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ORIGINAL PAPER

Monitoring of torrent control structures through a multi-parameter index

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Abstract

Transversal torrent control structures (TTCSs) are one of the most emblematic measures for erosion control and sediment retention in mountain streams. TTCSs are prone to decay that may undermine their stability and effectiveness: their monitoring is essential to plan appropriate conservation strategies. This work aims to develop an index applicable at the regional scale as a screening tool to identify the structures potentially more prone to damage. For this purpose, a Potential Fragility Index (PFI) is developed. This index is applied to TTCSs (check dams and bed sills) and is based on intrinsic and extrinsic characteristics of the structures. Specifically, intrinsic factors include structural height, year of construction, and construction material, while extrinsic factors include the location along the watercourse and lithology. The index has been developed and tested in three catchments located in the easternmost sector of the Italian Alps (Friuli-Venezia Giulia Region): Fella, But, and Degano catchments with areas of 700 km^2, 325 km^2 and 320 km^2, respectively. The PFI is intended to: (i) classify TTCSs according to their potential fragility; (ii) identify potential hotspots; and (iii) support monitoring activities during an initial screening phase. The results are qualitatively assessed for 282 structures within selected sub-catchments through field surveys to evaluate the conceptual coherence of the index.

Keywords Torrent control structures · Check dams · Monitoring · Index

1 Introduction

Transversal torrent control structures (TTCSs), such as check dams and bed sills, are widespread in the European Alps, as well as in other mountainous regions (Eisbacher 1982; Kronfellner-Kraus 1983; Hungr et al. 1987; Ikeya 1989; Chatwin et al. 1994; VanDine 1996; Huebl and Fiebiger 2005; Patel 2012; Carladous et al. 2016; Moase 2017; Marchi et al. 2019; Piton et al. 2024; Galia et al. 2025). These structures play a key role in stabilising riverbeds, hillslope consolidation, and managing sediment transport (Piton et al. 2017; Abbasi et al. 2019; Lucas-Borja et al. 2021).

Extended author information available on the last page of the article

However, their effectiveness (i.e., an evaluation of the beneficial effects of the structures in relation to what could be expected from them; Piton et al. 2017) is strongly dependent on their physical condition, which deteriorates over time due to the same processes they are intended to mitigate (Mazzorana 2008; Dell'Agnese et al. 2013; Mazzorana et al. 2014, 2017; Chahrour et al. 2021a, b).

The stress on torrent control structures (TCSs) is exacerbated by current climate changes, which result in increased hydrometeorological forcing (Crozier 2010; Kundzewicz et al. 2014; Gariano and Guzzetti 2016; Lin et al. 2022). The correlation between mass movements (e.g. rockfall, rock avalanches, debris flows, ice avalanches, and snow avalanches) and climate change in the European Alps was investigated by Jacquemart et al. (2024) through a review of the scientific literature. Their findings confirm that climate change is already altering the frequency, magnitude, and spatial distribution of alpine mass movements, while underlining the inherent complexity of these process changes, particularly with respect to their predictability and modelling at regional scales.

1.1 Maintenance priorities and assessment of structural deterioration

Regular monitoring is essential to ensure effectiveness and to support appropriate risk management strategies. It is important to prevent the failure of such structures, as this could increase the risk level (Piton et al. 2017; Hübl et al. 2024). Indeed, structural failure can further increase the severity of impacts by mobilising large sediment volumes, thereby amplifying the debris-flow magnitude and hazard and potentially transforming an already severe event into a much larger disaster, as occurred on 29 October 2018 in the Rotian creek (Eastern Italian Alps; Dallan et al. 2025). Another emblematic example of check dam failure occurred during a severe flood in 1996 in the Central Pyrenees (Benito et al. 1998), where intense rainfall, combined with a lack of maintenance of TCSs, led to the collapse of 31 out of a series of 36 dams. This released large volumes of stored sediment, significantly amplifying flood magnitude and destroying a camp site with the loss of 87 lives.

Consequently, regular monitoring is crucial to ensure effectiveness and to support appropriate risk management strategies, taking into account both the vulnerability and the fragility of these structures (Jakob and Hungr 2005; Suda et al. 2009). Vulnerability is intended to represent the degree of the relationship between the structural damage and the event intensity whereas fragility refers to the intrinsic predisposition of a structure to damage based on its characteristics. The literature provides numerous examples of vulnerability assessments for TCSs, particularly for check dams.

Dell'Agnese et al. (2013) developed a damage index to assess the vulnerability of consolidation check dams in mountain streams by comparing their residual functionality before and after debris flow, debris flood and bed load events. The damage index is based on the comparison between pre- and post-event structural conditions, whereas residual functionality is defined by Dell'Agnese et al. (2013) as an integrated evaluation of the remaining capacity of the structure to maintain its intended function. The damage index and residual functionality were shown to be strongly correlated. Their findings show that older structures (over 20 years) have a higher damage index, while concrete structures exhibit a lower damage index compared to masonry ones. Additionally, some structural dimensions appear to be correlated with damage, such as structure height, thickness, and width, whereas channel slope does not seem to be correlated. The approach links event intensity to structural response, providing a tool for maintenance prioritisation and risk management in alpine streams.

Later, Mazzorana et al. (2017) quantified the potential damage due to extreme events affecting the check dams in the Autonomous Province of Bozen/Bolzano (northern Italy) confirmed that concrete structures compared to masonry exhibited more uniform and predictable damage patterns. Lee et al. (2022) compared stone and concrete check dams and found that stone check dams deteriorate more rapidly than concrete ones after 20 years of construction. Additionally, according to the literature, wooden structures have a lifespan ranging between 20 and 50 years (Boll et al. 1999; Noetzli et al. 2002).

Davidescu et al. (2012) created an indicator to analyse the impact of the different factors on the condition of TCSs in Romania. These authors found a correlation between the damage and the age of the structures, with the condition rate decreasing with age; however, they also observed that well-built and constantly repaired check dams show better condition than some recent structures that were poorly built or exceeded the service life without undergoing adequate maintenance. Moreover, the condition of the structures is influenced not only by age and material but also by environmental factors such as lithology and channel morphology.

Various decision-supporting tools and maintenance prioritisation approaches have been proposed to manage TCSs.

To establish priorities for maintenance and intervention, an indicator was developed by Mazzorana (2007). This composite indicator integrates three main components: the first links the relevance of a structure to the assets it is designed to protect; the second assesses the structural condition and functionality of the structure in terms of hazard reduction; and the third identifies situations of local overloading. The integration of these components provides a decision-support tool for evaluating the functionality of protection structures and identifying key elements within the system.

Another decision-supporting tool was developed by Tacnet et al. (2012). It is used to evaluate the efficiency of the structures and their potential to generate downstream hazards in the case of degradation or failure. Following a similar approach, Paratscha et al. (2018) proposed a probabilistic model to predict the deterioration of TCSs using data from the Austrian national condition rating system. The approach allows the estimation of time to repair and time to failure for different structure types and materials, supporting data-driven maintenance planning and life-cycle management. Further advancing maintenance prioritisation, Chahrour et al. (2021a, b) integrated hydraulic modelling, global stability indices, and stochastic simulations. Their findings indicate that preventive and minor maintenance strategies are more effective and cost-efficient than corrective interventions implemented only after severe structural degradation.

More recently, Cucchiaro et al. (2024) proposed a Maintenance Priority Index (MPI) based on the status and functionality of TCSs. Integrated with multi-temporal High-Resolution Topography (HRT) data on sediment dynamics, the MPI allows for evaluating the effectiveness of existing interventions, identifying areas more prone to hazards, and supporting sustainable planning, intervention prioritisation, and maintenance in watershed management.

In this context, Cislaghi et al. (2025) proposed an integrated framework for the monitoring and management of TCSs, combining first-level visual inspections with the development of a comprehensive structure database and the application of a model to predict the fragility and the service life of the structures. The approach allows the assessment of both structural damage and loss of functionality, the identification of key factors influencing deterioration, and the probabilistic prediction of service life under different maintenance strategies. Their results demonstrate that regular inspections and maintenance planning are essential to preserve the protective capacity of TCSs and to support decision-making in watershed management.

1.2 Research gap and objectives of this study

Despite existing research, a gap in the literature remains the lack of standardised, regional-scale tools for assessing the potential fragility of TCSs as a preliminary screening method. To address this gap, the objective of this study is to develop and test a standardised tool, the Potential Fragility Index (PFI), for the regional-scale assessment of TTCSs, aiming to provide a replicable framework to evaluate their structural condition and support decision-making in torrent management. The index is built on the work of Marchi et al. (2022), who developed an indicator specifically tailored for the Autonomous Province of Trento (Italy). The aim of this study is to refine and generalise this index to enable potential applications beyond the context in which it was originally developed. The index proposed in this study exploits data from the TTCSs inventory, information on lithological characteristics, and data derived from HRT. To develop and test the PFI, three mountainous catchments in the Friuli-Venezia Giulia Region (northeastern Italy) were selected. The conceptual coherence of the index was qualitatively assessed through field surveys. PFI aims at scalability and ease of implementation. As a screening tool, it is intended to identify structures with higher potential fragility even in the absence of field inspection, thereby contributing to regional-scale planning and prioritising maintenance interventions on TTCSs.

2 Study areas

The study areas are the But, Fella and Degano catchments located in the northern portion of Friuli-Venezia Giulia Region (Italy) within the Carnic and Julian Alps (Fig. 1), together with the sub-catchments where the structures were selected to verify the consistency of the results (Fig. 1B, C, D). The morphological characteristics are shown in Table 1. The lithology of the three study catchments mainly consists of sedimentary rocks. Dolomite and limestone are present in all three catchments and prevail in the Fella, with a lesser presence of marls, siltstone and sandstone sequences. These lithologies are more common in the But and Degano. Quaternary deposits (moraines, scree, alluvial sediments) are widespread. The topographic basis is the LiDAR-derived regional Digital Terrain Model (DTM) acquired during the 2017–2020 campaign (INSPIRE Geoportal 2025).

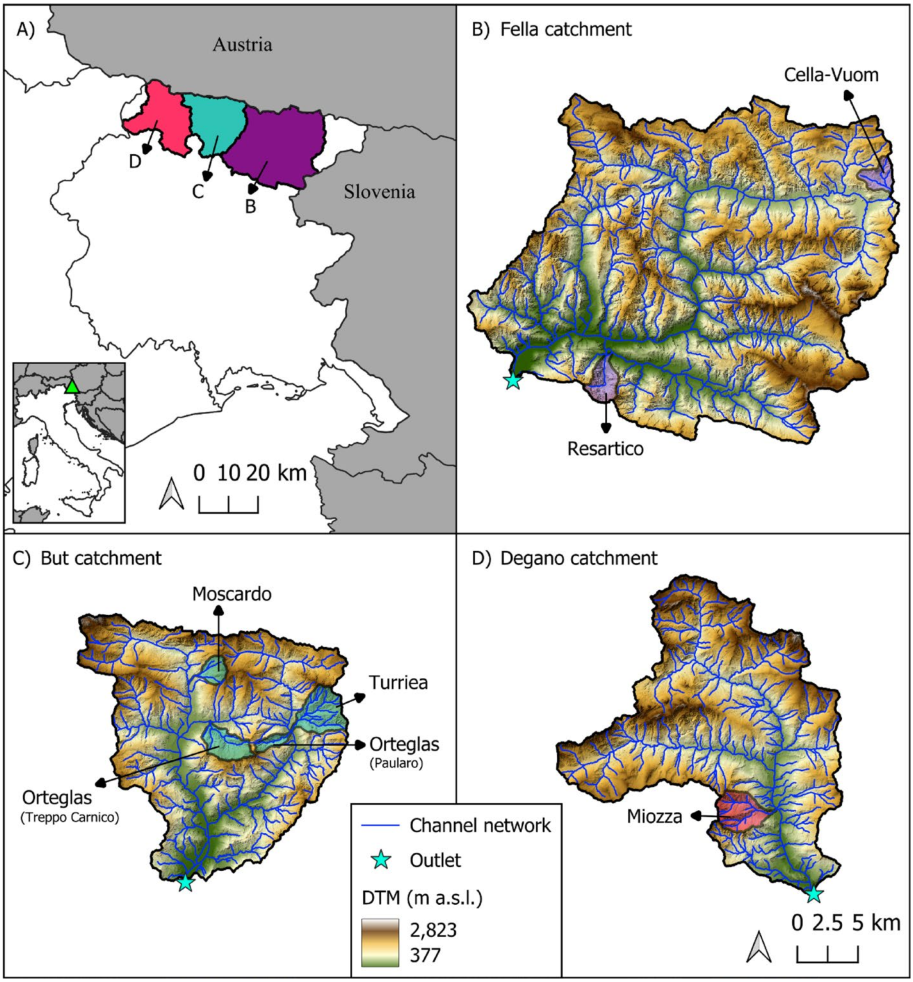


Fig. 1 Location of the study sites in the Friuli–Venezia Giulia Region (**A**) and of the main catchments and their sub-catchments where the TTCSs used to verify the conceptual coherence of the index, are located: **B** Fella catchment and the Resartico and Cella–Vuom sub-catchments; **C** But catchment and the Moscardo, Turriea, Orteglas (Treppo Carnico), and Orteglas (Paularo) sub-catchments; **D** Degano catchment and the Miozza sub-catchment

Table 1 Main characteristics of the But, Fella and Degano catchments (*ARPA FVG – OSMER, & Protezione Civile FVG 2024)

	But	Fella	Degano
Area (km^2)	325	700	320
Elevation (m a.s.l)	377–2780	288–2753	419–2780
Mean catchment slope (°)	31.1	35.5	30.7
Main channel length (km)	32.6	52.8	36.6
Mean annual precipitation 1991–2020 (mm) *	1805	2017	1645

3 Materials and methods

3.1 Torrent control structures inventory

A regional inventory of TCSs is available for the entire region, covering an area of 7924 km^2 (IRDAT 2025). It censuses a total of 24,090 structures, among these, 8037 are TTCSs (check dams and bed sills). It contains detailed information on the location, municipality, province, catchment, category, typology, construction material, coating material, height, length, width, and year of construction for each structure.

In the Fella catchment, the inventory includes 1376 TTCSs with varying levels of data completeness. Specifically, the year of construction is indicated for 1353 structures, the height is reported for 1311, and the construction material is specified for only 569. In the But catchment, the inventory includes 1590 TTCSs, also with varying levels of data completeness: the construction material is reported for 999 structures, the height for 1534, and the year of construction for 863. In the Degano catchment, the inventory includes 628 TTCSs, for which the construction material is reported for 465, the height for 530, and the year of construction for 250 (Fig. 2).

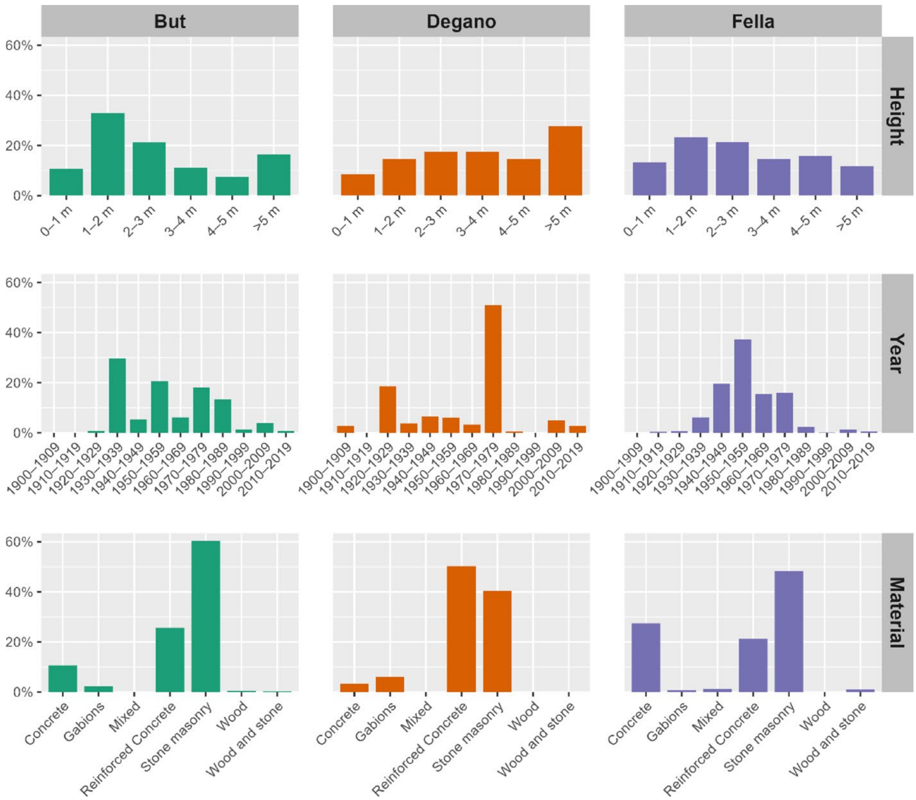


Fig. 2 Percentage distribution of available factors for each basin from the TTCSs inventory in terms of structure height classes, construction period, and construction material

Table 2 Construction material categories adopted in the TTCSs inventory

Construction material	Description
Stone masonry	Structures built using stone blocks bound with mortar
Concrete	Structures made of plain (unreinforced) concrete
Reinforced concrete	Concrete elements reinforced with embedded steel bars
Wood and stone	Structures built with logs and stones
Wood	Structures built with logs
Gabions	Stones material organised into metal cages
Mixed	Structures combining two or more construction materials

Table 3 Catchments and sub-catchments considered for this study

Catchment	Sub-catchment	Length of the main channel (km)	Area (km^2)	Melton Index	Number of TTCSs	Number of check dams	Number of bed sills
Fella	Cella-Vuom	6.3	5.2	0.4	64	64	–
	Resartico	5.2	7.0	0.6	31	10	21
But	Moscardo	4.5	3.8	0.6	50	37	13
	Orteglas (Treppo Carnico)	5.7	8.0	0.4	26	20	6
	Turriea	13.9	11.9	0.4	64	51	13
	Orteglas (Paularo)	3.5	2.6	0.7	14	13	1
Degano	Miozza	8.8	10.6	0.5	33	32	1

To clarify the classification adopted in the inventory and to support the interpretation of results, Table 2 provides a brief description of the construction material category.

The regional TTCSs inventory was updated for 282 structures across seven sub-catchments (Table 3; Fig. 1B, C, D) through field surveys, resulting in a comprehensive dataset for the qualitative assessment of the conceptual coherence of the index. The field survey campaign was conducted in 2024 to verify that the structures were still present, accurately geolocated, and correctly classified in the regional historical database, ensuring that the comparison would be meaningful.

3.2 Potential Fragility Index (PFI)

The PFI combines intrinsic and extrinsic factors to the structure, each weighted according to its relative contribution to structural fragility. The weighting scheme reflects the perceived influence of each factor on potential fragility. The term "fragility" refers to a structure that is more prone to damage according to its characteristics.

The index, grounded in the work of Marchi et al. (2022), was based on three intrinsic factors (age of the structure – from the year of construction, height of the structure, construction material) available from the inventory of torrent control works of the Autonomous Province of Trento (Italy) and three external factors (landslide hazard, substrate – derived from a 1:10,000 geo-lithological map, and an instability index) also available in that specific region. The version developed in this work relies less on local datasets for the extrinsic factors and is thus easier to apply in different contexts.

3.2.1 Intrinsic factors

The intrinsic factors obtained from the regional inventory of TCSs include – like the original index developed for the Autonomous Province of Trento – the year of construction as an indicator of structure ageing (Rudolf-Miklau 2005; Suda et al. 2009; Davidescu et al. 2012), the height of the structure and the construction material. Structure height may itself represent a discriminating factor between check dams and bed sills, as check dams are typically taller and therefore more exposed to hydraulic stress and sediment impact. Bed sills, due to their lower height, are generally less prone to damage from intense sediment transport events. The PFI therefore implicitly accounts for this difference through the height parameter.

3.2.2 Extrinsic factors

The extrinsic factors refer to the lithology, derived from the 1:150,000-scale geo-lithological map of Friuli-Venezia Giulia (Carulli 2006), and to the channel reach in which each structure is located, identified using the classified hydrographic network tool developed by Cavalli et al. (2017).

The classified hydrographic network is an integer raster with the same resolution as the DTM, where each cell is assigned a numerical code identifying the potential debris-flow process domain: (1) propagation zones, (2) triggering zones, (3) deceleration zones, (4) stop zones (additional data are provided in Online Resource 1).

The input of the procedure is the DTM of the three catchments, while the output is the classified hydrographic network, which allows the identification of potentially debris-flow-prone stream reaches.

Potential debris-flow triggering zones are identified following the empirical slope-drainage area threshold proposed by Zimmermann et al. (1997).

Moreover, a local slope threshold of 38° is adopted, as this angle reflects the approximated typical frictional properties of materials found in debris-flow initiation zones in alpine environments; above this threshold, the availability of sediments is generally low or negligible.

According to the same procedure, DTM cells with slopes between 3° and 8° are classified as deceleration zones, whereas cells with slopes lower than 3° are classified as stopping zones. The cells which do not belong to triggering, deceleration and stop are assigned the propagation class.

To homogenise the channel network and obtain more consistent channel reaches, the original DTM with a spatial resolution of 0.5 m was resampled to 5 m. Subsequently, the classified hydrographic network was processed using a majority filter with a 4 × 4 kernel. This filtering reduces the influence of local micro-topographic variations and isolated raster cells that may act as outliers within channel reaches, thereby ensuring a more reliable and spatially consistent classification of the process domains along the channel network. Within each channel reach, where most cells belong to the same class (e.g., propagation), the majority filter smooths local inconsistencies and minimises noise effects.

Each TTCS was assigned the code of the corresponding zone along the channel reach, based on a 15 m sampling buffer. Structures falling outside this buffer, and therefore lacking classified network information, were assigned a code according to a slope-based threshold. The threshold was defined as the mean slope of the main channel/valley. Specifically, for the Fella catchment, slopes above 8.56° were assigned a code of 1 and those below 8.56° a code of 4. For the But catchment, the threshold is 13.47° and for the Degano catchment it is 12.63°. This allows distinguishing structures located on steep slopes potentially within a triggering zone, from those on low slopes, potentially within stop zones.

Lithological classes have been delineated based on the relative and intrinsic predisposition of lithological groups to instability. Some lithologies are inherently more prone to failure than others; therefore, a generalised classification of lithotype groups can be established (Cazorzi and Merci 2008; additional data are given in Online Resource 2).

Each factor was divided into classes of potential fragility on a scale from 1 (low) to 3 (high). These classes are shown in Table 4.

3.2.3 PFI computation

The PFI was calculated as the sum of the classes of the factors multiplied by their weights, divided by the sum of the weights (Eq. 1). The division by the sum of the weights is to ensure the comparability of results between structures in case of missing factors.

$$PFI = \frac{\sum (F_n * w_f)}{\sum w_f} \tag{1}$$

where F_n is the class of the factor class (Table 4) and w_f is the weight of the factor.

A questionnaire was developed to determine the weights of factors influencing the fragility of TTCSs.

Table 4 Factors and classes of potential fragility

		Class		
		1	2	3
Factor	Construction year	After 1980	1950 to 1980	Before 1950
	Height	Less than 1 m	1 to 3 m	More than 3 m
	Construction material	Concrete,reinforced concrete	Stone masonry, wood and stone, mixed	Gabion, wood
	Lithology e.g. (Additional data are given in Online Resource 2)	Dolomites and dolomitic limestones	Whitish saccharoidal gypsum alternating with black brecciated dolomites	Quaternary deposits
	Channel reach	Stop	Deceleration	Triggering/Propagation

The questionnaire targeted practitioners (freelance consultants and regional authority staff in charge of watershed management) and academic experts.

Respondents were asked to rate the potential influence of each factor on the fragility of TTCSs.

The question posed was: "*What importance would you assign to the -Factor- when assessing the fragility of check dams and bed sills on a scale of 0 (low potential fragility) to 1 (high potential fragility)?*". The mean score of the responses for each factor was used to determine its final weight.

3.2.4 Robustness

Since not all the factors were available for each structure, a robustness parameter was introduced to quantify the completeness of the factors used to compute the index. This metric provides additional information by indicating how representative the calculated index is with respect to the full set of factors available.

The robustness value, ranging from 0 to 100, represents the proportion of the total factor weights that effectively contribute to the index of each structure.

The robustness of the index is defined in Eq. (2) and is calculated as:

$$\mathrm{Rob_{PFI}} = \frac{\sum \mathrm{w_f}}{\sum \mathrm{w_{tot}}} * 100 \tag{2}$$

where $\mathrm{w_f}$ is the weight of the available factor and $\mathrm{w_{tot}}$ is the sum of the weights of all factors included in the index computation.

By normalising the sum of the weights of the available factors by the total weight of the index, the robustness parameter provides a measure of data completeness, allowing the PFI results to be interpreted in relation to the amount of information available. Consequently, robustness supports the PFI interpretation by highlighting cases in which low PFI values may be influenced by the absence of a significant number of contributing factors.

4 Results and discussions

The analysis of the regional inventory of TTCSs shows a clear evolution in construction practices over the last century (Fig. 3), similar to the results reported by Paratscha et al. (2018). In the early decades (1900–1960), stone masonry dominated, while from the mid-20th century onwards, concrete and reinforced concrete progressively replaced stone masonry. Reinforced concrete became increasingly common after the 1960s. More recent decades reveal a diversification of materials, including wood and gabions, although reinforced concrete remains the prevailing choice. This trend illustrates the transition in construction materials within the regional context.

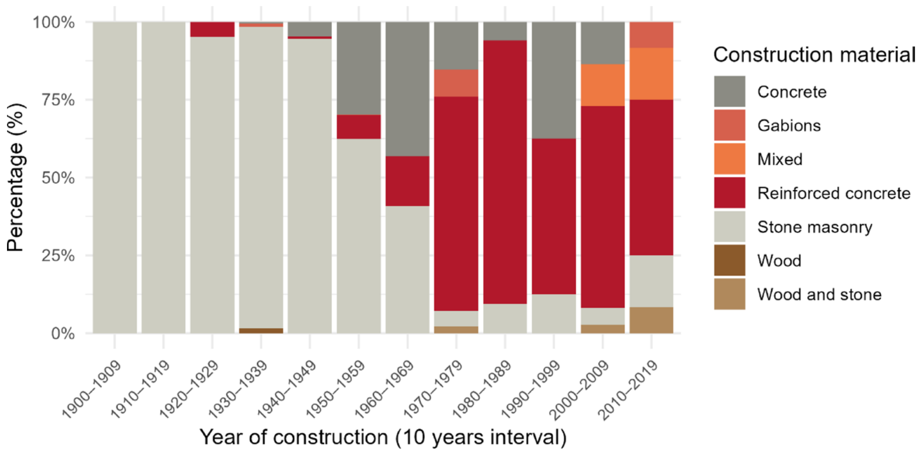


Fig. 3 Percentage distribution of construction materials by year

4.1 PFI applied at a large scale

The responses to the questionnaire, aimed at defining the relative weights of the factors, are shown in Fig. 4. A total of 37 responses were collected. The mean score of the responses for each factor was used to determine its final weight.

Regarding structure height, 29.7% of respondents assigned a medium level of influence. For the construction year, the highest frequency of responses (24.3%) corresponds to a weight of 0.8, indicating a generally high perceived importance. The channel reach in which the structure is located, in terms of "triggering," "propagation," "deceleration," and "stop", is predominantly associated with higher weights, with a peak of 37.8% of responses at 0.8. Similarly, lithology shows a peak at a weight of 0.7, assigned by 29.7% of respondents. Finally, the importance attributed to construction material is skewed toward high values, with 24.3% of respondents assigning weights of both 0.8 and 0.9.

The PFI distribution was analysed for the 3556 structures and classified into three fragility classes (low, medium and high) based on the 25th and 75th percentiles of the index distribution as thresholds: low (< 1.76), medium (1.76–2.26), and high (> 2.26; Fig. 5). Subsequently, the PFI was computed at the regional scale according to the Eq. (1) for the But, Fella and Degano catchments (Fig. 6).

4.2 The PFI coherence with field observations

To qualitatively assess the conceptual coherence of the PFI, the results were evaluated through a field survey for 282 TTCSs across seven sub-catchments. The sub-catchments do not claim to be representative of the catchment within which they are located. Nevertheless, the surveyed structures reflect the diversity of TTCSs in terms of construction materials, height classes, and construction periods, and can therefore be considered representative of the broader population of structures found across the three main catchments.

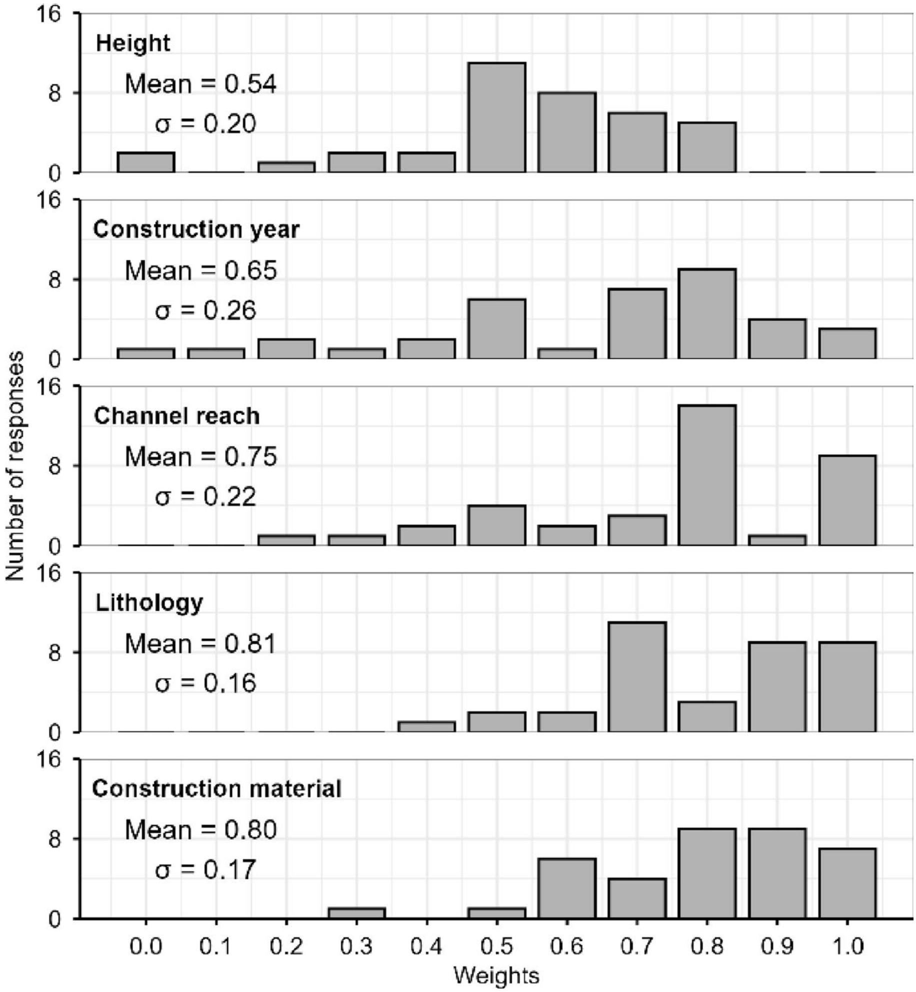


Fig. 4 Responses to questionnaire (total respondents = 37): the mean score of each factor was calculated and used as the weight of the factor

According to the index calculation, similar configurations are expected to result in comparable potential fragility classes, while differences in the current structural status should primarily reflect variations in dominant geo-hydrological processes.

Figure 7 shows the first case study to qualitatively assess the coherence of the results obtained from the application of the PFI. Two check dams (no. 31 and 32 in Cucchiaro et al. 2019) within the Moscardo catchment (Fig. 1C) were analysed; both are located in the upper part of the catchment in a steep-slope environment. The Moscardo basin has been affected by numerous events, some of them of high intensity (Marchi et al. 2021).

Figure 7A shows the check dam (no. 32) located upstream, which was classified as having *high potential fragility*. Its current condition reveals significant damage affecting the spillway, wings, and main body.

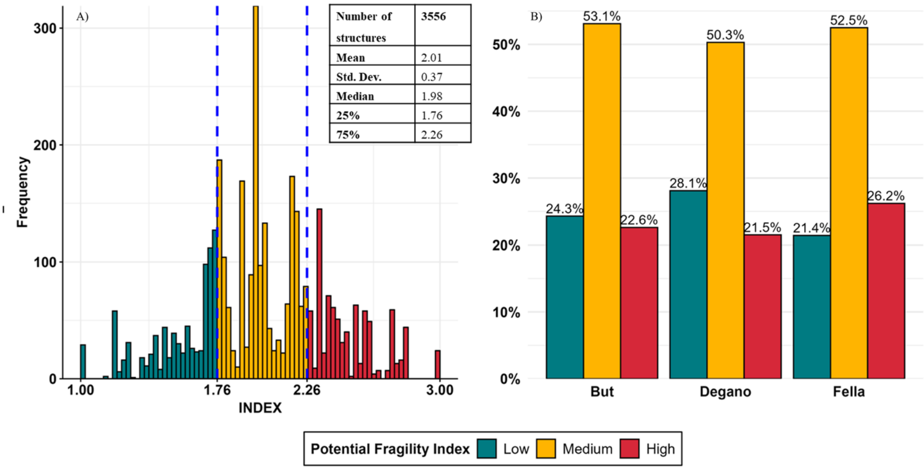


Fig. 5 PFI results. **A** The total PFI distribution was analysed across all catchments, and structures were classified into three fragility classes based on quantiles. **B** The percentage of structures in each class is reported for each catchment

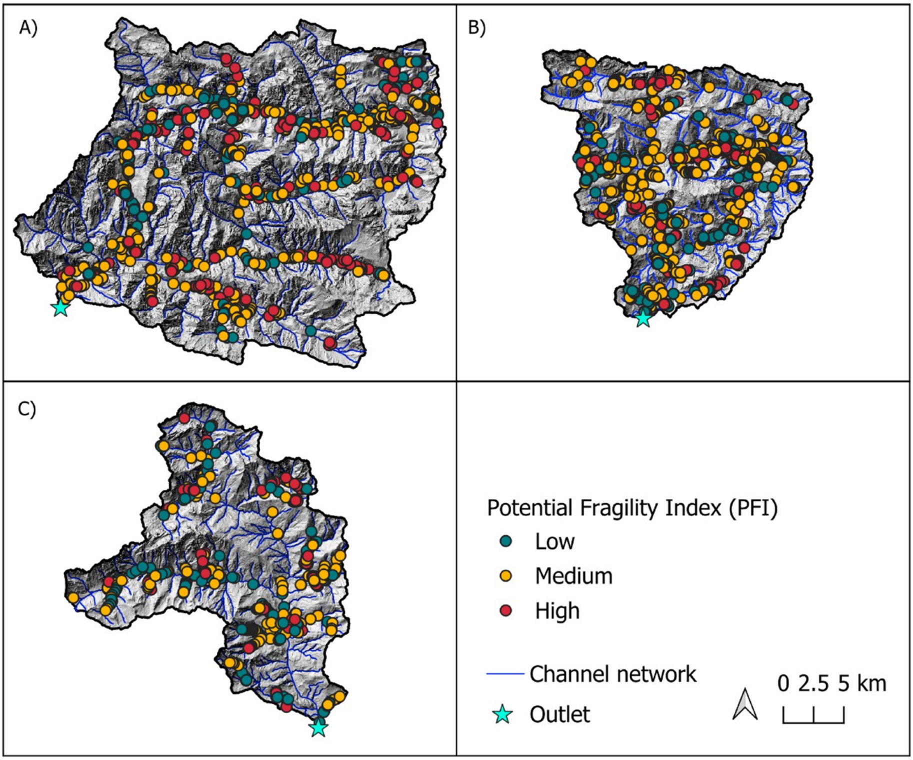
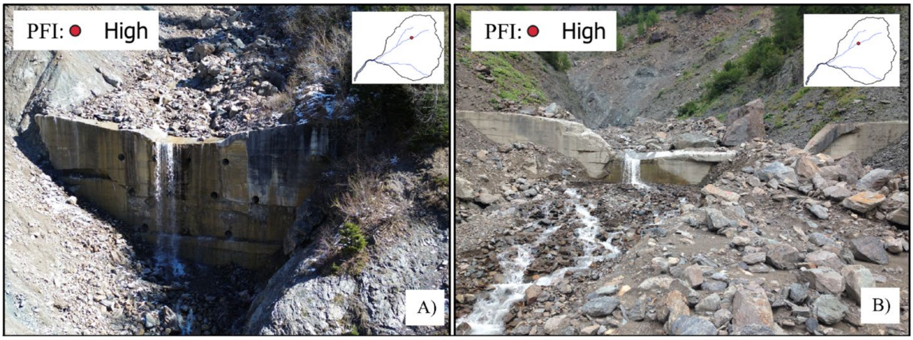


Fig. 6 Application of the index at the regional scale. **A** Fella catchment; **B** But catchment; **C** Degano catchment



Year	1980	1980
Height (m)	7	5
Material	Reinforced concrete	Reinforced concrete
Lithology	Recent and current slope debris	Recent and current slope debris
Channel reach	Propagation	Propagation
Rob_{PFI}	100	100

Fig. 7 Structures located at the head of the Moscardo catchment. **A** Upstream check dam (no. 32); **B** Check dam (no. 31) located immediately downstream of the structure A

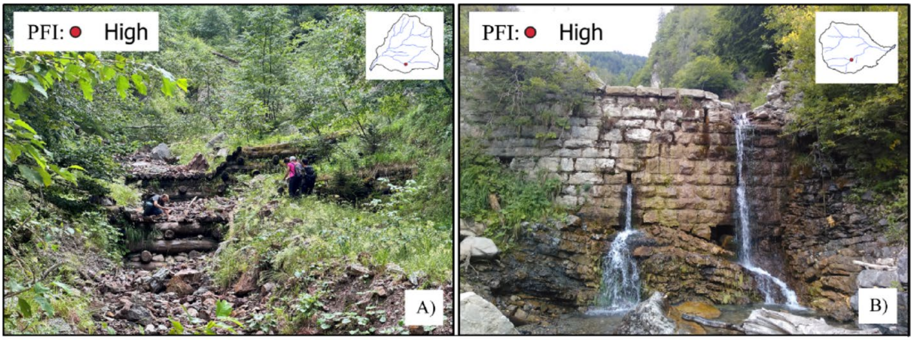
Figure 7B presents the immediately downstream check dam (no. 31), which was also classified by the PFI as having *high potential fragility*. Field surveys indicate that this structure exhibits signs of structural damage, particularly at the spillway, wings, and main body.

It is important to note that the analysed check dams, constructed around 1980, were founded on recent and current debris deposits, and repeatedly impacted by debris-flow events, were consistently classified by the index, demonstrating the coherence of the PFI in reflecting both structural characteristics and geomorphological context.

The other two TTCSs located at the catchment head are here considered as examples: one in the Turriea catchment (Figs. 1C and 8A) and the other in the Miozza catchment (Figs. 1D and 8B) both situated in a channel reach classified as propagation zone. The Turriea check dam exhibits *high potential fragility* due to its location in a propagation reach and its wooden construction. The field surveys reported that this structure is partially degraded due to an upstream landslide and intense sediment transport, which compromises its structural integrity. The Miozza check dam (no. 320 in Martini et al. 2023), located on the right tributary of the Miozza catchment in a step-pool reach, is also classified as having *high potential fragility*. Field observations indicate damage to the spillway, where deterioration processes are evident.

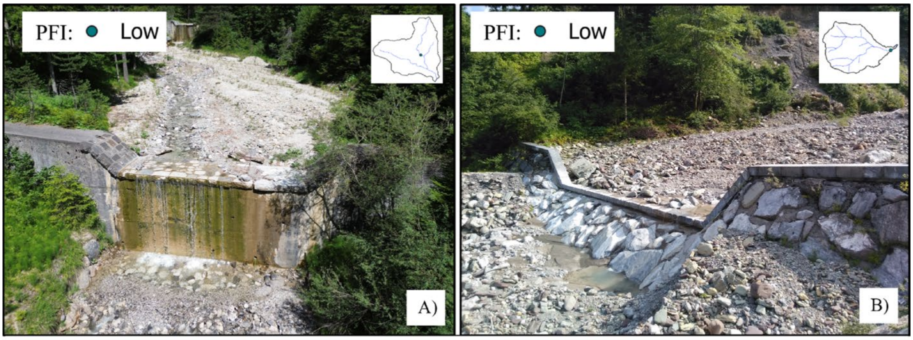
About the Miozza check dam, one factor that may contribute to its long-term stability (given that its year of construction is 1927) is its foundation on bedrock, which provides structural support (Dell'Agnese et al. 2013), independently of age, height, or construction material (Boll et al. 1999; Rudolf-Miklau 2005; Davidescu et al. 2012). Despite these differences in condition and stabilising factors, the PFI classification remains coherent with conceptual expectations, as structures located in headwater zones are generally more exposed to fragility due to steep slopes and dominant erosional processes.

In contrast to the previous case study, Fig. 9 shows two check dams located in low slope areas and within the alluvial fan zone, both classified by the index as having *low potential fragility*.



Year	-	1927
Height (m)	2.10	5.30
Material	Wood	Stone masonry
Lithology	Whitish saccharoidal gypsum alternating with black brecciated dolomites	Oolitic limestones*
Channel reach	Propagation	Propagation
Rob_{PFI}	81.74	100

Fig. 8 Structures located on the head of the catchment. **A** Turriea check dam; **B** Miozza check dam (no. 320). * Oolitic limestones with marls, yellow-ochre dolomites and dolomitic limestones, grey and hazel micrites interbedded with red pelites, fine micritic limestones, pelites and marly pelites, sandstones and pelites, micritic limestones with pelites, oolites with dolosiltites and pelites



Year	1950	2009
Height (m)	4	2
Material	Concrete	Reinforced concrete
Lithology	Dolomites and dolomitic limestones	Dark limestones alternating with marls
Channel reach	Stop	Propagation
Rob_{PFI}	100	100

Fig. 9 Structures located in a low-slope area. **A** Cella-Vuom check dam; **B** Miozza check dam (no. 030)

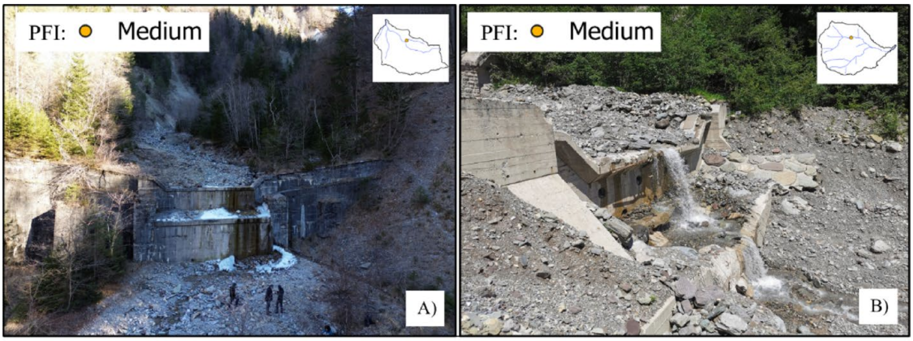
The first structure, within the Cella-Vuom catchment (Figs. 1B and 9A), currently shows no signs of damage despite having been constructed in 1950. Its good present condition is mainly related to its location in a low slope channel reach, its foundation on stable lithological formations and the absence of high-impact events.

The check dam no. 030 (Martini et al. 2023) in the Miozza catchment (Figs. 1D and 9B) is relatively recent and built of reinforced concrete faced with stone masonry; it also shows no evident structural damage.

Also in this case, the index, based on qualitative assessments, consistently classified the structures in accordance with their current conditions.

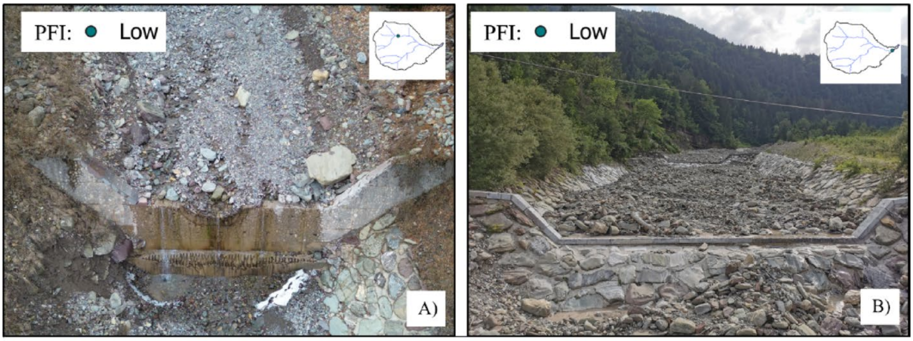
In the case shown in Fig. 10, two check dams of similar age, founded on the same lithology and located in the same channel reach, are situated in two different catchments characterised by different dominant geo-hydrological processes. The Orteglas catchment (Treppo Carnico; Fig. 1C) is mainly characterised by bedload transport, whereas the Miozza catchment (Fig. 1D) is dominated by debris-flow activity (Cucchiaro et al. 2024). Both structures, classified as having *medium potential fragility*, are located within a propagation channel reach. However, the Miozza check dam (no. 110 in Martini et al. 2023; Fig. 10B) is repeatedly exposed to debris-flow events with erosion observed on the apron and spillway. In contrast, the Orteglas (Treppo Carnico) check dam (Fig. 10A) currently shows good conditions. This comparison highlights the key role of dominant geomorphic processes in influencing the potential fragility and performance of TTCSs, even when structures share similar characteristics.

Like the previous example, structures built within the same catchment, even when constructed during the same period and using similar materials, may exhibit different responses depending on their location within the hydrographic network (Osti and Egashira 2008). Figure 11 presents two check dams along the Miozza torrent (Fig. 1D): one (no. 200 in Martini et al. 2023; Fig. 11A) located in the upper part of the channel reach and the other (no. 020; Fig. 11B) close to the alluvial fan. Both structures were classified by the PFI as having *low potential fragility*, reflecting their comparable intrinsic and extrinsic factors. However, field observations revealed contrasting current conditions. The upstream structure shows damage



Year	1972	1977
Height (m)	7	3
Material	Concrete	Reinforced concrete
Lithology	Oolitic limestones*	Oolitic limestones*
Channel reach	Propagation	Propagation
Rob_{PFI}	100	100

Fig. 10 Structures located in two catchments affected by different dominant processes. **A** Orteglas (Treppo Carnico) check dam; **B** Miozza check dam (no. 110). * Oolitic limestones with marls, yellow-ochre dolomites and dolomitic limestones, grey and hazel micrites interbedded with red pelites, fine micritic limestones, pelites and marly pelites, sandstones and pelites, micritic limestones with pelites, oolites with dolosiltites and pelites



Year	2010	2009
Height (m)	3.50	2
Material	Reinforced concrete	Reinforced concrete
Lithology	Oolitic limestones*	Dark limestones alternating with marls
Channel reach	Propagation	Propagation
Rob_{PFI}	100	100

Fig. 11 Miozza check dams: **A** head of the catchment (no. 200); **B** alluvial fan (no. 020). * Oolitic limestones with marls, yellow-ochre dolomites and dolomitic limestones, grey and hazel micrites interbedded with red pelites, fine micritic limestones, pelites and marly pelites, sandstones and pelites, micritic limestones with pelites, oolites with dolosiltites and pelites

at the spillway and exposed foundation, whereas the downstream structure remains in good condition, with no visible deterioration.

This comparison further emphasises the influence of the localisation of the structure within the catchment. At the same time, the PFI classification remains conceptually coherent, reflecting the generally low potential fragility associated with similar structural characteristics, while recognising that local geomorphological settings can produce different degradation patterns over time.

The choice to divide the index distribution using the 25th and 75th percentiles reflects the preliminary nature of the index, which is designed as a screening tool in the absence of established absolute thresholds. By adopting these percentiles rather than an equal-thirds subdivision, we retained a broader intermediate class, concentrating attention on the extremes: structures falling below the 25th percentile are considered non-critical, while those exceeding the 75th percentile are classified as potentially critical. This conservative approach reduces the proportion of structures classified within the extreme fragility classes. We acknowledge that the threshold selection remains arbitrary; the 33rd and 66th percentile subdivision, which provides a more balanced distribution across classes, was also tested. However, the wider intermediate class resulting from the 25th to 75th percentile approach was preferred, as it better suits the intended use of the index as a screening tool for relative comparison across structures and catchments rather than an absolute classification system.

5 Conclusions

Due to rapid changes in climatic conditions and the increasing frequency of intense rainfall events, it is crucial to evaluate TCSs efficiently to identify those requiring attention. This study proposes a regional-scale Potential Fragility Index (PFI) for TTCSs, designed to provide a screening tool for identifying structures with the highest potential susceptibility to damage. To assess the conceptual coherence of the PFI, 282 structures located in seven sub-catchments were investigated through field surveys. The surveys aimed to update the TTCSs inventory and to evaluate the PFI classification under known conditions, considering geomorphological settings and recurrence of events. This evaluation was carried out through comparison with the PFI and the status of conservation. Although the PFI is not intended as a predictive tool of the current structural condition, the conceptual assessment generally yielded results consistent with the present state of the structures.

The comparative analysis of structures located in different geomorphological contexts, such as alluvial fans, propagation zones, and headwater areas, highlighted the decisive role of structural location within the catchment in controlling potential fragility.

Structures located in the headwater of the catchment and in propagation zones, which are characterised by steep slopes and dominant erosional processes, were generally associated with higher PFI values. Conversely, TCSs situated on alluvial fans, where depositional processes prevail and slope gradients are lower, tended to exhibit low to medium potential fragility.

Moreover, structures within the same catchment, characterised by similar intrinsic factors and identical PFI classifications, may display different current structural conditions when located in different channel reaches. Comparisons among structures located on alluvial fans, in middle channel reaches, and at channel heads, both within and across sub-catchments, further emphasised the importance of considering both the prevailing processes within each sub-catchment and the specific construction site when evaluating potential fragility. It is important to stress that a structure classified as having “high potential fragility” may still be in good structural condition due to the absence of triggering events or due to recent maintenance activities, whereas a structure with “low potential fragility” may appear damaged if affected by recent extreme events or neglected maintenance. Field surveys were therefore used to assess the conceptual consistency of the index rather than to quantitatively validate its predictive capability.

The strength of the PFI lies in its applicability across diverse contexts, as it relies on readily available data, and it provides a practical regional-scale screening tool for guiding resource allocation and management strategies. This study further underscores the importance of maintaining an up-to-date inventory, which constitutes a fundamental resource for regional-scale analyses and for effective planning and prioritisation of maintenance efforts.

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