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Assessing the effect of torrent control structures on sediment continuity and connectivity

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ABSTRACT

The study investigated the effect of torrent control structures on the sediment cascade in the Vegliato mountain basin (Italy) related to an intense rainfall event of 50 years return interval. The Index of Connectivity (IC) was exploited to analyze the interaction of structures with longitudinal sediment (dis)connectivity. Moreover, the Sediment Continuity Ratio (SCR) was used to assess the effect on sediment (dis)continuity. The SCR is a novel parameter considering for each torrent control structure, the net balance of sediment deposition and erosion, and the cumulative proportion of the sediment cascade arriving from upstream. The SCR emphasises which structure was more prone to continuity or discontinuity during an event and to what extent compared to other structures. Moreover, a multi-perspective framework was carried out to help the interpretation of the SCR results within the context of the study area. The results of the (dis)connectivity assessment showed that the torrent control structures impacted sediment dynamics by influencing the slope and flow confinement, which in turn affected the IC. The (dis)continuity assessment showed structures prone to continuity mainly located in the upstream part of the catchment, where most of the over 60000 m^3 of sediment was generated. In contrast, structures prone to discontinuity were located in the downstream part, where deposition processes were favoured during the analyzed period. A total of 65 % of the structures similarly affected both (dis)continuity and (dis)connectivity. Data on individual structure functions and maintenance conditions were also included, emphasizing the importance of these factors in planning mountain basins management interventions. The study proposed a new metric that, despite being based on a single large event and a single basin, still provides a useful approach to investigate the interaction between sediments and individual structures, the entire sediment cascade and the channel control system.

1. Introduction

In steep alpine catchments barriers like torrent control structures are fundamental to control water, sediment and wood fluxes. Their presence in mountain areas is justified by the existence of sensitive infrastructures and inhabitants for which risk reduction, especially during extreme events, is sought (Comiti, 2012). The expansion of anthropization associated with the increasing occurrence of extreme flood events due to climate change (Blöschl et al., 2017) calls for watershed management solutions capable of reducing the risk in specific locations. Particularly, flash flood events can rapidly affect the ordinary conditions of mountain streams. These occur due to intense and short precipitation (i.e., less than 24 h) within a limited area, producing high peak discharge and causing abrupt hydrogeomorphic responses (Gaume et al., 2009). The responses of the catchment to flash floods include slope instabilities such as landslides and debris flows, as well as morphological changes within the channel network, including bank erosions, streambed aggradation and degradation, boulder mobility and more (Turowski et al., 2009).

Common engineering solutions against these phenomena include check dams and bed sills. Both are built transversally across the channel, with the latter at bed level to prevent bed degradation (Marchi et al., 2019). Check dams, on the other hand, are constructed above the

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original bed profile and provide different functions such as slope reduction, channel and bed stabilization, regulation and retention of sediment transport, prevention of sediment production, sediment sources consolidation, and debris flow energy dissipation (Piton et al., 2024). Nonetheless, it is well established that their effectiveness tends to progressively diminish over time if not adequately maintained (e.g., sediment retention check dams left unemptied when filled; Marchi et al., 2019). Therefore, when poorly designed or irregularly maintained, torrent control works are observed to have minimal effect against extreme floods (Lucas-Borja et al., 2021). At the same time, under these poor conditions, check dams can generate unwanted effects that, if not prevented or controlled, can lead to structural instabilities and, eventually, to their collapse and consequent sudden release of sediment stored upstream (Baggio and D'Agostino, 2022; Mazzorana et al., 2018). Therefore, the assessment of the physical and functional condition of channel control systems is of major importance for the maintenance of the existing structures and the design of new ones (Mazzorana et al., 2014).

In addition to evaluating the integrity and functionality, the analysis of sediment morphology dynamics is crucial to recognize the true effectiveness of torrent control works (Piton and Recking, 2017). Morphological changes represent a proxy for inferring sediment dynamics, and a quantitative assessment of these changes over time can provide important information on watershed management strategies. For example, the identification of erosion and deposition patterns, the quantification of sediment volumes mobilized during a flood event, and the understanding of areas more prone to delivering sediment into the channel network can support the development of a priority intervention plan for torrent control structures (Cucchiaro et al., 2024). To this end, the number of studies exploiting High-Resolution Topography (HRT) products, like the DTM (Digital Terrain Models) of Difference (DoD), has rapidly increased to achieve the aforementioned outcomes (Carrivick et al., 2016; Pellegrini et al., 2021; Oss Cazzador et al., 2021; Wheaton et al., 2010). Moreover, recent analyses based on HRT data employed geomorphometric approaches to understand how the torrent control structures affect the sediment pathways, thus modifying the connectivity linkages among the catchment's compartments (Marchi et al., 2019).

The connectivity paradigm expresses the degree of linkage to which a catchment transfers sediment particles from sediment sources to sink areas, being them on the hillslopes, between hillslopes and channels, or between channel reaches (Brierley et al., 2006; Heckmann et al., 2018; Hooke, 2003; Najafi et al., 2021). Unravelling the connectivity pathways permits the identification of those areas more likely to generate, transfer, and store sediment within a river basin (Fryirs, 2013). However, these pathways can be affected by anthropic infrastructures built along the channel network at multiple dimensions according to positive and negative feedbacks (e.g., dams interrupt longitudinal connectivity; embankments reduce lateral connectivity; channel lining reduce vertical connectivity; Poeppl et al., 2017). Moreover, torrent control structures are built specifically to influence the sediment transport mechanisms, thus altering the sediment cascade (Piton and Recking, 2017). Investigating how these structures reduce or not the continuity of the sediment cascade helps to comprehend their overall effectiveness during flood events. Sediment continuity focuses on the principle of mass conservation within a system (Hinderer, 2012; Slaymaker, 2003) and refers specifically to the physical exchange of mass from one part of the fluvial system to another (Joyce et al., 2018). Although closely tied to the concept of sediment connectivity, as the degree of connectivity influences the extent to which various parts contribute to the sediment cascade (Fryirs and Brierley, 2013; Fryirs et al., 2007), in this work continuity is conceived as a sediment conservation issue. Hence, when referring to sediment continuity, it is important to consider the progressive sum of sediment conveyed downstream. It results from unravelling the balance among erosion, deposition and storage of sediment volumes that are moved and transported downstream during floods, hence the sediment cascade (Burt and Allison, 2010, Schumm, 1977). To summarize, while connectivity appraises how different basin's compartments are interlinked, continuity concerns the variation of storage and the dynamics of sediment volumes.

Quantifying the effect of torrent control structures on longitudinal sediment continuity and connectivity is challenging, given the complexity of mountain streams and the multiple spatial and temporal dimensions in which such concepts are investigated (Marchi et al., 2019). In piedmont areas, Galia et al. (2021) tracked the displacement of tagged particles to conclude that connectivity was higher in a reach managed with a series of check dams compared to one without structures. On the contrary, according to the variation in grain sizes found by Galia and Škarpich (2017), it was possible to conclude that check dams have a significant impact on coarse longitudinal connectivity. In headwater reaches, where torrent control structures are built to reduce downstream sediment fluxes, Torresani et al. (2021) and Cucchiaro et al. (2019) used geomorphometric approaches based on IC (Index of Connectivity, Cavalli et al., 2013) and DoD, to verify if check dams can suppress connectivity. Only a few studies addressed the role of torrent control structures in the regulation of sediment continuity (Langhammer, 2010; Simoni et al., 2017), as intended in the present work. Whether it is about continuity or connectivity, the actual condition of the structures is a fundamental factor as the longitudinal fluxes of sediment can be disrupted when the check dams are empty, but restored to a certain degree when they are overfilled (Marchi et al., 2019). For this reason, integrating the analysis of continuity and connectivity with an up-to-date assessment of the current state of maintenance of torrent control structures is of uttermost importance to design and support a sustainable and effective plan of interventions in mountain streams.

The primary aim of the present study is to assess the effect of torrent control structures on sediment continuity and connectivity in a mountain basin, exploiting HRT data covering three years.

The specific objectives are: i) to assess the impact on longitudinal (dis)connectivity through a geomorphometric index; ii) to develop and apply a new approach to measure how prone the torrent control structures are to permit or reduce the (dis)continuity of the sediment cascade during a flash flood event; iii) to provide a framework that can be used to interpret the results of the assessment within the context of the study area, aiming to improve watershed management interventions. Despite the study deals with a single large event and with a single basin, the proposed framework could be useful, after further validations, even beyond the study area.

2. Study area

The study area is the Vegliato catchment, located within the municipality of Gemona del Friuli (UD), NE Italy, in the Julian Prealps (Fig. 1**A**). The catchment spans an area of 4.4 km^2 considering the outlet as visible in Fig. 1**B**, and it features elevation ranging from 355 to 1739 m a.s.l, with an average slope of 35°. The channel network extends approximately 9 km, draining from Mount Chiampon (1709 m a.s.l.), Mount Deneal (1701 m a.s.l.) and Mount Cuarnan (1372 m a.s.l.), before converging into the Ledra River, a tributary of the Tagliamento River. A large alluvial fan develops at the base of the reliefs, where the municipality of Gemona del Friuli is situated. The valley's central line aligns with a significant east–west oriented fault known as the Periadriatic (Barcis-Staro Selo in Carulli, 2006 and Gemona-Kobarid in Zanferrari et al., 2013). The lower part of the catchment is mainly covered by a typical mesophytic mixed deciduous forest comprising manna ash (*Fraxinus ornus*), hop hornbeam (*Ostrya carpinifolia*) and beech (*Fagus sylvatica*). In contrast, vast areas in the upper part and channel banks have been reforested with coniferous species, primarily black pine (*Pinus nigra)* and spruce (*Picea abies*). Notably, a consistent portion of the study area is covered by bare rock and loose sediments, while grasslands and open meadows constitute only a minor portion of the overall land cover (Fig. 1**C**).

The Vegliato Torrent is typically dry for most of the year, except

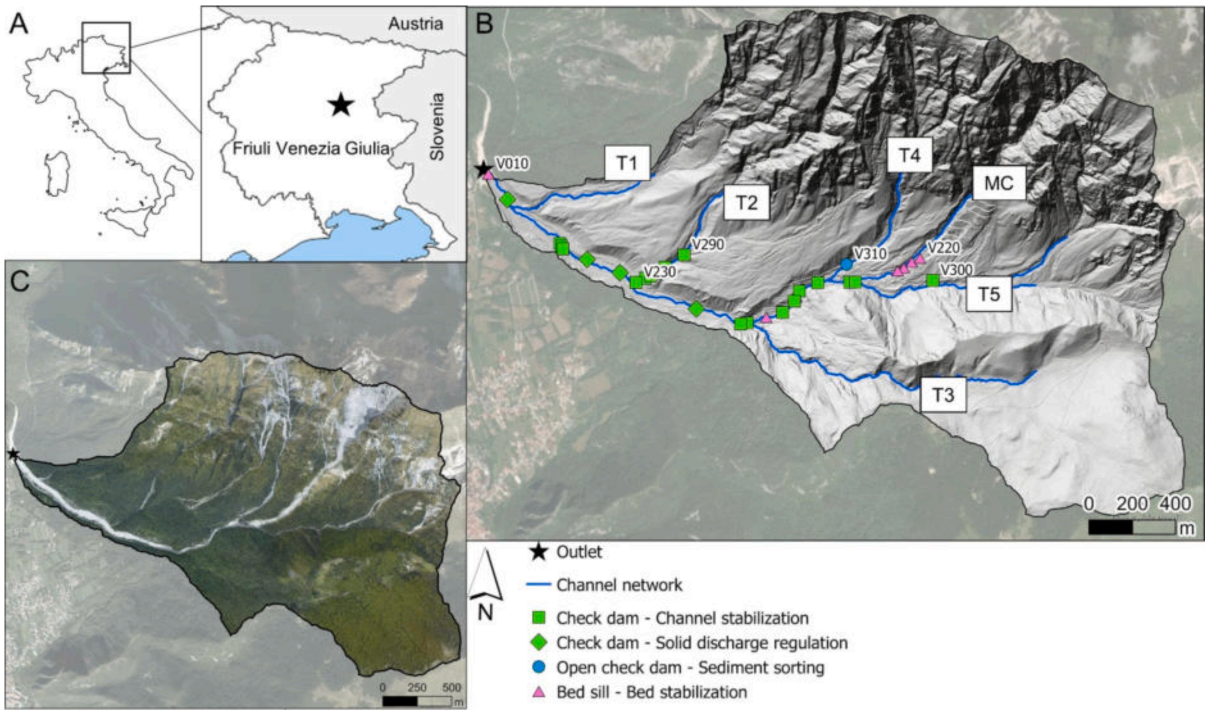

Fig. 1. Location of the study catchment (A) in the Friuli Venezia Giulia Region (Italy). The Vegliato (B) is characterized by several torrent control structures, located along the main channel (MC) and tributaries (T1-5), classified according to different functions. The active channel and sediment sources are visible even though the forest covers most of the catchment (C).

during intense summer storms or prolonged rainfall events characteristic of the spring and autumn seasons. Abundant precipitation is recorded in these seasons, considering that the annual rainfall in this subalpine zone ranges from 2400 to 3400 mm (ARPA Fvg and – OSMER, 2023). Rainfall events trigger sediment transport in the form of debris flows and debris floods in the steeper channels and hyperconcentrated and alluvial fluxes in the lower channels. Notably, past major events in the study area have been reported by Coccolo and Sgobino (1996). The 1976 earthquake (Mw6.5 on 6th May and Mw6.1 on 15th September) deeply affected the whole Friuli Venezia Giulia Region, resulting in massive landslides and rockfall from Mount Chiampon and Mount Deneal (Govi and Sarzana, 1977). In the following years, multiple debris floods were initiated by intense rainfall events, such as that on June 9th 1987, where 125 mm of rainfall generated a debris flood of over 8×10^5 m^3 of sediment.

In response to the geomorphic challenges in the area, a diverse torrent control system was built up, consisting mainly of check dams, bed sills and bank protection structures (Fig. 1**B**). Focusing on the transverse structures, currently the Vegliato Torrent has 24 check dams and 7 bed sills (Martini et al., 2023). These structures are located along the main channel and in some of the tributaries and were identified by a unique code with the initial letter of the basin and a progressive number (e.g., V010). Thus, in this study, the channel network has been divided into six distinct reaches: the main channel and five tributaries. The main characteristics of the six study reaches are presented in Table 1.

Table 1
Characteristics of the Vegliato channel network subdivided into main channel (MC) and tributaries (T1-5).

Study reach	Length (km)	Average width (m)	Slope (%)	Structures
MC	3.03	25	22	V010-V220
T1	0.77	3.8	26	–
T2	0.75	5.3	33	V230-V290
T3	1.69	<1	26	–
T4	0.88	16	48	V310
T5	1.43	14.9	27	V300

In July 2021, after intense rainfalls, signatures of rockfall in the upper part of the catchment and sediment transport in the lower part were found together with massive morphological variations in correspondence to some hydraulic structures. Therefore, an analysis to characterize the rainfall event that likely triggered the sediment cascade was developed, involving continuity and connectivity assessments. Moreover, two airborne laser scanner (ALS) surveys, realized at high-resolution in 2019 and 2022, were considered for the entire basin to assess the morphology changes before and after the July 2021 event.

3. Material and methods

3.1. Rainfall data

The rainfall data were collected by a rain gauge with an accuracy of 0.2 mm located in the meteorological station of Gemona del Friuli (elevation 307 m a.s.l., ~1 km to the Vegliato) and obtained through the Regional Meteorological Observatory of FVG (https://www.osmer.fvg.it). Rainfall analysis was carried out at multi-scale.

First, using daily data, it was possible to: i) obtain an overview of historical precipitations in the area from April 2003 to October 2023; and ii) thin out the historical precipitation by focusing on the larger events that occurred during the period 2019–2022 for which the geomorphometric analysis was computed (**see Section 3.3**). Then, using hourly data it was possible to calculate the maximum rainfall intensity in 1 h (I_{1h}) to compare the selected events. To better understand the magnitude expressed by the events in the Vegliato, the measured rainfall intensities (I_{1h}) were compared with the rainfall depth-duration-frequency (DDF) curves compiled for the Friuli Venezia Region through RainMapFVG, a software for rainfall regionalization exploiting hourly rainfall time series (1920–2013) from 130 rain gauge stations (Borga et al., 2005). Consequently, it was possible to obtain the Return Intervals (RI). Finally, a targeted and deeper analysis was carried out using data collected every minute from the same station to characterize the event occurred in July 2021, to which the cascade is primarily ascribed. In particular, the maximum rainfall intensity in 60 min was recalculated on a mobile window rather than fixed hours (I_{060}), alongside those in 5 (I_{005}), 10 (I_{010}), 15 (I_{015}), 30 (I_{030}) and 120 (I_{120}) min.

3.2. Torrent control works and longitudinal sediment connectivity

Sediment connectivity and torrent control structures along the Vegliato channel network were analyzed using the geomorphometric Index of Connectivity (IC; Borselli et al., 2008; Cavalli et al., 2013). The IC involves two components according to its formula (**eq.1**):

$$IC = log_{10}\frac{(Dup)}{(Ddn)} = log_{10}\frac{(\overline{WS}\sqrt{A})}{(\sum_i \frac{d_i}{S_i W_i})} \quad (1)$$

where, upslope component (D_{up}) includes the topographic parameters related to the upslope area draining to a specific raster cell. Hence, A is the contributing area (m^2), and W and S are the average values of the weighting factor and slope (m/m) of the upslope area, respectively. The downslope component (D_{dn}) instead includes the features affecting the transfer of sediment along the pathway from the specific raster cell to a target. Furthermore, d_i is the length (m) of the path along the i^{th} cell, W_i is the weighting factor and S_i is the slope gradient along the i^{th} cell. Finally, the IC value for each cell is obtained from the logarithmic ratio between the upslope and downslope components.

In this study, a roughness parameter was used as W factor as calculated in Cavalli and Marchi (2008). Moreover, the target of the IC computation was set at the outlet of the catchment to infer also the longitudinal connectivity, i.e., the linkages along the channels. The computation of all the parameters presented in this section was carried out in Rstudio (Posit team, 2023), through a new set of scripts R_IC (Baggio et al., 2022; Martini et al., 2022a). The IC map for the Vegliato catchment was generated using the 2022 DTM at 1 m resolution. The 2022 DTM was selected over the 2019 DTM to meet the purpose of the study, which aims to assess the effect of torrent control works on (dis) connectivity affected by a flood event. The use of the 2022 DTM enabled the generation of an IC map capable of capturing the results of the event, thus serving as a post-event tool to reconstruct the interaction between torrent control works and sediment connectivity.

To quantify the impact of torrent control structures on longitudinal connectivity, differences between downstream and upstream IC values were considered for each structure. IC values were extracted from buffer zones of the active channel within a distance of 15 m upstream and downstream of the structure. This distance was chosen based on the minimum inter-distance among the structures. Moreover, this distance ensures that the IC variations are more likely attributable to the effects of the structure under investigation. A structure showing a significant difference between upstream and downstream IC values is associated to disconnectivity, whereas a structure showing no significant difference is associated to connectivity. Differences between upstream and downstream values' distribution were tested using the non-parametric Mann-Whitney (p-value < 0.01).

3.3. Torrent control structures and sediment continuity Ratio

The effects of torrent control structures on the sediment cascade generated in the period between the two ALS surveys, and mostly during the only significant event of July 2021 (**Section 2**), was primarily assessed through the implementation of a novel parameter, namely the Sediment Continuity Ratio (SCR). This parameter evaluates the ability of a torrent control system to intercept and store a proportion of the sediment volumes constituting the cascade. It helps identify which structures were most prone to either permitting or limiting sediment (dis)continuity during a flood event.

The following steps were taken to derive the required data and to elaborate the SCR.

Within the study catchment, a spatial domain was delineated (**Step *i*,** Fig. 2), representing the area in which a DoD analysis was performed. The domain was shaped starting from the active channel and applying a variable buffer along the channel network (1 to 50 m) to ensure that all morphological variations and torrent control works were included. In the Vegliato Torrent, the domain included the five tributaries (T1, T2, T3, T4, T5) and the main channel. Within the spatial domain, an Area of Influence (AoI) was delineated for each structure (**Step *ii*,** Fig. 2**)**, using the exact position obtained from the database (Martini et al., 2023). For the computation of the SCR in the Vegliato catchment, where multiple torrent control works are built along the channel network, an AoI was defined as the channel reach that extends from a structure to its closest upstream one. In other contexts, different approaches might be considered, such as those based on slope breaks in the longitudinal profile, main sediment transport process (e.g., debris flows, debris flood, bedload), or multi-criteria methodologies (e.g., Rinaldi et al. 2013).

To obtain volumetric data on sediment mobilization between 2019 and 2022, the 2022–2019 DoD of the Vegliato catchment (**Step *iii*,** Fig. 2**)** was used. The DoD was generated starting from two DTMs with a spatial resolution of 1 m, which were derived from the interpolation of co-registered point clouds (point density between 16 to 21.6pt/m^2) acquired by ALS surveys conducted in 2019 and 2022. The error propagation procedure, based on the Fuzzy Inference System (FIS) approach, and the probabilistic minLoD thresholding were adopted to ensure robustness of the final DoD (more information in Cucchiaro et al., 2024).

The DoD budget segregation function, available in the Geomorphic Change Detection toolkit (GCD; Wheaton et al., 2010), was used to extract the volumes of sediment displacement (m^3 of sediment erosion and disposition) in each AoI (**Step *iv*,** Fig. 2**)**.

The SCR for each i^{th} structure was computed (**Step *v*,** Fig. 2**)** after few mathematical steps (Supplementary material**,** table S.1) using the final formula (**eq.2**)

$$SCR = \left[\frac{D_i\_E_i}{E_i + \sum_{j=1}^{i-1}(E_j - D_j)}\right] \times 100 \quad (2)$$

Where, D_i represents the volume of sediment deposited within the AoI of the structure i under investigation, E_i represents the volume of sediment eroded within the AoI of the same structure i, E_j and D_j represent the volume of sediment eroded and deposited within the AoI of the j^{th} upstream structures, respectively. The SCR is the ratio between the net sediment displacement in each structure's AoI and the overall sediment input. The net sediment displacement (numerator in eq.2) represents the balance between two processes, deposition and erosion. The sediment input (denominator in eq.2) consists of two components: the erosion within the same AoI and the cumulative net fraction of sediment passed over the upstream structures, hence the available sediment delivered from upstream, representing a share of the sediment cascade (Fig. 3). If present, the net fraction conveyed by the tributaries is added to the overall sediment input. If a positive net budget (i.e., sediment surplus) results from the DoD, the value is reintegrated into the sediment cascade, as long as it remains within the error range defined and specified by the GCD analysis. Sediment surplus can result from inaccuracies ascribable to errors related to DoD computation (e.g., DTMs not properly co-registered; FIS scheme poorly calibrated; DoD probabilistic thresholds inadequately chosen). An inaccurate delimitation of the AoI (**Step *ii*,** Fig. 2**)**, excluding major sediment sources that actively supplied sediment, could represent another source of error.

The SCR ranges from -100 % to $+ 100$ %, where negative values indicate structures prone to continuity and positive values indicate structures prone to discontinuity. Moreover, the lower the negative values of the SCR, the greater the continuity. In the same way, the higher the positive values, the greater the discontinuity.

The SCR provides a quantitative metric of (dis)continuity. For example, a value of -10 % indicates continuity and suggests that the net sediment displacement within the AoI shows more erosion than

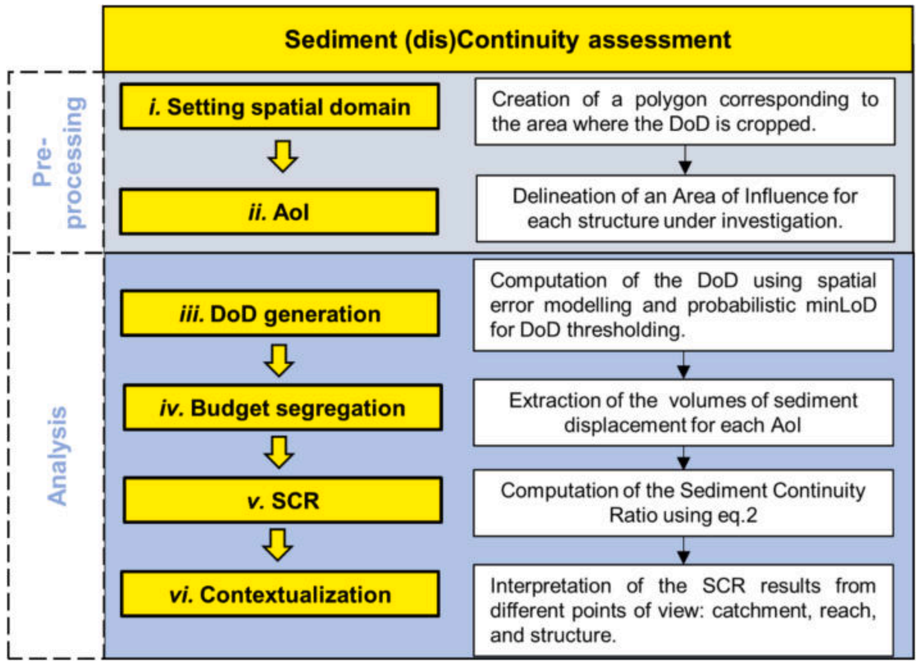

Fig. 2. Workflow of the (dis)continuity assessment carried out in this study. Progressive steps were followed and grouped according to two main sections concerning data pre-processing and analysis.

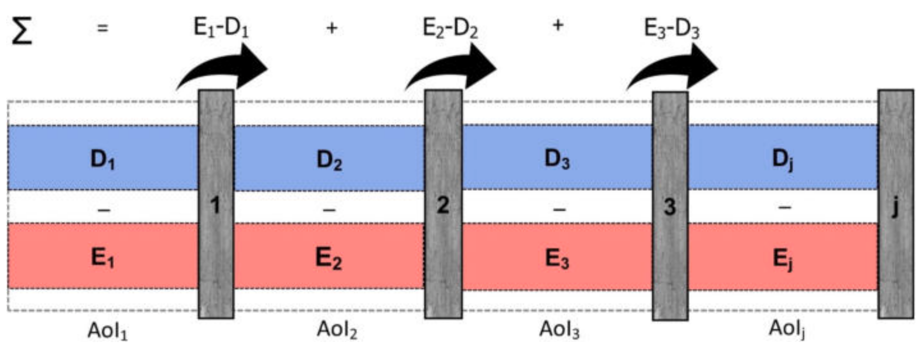

Fig. 3. Schematic representation of the SCR. For each AoI, the volume of sediment eroded (E), deposited (D) and the difference between the two, is involved. The cumulative net fraction of sediment passed over the upstream structures is also considered.

deposition, proportionate to the overall sediment input by 10 %, for example -100 m^3/1000 m^3. Conversely, positive values indicate that the net sediment displacement favours deposition over erosion.

3.4. Contextualizing sediment (dis)continuity: A multi-perspective framework to interpret the SCR

The SCR provides a snapshot for each structure based on geomorphic variations that occurred within a selected time window covered by the DoD. However, to effectively use the SCR for management purposes, it is essential to contextualize it within a framework that takes into account the characteristics of the study site. In this work, it was chosen to frame the (dis)continuity assessment within three points of view:

i) Catchment: the SCR was assessed together with the distribution of sediment sources of the Vegliato catchment to understand the location of the torrent control structures with respect to the areas potentially providing sediment supply to the channel network. The sediment sources were manually mapped in ArcGIS Pro 3.1.0, using the 2019 and 2022 orthophotos at 20 cm pixel resolution (Cucchiaro et al., 2024), thus allowing to detect potential active zones during the 2019–2022 period.

ii) Reach: the SCR was analyzed in respect to the area, length and slope of the AoIs to observe potential patterns related to the characteristics of the reaches, since the sediment eroded or deposited within an AoI can be intrinsically limited or promoted by its length, area and slope. Therefore, to compare the results of SCR among different structures, these three variables were extrapolated from the AoIs (**Step *ii*,** Fig. 2**).**

iii) Structure: the effect on (dis)continuity was compared to the effect on the (dis)connectivity. Therefore, SCR (**section 3.3**) and IC (**section 3.2**) were used jointly to point out structures prone to either (dis)continuity or (dis)connectivity, or both. Moreover, the combined SCR and IC results were contextualized with respect to the functions and maintenance conditions of the structures. According to Cucchiaro et al. (2024), primary functions in the Vegliato are classified as:

- solid discharge regulation, which should guarantee a buffer effect, where sediment is stored during large events and progressively released during small events. To guarantee a buffer effect, the structure should not be buried by sediment deposits.
- sediment sorting, which should allow the passage of a specific fraction of sediment particles;

- bed stabilization, which should avoid bed incision and localized sediment erosion;
- channel stabilization, which should prevent channel wandering and bed incision.

Despite this subdivision, in practice, during a massive flood event all the structures work synergistically to regulate the solid discharge, making it difficult to distinguish the different functions. Therefore, the proposed SCR indicator is particularly useful, in this context, to evaluate the interaction between the structures and sediment regulation although all other functions were analyzed as well.

Maintenance status, instead, was considered using the Maintenance Priority index (MPi), which gives scores and colour ranks from 0 (green; no maintenance required) to 1 (red; high maintenance required) based on the maintenance condition and related priority of intervention (Cucchiaro et al., 2024). The combined use of SCR, IC, functions and MPi allowed to understand how the (dis)continuity and (dis)connectivity assessment is consistent to the expected function and to the maintenance condition. For instance, a check dam designed to stabilize the channel and reduce sediment production is expected to limit continuity and connectivity when it is well-maintained. Functions and MPi were recalled from the database (Martini et al., 2023).

4. Results

4.1. Rainfall characterization

The chart of daily precipitations is shown in Fig. 4, where 20 years of data are presented. The largest event ever recorded was in 2004, when more than 320 mm were measured on November 10th. Focusing on the time window under investigation (2019–2022), it is possible to notice the highest peak corresponded to 168.6 mm (08/12/2020–09/12/2020). Furthermore, other two events showed remarkable daily precipitations, with cumulated values over 130 mm (30/07/2021 and 05/01/2022–06/01/2022).

In Table 2 a basic comparison of these three events is derived using the hourly data: two events occurred in autumn–winter and one in summer. In particular the summer event, when the flash flood occurred, stands out in terms of mean rainfall intensity and maximum intensity (I_{1h}). However, more precise information can be extrapolated from the sub-hourly analysis, carried out specifically for the July 30th event. In the Vegliato catchment, the disturbance induced a rainfall event that lasted 2 h and 30 min, starting on July 30th at 18:30 (CET) and ending on the same day at 21:00 (CET).

During this interval, a total cumulative rainfall of 144.2 mm was recorded, with a peak of 4.6 mm in a single minute. Furthermore, with more detailed data, it was possible to update the maximum intensity (i.e., $I_{060} = 115.8$ mm 60 min^{-1}). The maximum rainfall intensities ($I_{005} - I_{120}$), reported in Table 3, demonstrate the exceptionality of the event.

Table 2
Characteristics of the three main rainfall events identified within the 3 year-period analyzed in the present study. The results were derived using hourly data from the Gemona del Friuli (307 m a.s.l.) meteorological station.

Event date	08/12/2020-09/12/2020	30/07/2021	05/01/2022-06/01/2022
Total event duration (h)	15	3	27
Total rainfall (mm)	169	144.2	133.2
Mean rainfall intensity (mm h^{-1})	11.2	48.1	4.9
I_{1h} (mm 1 h^{-1})	27.4	86.0	14.6
RI (yrs)	<2	50	<2

4.2. Longitudinal sediment connectivity

The effect of torrent control structures on (dis)connectivity was determined by the Mann-Whitney test, depicting significant difference (p-value < 0.01) between downstream and upstream IC values (full results in the supplementary material, Fig. S.1). There is a slight imbalance between the number of structures showing disconnectivity (39 %) and connectivity (61 %; Fig. 5**A**). Considering the spatial distribution, in the lower and flatter part of the main channel (V010-V090), the series of check dams including V040 is characterized by connectivity. In the middle part of the main channel (V090-V160) and along T2, the structures are alternating between disconnectivity and connectivity, whereas in the upper part of the catchment most of the structures (e.g., V210, V310) show connectivity.

Table 3
Main characteristics of the rainfall event that occurred on July 30th 2021. Sub-hourly data were used to derive the results. Maximum rainfall intensities are also standardized to the mm h^{-1}.

Event date	30/07/2021	
Time of rainfall initiation (CET)	18:30	
Time of rainfall end (CET)	21:00	
Total event duration (min)	150	
Total rainfall (mm)	144.2	
Rainfall peak (mm min^{-1})	4.6	
Maximum rainfall intensity		
I_{005}	18.8 mm 5 min^{-1}	225.6 mm h^{-1}
I_{010}	30.4 mm 10 min^{-1}	182.4 mm h^{-1}
I_{015}	44.8 mm 15 min^{-1}	179.2 mm h^{-1}
I_{030}	71.0 mm 30 min^{-1}	142.0 mm h^{-1}
I_{060}	115.8 mm 60 min^{-1}	115.8 mm h^{-1}
I_{120}	141.6 mm 120 min^{-1}	70.8 mm h^{-1}

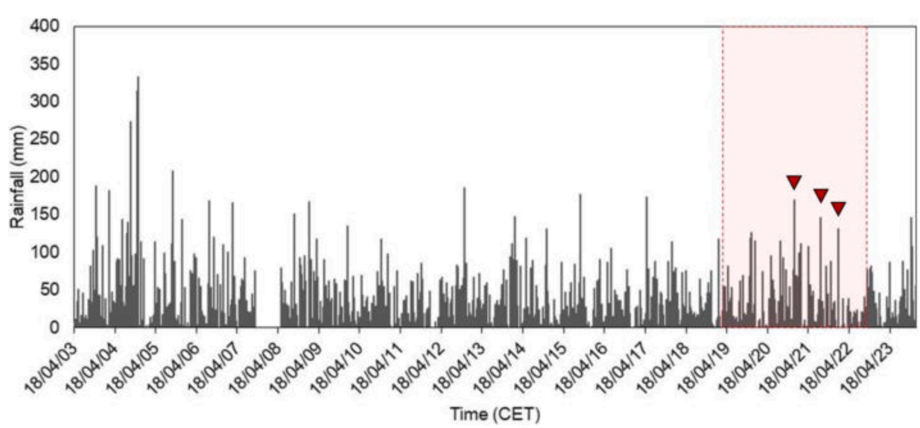

Fig. 4. Daily rainfall recorded by the Gemona del Friuli (307 m a.s.l.) meteorological station from April 2003 to October 2023. The red area refers to the 3-year study period, in which the three main rainfall events are identified.

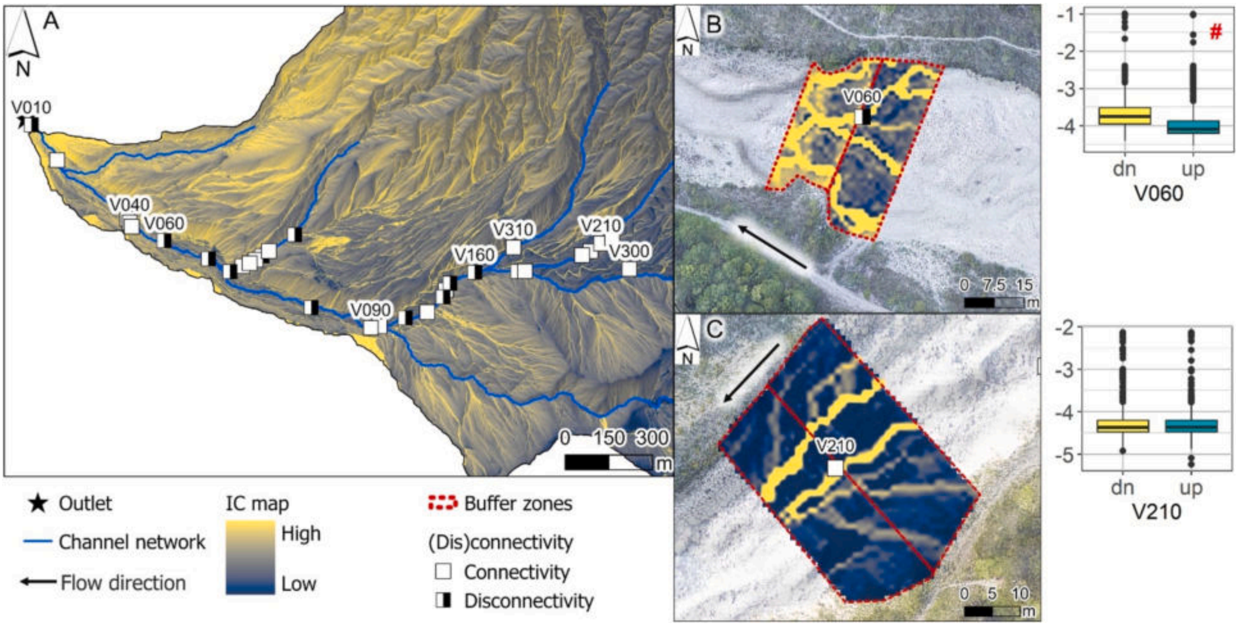

Fig. 5. Map of the torrent control works showing connectivity or disconnectivity (A). Downstream (dn) and upstream (up) IC values were extrapolated from the catchment-scale IC map within buffer zones located in proximity of each structure. Difference between upstream and downstream distributions of IC values was tested ($p < 0.01$) for statistical significance (#). The figure includes an example of a structure with statistically different IC values, hence showing disconnectivity (B), and a structure with statistically similar IC values, hence showing connectivity (C).

Whether a structure shows connectivity or disconnectivity depends on the difference between upstream and downstream geomorphic conditions, which in turn influences the IC values. In the Vegliato catchment, torrent control works exhibiting significant differences in IC, indicating disconnectivity, also show lower IC values upstream than downstream. Fig. 5**B** shows the example of check dam V060. In the upstream zone, the presence of thick alluvial sediment deposits reduces the IC by decreasing the slope and concentrating the flow toward the spillway. In contrast, in the downstream zone, the slope increased due to a significant step in the profile caused by deep erosion processes, which in turn increased the IC. On the other hand, structures showing connectivity have no statistically different IC distributions. In the example of V210 (Fig. 5**C**), no substantial geomorphic differentiation was provided by channel bed topography to alter the two main visible sediment pathways considerably, making the difference in the distribution of IC values not significant.

4.3. Sediment (dis)continuity assessment

4.3.1. Catchment

The catchment during the event of July 30th 2021 underwent notable morphological changes, which presumably caused the erosion and conveyance of the vast majority of the 60121 m^3 of sediment detected in the DoD budget.

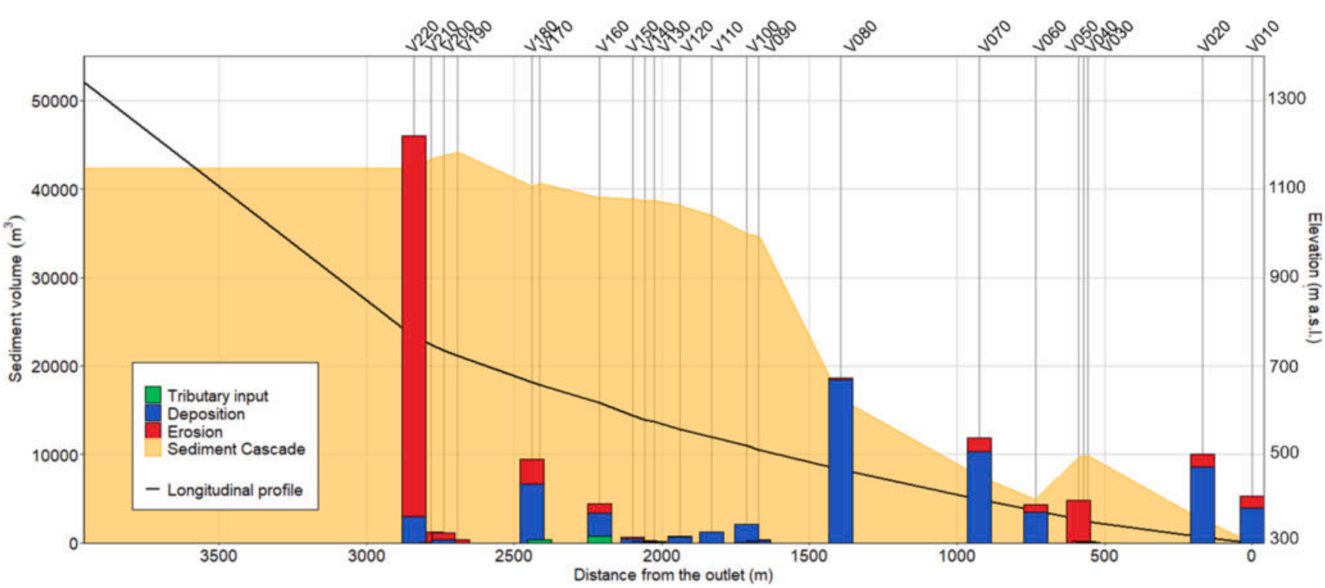

Fig. 6. Summary chart of the sediment volumes displaced during the event along the channel network of the Vegliato. The sediment cascade is visualized with regard to the main channel, with erosion and deposition volumes isolated for each Area of Influence (AoI) and presented at each structure. The net sediment fraction from the tributaries is also presented as it provides an additional input to a specific AoI along the main channel and to the overall sediment cascade.

Most of the volume mobilized during the 2021 event, was eroded from the headwaters (42290 m^3), upstream structure V220 (Fig. 6), where the steep channel (slope of 54 %) facilitates the downstream sediment transfer. In Fig. 6, the distribution of the volumes of erosion, deposition, and overall sediment cascade is represented throughout the main channel. From the upstream part, the sediment cascade was partially discontinued in correspondence of two close structures, V180 and V170, where the slope decreases to 25 % and 16 %, respectively. A large deposition corresponding to 6642 m^3 is visible, although associated with 2818 m^3 of erosion. However, the largest depositions are registered at V080 and V070 AoIs, where 18486 m^3 and 10306 m^3 were recorded, respectively. At this point, the sediment cascade was greatly reduced. Moving downstream, it increased again at V050, where 4853 m^3 were eroded, and finally, it balanced out at V020 and V010, where the slope reach the minimum of 8 %. The input of the tributaries, highlighted in green as part of the sediment cascade, was maximum 714 m^3. All volumes can be found in table S.2 (Supplementary material).

The spatial distribution of SCR is indicative of how structures influenced the continuity or discontinuity of the overall sediment cascade (Fig. 7). For instance, continuity is more evident in the upper catchment, near the four bed sills built in series (V190, V200, V210, V220), and close to the major channel erosion and the largest sediment source (13.5 ha), which accounts for the 3 % of the entire area of the basin. Therefore, due to their position, these structures were inevitably more prone to erosion processes rather than deposition. Other examples of torrent control works that showed high continuity were V310 (SCR of −71.4 %) and V050 (SCR of −49.9 %). The former is located in the downstream section of T4 and potentially receives sediment supply from two large branching sediment sources contributing to the tributary; the latter is located in the downstream main channel, affected by local channel erosions and far from being affected by sediment supply from the hillslopes. On the contrary, it is possible to observe multiple structures that favoured discontinuity in the middle and downstream reaches of the main Vegliato channel, where deposition processes became predominant (Fig. 6 **and** Fig. 7) and the sediment sources can contribute through T1 and T2.

Finally, the two extreme values of SCR were represented by V220 (−88.4 %), and V230 (100.0 %) along T2, whereas V270 and V300 exhibited a SCR of 0 due to the absence of sediment mobilization.

4.3.2. Reach

The variability of SCR values compared to the characteristics of the AoIs was explored, starting with the size of the AoIs (full details in the supplementary material, Fig. S.2). In fact, with larger areas, the chances of having overall greater sediment volumes within the AoI is higher, so the ratio to the sediment cascade increases, resulting in higher positive SCR and lower negative SCR. However, no evident pattern was found. Therefore, large geomorphic variations were not necessarily associated with large reaches, and structures having a greater effect on (dis)continuity did not always have larger areas of influence. Similarly, the length of the AoI potentially controls the overall volume of sediment mobilized in a reach. However, only in few cases the structures with high positive or low negative SCR were also those having long AoIs, indicating that the overall variation in SCR was not fully dependent on the length of the structures' area of influence. Finally, even though slope controls the sediment transport capacity, thus influencing deposition and erosion processes, it did not explain completely the variability of SCR assessed in the Vegliato catchment in respect to the event. While few very large positive or negative SCR values are located in flatter and steeper reaches, respectively, a significant cluster of lower SCR values appears to be independent of the slope factor.

4.3.3. Structure

The SCR and IC results are combined in Fig. 8 to provide a joint assessment. The 36 % of the torrent control works show both sediment discontinuity and disconnectivity, being characterized by a positive SCR and a significant difference of IC upstream against downstream. A peculiar example is V070, a traditional check dam with a solid discharge regulation function. In Fig. 8**A**, the check dam V070 presents upstream deposition rather than erosion and it also shows longitudinal disconnectivity. The 29 % of the torrent control works has intermediate behaviour, namely they favoured discontinuity (i.e., positive SCR) but

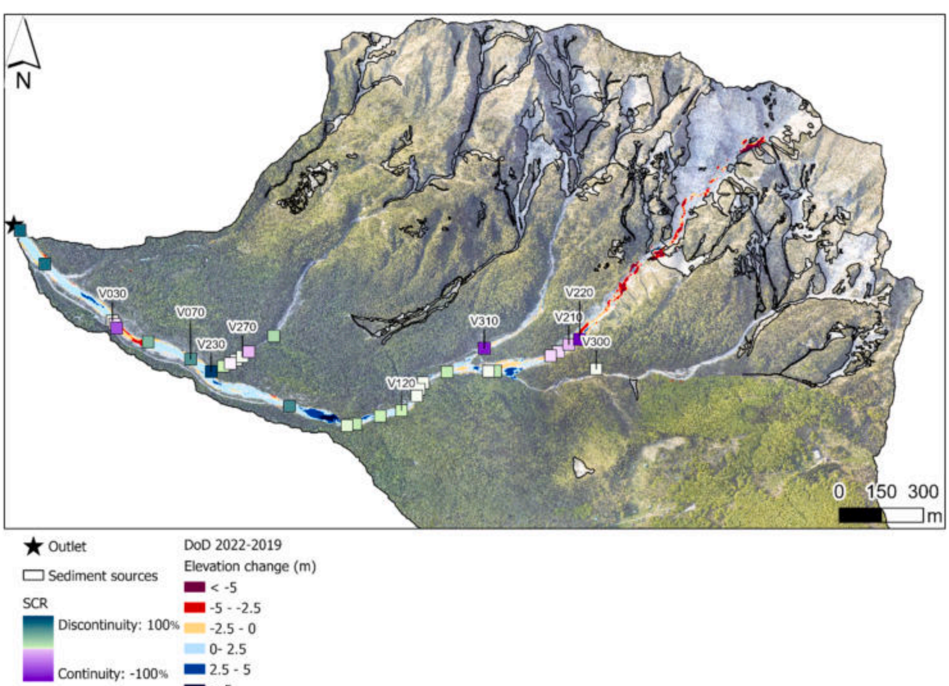

Fig. 7. Map of the torrent control structures and corresponding SCR. The geomorphic changes are also visible thanks to the 2022–2019 DoD, with negative values indicating erosion and positive values deposition. Sediment source areas represent active areas potentially supplying sediment. No significant newly formed areas were detected between 2019 and 2022.

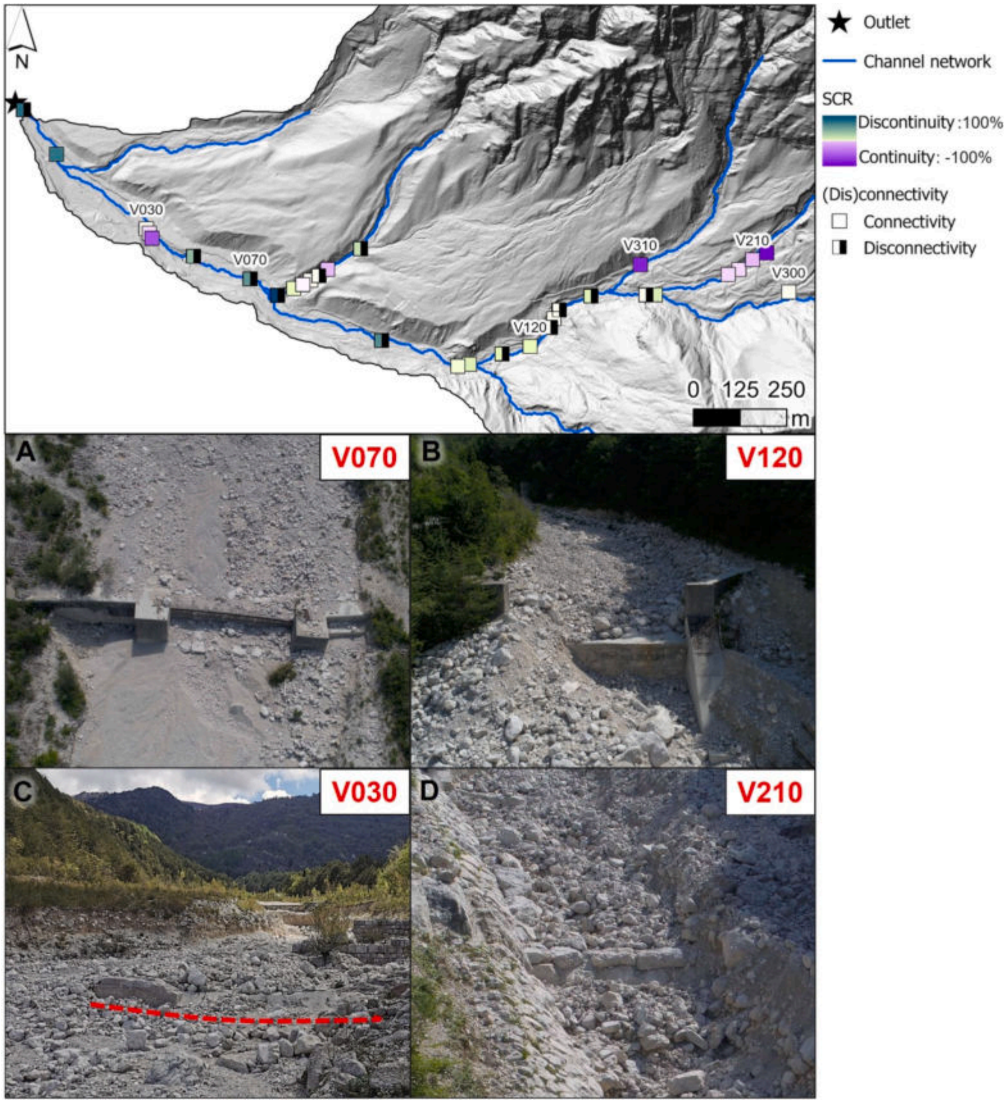

Fig. 8. Map of the torrent control works classified according to the effect on (dis)continuity (negative or positive SCR) and sediment (dis)connectivity (difference in IC). Examples of: check dam (V070) prone to both connectivity and continuity (A); check dam (V120) limiting continuity but not connectivity (B); collapsed check dam (V030), highlighted in red, again limiting continuity but not connectivity (C); bed sill (V210) prone to both continuity and connectivity (D).

they do not show significant variations of IC from upstream to downstream. For instance, check dam V120 (Fig. 8**B**) shows an uninterrupted sediment deposit wedge on the spillway and evidence of outflanking. This indicates a propensity for deposition and discontinuity, as well as an inability to confine the sediment pathways in the spillway and to create a slope break in the longitudinal profile, thus not creating disconnectivity. Another example is check dam V030, which is mostly collapsed but still exerts some residual effect on continuity by acting as a groyne, protecting the left bank and favouring deposition (i.e., positive, although low, SCR), while not affecting significantly the IC pathways, hence showing connectivity (Fig. 8**C**). On the contrary, no structures show both continuity and disconnectivity. Finally, 29 % is the proportion of structures that show both continuity and connectivity (i.e., negative SCR and no significant difference in IC). Among this group, bed sill V210 (Fig. 8**D)**. The remaining 6 % regard those elements that scored an SCR of 0, hence no effect on the sediment cascade.

Fig. 9 presents how three groups of torrent control works, specifically discontinuity-disconnectivity, discontinuity-connectivity, and continuity-connectivity, are sorted by function and maintenance condition. For solid discharge regulation function, most of the structures are characterized by discontinuity and disconnectivity (3 out of 4), aligning with the goal of buffering upstream deposits and preventing sediment continuity during extreme events. The MPi values indicate that no severe maintenance is required for these structures. The only structure expected to sort sediment particles (open check dam V310) is built to permit the longitudinal continuum of sediments fluxes while selectively retaining only the largest boulders. The results are consistent to this mechanism, since the check dam is prone to both continuity and connectivity and the MPi (0.25) points out a partial clogging (between 33 % and 66 %) caused by the largest grains. Bed sills, intended to stabilize the bed and prevent localized erosion, should limit continuity as intended in this work. However, more than 50 % (4 out of 7) of the bed stabilization sills were prone to continuity and connectivity and in fact the MPi values (0.88–1) indicate severe lacks functionality and poor physical status. Finally, channel stabilization structures are supposed to prevent sediment production by reducing channel wandering and bed incision, hence they should theoretically favour discontinuity and disconnectivity. Four structures did not favour discontinuity and disconnectivity and these are mainly characterized by poor maintenance conditions (MPi equal to 0.63 and 1). Worth mentioning are the structures characterized by good status but low functionality (i.e., MPi between 0.25 and 0.5), which all showed intermediate discontinuity and

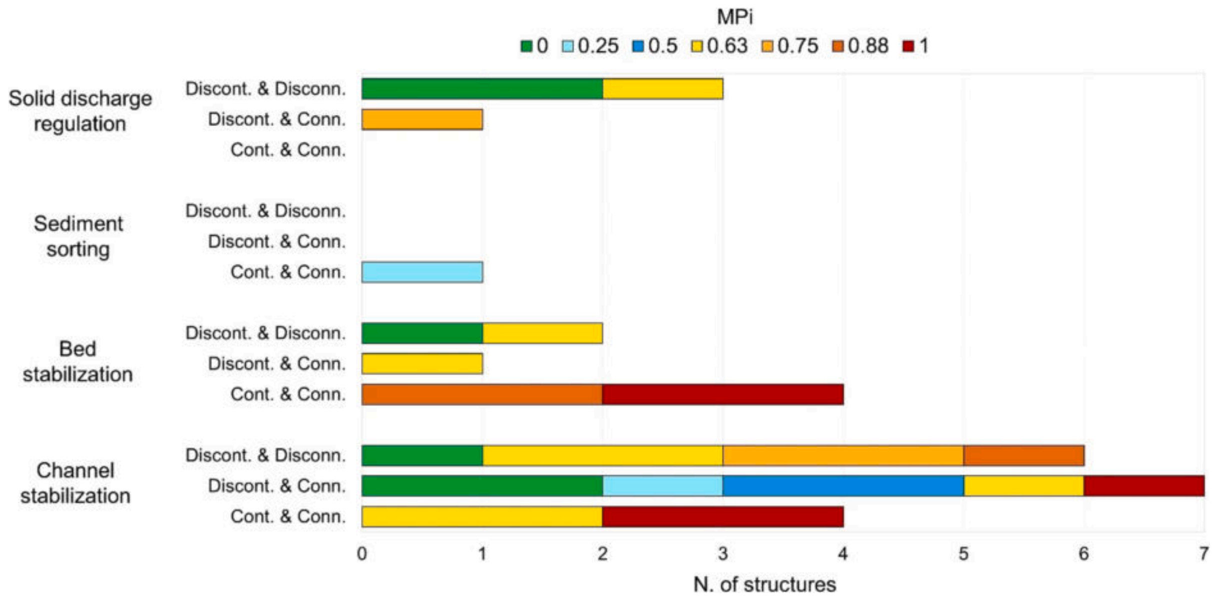

Fig. 9. Stacked bar chart of the torrent control works grouped according to their classified function and to their effect on (dis)continuity (Discont. or Cont.) and (dis) connectivity (Disconn. or Conn.). The Maintenance Priority index (MPi) is also visualized for each structure.

connectivity.

5. Discussion

Analysing and isolating the various components of sediment budgets have become necessary to understand and manage the response of hillslopes and mountain fluvial systems to disturbances (Slaymaker, 2003; Trimble, 2010; Verstraeten et al., 2009). In this context, (dis) continuity and (dis)connectivity metrics, derived or integrated with geomorphic change detection, represent valuable tools for reconstructing and analysing the sediment cascade associated with extreme events, as presented in this work. Furthermore, such set of tools has recently been employed to investigate larger events in mountain catchments in Europe, including the impact of the 2015 Storm Desmond in the UK (RI > 1000 yrs; Joyce et al., 2018), the 2018 Storm Vaia in the Dolomites, Italy (RI > 100 yrs; Pellegrini et al., 2021; Rainato et al., 2021), and the 2020 Storm Alex in SE France (RI > 1000 yrs; Liébault et al., 2024). In the Vegliato catchment, the effect of torrent control structures on the continuity and connectivity was investigated thanks to indicators derived from geomorphometric approaches. This impact was assessed taking advantage of an extreme rainfall event that favoured the mobilization of a massive sediment volume presumably generated in combination with rock falls from Mount Chiampon and Mount Deneal, as already happened in the previous century (Govi and Sarzana, 1977). The triggering rainfalls of July 2021 were analyzed using a precipitation dataset at different temporal resolutions. Although the event was identified within the historical dataset using daily and then hourly data, the characterization was further accomplished using sub-hourly data, which emphasized the exceptionality of the event. The variability of rainfall sampling intervals (i.e., hourly vs sub-hourly) affected the maximum intensity, with coarser resolution underestimating the results. Discretization of continuous variables such as the rain is often a tricky challenge, and the coarser the resolution, the greater the effect on rainfall maxima (Hershfield, 1961; Papalexiou et al., 2016). This effect can be particularly relevant for short and intense events like flash floods, for which proper characterization is still needed (Gaume et al., 2009).

The Index of Connectivity was applied to distinguish those hydraulic structures showing a significant impact on (dis)connectivity after the event. In recent years, the IC has served multiple purposes and it was applied in different contexts to highlight the role of anthropic structures (Calsamiglia et al., 2018; Cucchiaro et al., 2019; Kalantari et al., 2017). Taking advantage of the connectivity analysis presented in this work, several important issues can be addressed. The traditional IC is more reliable for describing the sediment transfer pathways in mountain areas (Cavalli et al., 2013; Martini et al., 2022b), while it is less advised for analysing connectivity linkages in lowlands, where different sediment transfer processes (e.g., suspended sediment transport) are operating. Therefore, the application of IC fitted quite well in the Vegliato catchment, characterized by hydraulic works built in steep channels and subjected to torrential processes. Moreover, the availability of HRT data allowed us to carry out a robust IC analysis, which is less feasible at global scales where coarse DTMs are usually employed and lowlands are inevitable included (e.g., Michalek et al., 2023). Although high-resolution DTMs are recommended for computing IC in mountain areas, the optimal spatial resolution is a compromise between the study's objective, DTM uncertainty, computational demand, and the scale of the processes and landforms involved (Heckmann et al., 2018). In the Vegliato catchment, a 1-meter resolution was chosen as a compromise, consistent to the original DoD analysis by Cucchiaro et al. (2024), and consequently to the SCR as derived in this work. Moreover, such resolution is suitable to represent IC routes and geomorphic features near torrent control works of varying sizes and functions. While a coarser resolution might suffice for representing thick boulder lobes or steep erosion edges near large check dams in steeper reaches (Torresani et al., 2023), it would oversimplify the effects of smaller structures like bed sills, and excessively smooth flatter alluvial landforms of smaller grain sizes in the lower catchment, where even higher resolution could be appraised (Alfonso-Torreño et al., 2019). The same critical thinking applies to the temporal scale of the DTM. The 2022 IC was selected over the 2019 IC to evaluate the outcome of the interaction between torrent control works and sediment connectivity as stated in the objectives. Finally, the effect on longitudinal (dis)connectivity was determined through the computation of IC statistics on areas situated 15 m upstream and downstream of each structure. In this work, the 15 m buffer zones allowed to detect potential IC differences or similarities, maximizing the effect of the structures on the geomorphic features driving IC and minimizing the effect of external agents like tributaries or other structures. While this distance was adequate for the study, further testing is needed to evaluate its effectiveness in other contexts.

Thanks to the use of the novel parameter Sediment Continuity Ratio, it was possible to assess the (dis)continuity with reference to the period analysed and to the main flood event occurred in 2021. First, it was possible to determine whether a specific torrent control structure was prone to sediment continuity or not. A check dam that reduces continuity (or in other words favours discontinuity) is characterised by an AoI showing net positive sediment balance, hence more deposition than erosion and indicating that sediment production is attenuated, which is a fundamental requirement for preventing and mitigating hazardous events in torrents (Armanini et al., 1991; Lucas-Borja et al., 2021). On the contrary, more erosion than deposition translates into more sediment production, boosting sediment transport, and overall increasing, instead of reducing, the potential risk for downstream areas. It is well known that the creation of hydraulic structures in the longitudinal profile should prevent the propagation of headwater erosion to the downstream part (Piton et al., 2017). In the Vegliato basin, this dichotomous classification pointed out more structures reducing continuity than enabling it, with almost a ratio of 2 to 1. However, this result is only valid for the 3-years period analyzed, as different events might generate different responses in terms of erosion and deposition volumes, affecting the final SCR assessment. Second, the SCR allowed us to further assess the different degrees of (dis)continuity by quantifying how much each structure affects the sediment cascade during an extreme event. The most original part of the parameter is the integration of the cumulative net fraction of sediment passed over the upstream structures. In this way, it is possible to keep track of the progressive alteration of sediment erosion, transfer, and deposition (otherwise, supply, transfer, and deposition according to the most known sediment cascade frameworks; Burt and Allison, 2010) throughout the channel control system, thus becoming an instrument to highlight localized, but perhaps only temporary, management issues. From the results of this study, it was observed that the structures prone to discontinuity were mainly located in the downstream and wider sections of the main channel and those prone to continuity were located in the upstream reaches and closer to the largest source area (Fig. 7). Third, although quite simple to calculate, the SCR provides a quantitative and organic snapshot not only of a single structure but of the entire torrent control system. This information can be further compared with other geomorphometric indices, such as the one in Fig. 8, and contextualized according to different perspective to improve the interpretation of the SCR and the overall vision on the whole watershed management system (e.g., Fig. 9). Ultimately, it might be also integrated into broader conceptual frameworks and stepwise procedures for revising mitigation measures, as proposed by Hübl (2018) in an alpine catchment.

However, the SCR and its application need particular attention to be effectively used for management purposes. As previously mentioned, the assessment addresses the effect of torrent control works on (dis)continuity within a limited time window, during which a significant event occurred. The advantage of having two closely repeated catchment-scale topographic surveys is that it isolates this significant event, offering a targeted snapshot of the effect of torrent control works on the sediment cascade. However, the SCR might vary substantially based on how the system has responded and will respond to past and future disturbances. In other words, the smaller the time window considered by DoD, the more reliable the SCR is for assessing the interaction between structures and the sediment cascade at the event scale, but the less representative it is of the overall catchment's geomorphic evolution.

To understand how the SCR might change or not under different scenarios, a combination of multiple factors and point of views has to be analyzed. The position and number of the hydraulic structure is surely of uttermost importance, as pointed out in Osti and Egashira (2008). The distance from the main sediment input (i.e., how far from the main erosion) influences the resulting SCR value: for instance, being closer to the major sediment input, V210 is indeed more prejudiced in reducing continuity than V070. The general geomorphic setting of the basin is a major factor in determining whether erosion or deposition processes are favored (Cavalli et al., 2017). The steep and unmanaged upstream part of V210 is closely tied to the major sediment source and has historically (Govi and Sarzana, 1977) and recently (Cucchiaro et al., 2024) shown high activity and sediment production. Therefore, this pattern is likely to continue. As a result, the upper structures will tend to be more prone to continuity than downstream structures, like V070. Moreover, V210 is a stone-built bed sill and V070 is a concrete consolidation check dam, hence the intrinsic features (e.g., type, primary function, construction material, dimensions) can also play a fundamental role (Piton et al., 2017). From the point of view of the single structure (**Section 4.3.3**), maintenance was also demonstrated as a pivotal intrinsic component, because it reports the information on functionality and structural status that can validate or support the interpretation of the assessment (Dell'Agnese et al., 2013; Cucchiaro et al., 2024). Finally, it was found that SCR values do not show a strong trend based on the intrinsic characteristics the AoIs. This suggests that while the general (dis)continuity pattern can be grasped (continuity in the upstream reaches and discontinuity in the downstream reaches), the nuanced variability of SCR values must be analyzed on a case-by-case basis, taking into account local dynamics and the characteristics of the structures, such as function and state of maintenance. Therefore, considering the potential large interplay among all these factors, and potentially many more (e.g., geology, compound disturbances, climate change), it becomes motivating to test the SCR with regards to other events and other mountain streams with different watershed management systems.

Comparing the effects of torrent control works on sediment (dis) continuity and (dis)connectivity, the results were mainly consistent, with a total of 65 % of the cases in which a structure is impacting both in the same way. In the Vegliato, structures prone to continuity and connectivity were in most of the cases (7 out of 9) found either in very poor conditions or they were supposed to allow the passage of sediment (V310). Structures prone to discontinuity and disconnectivity showed predominant upstream deposition, which led to a reduction of upstream slope and, if functioning properly, to a significant difference between upstream and downstream configuration of sediment pathways, resulting in disconnectivity. On the other hand, the intermediate cases, where a structure is having an opposite effect on the two properties, were less represented. Among the contributing causes for this discrepancy, again the maintenance condition, and primarily the poor functionality, is a key factor as highlighted in the examples of V120 and V030 (Fig. 8**B-C**) and reported in the channel stabilization group presented in the bar chart (Fig. 9). Finally, the two structures did not show any deposition or erosion, resulting in an SCR of 0. This indicates that their reaches are not particularly active in terms of sediment dynamics. Specifically, V300 is located in a part of the basin that has shown no significant activity even in past surveys (Cucchiaro et al., 2024).

Reconstructing how the torrent control system functioned after a significant, albeit singular, event can provide valuable insights for managing the channel control system of the Vegliato. For example, our results showed that bed sills built along the upper main channel (V190-V220) were not particularly useful in preventing erosions during the event due their critical position close to the sediment sources and exacerbated by their poor maintenance condition. In that position, different solutions might be considered either concerning the construction of new structures primarily designed to promote deposition or focusing on the maintenance and restoration of those that showed discontinuity more downstream. However, further events and dynamics are needed to plan the installation of new torrent control works. Nonetheless, the present case study represents a starting point, emphasizing how important could be the implementation of new tools to support decisions and interventions in mountain catchments, where management plans do not fully leverage on novel data acquisition strategies. Observing a management issue from multiple perspectives can help in finding the most appropriate strategy to preserve existing structures or perhaps consider other more effective engineering or natural solutions to efficiently allocate public resources.

6. Conclusions

In conclusion, the study investigated the impact of torrent control structures on sediment cascade in the Vegliato mountain basin with regard to an intense rainfall event of 50 years return interval. The rainfall event and associated flash flood generated morphological changes resulting in the erosion, transport and deposition of more than 60000 m^3 of sediment. First, the effect on longitudinal sediment connectivity was evaluated considering the variation of IC upstream and downstream of the torrent control works. Second, the Sediment Continuity Ratio (SCR) was conceived and then employed to assess how structures influenced sediment (dis)continuity in a specific time window. In the Vegliato catchment, the SCR pointed out structures more prone to continuity mainly in the upstream reaches and structures favouring discontinuity in the downstream reaches. Moreover, the results of the SCR were discussed within a framework of three points of view to understand how this indicator is affected by the context of the study site. While the overall patterns of (dis)continuity can be affected by the position of the structures with respect to the geomorphic configuration of the Vegliato, the variability of SCR values is less predictable and driven by local sediment dynamics, which might change even considerably after other disturbances. The combined use of IC and SCR provided an overview of the overall effect of torrent control structures on the sediment cascade. On one hand, continuity and connectivity metrics, as proposed in this work, were found to be consistent in 65 % of the cases, with a clear majority of structures limiting both. On the other hand, the discrepancies among the two metrics were shown by structures that effectively disrupted continuity but not connectivity. Although multiple factors can influence the SCR and the IC, we stressed the importance of maintenance when evaluating the role of torrent control structures in regulating sediment dynamics. Furthermore, placing the assessment in the local context, by associating the effect on (dis)continuity and (dis)connectivity with the actual function of the structure, shed light on the current effectiveness and management condition of the whole torrent control system of the Vegliato catchment. Finally, considering that the present study deals with a single large event and with a single basin, it will be fundamental to apply the proposed approach after other events and to test its reproducibility in other study areas.

CRediT authorship contribution statement

Lorenzo Martini: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Sara Cucchiaro:** Writing – original draft, Methodology, Conceptualization. **Francesco Piccinin:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Giacomo Pellegrini:** Writing – review & editing, Investigation, Conceptualization. **Eleonora Maset:** Writing – review & editing, Conceptualization. **Tommaso Baggio:** Writing – review & editing, Formal analysis. **Giorgia Chiarel:** Writing – review & editing, Investigation. **Federico Cazorzi:** Writing – review & editing, Supervision, Conceptualization. **Lorenzo Picco:** Writing – review & editing, Supervision, Conceptualization.

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.

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