the findings of geomorphic change detection analyses (see **Section 4.2.2**) could give important insights into the effectiveness of the torrent control structures over time to assess and support the planning of interventions (Step *viii.* in Fig. 2).

3.2. ALS data and point clouds processing

The ALS data were acquired by the same private company during four survey campaigns, performed in the periods of 2003–2004, 2006–2009, and 2018–2019. Table 5 summarizes the characteristics of each survey.

Over the last twenty years, multi-temporal ALS data have become available for many areas, albeit with significant differences in terms of point cloud density, accuracy, and precision (Pfeifer et al., 2014). Therefore, old "legacy" data sets and recent surveys have a different metric quality that often leads to comparison problems (Cucchiaro et al., 2020; Passalacqua et al., 2015).

To address these issues, at first, the different point clouds acquired at the various epochs were transformed in the same reference system (RDN2008/UTM-33 N) through a local specific Bursa-Wolf transformation, also converting height information into the same vertical

Table 2
Markers and scores related to the primary function of the different types of torrent control structures. *It should be noted that slope reduction was considered as a secondary and common function for all the check dams, it is not under evaluation. ** Sediment retention is nowadays achieved through modern open check dams (Piton et al., 2017).

Type of structure	Primary function*	Expected effects	Markers	Score of current functionality
Traditional check dam	to stabilize channel	Prevent channel wandering and bed incision	- Bed incision; - Sediment fluxes outflanking the structure; - Sediment fluxes bypassing the spillway;	1 = none of the listed markers present 0.5 = at least one marker present 0 = at least two markers presented
	to consolidate sediment source	Stop massive sediment supply from sediment sources by favoring deposition in the check dam's upstream area	- Sediment source activity; - Bed incision or lateral shifts;	1 = none of the listed markers present 0.5 = at least one marker present 0 = at least two markers presented
	to regulate the solid discharge	Buffering sediment fluxes in the check dam's upstream area	Sediment deposit overpassing the check dam, i.e., stopping the buffer effect	1 = No evidence of sediment deposit passing over the structure 0.5 = evidence of sediment deposit e overpassing check dam spillway 0 = evidence of sediment deposit overpassing the spillway and the wing(s).
	to retain sediment**	Storing sediment supply in the check dam's upstream area	Check dam overfilling	1 = Check dam is not filled up to the spillway 0.5 = Check dam filled up to the spillway 0 = Check dam filled up to crest and/or evidence of sediment passing over the wings
Open check dam	to sort sediment particles	Regulating sediment transport by sorting specific particles	Ratio of filters clogged	1 = less than 1/3 of the filters clogged 0.5 = between 1/3 and 2/3 of the filters clogged 0 = more than 2/3 of the filters clogged
Bed sill	to prevent bed erosion	Bed stabilization	Erosion around the structure: - Upstream - Downstream - Lateral	1 = none of the listed markers present 0.5 = at least one marker present 0 = at least two markers presented

Table 3
Markers and scores related to the structural status of the different types of torrent control structures.

Type of structure	Primary structural parts	Markers	Score of current structural status
Traditional check dam	Spillway (and its covering), counter dam, central body, foundation, wings	No remarkable damages were detected	1 = Good
		Remarkable damage to at least one part	0.5 = Damaged
		Structure collapsed	0 = Destroyed
Open check dam	Spillway (and its covering), counter dam, central body, foundation, wings, filters	No remarkable damages were detected	1 = Good
		Remarkable damage to at least one part	0.5 = Damaged
		Structure collapsed	0 = Destroyed
Bed sill	Covering, body, wings	No remarkable damages were detected	1 = Good
		Remarkable damage to at least one part	0.5 = Damaged
		Structure collapsed	0 = Destroyed

datum using a proper Geoid model. The older ALS data (i.e., 2003–2004 and 2006–2009), indeed, were originally referenced in the former national coordinate systems (Step *x.* in Fig. 2).

To compute accurate and reliable DoDs, it is necessary to remove eventual and residual inaccuracies of the original georeferencing process through a co-registration (or alignment) step (Step *xi.* in Fig. 2; Cucchiaro et al., 2020). The co-registration procedure first required the supervised identification of unchanged stable areas on the multi-temporal point clouds (i.e., natural and/or anthropogenic features like rocky outcrop, forest roads, stable meadows, and human infrastructures where no change occurred between the survey acquisitions); to this end, orthophotos were used to facilitate the recognition. Then the Iterative Closest Point algorithm (ICP; Besl and McKay, 1992) was applied to minimize the misalignments among the point clouds, pairwise, and finally the transformations estimated on stable areas by ICP were extended to the whole original ALS point clouds (Cucchiaro et al., 2020). In this way, the transformations estimated on stable areas were applied to the whole original ALS point clouds. Subsequently, ALS point clouds were filtered into overground points (vegetation and buildings), and bare ground points (Step *xii.* in Fig. 2) using classification routines and algorithms of the TerraScanTM package, produced by TerraSolid (TerraScan, 2023; https://www.terrasolid.com). A manual check was then carried out to remove possible errors left by the automatic classification functions.

Moreover, it should be considered that ALS surveys carried out over large areas (e.g., publicly funded national or regional mapping projects) may require several months to complete, and during this time span environmental conditions could be changed and extreme weather events could occur, causing sudden and significant morphological changes in the studied basins or part of them. Therefore, the ALS data of different parts of the catchment area may be inhomogeneous on a time scale and intersect the timeline of extreme events. As the present research, the important Vaia storm (Chirici et al., 2019; Pellegrini et al., 2021), which occurred in October 2018 in the middle of the ALS 2018–2019 campaign, involved the Miozza and Agozza catchments and triggered hillslope instabilities that increased the availability of mobilizable sediment. Therefore, during the point cloud processing and the

Table 4

The MPi is calculated from the scores assigned to each functionality and status level qualitatively assessed in the field. Colour ranks were then assigned to the final MPi: green-rank (0); blue-rank (0.25–0.50); orange-rank (0.63–0.88); and red-rank (0).

Functionality		Status		
		Destroyed	Damaged	Good
	Score	0	0.5	1
Low	0	1	0.88	0.50
Medium	0.5	1	0.75	0.25
High	1	1	0.63	0

Table 5

ALS flight parameters and point cloud data specifications.

ALS survey period	2003–2004	2006–2009	2018–2019	2022
Basins and survey time	**Agozza**: 19/11/2003	**Agozza**: Jul-Sept/2007 and Aug-Nov/2009	**Agozza**: Jun-Jul-Dec/2018 and Jun/2019	
	Miozza: 15/06/2004	**Miozza**: Jul-Oct/2009	**Miozza**: Jun-Dec/2018 and May-Jul/2019	
	Uccelli: 06/11/2003	**Uccelli**: Jun-Jul/2008 and Jul-/2009	**Uccelli**: Jun-Jul/2018 and May-Jun/2019	
		Vegliato: Jul-Oct 2010	**Vegliato**: Feb-Jun/2019	**Vegliato**: 18–19/05/2022
LiDAR system	Optech ALTM 3033	Optech ALTM Gemini	Riegl LMS-Q780	Riegl LMS-Q780
Acquisition mode	First and last returns	Up to 4 returns	Full-waveform	Full-waveform
Average flight height (a.g.l.)	1000 m	850 m	500 m for areas with elevation < 1000 m 700 m for areas with elevation > 1000 m	550 m
Flying speed	80 knots	80 knots	45 knots	45 knots
Swath angle	20°	25°	30°	30°
Laser frequency	33 kHz	57 kHz	400 kHz	400 kHz
Requested point density	2.5–5pt/m^2	4pt/m^2	18pt/m^2 for areas with elevation < 1000 m 12pt/m^2 for areas with elevation > 1000 m	16pt/m^2
Mean ground point density	0.5pt/m^2	1.5pt/m^2	6.8pt/m^2	21.6pt/m^2
Commissioned by	University of Udine	FVG Region	FVG Region	University of Padova

following DTM generation, it was necessary to split the ALS 2018–2019 surveys into “Pre” and “Post-event” point clouds for the catchments affected by the weather event, exploiting the GPS (Global Positioning System) time attribute associated to each measured point. This further filtering of ALS 2018–2019 point clouds was done through the classification routines of the TerraScanTM package, as well as the following operations.

The co-registered ALS point clouds were interpolated into Triangulated Irregular Networks (TINs), then converted into a raster to obtain the multi-temporal DTMs (Step *xiii.* in Fig. 2). A grid spacing of 1 m was chosen according to the lowest density that characterizes the ALS point clouds (i.e., the survey of 2003).

3.3. *DoDs generation and error analysis*

The multi-temporal DTMs were used to realize two DoDs for each of the four studied catchments and analyze the sediment dynamics of the channel network over time. To obtain reliable DoDs and to discriminate the actual changes in surface elevation from noise, the analyses of DTMs uncertainties and error propagation were carried out (Step *xiv.* in Fig. 2) following the Fuzzy Inference Systems (FIS) approach proposed by Wheaton et al. (2010). The approach is mainly constituted by three steps carried out on a cell-by-cell basis: *i*) computation of DTM error using the FIS; *ii*) propagation of the error into the DoD (Brasington et al., 2000); *iii*) use of a probabilistic threshold to define the statistical significance of the propagated uncertainty (Taylor, 1997; Lane et al., 2003). The final output is a unique value of *elevation uncertainty* (δz) for each cell (Jang and Gulley, 2007; Wheaton et al., 2010). In this work, three inputs-FIS were used, i.e., point density, slope, and roughness. Particularly, the roughness information was derived using the Roughness Index, proposed by Cavalli and Marchi (2008), and already applied in other geomorphological studies as part of the three inputs-FIS (e.g., Rainato et al., 2021; Oss Cazzador et al., 2021). Considering that slope, point density, and roughness change among the basins and the topographic ALS surveys, multiple ad-hoc FIS schemes were built. In this work, we applied a conservative 95 % confidence interval (t-value = 1.96; Kim et al., 2019) for all DoDs. Therefore, using the Geomorphic Change Detection (GCD) toolkit developed by Wheaton et al. (2010), the multi-temporal DTMs were compared to obtain thresholded DoDs (Step *xv.* in Fig. 2), where changes above the minimum level of detection (*minLoD*), defined by the confidence interval, were considered real while the changes below the *minLoD* were considered uncertain and not used in the final computation of volumes.

4. Results

4.1. *Torrent control structures inventory*

As a result of the field surveys, an updated inventory of torrent control structures for the four studied catchments was obtained (https://zenodo.org/records/10015015; Marini et al., 2023). The cadastre provides information on both the structures surveyed and updated during the recent field campaigns (Fig. 3) and the ones listed in the regional cadastre but not identified during the investigations (Fig. 1). Fig. 3 reports examples of torrent control structures surveyed in the Miozza catchment and entered into the updated database. Within the latter, it is possible to find torrent control structures that have been

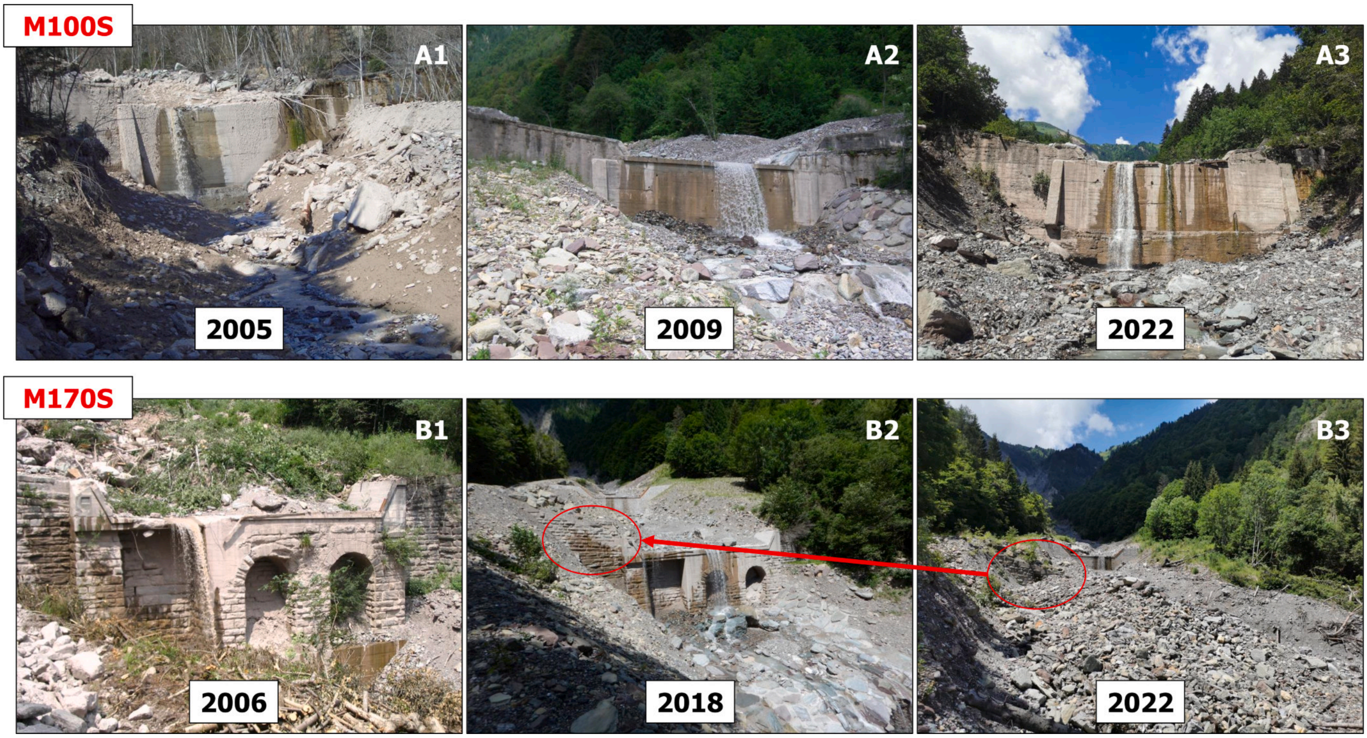

Fig. 3. Examples of torrent control structures (i.e., check dam M100S and M170S) surveyed and entered into the updated database: (A) check dam M12S in the Miozza Torrent damaged in 2005 (A1; Photo Cavalli, 2005), rebuilt in 2007–2009 (A2; Photo Marchi, 2009), and damaged again in 2022 (A3); (B) check dam M21S visible in the Miozza Torrent in 2006 and 2018 (B1 and B2; Photo Cesca in 2006 and Friuli Venezia Giulia Region in 2018) but over-filled in 2022 (B3), red circles indicate the same part of the structure. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

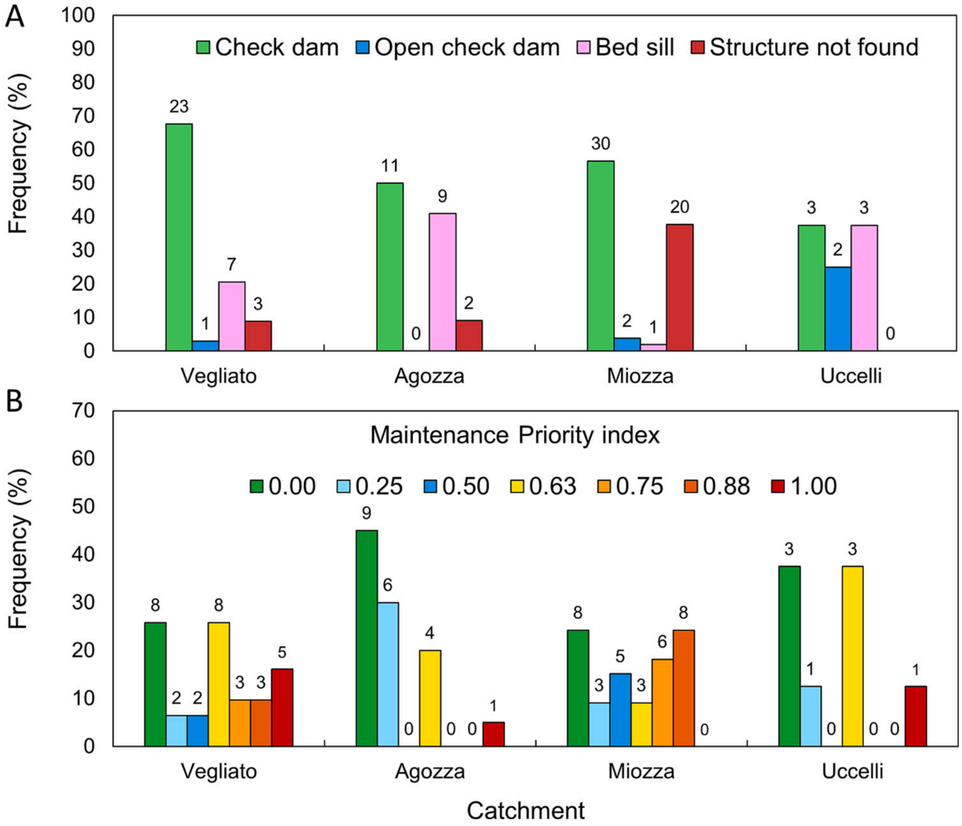

Fig. 4. (A) Relative frequency and number (at the top of each bar) of the type of torrent control structures. (B) Relative frequency and number (at the top of each bar) of the structures with a specific value of the Maintenance Priority index (MPi), for each study catchment.

damaged (e.g., check dam M100S built before 1979; Fig. 3A1), rebuilt in 2007–2009 (Fig. 3A2) and damaged again (Fig. 3A3) over time, but also the presence of impressive works that were present in the past (e.g., check dam M170S built in 1976 and rearranged in 2007–2010; Fig. 3B1 and B2) and are now almost over-filled (Fig. 3B3).

Overall, 117 structures are included in the inventory but 25 of them were not found anymore (Fig. 1) and were not considered in the following statistical calculations. Out of the remaining 92 structures, 67 are check dams, 5 are open check dams, and 20 are bed sills. Fig. 4A reports the relative frequency of structures' classification and the number of different types of interventions in the four catchments. The Vegliato catchment presents 31 structures (7.04 structure/km along the channel network in Fig. 1), most of which are traditional and open check dams (77 %) located along the main channel and a short and steep tributary joining right upstream of the study reach (Fig. 1A). In the Agozza and Uccelli streams (1.99 and 0.58 structure/km along the channel network in Fig. 1, respectively), the number of bed sills is almost equal to the check dams, and all the structures are located in the downstream part of the catchments, in correspondence to the alluvial fans formed as the streams exit the more steep and confined sections (Fig. 1B and 1D). In the Miozza catchment instead, almost 38 % of the structures (2.72 structure/km along the channel network in Fig. 1) in the inventory were not found. The traditional and open check dams are the most abundant type of structure, with a relative frequency of 72 %, and they were mostly built along the main Miozza torrent, while a minor part is located along the D'Archia tributary (Fig. 1C).

Concerning the main objectives of the torrent control systems, in the Vegliato catchment 83 % of the structures were built to stabilize the channel (upstream part) and to regulate solid discharge (downstream part), whereas in the Agozza catchment the primary goal was to stabilize the channel and prevent bed erosion (80 % of the structures). Miozza catchment presents 78 % of the structures built to either stabilize the channel or to retain sediment (45 % and 33 %, respectively), and finally the structures in Uccelli catchment were mainly built to regulate solid discharge and to prevent erosion (75 %).The assessment of the status and functionality of the torrent control structures pointed out significant differences in terms of the *MPi* in the studied catchments, as shown in Fig. 4B. In total, out of 92 structures, 41 % (i.e., 38 structures) are characterized by an orange-rank (i.e., *MPi* of – 0.63——0.88), hence indicating important maintenance priority. The irreversible condition, underlined in Fig. 4 by red-rank (i.e., 1 of *MPi*) affects the 8 % of the torrent control structures. The 21 % of works are blue ranked (i.e., *MPi* of 0.25 – 0.50), suggesting a careful review of the torrent control structure planning or design intentions while the 30 % of interventions show a green-rank (i.e., *MPi* of 0) as they are still operative and in good conditions.

Comparing the *MPi* among the study catchments, as visible in Fig. 4B, the Vegliato catchment presents the highest percentage of red-ranked torrent control structures, the Agozza has the highest number of green and blue-ranked works, while the Miozza shows the highest percentage of orange-ranked structures. Furthermore, the Miozza and Agozza catchments also present the lowest number of green-ranked and red-ranked structures, respectively. It is useful to point out that in the Uccelli catchment, 37 % of the structures are both operative and in good condition (i.e., green-rank), but the same number of structures are also damaged (i.e., orange-rank).

Fig. 5 shows the spatial arrangement of the torrent control structures, with the relative *MPi*, within the catchments. As visible, the Vegliato torrent control system displays high *MPi* values in two spots where red-ranked structures are concentrated: in the downstream part and most upstream part of the main channel (Fig. 5A). Instead, the Agozza basin, displays a lot of structures with low values of the *MPi* located in the lower part of the catchment (Fig. 5B). Notably, in the Miozza torrent most of the structures, need substantial interventions (i.e., orange and red ranks) or rethinking on the design choices made (i.e., blue-rank), whereas the D'Archia tributary (Fig. 1C) and the lower part of the catchment hosts structures with good status and functionality (Fig. 5C). Lastly, in the Uccelli catchment, the green-ranked structures are located in the narrowest stream sections, whereas the torrent control structures placed in the central part show higher values of *MPi* (Fig. 5D).

Relevant examples of the seven *MPi* values are found within each catchment's study reach. An example of a green-ranked structure is visible in Fig. 6A, where the check dam A120 in the Agozza catchment is characterized by an *MPi* value of 0 due to operative functionality and good status. In the Uccelli basin, Fig. 6B presents a case of a blue-ranked ($MPi = 0.25$) check dam. Even though the open check dam shows good status, a reduced functionality was observed, as the sediment is clogging almost 50 % of the filters, impeding correct sediment sorting and retention during intense floods. Fig. 6**C** shows a check dam (M130S in the Miozza Torrent) with low functionality in terms of channel stabilization but good structural status, leading to a blue rank ($MPi = 0.5$). Fig. 6D shows check dam V060 along the Vegliato Torrent, whose *MPi* corresponds to 0.63, hence ranked orange. Even though it still can exert its primary function of sediment regulation, the physical condition is in a precarious state. A deep scour visible in the downstream part already caused the collapse of the counter dam and is now affecting the main check dam's foundation as well. The check dam M100S in Fig. 6E is characterized by reduced functionality in terms of sediment retention due to upstream massive sediment overfilling. In addition, there was evidence of important siphoning at the base of the check dam, which affects both the functionality (potential fluxes passing underneath) and the future stability of the structure itself. Indeed, the degree of siphoning in this structure is bound to widen considerably over time, because, from field inspections and as seen in Fig. 6E, there is the presence of runoff under the check dam body along the entire spillway even in areas not directly affected by crest flow. For these reasons, an *MPi* value of 0.75 and the orange-rank were assigned. Fig. 6F, in the Vegliato torrent, presents an example of an orange-ranked ($MPi = 0.88$) bed sill (V190) due to low functionality of bed stabilization, showing important signs of lateral and downstream erosion. Finally, Fig. 6**G** displays the completely destroyed V050 check dam (only the left wing is visible) that is unable to perform its function of stabilizing the channel, therefore the *MPi* is 1 (i.e., red-rank).

4.2. *Geomorphic change detection analysis*

4.2.1. *Error analysis*

The methodological workflow used to process the ALS data (**Section 3**) allowed the realization of accurate and reliable DTMs and DoDs. To underline the usefulness and effectiveness of the approach used, Fig. 7 shows two examples regarding the effects of the co-registration procedure and a manual check on the automatic classification of the ALS point cloud. Fig. 7A1 displays a stable area (i.e., an alpine meadow) in the Miozza catchment, where, thanks to the 2018–2009 point cloud co-registration (step *xi.*, Fig. 2), it was possible to minimize the residual alignment errors and obtain more accurate estimates of the DoD elevation changes. The raw DoD (i.e., without any type of thresholding procedure of errors; see **Section 3**) computed before the co-registration process (Fig. 7A2) shows elevation changes values mainly within −1 and −0.2 m, whereas after the co-registration (Fig. 7A3) the same stable area displays much lower values (i.e., ranging between −0.2 and 0.2 m). The results of the co-registration procedure, in terms of more accurate DoD elevation changes, carried out simultaneously in all the stable areas of the Miozza catchment for the two DoDs report the following improvements: the mean distance for 2009–2004 DoD improved from 0.56 m (std. 0.13 m) to 0.01 m (std. 0.13 m); the mean distance for 2018–2009 DoD enhanced from 0.18 m (std. 0.09 m) to 0.01 m (std. 0.09 m). The results improve further when considering the values of the DoDs thresholded in the same stable areas as these all tend to be zero.

Fig. 7B instead, represents an example of the improvement due to manual classification refinement of the point cloud versus automatic classification (step *xii.*, Fig. 2) performed in the Vegliato catchment. As

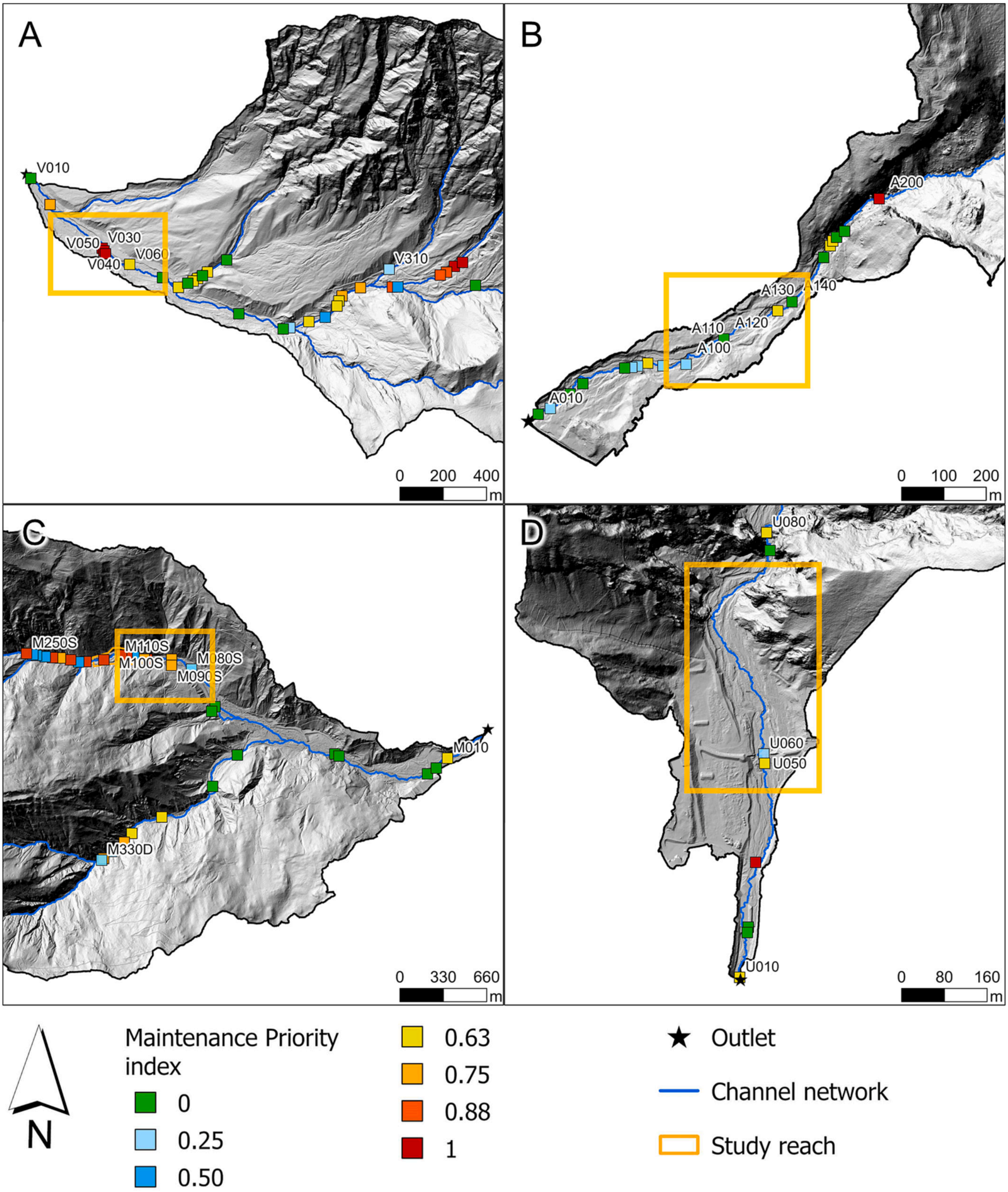

Fig. 5. The spatial arrangement of the torrent control structures with their relative classification according to the Maintenance Priority index (MPi) in the Vegliato (A), Agozza (B), Miozza (C), and Uccelli catchments (D).

Fig. 6. Examples of check dams with different MPi values associated. (A) Check dam A120 in the Agozza Torrent was assigned 0 of the MPi and green-rank. (B) Open check dam U060 in the Uccelli Torrent was assigned 0.25 of the MPi and blue-rank. (C) Check dam M130S in the Miozza Torrent was assigned 0.5 of the MPi and blue-rank. (D) Check dam V060 in the Vegliato Torrent was assigned 0.63 of the MPi and orange-rank. (E) Check dam M100S in the Miozza Torrent was assigned 0.75 of the MPi and red orange-rank. (F) Bed sill V190 in the Vegliato Torrent was assigned 0.88 of the MPi and orange-rank. (G) Check dam V050 in the Vegliato Torrent was assigned 1 of the MPi and red-rank. Photos taken in summer 2022. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

visible, the ALS 2010-point cloud was misclassified along the hillslope, leaving a large area with no ground points and thus generating a biased thick deposition in the 2018–2010 DoD. After the manual point cloud classification, the error was minimised as visible in Fig. 7B3.

4.2.2. DoDs analysis and interactions with torrent control structures

The DoDs generated for two specific time windows based on the ALS surveys available in the different catchments (see Table 1), report high variability among the study areas. An example of multi-temporal DoD for the whole Miozza channel network is presented in Fig. 8. As visible, the 2009–2004 DoD (Fig. 8A) displays an important alternation of

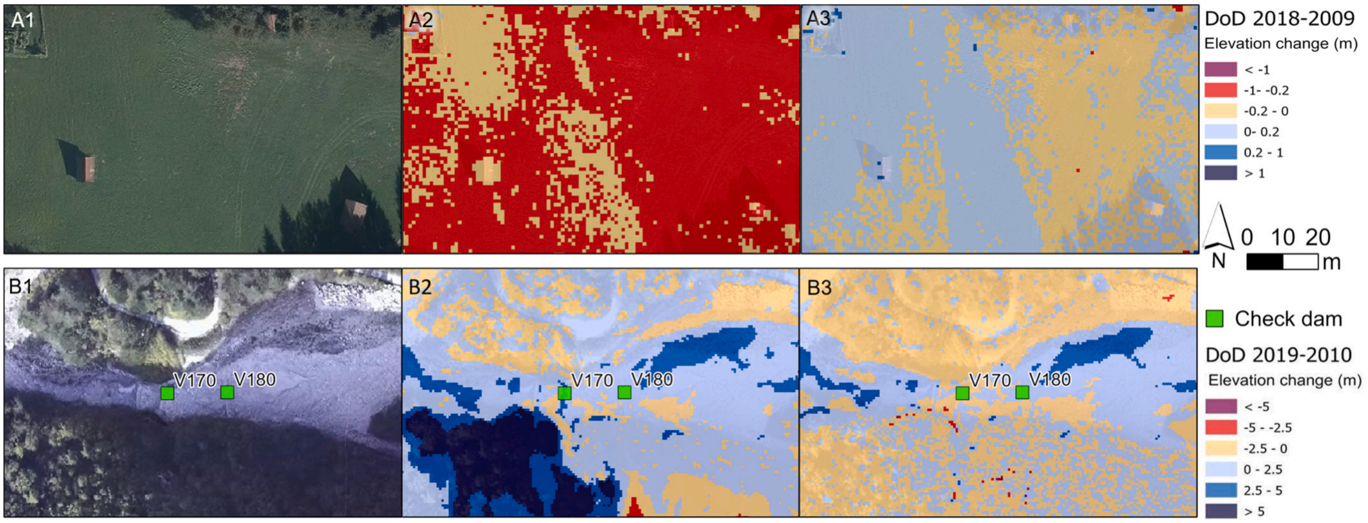

Fig. 7. A few examples of the importance of conducting robust ALS data post-processing. The effects of point cloud co-registration (A) and low point density (B) on raw DoDs: a stable area in the Miozza catchment (A1) before (A2) and after (A3) the co-registration process. The effects of low point density in the Vegliato catchment (B1) due to ground point misclassification before (B2) and after (B3) the manual classification.

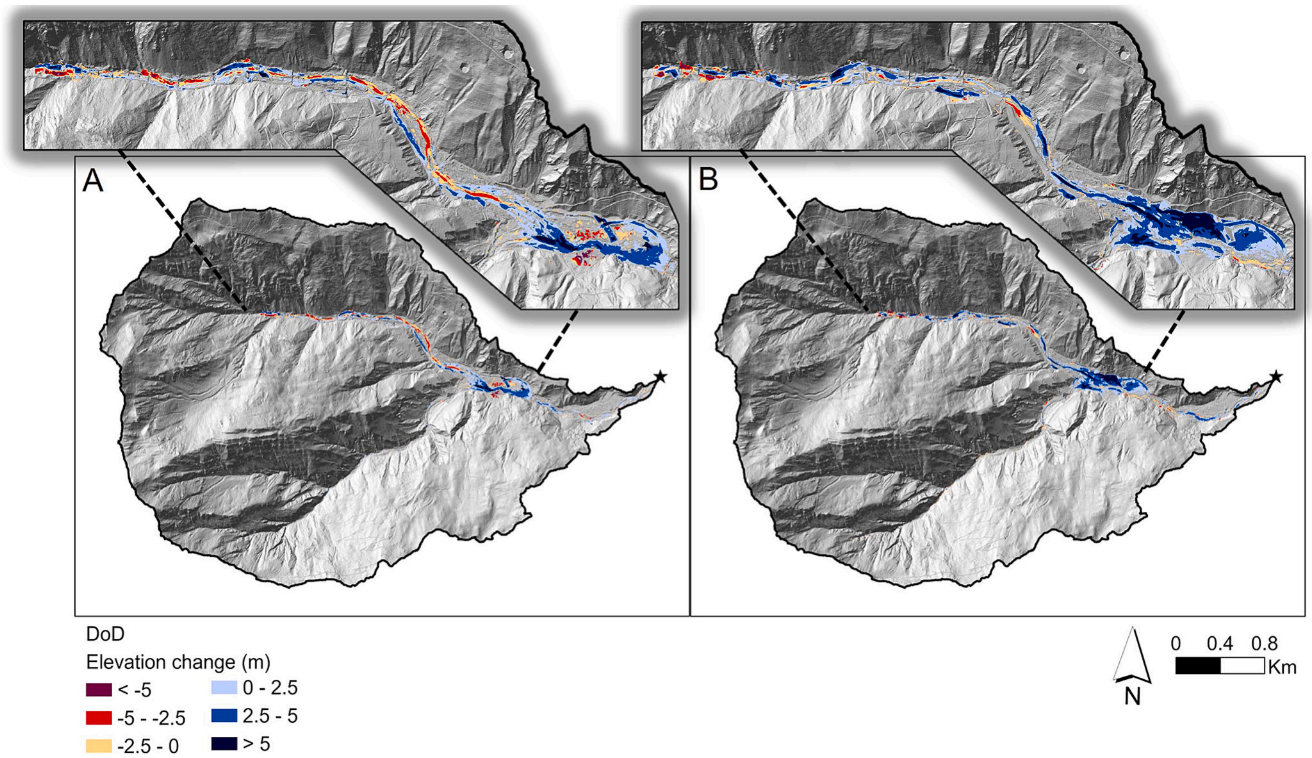

Fig. 8. Example of geomorphic changes along the Miozza channel network derived from 2009 to 2003 DoD (A) and 2018–2009 DoD (B) thresholded with the methodology described in Section 3.3.

erosion and deposition patterns (due to several debris flows that occurred in the past, e.g., 1st November 2003 and 25th March 2005 debris-flow events) in the upper part and a massive deposition downstream the confluence with the D'Archia tributary (Fig. 1**B**), along which no significant morphological changes emerge. This dynamic is recurrent also in the 2018–2009 DoD (Fig. 8B). The Agozza channel is the only channel not showing notable geomorphic changes in the older DoD (i.e., DoD 2009–2003), while Vegliato (i.e., 2019–2010 DoD) and Uccelli (i.e., 2009–2003 DoD) torrents display large and deep erosions throughout the whole channel network. Instead, the Vegliato and Uccelli catchments, in their most recent DoD (i.e., 2022–2019 and 2018–2009, respectively), show balanced erosional and depositional areas, with the former mostly located in the upper part of the basin and the lower part. A complete overview of the geomorphic changes for the whole channel network can be seen in the supplementary material (Fig. S1).

A deep focus on the DoDs is presented in the reaches under investigation (orange frames in Fig. 1), where the interaction with the aforementioned structures (Fig. 6) and sediment dynamics is particularly interesting and quite representative of each basin. In the Vegliato catchment, the alternation of depositional and erosional processes is evident through the years. Fig. 9A1 shows the geomorphic changes during 2019–2010 and, as visible, mostly erosion within 2.5 m was

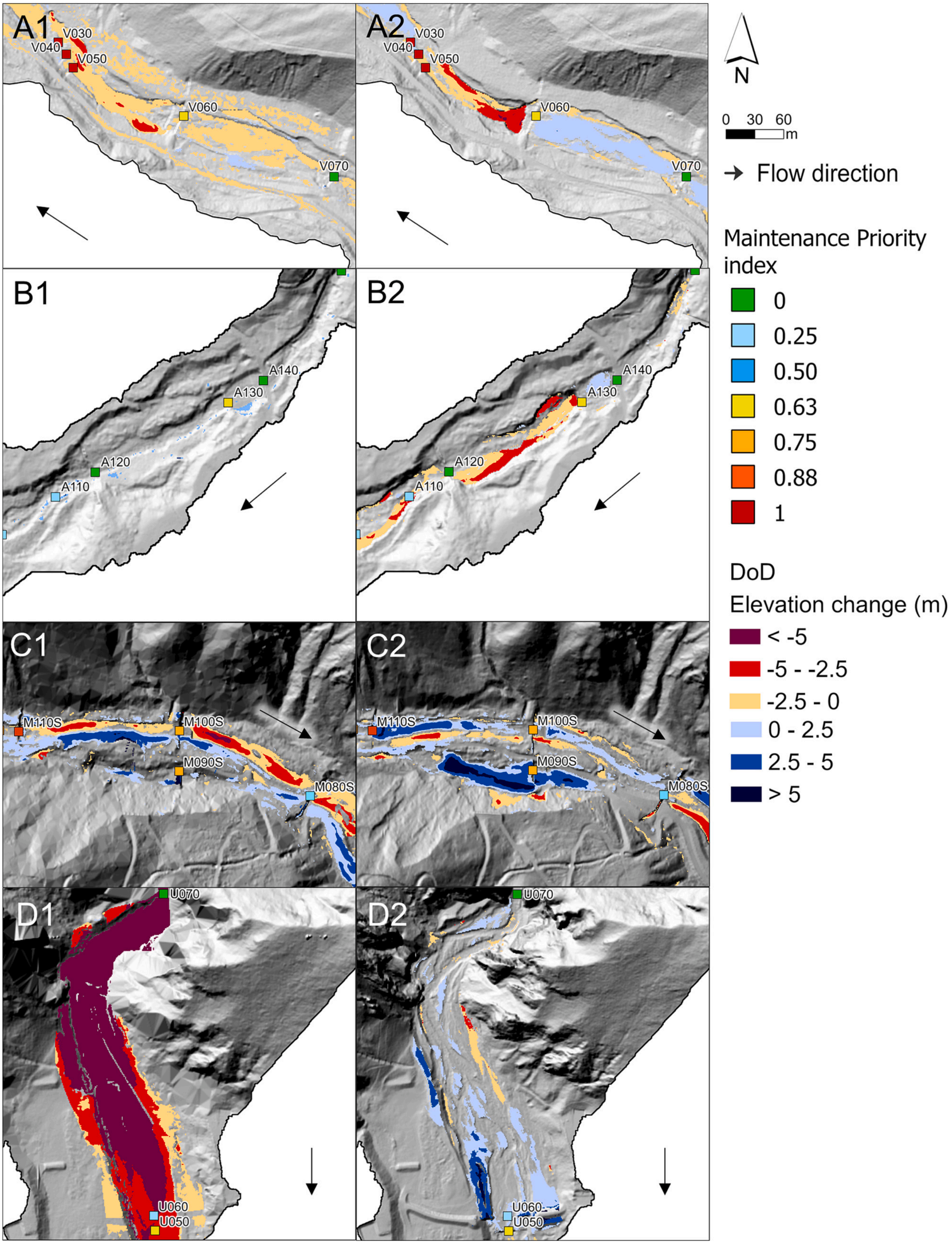

Fig. 9. Multi-temporal geomorphic changes for the reach under investigation obtained from two DoDs: Vegliato catchment (A1, 2019–2010; A2, 2022–2019); Agozza catchment (B1, 2009–2003; B2, 2018–2009); Miozza catchment (C1, 2009–2004; C2, 2018–2009), Uccelli catchment (D1, 2009–2003; D2, 2018–2009).

detected, both upstream and downstream of the check dams with a medium–high *MPi* (i.e., from check dam V030 to V060), involved in the studied reach. In the second time window 2022–2019 (Fig. 9A2), a clearer distinction of the process is reported upstream and downstream check dam V060, which promoted large deposition upstream and deep erosion (even more than 5 m) downstream. The latter is responsible for the scour that currently is undermining the status and functionality of the structure. The quantification of geomorphic changes around the check dam V060 is reported in Table S1 (supplementary material), where the different patterns between the two DoDs are confirmed: downstream and upstream erosions (-4849 m^3 and −3917 m^3, respectively) in the 2019–2010 DoD; downstream erosion and upstream deposition (-4519 m^3 and 2690 m^3, respectively) in the 2022–2019 DoD.

Concerning the Agozza reach (Fig. 9B), the 2009–2003 DoD did not point out any significant change in elevation, as visible in Fig. 9B1. Conversely, the 2018–2009 DoD reported large areas of erosion between check dams A120 and A130. Even though these erosional processes changed the stream morphology, they did not affect significantly the functionality and status of check dam A120, which, in the last survey, was assigned the lowest *MPi* value and greed-rank (Fig. 6B). A depositional area is visible upstream of the check dam A130. This deposition was quantified in 203 m^3, while between the check dam A120 and A130 the net sediment volume was −3921 m^3 (more details in Table S2 in supplementary materials).

The Miozza catchment shows a high sediment dynamic given the large and deep areas of geomorphic changes visible in both DoDs (Fig. 8). In the study reach, during the period 2009–2004 (Fig. 9C1), two parallel patterns of erosion and deposition characterize the main channel between check dams M100S and M110S, while an almost inactive diversion is visible on the right. Indeed, the erosion deepening downstream check dam M100S was more than 5 m while the deposition process prevailed upstream (around 2.5 m; Fig. 9C1). In the period 2018–2009, the patterns of erosion and deposition in the same reach changed, also showing more pronounced dynamics in the right stream with important upstream sediment deposits (around 15000 m^3) stored by the open check dams M090S and marked erosion (up to 2.5 m; Fig. 9C2) at the toe of check dam M100S, as seen in Fig. 6C. Therefore, it is plausible to ascertain the causes of the siphoning and the lack of effectiveness of the check dams M090S and M100S, evaluated in the last field survey (Fig. 6C). The net volumes mobilized between check dams M100S/M090S and M110S are 5406 m^3 and 14991 m^3 in the periods 2009–2003 and 2018–2009, respectively (Table 6). It is useful to point out the order of magnitude of the average depth of deposition (surface raising), which reaches up to 3 m.

Finally, the sediment dynamics in the Uccelli Stream are very different in the two periods (Fig. 9D). The 2009–2003 DoD pointed out large and deep erosion throughout the whole area under investigation (net difference −223425 m^3 upstream the check dam U060, Table S3 in supplementary materials). The extreme erosions are indeed the results of multiple agents. First, the important flash flood of 29th August 2003 (396.2 mm of rain recorded in 24 h in Pontebba) that deeply affected the whole area generated debris flows capable of transporting large quantities of sediments, and second, the removal of such sediment by anthropogenic interventions (carried out immediately after the flash flood) aimed at reducing the risk of future extreme events. In the second period the 2018–2009 DoD reports mainly deposition upstream of the open check dam U060 (net difference 12609 m^3 upstream U060, Table S3 in supplementary materials).

Table 6

Example of erosion and deposition process, and net volume change estimations from the different DoDs in the Miozza reach (Fig. 1). The ± volumes were estimated based on the errors associated with the FIS methodology described in **Section 3.3**.

Study reach	**Downstream check dams M090S and M100S**		**Upstream check dams M090S and M100S**	
DoD	2009–2003	2018–2009	2009–2003	2018–2009
Erosion (m^3)	7146 ± 1117	1983 ± 611	3242 ± 715	3158 ± 907
Deposition (m^3)	3613 ± 806	6775 ± 3039	8649 ± 1592	18148 ± 3039
Net Volume difference (m^3)	−3533 ± 1377	4791 ± 3172	5406 ± 1746	14991 ± 3172
Average Depth of Surface Lowering (m)	2.52 ± 0.39	1.75 ± 0.54	1.82 ± 0.40	1.81 ± 0.52
Average Depth of Surface Raising (m)	1.74 ± 0.39	2.31 ± 0.56	2.47 ± 0.45	2.98 ± 0.50

5. Discussion

The enrichment of cadasters with a Maintenance Priority index provides a snapshot of the state of the torrent control structures within the mountain basins. Indeed, an updated inventory with frequent field surveys permits to identify the most active catchments from the perspective of torrential dynamics, such as in the Miozza basin, where the largest number of structures were no longer found during the field surveys (Fig. 4A). Moreover, the proposed workflow may be a useful indication to mark areas most prone to hazards and could provide more information than in the past to improve intervention planning. An example of this is the check dam M100S (Fig. 3A and 6C) in the Miozza catchment, which, even after reconstruction, shows the same signs of damage caused by erosive processes over time. This issue has also been reported in other debris-flow catchments (Cucchiaro et al., 2019a). Adding an *MPi* as a permanent feature into the cadastral data with classes that emphasize possible intervention priorities is useful to derive spatial distribution, numbers, and statistics about torrent control structures and then compare different basins. In this way, decision-makers can obtain relevant indications on where to primarily invest resources and interventions. Indeed, an analysis and a categorized map like the one shown in Fig. 4B and 5, can provide valuable assistance to local authorities in identifying the basins with either critical or favorable conditions. For instance, during risk analysis the local authorities could assume priority maintenance interventions in the Vegliato basin, where torrent control structures present the highest percentage of red-ranked structures (e.g., Fig. 6A), rather than in the Agozza catchment where the *MPi* of the structures shows mostly green-ranked values (e.g., Fig. 6B), always taking into account the risk elements in each catchment. The proposed *MPi* is simpler compared to the few found in the literature that consider multiple parameters to assess the status and functionality of a channel control work. Dell'Agnese et al. (2013) compared check dam pre- and post-event conditions and quantify the damage in terms of structural deterioration relative to the pre-event conditions, considering event intensity and type, resistance descriptors for each check dam, and linking them to residual functionality. However, the authors highlighted how this index has several limitations because it requires recent events to be surveyed or events from the past to be very well documented. In South Korea, Lee et al., (2022) evaluated the degree of deterioration of existing check dams regarding their service time and localized environmental condition factors through a condition index, which was expressed as condition grades based on assessment criteria that reflected the type, size, and location of the damage. The latter index is certainly more detailed but requires more in-depth field surveys and data processing that are time-consuming. Once the most critical areas have been identified, a simpler and more intuitive index could serve as a guideline and a starting point for further analysis. Indeed, the *MPi* also makes it possible to identify the structures that require more in-depth studies, possibly regarding the objectives for which the interventions were thought and the design choices applied. An example of this is the structure M130 classified with blue-rank of *MPi (*i.e., good structural condition but poor functionality of channel stabilization*)*, in the Miozza Torrent. The check dam (M130S) although recently built (i.e., in 2012), did not show any functionality, as the sediment fluxes outflanked the structure on both banks like most of the torrent control works nearby. Therefore, in a context such as the upper part of the Miozza Torrent, where sediment dynamics are very active and the amount of material transported is high, the planning choices to find more effective strategies should, perhaps, be reconsidered.

The index data can also provide useful numerical parameters for the probabilistic model of structure time to failure as in Paratscha et al. (2019a and 2019b), the stochastic life-cycle performance analysis to assess the long-term effects and costs of prevention structures in managed torrents as in Ballesteros Cánovas et al. (2016), and the physics-based deterioration model and maintenance assessment as in Chahrour et al 2021. Moreover, the *MPi* can also be used as a tool for all technicians or volunteers who work in the field but may not have much prior knowledge of the subject. In this regard, Cortes Arevalo et al. (2016) suggested how a balance between complexity and user-friendliness should be maintained for the development stages of the check dam status pre-screenings in the decision support method. There is an awareness that the simplicity of the proposed index as well as the inevitable simplifications on the assessment of the functionality and status of the torrent control structures may lead to a loss of detail and differentiation of the various cases that may be present. For assessing status and functionality very simple markers are used in Tables 2 and 3, so that they could be easily recognized in the field. However, it is never trivial to identify the main functionality of a torrent control structure (choosing among the multiple ones it may have) in a channel control system where structures were built at different times, with different materials and by different authorities whose objectives were often not declared. Nevertheless, simplification is necessary to make the *MPi* a quick solution for technicians who carry out constant field monitoring of torrent control structures on numerous basins and want to continuously update the cadastre with operations that are sustainable in terms of cost and time. Finally, a simple index has the advantage of being adaptable and editable according to local needs and preferences. For instance, the *MPi* proposed in this work results from the average between the functionality and status scores, weighted by the status factor (**Eq. (1)**, since the intent is to be very conservative and strongly emphasize criticalities. In addition, using the status score as a weight factor enables to directly obtain a $MPi = 1$, independently from the actual functionality, for completely destroyed structures (i.e., from structures with 0 of status score; e.g., Fig. 6G) on which it should be a priority to act. At the same time, for low values of *MPi* (i.e., the intervention is not a priority), the index value suggests reflecting on the design choices that realized interventions intact from a structural but not functional point of view.

An innovative aspect of this work is to link an up-to-date Maintenance Priority index with sediment morphology dynamics analyses over an extended time window by exploiting topographic information. Various kinds of research emphasize the lack of information and knowledge on natural phenomena and the reliability of the data sources available in the risk management process (Chahrour et al., 2021; Tacnet et al., 2014). For example, Paratscha et al. (2019a) highlighted how the biggest uncertainty of the performance prediction models for torrent control infrastructure is not only caused by the limited availability of structure data but also by location-based environmental loads and the individuality of each channel control work. They suggested that workflow optimization could be achieved by incorporating ongoing torrent processes and their frequency through a semi-probabilistic method. Therefore, having accurate multi-temporal topographic data could undoubtedly serve as an important resource and starting point to conduct geomorphic change detection analysis and study the interaction of sediment morphology dynamics with torrent control structures. For instance, thanks to the DoDs in Fig. 8, it is possible to see the typical presence of scour-and-fill cycles in the Miozza torrent, as described by Berger et al. (2011) and Theule et al. (2015) in debris-flow catchments. The occurrence of scour-and-fill cycles is appreciable also in Fig. 3B where a huge deposit of sediment completely covered the check dam M170S, which was operational in the past and may re-emerge in the future as a result of the channel scouring of a debris-flow path. However, without a methodological and detailed workflow that considers the errors associated with the processes of coordinate transformation, co-registration of point clouds, and automatic classification, it would not have been possible to obtain accurate and reliable multi-temporal DoD, useful to distinguish real from noise in terms of morphological changes. Fig. 7 is a prime example of the importance of these aforementioned steps, which are too often overlooked in workflows. The benefits of co-registration were highlighted also in Cucchiaro et al. (2020), while Williams et al. (2018) emphasized, as in the present study, how geomorphic change detection can be biased by significant errors if a critical analysis of the DoD data sets is not carried out, especially in mountain basins with steep slopes (Cavalli et al., 2017; Pellegrini et al., 2021).

The information obtained from the DoDs can corroborate and enrich the observations made during field inspections of the torrent control structures, adding knowledge to be further investigated in the post-processing evaluation of the status and functionality of the field results. For example, DoDs can support or enrich (even quantitatively) assessments made in the field through markers (in Table 2) on erosion and deposition processes over time for check dams whose main function is sediment retention. DoDs can also help to confirm structural status assessments evidenced by field markers, such as foundation erosion due to local scouring processes. Thus DoDs, combined with field evidence, are also useful to monitor and highlight the undesirable effects of the torrent control structures (e.g., downstream incision by sediment starving, ill-positioned dams increasing bank erosion, etc.), that could be corrected (or not) in further maintenance operations. At the same time, the integration of the *MPi* of torrent control structures with data on the evolution of sediment morphology dynamics (i.e., DoDs at catchment and reach scale) over long periods can certainly support a post-evaluation of the effectiveness of interventions and give relevant indications on future trajectories. Various examples of the usefulness of exploiting the proposed integrated approach can be found in the case studies analyzed. In the Miozza catchment, several check dams built along the main channel have certainly influenced the patterns of erosion and deposition but, at the same time, the structures have been heavily damaged by these processes. For instance, the local scouring due to energy dissipation and erosion observed downstream of some check dams (e.g., Fig. 6C) undermine their stability as highlighted by several researchers (e.g., Lenzi and Comiti, 2003; Piton and Recking, 2017; Victoriano et al., 2018). Other torrent control structures, such as the open check dam M090S (Fig. 9C2), successfully fulfilled their task of storing and retaining sediment. However, due to the challenging location of the frame dam, emptying the sediment storage proved to be a difficult operation. As a result, the stream was forced to find an alternative path, rendering the protective action of the structure useless. Integrating DoD information with *MPi* maps allowed the identification of areas with less or more sediment dynamics interaction with the structures. An example of this can be seen in Fig. 5C where the right tributary of the Miozza torrent (i.e., the D'Archia stream) shows little active dynamics, and the torrent control structures are for the most part orange and green in terms of *MPi* rank. Also, in the Agozza catchment, the study of sediment morphology dynamics could direct the choices of decision-makers toward non-priority interventions. Indeed, the recent maintenance works (i.e., numerous check dams in the lower part of the basin were reconstructed in 2020, such as structure A120 in Fig. 6B) carried out after the Vaia Storm, appear to have stabilized the situation, as observed in the 2018–2009 DoD (see Fig. S1C2 in supplementary materials). The interweaving of DoDs and *MPi* information can provide more data, perhaps not available in the past, to better plan future interventions or find more appropriate solutions. For instance, the check dams along the Miozza torrent successfully reduced the slope and temporarily stored the sediment. However, these structures did not prove to be an optimal solution in terms of costs/benefits considering the frequent occurrence of high-magnitude debris flow events. A long-term useful answer for debris-flow control could be dictated by the morphological conformation of the Miozza basin, which has a low gradient area downstream of the confluence with the D'Archia stream (Fig. 1C) and where natural sediment retention has already been overfilled by now (as seen in Fig. 8B). This area could be exploited as a sediment retention basin by coupling it with the transformation of the check dam M050 (currently a non-functioning water intake system as it is filled by sediment) into an open check dam so that some of the stored debris would slowly flow downstream. The sediment morphology dynamics of the Vegliato torrent, when analyzed together with the *MPi* of the present works, could also provide interesting information to plan more targeted maintenance of structures. Indeed, the significant ongoing erosional processes caused considerable damage to the torrent control structures (e.g., the scour-hole of the check dam V060; Fig. 6D). Knowing this current activity of the system associated with the condition of each structure it is possible to identify structures that are going to collapse and release stored material, becoming new sediment sources and increasing the risk downstream (e.g., check dam V060; Fig. 6D), as stated in many studies (Cucchiaro et al 2019b; Mazzorana et al., 2014; 2018). In the Vegliato basin, there are numerous torrent control structures built after the 1976 earthquake, which are severely damaged by the ongoing erosional processes generated by the Mount Cjampon landslide (present in the upper part of the basin), which is increasingly active as evident from the DoDs (see Fig. S1A in supplementary materials). This information can help in finding the most appropriate strategies to preserve the status and functionality of existing torrent control structures and maybe consider other more effective engineering solutions (e.g., flexible ring-net barriers, retention basins, the relocation of some element at risk, the building of channel or diversion berms) to reduce the debris-flow risk, but also to efficiently allocate public financial resources. Another example of how the data obtained by the DoDs and the *MPi* could be useful to direct the maintenance plans of the torrent control structures is the case of the open check dam U060 (Fig. 6B), which has lost its filtering capacity and had a huge deposit of material upstream as shown by 2018–2009 DoD (Fig. 9D2). Moreover, the structure U060, recently built, was classified with blue-rank of *MPi* (i.e., good structural condition but poor functionality of regulating sediment transport by sorting specific particles), underlining how important is maintenance but also the planning and design of the filter openings in terms of optimal size. As underlined by Marchi et al. (2019) and Mazzorana et al. (2008 and 2014) the maintenance costs are often not considered when planning interventions. Indeed, it is important to include maintenance operations as well as the impact of progressive deterioration of existing infrastructures in risk analyses of managed torrents, to obtain more realistic cost-benefit ratios of the adopted strategies and choose the best solutions (Ballesteros Cánovas et al., 2016). Furthermore, DoDs and *MPi* index could provide a starting database of numerical values for risk prediction models. Mazzorana et al. (2018) stated how it is essential to systematically collect data about the ongoing scouring process downstream of the considered check dams, to monitor seepage filtration phenomena, and to use such data for broader prediction purposes.

Therefore, constant monitoring of the status and functionality of torrent control works is fundamental. Field surveys are preferable after extraordinary events but also during ordinary conditions to maintain the cadastre up to date. The same suggestion might work for HRT data, which must cover a sufficient time span to recognize morphological changes. This temporal window is however strongly dependent on the basin and the nature of sediment dynamics. It is not easy to have multi-temporal basin-scale DTMs available for large time spans (e.g., 10–20 years), mainly because in the past the cost of HRT data was high. Nowadays it is possible to carry out low-cost surveys by taking advantage of new technologies and techniques (e.g., Unmanned Aerial Vehicle with Structure from Motion; Cucchiaro et al., 2018). Moreover, by identifying with post-event geomorphological surveys (e.g., Borga et al., 2008; Marchi et al., 2009) or remotely (e.g., exploiting high-resolution satellite images; Cislaghi and Bischetti, 2022) the areas affected by significant changes, it permits to carry out ad hoc HRT surveys and structures inspections only in specific zones (e.g., a buffer around the main channel or torrent control structures), if it is not feasible to cover the entire catchment due to cost and time constraints.

6. Conclusions

The proposed approach based on the integration of a simple *Maintenance Priority index* of torrent control structures with the multi-temporal data on the evolution of sediment morphology dynamics (i.e., multi-temporal DoDs at catchment and reach scale), proved to be very valuable in the test-catchments analyzed to support a post evaluation of the effectiveness of interventions over time. In this research, various real examples of the proposed methodology emphasized the usefulness of providing more complete information by exploiting field surveys and remote sensing data, in a context such as the risk management process where uncertainty and incomplete information on the ongoing phenomena prevails. Indeed, it is important to underline the need to use a methodological and detailed workflow that considers and reduces the errors associated with different HRT data, without which it would not have been possible to obtain accurate and valid multi-temporal DoD.

An updating cadastre of torrent control structures with the addition of a very simple, quick, and user-friendly *MPi* of works certainly help to constantly identify areas most prone to hazards and provide guidelines on where decision-makers could better primarily invest resources. Furthermore, by integrating also the information about the sediment morphology dynamics with torrent control structures over time, it is possible to exploit more data than in the past to improve the intervention planning, find more appropriate solutions or direct the maintenance works. The realized database could be a starting point for carrying out further analysis or provide numerical data for prediction models of the life-cycle of torrent control structures in risk management processes.

This research and the methodological workflow carried out in a few test basins are certainly a basis from which to draw up guidelines to be exported and used in other catchments equipped with torrent control structures. This could provide increasingly up-to-date information and comprehensive tools to decision-makers for supporting sustainable and effective risk management decisions.

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

Data will be made available on request.

Acknowledgements

This study was carried out within the PNRR research activities of the consortium iNEST (Interconnected Nord-Est Innovation Ecosystem) funded by the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.5 – D.D. 1058 23/06/2022, ECS00000043). This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them. Finally, this research was developed within the project financed with PICC_BIRD2121_02 funds, Dept. TESAF, Università degli Studi di Padova.

We would like to acknowledge the efforts of Francesco Piccinin, Giorgia Chiarel and Michele Missoni during the intensive field campaign.

The authors wish to thank the Service for mountain land management, remediation, and irrigation of the FVG Region for providing information and images about the torrent control works carried out in the various basins of the FVG Region.

We would also like to thank Lorenzo Marchi, Marco Cavalli, and Matteo Cesca for the historical images of the Miozza catchment and Federico Sgobino for the valuable scientific documentation on the Vegliato Torrent.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2023.107599.

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