Università degli studi di Udine

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Published
DOI:10.1111/jfr3.13011

Received: 3 October 2023 | Revised: 19 March 2024 | Accepted: 9 May 2024

DOI: 10.1111/jfr3.13011

ORIGINAL ARTICLE

CIWEM Chartered Institution of Water and Environmental Management
Journal of Flood Risk Management
WILEY

Monitoring of torrent control structures: An integrated approach from first-level inspections to maintenance strategies

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Abstract

Torrent control structures are essential countermeasures against potential losses from flood to debris flow events. The durability of these structures hinges upon several factors, including the structure's design, construction materials and ongoing maintenance as well as the physical pressures they are under. Over the past half-century, a decline in investments allocated to routine maintenance activities, coupled with the natural degradation of these structures, has contributed to a reduction in their protective capacity. In this context, monitoring and maintaining existing structures are essential actions. This study presents a comprehensive proposal for a routine inspection process adopted for torrent control structures along four rivers in North Italy. The results of the first-level inspections consist of a dataset encompassing missing details (e.g., width, length, height, construction age, materials used), present condition of structures and functionality. The further step is to predict the vulnerability of the inspected torrent control structures; so, the Markov chain model is implemented for forecasting their service life, also in function of different maintenance strategies. Furthermore, this study serves as a valuable resource for reinforcing the role of the first-level inspections and ongoing monitoring, which is essential for planning future investments in watershed management, especially in the routine maintenance of torrent control structures.

KEYWORDS

check dams, flood risk, infrastructure planning, Markov chains, natural hazards, probabilistic models, service life, vulnerability

1 | INTRODUCTION

Mountainous catchments are susceptible to various sediment delivery events, ranging from flood with bedload transport to debris flows triggered by rainfalls and sudden snowmelt. These natural processes significantly contribute to shaping the mountain landscape due to their intense geomorphic action. Meanwhile, they also interact with human activities, often causing damage to agricultural areas, roads, railways, settlements and, tragically, even fatalities. Therefore, the imperative to safeguard human infrastructures has driven the implementation of both structural and non-structural countermeasures. These measures encompass land-use restrictions, reforestation, early warning systems and in-channel interventions (Boix-Fayos et al., 2008; Bombino et al., 2008; Cislaghi & Bischetti, 2019; Quiñonero-Rubio et al., 2016). Among these solutions, dating back to the second half of the 19th century, the primary approach to countering natural hazards has been the construction of torrent control structures (TCSs; Comiti, 2012; Marchi et al., 2019; Mazzorana & Fuchs, 2010). These structures play an integral role in the sustainable management of landscape, serving the dual purpose of preservation and, whenever feasible, enhancement of the mountainous environment (as discussed in Mazzorana et al., 2008). Specifically, TCSs are designed to reduce or control sediment production and channel erosion as active structural measures or minimising sediment deposition and overflow as passive structural measures (Chahrour et al., 2021; Huebl & Fiebiger, 2005; Piton et al., 2017). However, their function is not 'without risk' because they are susceptible to environmental conditions including the same processes they should mitigate (Marchi et al., 2019). So, the assessment of the service life (i.e., the expected period of effective performance of the structure) and the functionality of these structures over time (i.e., the ability to fulfil the functions for which they were built) is essential for planning their maintenance (Biondini et al., 2015; Decò et al., 2013; Mazzorana et al., 2014; Tacnet et al., 2012; Xiong et al., 2020). Partial or total damage to a specific component of the TCS can trigger a cascading 'domino effect', leading to the collapse of the overall structure. In turn, the failure generally triggers sediment mobilisation, altering sediment transport dynamics, provoking regressive erosion or excessive downstream deposition and unleashing subsequent repercussions such as the failure of other downstream or upstream structures (Baggio & D'Agostino, 2021; Chahrour et al., 2021; Cucchiaro, Cavalli, et al., 2019). Indeed, to ensure functionality, it is not enough to build them (Armanini et al., 1991), but it is necessary a vigilant approach encompassing ongoing monitoring and maintenance to register damages and to plan repair or reconstruction (Cortes Arevalo et al., 2016). Thus, monitoring the functionality, the difference between the current and the baseline functionality, entails evaluating if a stable structure might no longer fulfil its intended function or, conversely, whether a structure close to collapse might still perform its function.

To pursue this objective, river managers must rely on standardised protocols and procedures to determine the need for repairs or reconstruction of the inspected existing structures, as well as to evaluate risk reduction and cost-effectiveness associated with the construction of new structures (Piton et al., 2017). Key activities of monitoring are visual inspections and non-destructive testing (J.-H. Lee et al., 2018; K.-H. Lee et al., 2022; Mazzorana et al., 2018; Mizuyama, 1979). However, these methods are time-consuming and request professional human resources. River managers must grapple with the constraints of a limited budget, which necessitates to prioritise maintenance strategies (Morcous & Hatami, 2011). The maintenance plan must be supported by effective capital programs in upcoming years to conserve the natural hazards protection level (Li et al., 2016).

In this context, pioneering studies developed methodologies aimed at bolstering river maintenance planning. Davidescu et al. (2012) introduced a condition rating that assesses the cumulative impact of diverse damages, providing an indicator to guide maintenance prioritisation. Other studies delved into determining repair precedence through the exploration of various environmental factors, such as catchment area, streambed slope, river network length and land use within the catchment, as well as considering structural geometry such as height, width, age and function (e.g., Mihalache et al., 2020; Tesileanu et al., 2015). These factors are further completed by event characteristics such as event type and magnitude (Dell'Agnese et al., 2013) and by geomorphic change (Cucchiaro, Cazorzi, et al., 2019; Cucchiaro et al., 2024). To enhance decision-making, Tacnet et al. (2012) introduced decision-support tools that assess the overall efficiency of structures by considering simultaneously their structural integrity and functional capabilities. Another alternative was proposed by Mazzorana et al. (2018), who developed a scenario analysis technique to quantify damage susceptibility using the data collected after three different flood events. All the proposed procedures provide practical applications, however, the persistent scarcity of data on the existing structures (e.g., dimensions, age, condition, design, etc.) and the lack of connections between monitoring and planning remain serious obstacles that cannot be ignored.

To overcome this, the present study aims at (i) developing an integral approach to monitor the conditions of existing TCSs in terms of their state of damage and functionality; (ii) establishing a comprehensive data repository dedicated to TCSs that collects essential information such as structure type, materials, structure age and present degradation state. This repository is designed to facilitate empirical analyses; (iii) introducing a stochastic model based on the Markov process, serving as a robust tool for strategic planning of routine maintenance for

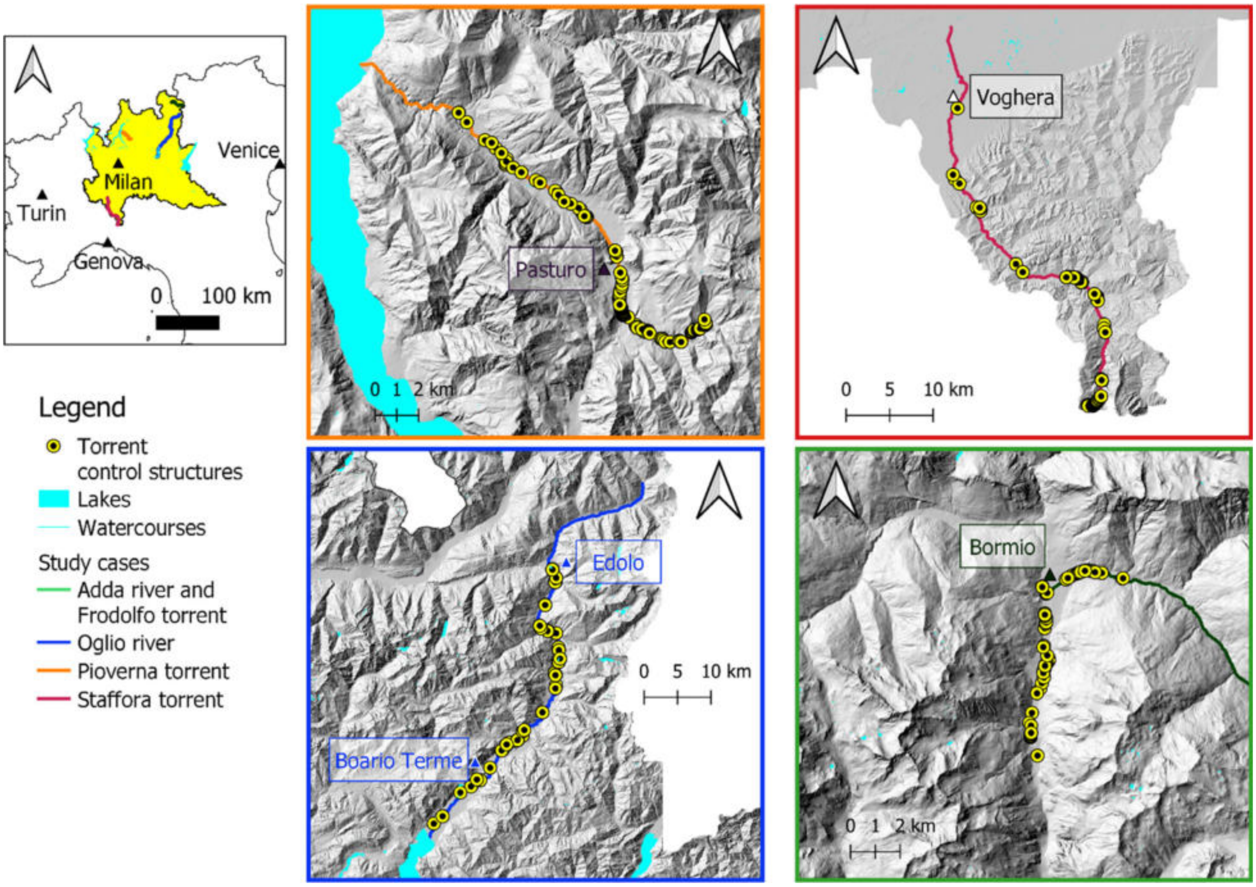

FIGURE 1 Location of study cases and of inspected torrent control structures.

TABLE 1 Main morphological characteristics of the four study watercourses.

Watercourse	Altitudinal range (m)	Length (km)	Area (km^2)	Geographic region
Pioverna torrent	200–1813	29	160	Prealps
Staffora torrent	70–1343	58	364	Apennines
Oglio river	185–1236	104	1434	Prealps
Upper Adda river				
Adda river	946–1938	20	563	Alps
Frodolfo torrent	1170–2444	23	225	Alps

TCSs. The proposed model provides the deterioration of new structure's functionality over time, forecasts a probabilistic estimate of their service life and, if adopted to the existing structures, offers a probabilistic framework of how many structures will require repairs or restoration. This comprehensive forecasting encompasses different maintenance strategies, including routine maintenance, repair and reconstruction. By addressing these three objectives, this study intends to provide a holistic and innovative framework for effective TCS management, even in the face of data limitations.

2 | MATERIALS AND METHODS

2.1 | Study area

The present study was conducted on the transverse torrent control structures, TTCSs hereafter, located along four watercourses in Lombardy (North Italy; Figure 1): Pioverna torrent, Oglio river, Staffora torrent and Upper Adda river (Table 1). All these watercourses belong to the primary hydrographic network, monitored and maintained by regional authorities. These study areas fall within the temperate ecoregional division (Blasi et al., 2014). The average annual precipitation across these study areas varies from 685 to 1647 mm.

2.2 | Description of TTCSs

The traditional classification of TTCSs considers the structure height as a distinctive factor (Paratscha et al., 2019). The structure height corresponds to the distance above the upper edge of the foundation plate and the crest of the structure. The present study combined this classification with specifications about structural functions. Four distinct groups were identified (Figure 2): (i) *check dams*: structures that control the sediment dynamics inside the watercourse by stabilising the transverse profiles of torrential bed, by consolidating the longitudinal bed (reducing the bed slope and the velocity of torrential water flood, and as a consequence of sediment transport), by sorting or dosing the sediment transport rate, by retaining the bed load in their storage area and by breaking of debris flow (Armanini et al., 1991; Kostadinov & Dragovic, 2010); (ii) *(ground and submerged) sills*: structures designed to stabilise the channel and prevent bed erosion; (iii) *bed protection structures*: interventions designed to consolidate the surface layer of the channel bed and to prevent erosion and sediment mobilisation; and (iv) *groynes*: deflectors that skilfully divert the flowing water away from the streambank and limiting the sediment movement.

2.3 | First-level inspection

The first-level inspection (FLI) consisted of a comprehensive visual assessment of TTCS (Dell'Agnese et al., 2013; Lee et al., 2022; Paratscha et al., 2019). This procedure encompasses meticulous scrutiny of the overall structure. Where possible, the FLI was conducted both on the top and around the hydraulic structure to identify damages and dysfunctionalities on the downstream and on the upstream side, walking along the watercourse. Where unsafe, the inspectors exploited unmanned aerial vehicles (UAVs) equipped with red–green–blue cameras (e.g., DJI Mavic Mini). Moreover, a global navigation satellite system receiver, a measuring tape, and a ground-based

FIGURE 2 Photographs and illustration of transverse torrent control structure types: (a) check dam, (b) groyne, (c) sill, and (iv) bed protection structures (modified from Paratscha et al., 2019).

FIGURE 3 Photographs of transverse torrent control structures (TTCSs) inspected during the first-level inspection: The left column shows the four levels of damage index (DI) values and the four conditions of loss of functionality index (LoFI) in worsening scale. Additional examples were reported in Appendices SA and SB in Supporting Information Materials.

TABLE 2 Description of common damages in function of the element of the TTCSs (see more details in Appendix SA in Supporting Information Materials).

Type of damages	Elements			
	Spillway	**Body**	**Foundations**	**Lateral abutment**
Cracking	X	X	X	
Joint spalling	X	X		
Joint deterioration	X	X	X	
Abrasion	X	X		
Erosion	X	X	X	X
Corrosion	X	X		
Leakage	X	X		
Efflorescence	X	X		
Uncontrolled vegetation	X	X		
Displacement			X	
Cavity			X	
Exposure			X	X
Local scouring			X	
Flow concentration				X

camera were used to georeference the TTCSs, to measure dimension and to detect damages/dysfunctionalities. The assessment of damages and dysfunctionalities hinged on the use of two qualitative indicators: the damage index (DI) and the loss of functionality index (LoFI). Appendices SA and SB in Supporting Information Materials contain a detailed description of these two indicators, and some examples of practical assessments were shown in Figure 3.

2.3.1 | Damage index

The DI served as a comprehensive indicator of the overall degradation state of the TTCS (Dell'Agnese et al., 2013; Lin et al., 2023). During the FLI, the inspector considered each element composing the TTCS, that is, (i) spillway or crest, (ii) body, (iii) foundations and (iv) lateral abutment. Then, the inspector assigned a DI value to the *i*-th element composing the structure (DI_i), using a straightforward scale ranging from 0 (no damage) to 3 (failure). This assessment allowed the distinction of the degradation processes involving the different elements of TTCSs (e.g., cracking, joint spalling, joint deterioration, etc.; Clinciu et al., 2010; Table 2). The computation of DI involved a weighted sum of DI_i, expressed through the following equation:

$$\mathrm{DI} = \sum_{i=1}^{k} w_i \times \mathrm{DI}_i, \tag{1}$$

where *i*-th is the constituent part (spillway or crest, body, foundations and lateral abutment), k is the number of surveyed elements and w_i is the vector of weights that can express different importance of each functional part. For the purposes of this study, uniform weights were assigned, with their collective sum equating to unity.

$$\sum_{i=1}^{k} w_i = 1. \tag{2}$$

2.3.2 | Loss of functionality index

The LoFI assessed the remaining performance of the structure function. As the damage indicators, LoFI is a qualitative metric derived from the FLI, ranging from 1 (unaltered functionality) to 4 (no residual functionality). The assessment of this index is based on the identification of the primary function of the TTCS (Table 3), and the evaluation of the effects on the functionality due to damages and/or material degradation. Among the functionality losses of all typologies of TTCSs, the most common causes are due to: (i) *sediment deposition* on spillway or apron. This process reduces the structure functionality to efficiently concentrate or divert the torrential streamflow and dissipate the kinetic energy; (ii) *coarse and large wood storage* on spillway or apron. This deposition obstructs the transverse section, often concentrating the torrential streamflow only on the side of the structure

TABLE 3 Description of primary function and common dysfunctionality in function of the TTCSs (see more details in Appendix SB in Supporting Information Materials).

Type of TTCSs	Primary function	Dysfunctionality
Check dam	Stabilisation	Streamflow bypasses the spillway. Streamflow outflanks the structure. Bed erosion.
	Consolidation	Streamflow bypasses the spillway. Streamflow outflanks the structure. Excessive erosion.
	Sediment retention	Deposition space is filled.
Sills	Bed stabilisation	Excessive deposition. Excessive erosion.
Bed protection structure	Bed stabilisation	Bed erosion. Excessive deposition.
Groynes	Streambank stabilisation	Streamflow bypasses the element. Streambank erosion.

(not designed to be surmounted by streamflow) or on a streambank; (iii) *erosion* on foundations, abutments, spillway or apron. This action can lead the streamflow to bypass the structure going around from side or below (and cause the entire collapse) or to concentrate over the streambed, exacerbating the sediment movement; (iv) *uncontrolled colonisation of riparian vegetation* around and over the structure. The vegetation increases flow resistance, hydraulic roughness and hydraulic depth, meanwhile reducing hydraulic velocity and impeding the adjusted (or 'designed') direction of streamflow. Moreover, the interplay of these factors collectively influences the functionality of the structure, culminating in a deterioration of its operational capability.

2.4 | Statistical analysis

2.4.1 | Markov chain model

The deterioration of functionality of TTCSs is a complex phenomenon influenced by a broad spectrum of external factors, generally not measurable and difficult to predict. This ongoing process can be treated using the homogenous Markov chain model (MCM), a stochastic approach based on the concept of probabilistic cumulative deterioration (Bogdanoff, 1978). MCM considers a stochastic process with discrete time and discrete states (Norris, 1998) that is, a succession of random variables $X_0, X_1, ..., X_n, ...$ where each X_n is a discrete random variable with values in a finite set $I = \{1, 2, ..., m\}$ called the space of states. The index n of X_n is considered as (discrete) time, and the values of X_n are referred to the possible states. The Markov property states that the conditional probability distribution P (for the system at the next step depends only on the current state of the system, and not also on the state of the system at previous steps), that is:

$$\begin{aligned} &P(X_{n+1} = i_{n+1} | X_0 = i_0, X_1 = i_1, ..., X_n = i_n) \\ &\quad = P(X_{n+1} = i_{n+1} | X_n = i_n). \end{aligned} \tag{3}$$

In addition, the model considered the transition probabilities $P(X_{n+1} = j \,|\, X_n = i)$ not dependent on n but only on i and j, so given $p_{ij} = P(X_{n+1} = j \,|\, X_n = i)$. It can calculate all the joint probabilities knowing only the number p_{ij} and the distribution of the process at time zero. To do this, it is convenient to introduce the following transition matrix $\boldsymbol{P}$:

$$\boldsymbol{P} = \begin{pmatrix} p_{11} & \cdots & p_{1m} \\ \vdots & \ddots & \vdots \\ p_{m1} & \cdots & p_{mm} \end{pmatrix} \tag{4}$$

where $p_{ij} \geq 0$ and $\sum_j p_{ij} = 1$ for any $i, j \in I$. In this setting, the distribution of the stochastic process X_n at the time step n (that is the probability of the future deterioration state after n time steps) can be assessed starting from the knowledge of the initial condition (X_0) using the following equation:

$$X_n = X_0 \times \boldsymbol{P}^n. \tag{5}$$

This approach is widely used in the field of civil engineering (Cesare et al., 1992; Dell'Oca et al., 2023; Frangopol et al., 2004; Frangopol & Neves, 2003; Li et al., 1996; Micevski et al., 2002; Morcous et al., 2002; Ng & Moses, 1998; Srikanth & Arockiasamy, 2020; Thomas & Sobanjo, 2016) to predict the performance of infrastructures facilities (especially, bridges).

In the present study, MCM is applied to the functionality deterioration of the TTCSs treated as a homogenous Markovian stochastic process with a time step of 10 years. The choice of this time span is a compromise between the information related to the year of construction of TTCSs and the watershed management timeline. In the present study, the construction information has been complete since 2000, whereas often partial before.

Moreover, $\boldsymbol{P}$ is simplified assuming that a structure can either remain in the current state or deteriorate to the next worse state in one time step, and the worst state is considered as an absorbing state, that is, $p_{44}=1$. Following these specifics, $\boldsymbol{P}$ changes as follows:

$$\boldsymbol{P}=\begin{bmatrix} p_{11} & 1-p_{11} & 0 & 0 \\ 0 & p_{22} & 1-p_{22} & 0 \\ 0 & 0 & p_{33} & 1-p_{33} \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{6}$$

where the size of the matrix represents the four deterioration levels of LoFI, and p_{ii} is the transition probability describing the probability to remain at the same state in a time step.

These transition probabilities can be calculated through the percentage method (e.g., Jiang & Sinha, 1989; Li et al., 2016) that estimates them as the ratio between number of state changes and total number of states before the change. This approach requires at least two consecutive condition records without any maintenance interventions (Morcous, 2006) as occurred in this study.

Moreover, once the transition probabilities are calculated, MCM can be used to implement different maintenance strategies. Indeed, $\boldsymbol{P}$ lends itself to being modified, inserting the probabilities that a structure can be repaired (e.g., coming back to LoFI = 2) or reconstructed (e.g., restoring to LoFI = 1). Six distinct maintenance strategies, commonly adopted by the hydraulic authorities, were implemented as follows:

- S1: No maintenance from the current condition X_0 (Equation 5).
- S2: Repair (restoring them to LoFI = 2) 20% of structures with LoFI ≥ 3 each 10 years.
- S3: Repair 50% of structures with LoFI ≥ 3 each 10 years.
- S4: Repair 10% of structures with LoFI ≥ 3 and reconstruct (restoring them to LoFI = 1) 10% of structure with LoFI = 4 each 10 years.
- S5: Repair 25% of structures with LoFI ≥ 3 and reconstruct 25% of structure with LoFI ≥ 3 each 10 years.
- S6: Reconstruct 25% of structure with LoFI ≥ 3 each 10 years.

2.4.2 | Determination of significant factors on structure degradation and deterioration

A comprehensive statistical analysis was conducted to ascertain the more significant factors influencing the degradation and deterioration of the structure. The structure database includes both qualitative and quantitative variables. To unveil significant effects due to categorical variables such as structure type and materials, preliminary one-way ANOVAs were carried out. Simultaneously, the assessment delved into quantitative variables such as structure size (i.e., height, width, thickness, age) as well as local topographic features (i.e., altitude, upslope area, local channel slope and mean annual precipitation), using the Pearson correlation coefficient (R) to determine the linear correlation. This screening analysis facilitates the elucidation of key insights into the intricate interplay between these multifaceted variables and the degradation/deterioration patterns observed by the FLIs. All statistical analyses were performed using R software (4.2.1).

3 | RESULTS

3.1 | FLI observations

The FLIs were conducted on 409 TTCSs (29 groynes, 145 check dams, 126 sills and 109 bedload protections) with a longitudinal density of 1.75 structures per km, on average (Table 4). Pioverna torrent had the highest

TABLE 4 Observations provided by the database of TTCSs for the four inspected watercourse.

	Upper Adda river				
TTCS	**Adda river**	**Frodolfo torrent**	**Oglio river**	**Pioverna torrent**	**Stafford torrent**
Bedload protections	0	3	12	67	27
Check dams	0	1	18	40	86
Groynes	3	0	3	0	23
Sills	41	22	14	49	0
Total	44	26	47	156	136
Density (# per km)	2.20	1.13	0.45	5.38	2.34

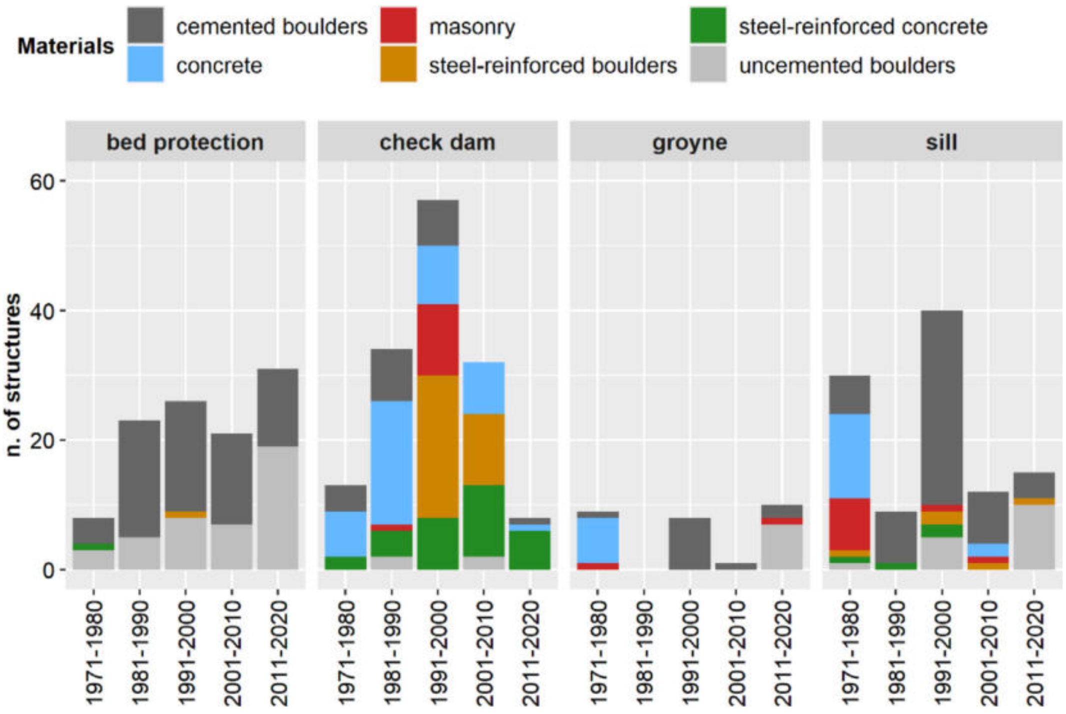

FIGURE 4 Frequency of existing structures in the function of (i) year of construction, (ii) structure type, and (iii) structure materials.

longitudinal density with more than 5 structures per km, probably due to the pronounced torrential character of the watercourse that necessitated human intervention to reduce hydro-sedimentological processes. Conversely, Oglio river showed the lowest longitudinal density with less than 1 structure every 2 km. Staffora torrent showed a moderate longitudinal density with 2.34 structures per km concentrated near the built-up areas. In general, most of TTCSs were check dams and sills, and were built in cemented boulders, followed by boulders, concrete and steel-reinforced materials. The less used material was the masonry. Bedload protections were exclusively built in cemented and uncemented boulders, whereas check dams and sills were built with different materials (Figure 4). The older groynes were built in concrete, masonry and cemented boulders, whereas since 1991 in boulders.

3.2 | DI observations

DI was successfully calculated for 365 TTCSs. Regrettably, 44 of 409 were concealed, entirely or partially covered by uncontrolled vegetation, sediment deposits, or turbid water traversing the structure. Among the hidden structures, sills and bed protection structures were the most numerous. The lack of visibility leads the inspectors to proceed with the FLIs, indicating the presence of a TTCS with unknown or indeterminate conditions. Obviously, among the elements, the survey of the foundations was the most challenging (only 30% of foundations have been detected), whereas spillway and lateral abutments were almost always visible (>94%), except for sills (85%; Figure 5). Foundations, when surveyed, were typically exposed, and in very poor conditions (43% of cases with $\mathrm{DI}=4$). Conversely, spillway and body had different levels of degradation, whereas lateral abutments exhibited generally good condition (70% of cases with $\mathrm{DI}\leq 2$). Totally, the calculated average DI was 0.361 with a large standard deviation of 0.342.

The correlation analysis detected the potential effects of quantitative variables on the DI (Table 5). A slight positive correlation was apparent with elevation and channel slope ($R=0.288$ and $R=0.299$, respectively), and a moderate negative correlation with the mean annual precipitation ($R=-0.409$). Negligible correlations were evident with structure geometry ($-0.157<R<0.163$), upslope area ($R=-0.046$) and structure age ($R=0.210$). Simultaneously, the one-way ANOVA investigated the main effects of the individual categorical variables (structure type and materials), as well as the interaction effects, that is, the combined effects between categorical variables over time (Table 6). The results indicated significant impacts of structure type and materials ($p<0.001$) on DI, as well as interaction effects with structure age and structure type ($p=0.018$). However, no discernible relationship emerged between structure age and materials ($p=0.349$). Remarkably, the degradation over time

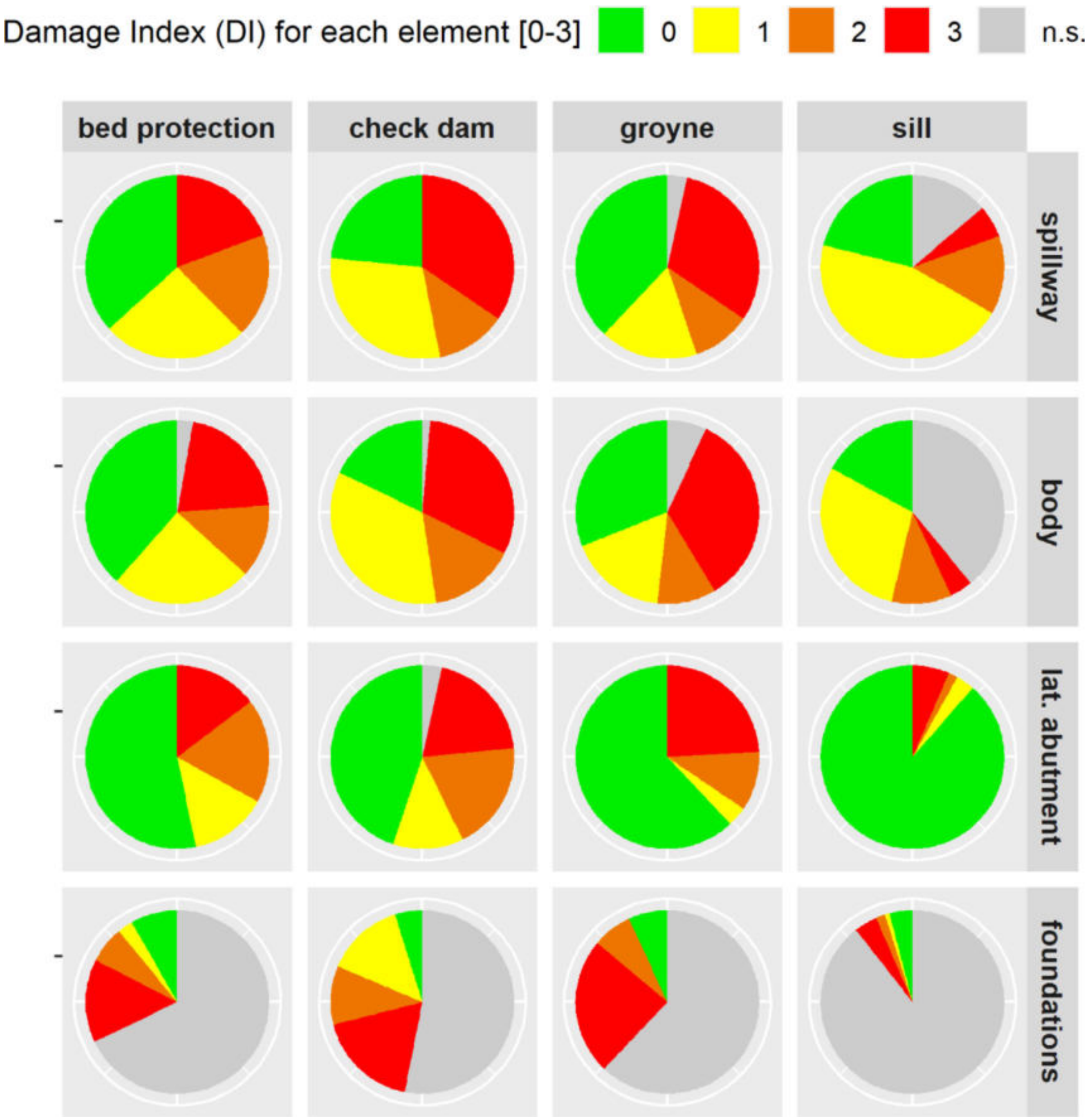

FIGURE 5 Distribution of damage index (DI) in function of structure type and structural elements.

TABLE 5 Pearson's correlation coefficient (*R*) between damage index (DI) and loss of functionality index (LoFI), and quantitative variables.

	Structure height	Structure width	Structure thickness	Elevation	Channel slope	Upslope area	Mean annual precipitation	Structure age
DI	0.163	0.068	−0.157	0.288	0.299	−0.046	−0.409	0.210
LoFI	0.164	−0.006	−0.160	0.332	0.344	−0.071	−0.404	0.172

appeared to be independent of materials (Figure 6) as (i) structures in cemented boulders showed a similar level of degradation regardless of structure age; (ii) structures in concrete and steel-reinforced concrete manifested a moderate level of damage after 10–30 years; (iii) still existing structures in concrete and steel-reinforced concrete with a +30 structure age showed a lower value of DI, on average; (iv) structure in uncemented stones partially showed a degradation over time; whereas (iv) structures in masonry and steel-reinforced stones were scarce in the database to interpret their degradation. If results were categorised based on the structure type, DI trended upward over time for bed protection structures and groynes, whereas showed limited sensitivity for check dams and sills (Figure 7). This intricate analysis, marked by its multifaceted approach, offered valuable insights into the complex dynamics of TTCS degradation across various structures, materials and timeframes.

TABLE 6 Analysis of variance (one-way ANOVA) between damage index (DI) and structure type and materials.

DI	Degrees of freedom	Sum of squares	Mean squares	*F*	*p* Value	Significance
Structure materials	5	8.872	1.7744	23.929	<2.00E−16	***
Structure type	3	3.381	1.1269	15.197	2.40E-09	***
Structure age	1	0.77	0.7703	10.387	0.00138	**
Structure type—Materials	11	4.517	0.4107	5.538	3.23E−08	***
Materials—Structure age	5	0.416	0.0831	1.121	0.3486	
Structure type—Structure age	3	0.759	0.2529	3.411	0.01767	*
Materials—Structure type—structure age	7	1.386	0.198	2.671	0.01045	*

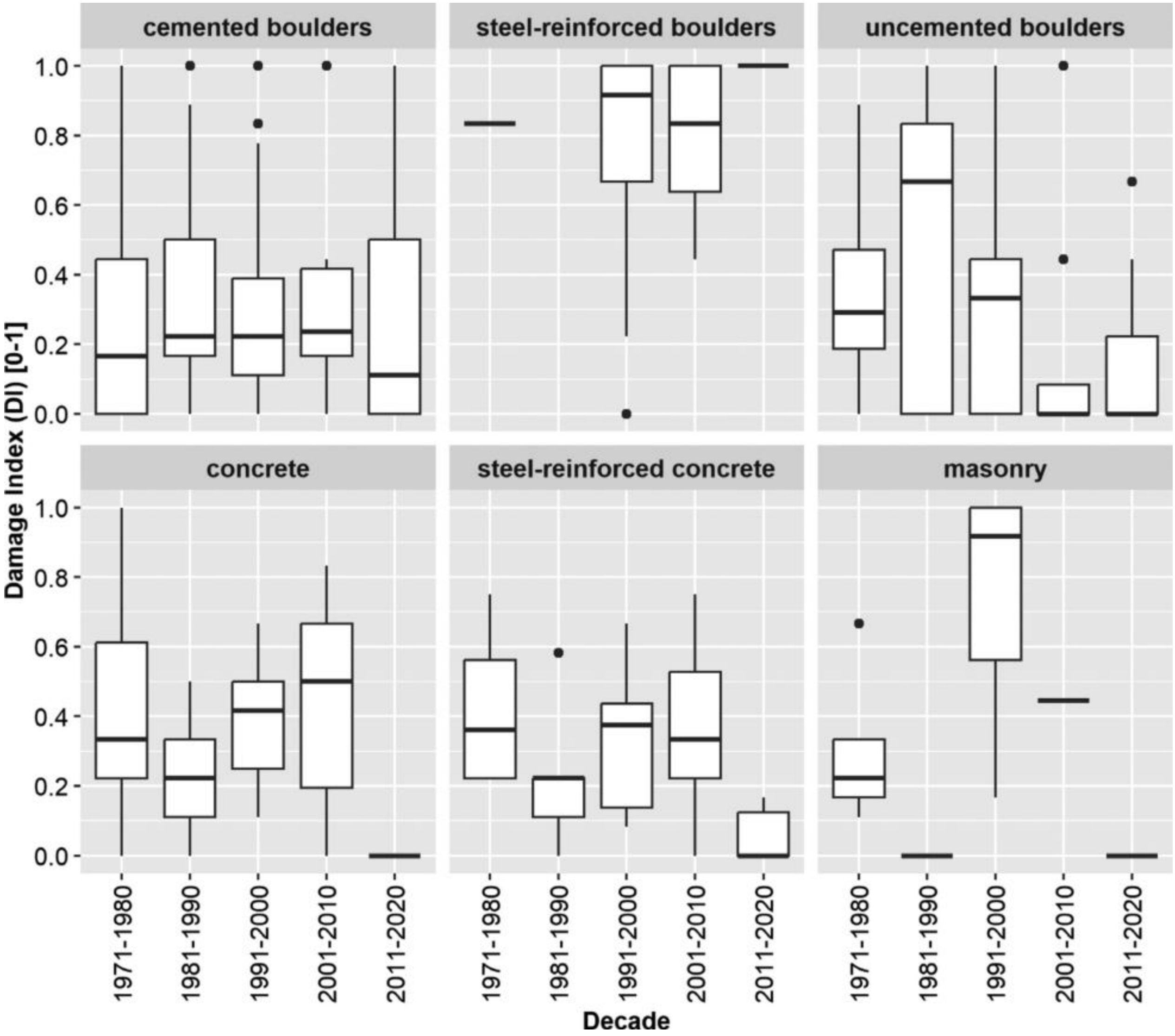

FIGURE 6 Results of damage index (DI) in function of materials and structure age.

3.3 | LoFI observations

In the study area, 44.65% of the structure showed an optimal performance (LoFI = 1), 22.45% a good performance (LoFI = 2), 14.00% a bad performance (LoFI = 3) and 18.90% a complete loss of functionality. The most recent structures were obviously the most functional: 83% of 10-year-old structures belonged with LoFI ≤ 2 (Figure 8).

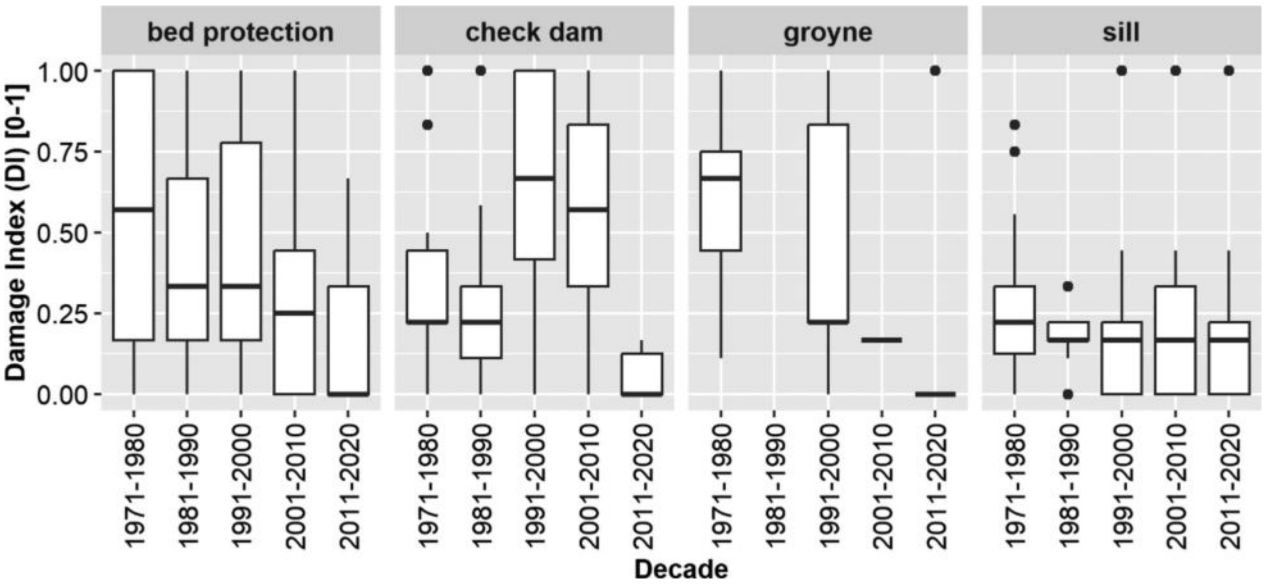

FIGURE 7 Results of damage index (DI) in function of structure type and structure age.

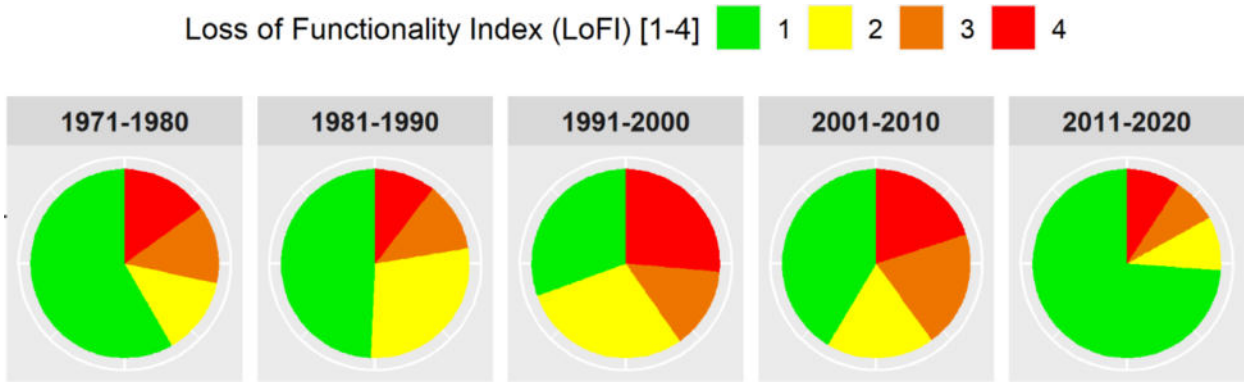

FIGURE 8 Loss of functionality index (LoFI) in function of structure age.

Notable loss of functionality was evident both in the structures built during 2001–2010 (20% with LoFI = 4) and 1991–2000 (26% with LoFI = 4). An intriguing trend was revealed within the dataset: most 'survived' structures built during 1971–1980 and 1981–1990 were in good condition (79% and 72% with LoFI ≤ 2, respectively).

Unsurprisingly, LoFI was strongly correlated with DI ($R = 0.953$) because the structure performance evidently depends on the interplay between hydrological and sedimentological regimes as well as the natural ageing and materials degradation over time. However, LoFI did not flawlessly mirror DI (Figure 9): (i) LoFI = 1 corresponded to DI values ranging from 0.000 to 0.333, with an average of 0.101; (ii) LoFI = 2 exhibited a distinct distribution of DI from the lower class, with an average value of 0.287; (iii) LoFI = 3 represented significantly higher DI values than the lower classes with an average of 0.606; and

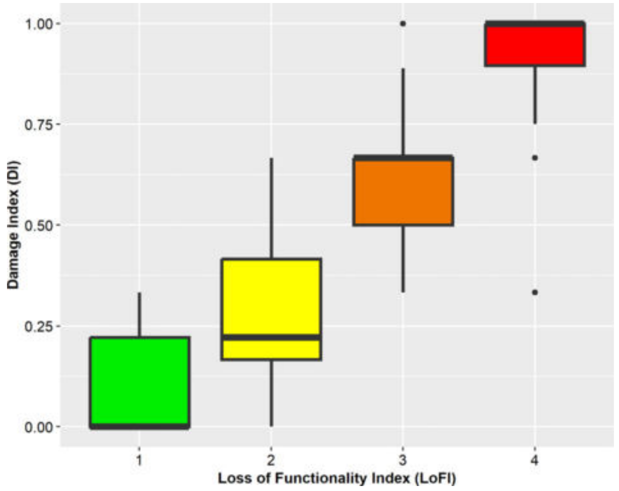

FIGURE 9 Relationship between loss of functionality index (LoFI) and damage index (DI).

(iv) LoFI = 4 unequivocally means the complete loss of performance that occurs when the structure is near to structural failure or imminent collapse, that is, values higher than 0.750.

Digging deeper, the lower classes (LoFI = 1 and LoFI = 2) revealed a good level of performance with structurally intact conditions, albeit with minor exceptions. The transition from LoFI = 2 to LoFI = 3 was more critical and involved those structures even with negligible levels of degradation. Moving from LoFI = 3 to LoFI = 4 encompassed structures, already partially inefficient, which showed a worsening of their conditions from the last FLI indicating an imminent risk. Exploring the relationship between LoFI and DI could enrich the investigation of the damage assessment of each constituent element. The highest correlation was with the level of damage of the body ($R = 0.925$) and with that of the foundations ($R = 0.910$). Particularly critical, foundations were prone to induce significant structural failures. In contrast, spillway and lateral abutment showed lower values of correlation with LoFI, $R = 0.859$ and $R = 0.822$, respectively.

3.4 | Markov chain model

MCM requested the calculation of the transition probability matrix $\boldsymbol{P}$ (Equation 6) by comparing the transition probabilities with the frequency of structure density distributed across LoFI classes over discrete time intervals (i.e., 10 years). The procedure provides $p_{11} = 0.816$, $p_{22} = 0.538$ and $p_{33} = 0.334$, with a root mean square error of 0.129. Once setting $\boldsymbol{P}$, MCM run forecasts, in terms of probability, the progression of state transitions over time for new structures using Equation (5), assuming $X_0 = [1\,0\,0\,0]$. The prediction revealed (Figure 10): (i) after 35 years, approximately 50% of the structure partially losses (25% with LoFI = 2) or almost completely (15% and 10 with LoFI = 3 and LoFI = 4) their functionality; (ii) after 40 years, approximately 31% of structures felled in LoFI ≥ 3; and (iii) the structures in poor conditions progressively increased with time: 42% after 50 years, 52% after 60 years, 61% after 70 years and so forth. Concerning the maintenance strategies, Equation (5) was applied modifying $\boldsymbol{P}$ in function of the strategies (see Appendix SC in Supporting Information Materials) and setting X_0 with the current distribution of frequency in the four LoFI classes, that is, [0.4465 0.2245 0.1400 0.1890]. The comparison among the different maintenance strategies was shown in Figure 11. The application of MCM highlighted how without any maintenance activities (*S1*), slightly fewer than 30% of structures maintained LoFI ≤ 2 after 50 years. Strategies *S2* and *S4* exhibited an enhanced performance, maintaining around 50% after 50 years. Increasing the percentage of repaired structures to 50% (*S3*), the probability of sustained performance climbed to 60%. However, it is only through the comprehensive reconstruction of a substantial portion of non-functional structures (*S5* and *S6*) that the consistent probability of good performance exceeded 70% after 30 years.

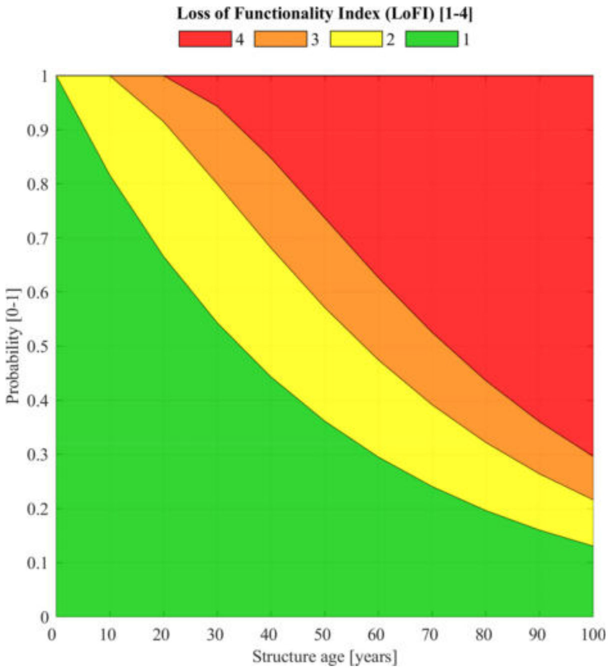

FIGURE 10 Prediction of the TTCSs loss of functionality index (LoFI) over time for new structures.

4 | DISCUSSION

4.1 | The importance of an updated database

Maintaining an up-to-date structures database stands as a foundation imperative to guarantee sustainable and dependable river management practices. A periodic analysis of an updated repository of torrent control activities, which includes costs, types, materials used, damages and functionality, could offer an evaluation of the sustainability of maintenance strategies. This would then facilitate the monitoring of improvements or the suggestion of adjustments. In fact, the TTCSs database could play a role in ongoing endeavours to curtail flood and landslide risk, ultimately contributing to the safeguarding of communities and infrastructures. Beyond this, the analysis of the database can provide a transparent picture of public investments, allowing a direct comparison with the

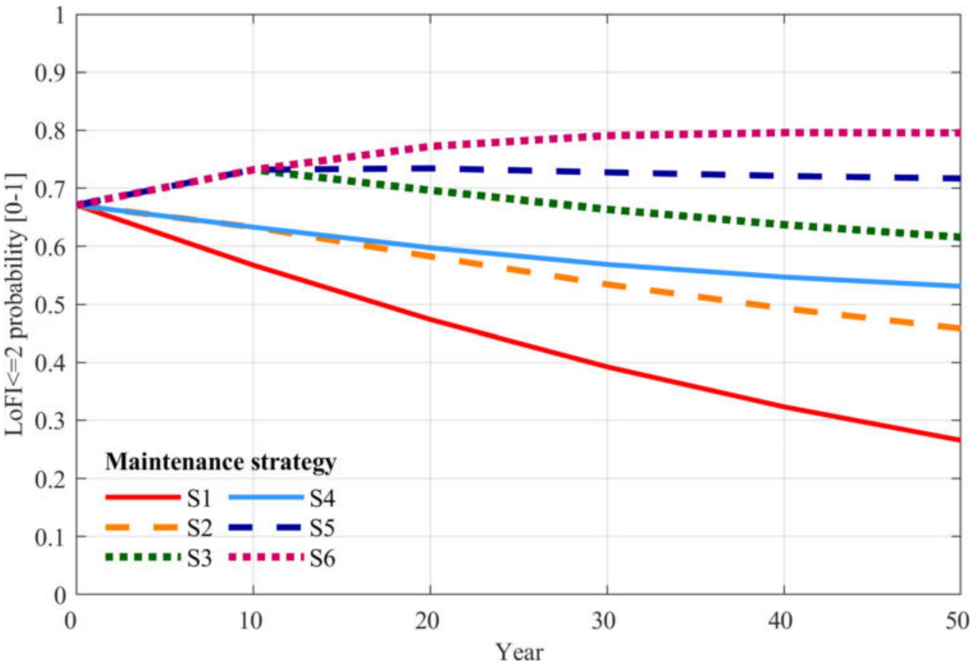

FIGURE 11 Deterioration prediction over 50 years adopting six different maintenance strategy from the surveyed condition: (S1) no maintenance; (S2) repair (restoring them to LoFI = 2) 20% of structures with LoFI ≥3 each 10 years; (S3) repair 50% of structures with LoFI ≥3 each 10 years; (S4) repair 10% of structures with LoFI ≥3 and reconstruct (restoring them to LoFI = 1) 10% of structure with LoFI = 4 each 10 years; (S5) repair 25% of structures with LoFI ≥3 and reconstruct 25% of structure with LoFI ≥3 each 10 years, and (S6) reconstruct 25% of structure with LoFI ≥3 each 10 years.

economic losses caused by natural extreme calamities. In the surveyed region, the adopted structural interventions have been constant over time. An average of 67 new TTCSs were built every 10 years (0.42 structures per km). Notably, the decade spanning 1991–2000 decade emerges as an exception. In these 10 years, 144 structures were constructed, more than twice the other count. This period was influenced by the catastrophic natural event of July 1987, when prolonged and intense rainfall swept through the entire area of Prealps and Alps in North Italy. The consequences were exceptionally devastating, that is, flood, rockfalls, debris flows and shallow landslides, which provoked 53 casualties and a huge economic damage amounted to 2 billion euros (Blahut et al., 2012; Luino, 2005). This fact increased the sensitivity to natural hazards, leading the politicians to invest in the construction of TTCSs. Furthermore, the records of the database provided some details on the time-dependency of construction materials, that is, the evolution of used materials. In agreement with previous studies (e.g., Paratscha et al., 2019; Suda & Rudolf-Miklau, 2009), a discernible shift away from masonry and concrete was evident (Figure 4). Striking is the marked decline in the use of masonry, attributed to its susceptibility to damage and loss of functionality. Particularly noteworthy is the trend observed among masonry structures built before 1970: when they collapsed, the new structures were subsequently rebuilt using alternative materials. Sills, groynes and bed protection structures, on the other hand, predominantly embraced the use of cemented and uncemented boulders. This choice fits with the sustainability principles and adheres to the 'zero-miles' milestone, as these boulders are often locally sourced by bedload solid transport or triggered debris flows. In addition, this aspect promotes a sort of 'circular economy'. Conversely, the records highlighted a different trend in the construction of check dams. In fact, steel-reinforced materials took precedence over traditional concrete and masonry choices. This discernible shift in material preference underlines how the engineers, where the sediment dynamic is dominant, prefer structural solidity, not always attuned to modern engineering principles and ecological considerations.

Within the scope of this study, there are no additional insights to provide regarding wooden structures, primarily due to their conspicuous absence from the existing repository. It is noteworthy that wooden structures hold significance within mountainous environments despite belonging to the category of water bioengineering techniques (Lucas-Borja et al., 2021). The study of degradation and deterioration of such structures could necessitate a distinct and tailored approach, as suggested in the literature (e.g., Akita et al., 2014; Previati et al., 2012).

4.2 | Service life of TTCSs

The present study presented a distinctive collection of insights that are notably scarce within the literature, concerning the service life of TTCSs. By combining the results of DI (Figure 7) and LoFI (Figure 12), some recommendations on the service life can be derived in function of structure type. The deterioration of check dams

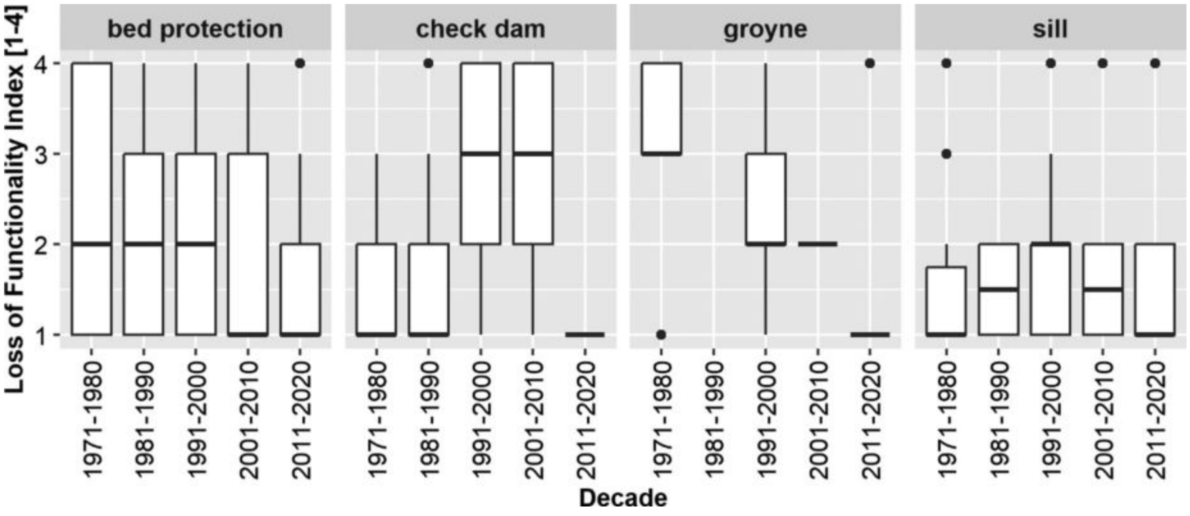

FIGURE 12 Results of loss of functionality index (LoFI) in function of structure type and structure age.

built with different materials proceeds rapidly during the initial 20–30 years and coincides with a pronounced decline in functionality. These findings underscored the necessity of careful and frequent inspections and timely repair/reconstruction within the first three decades. Interestingly, aged check dams that do not immediately necessitate adjustments/repair based on the FLI, showed a delayed escalation in deterioration. This trend became more conspicuous for structures exceeding 40 years, even though a reasonable level of functionality is retained. Different considerations shall be referred to as groynes and bed protections. Over 50 years, both degradation and deterioration undergo a gradual reduction. Probably, the deterioration of groynes appeared to outpace that of bed protection structures. Conversely, because of the structural characteristics (partially or totally submerged), sills showed poor deterioration and a slight loss of functionality except for a few cases. Finally, these results emphasise a noteworthy and obvious outcome: the functionality inevitably decreases with the structure's operational life. This fact is in agreement with some previous studies (Dell'Agnese et al., 2013; Lee et al., 2022; Mazzorana et al., 2018; Ogasawara & Kambara, 2015) that, however, focused only on the check dams. In addition, this study, investigating a large dataset, provided a general deterioration trend for different TTCSs built with different materials and with different structure's age. Undoubtedly, the success of the proposed framework hinges on several key aspects of data collection, including its frequency, completeness and standardisation, as well as the hydro-sedimentological processes characterising the basin under investigation. The methodology's ability to yield precise results for other case studies significantly increases when these characteristics closely match.

4.3 | Monitoring of TCSs

A meticulous monitoring of TTCSs bears paramount significance and mandates a judicious allocation of human resources employed in the management authorities. In fact, the core of planning the FLI, coupled with extraordinary visits following extreme events, proved expensive costs for local and regional authorities (Mazzorana et al., 2018). The FLIs should be performed at predetermined and fixed intervals (e.g., every few years) in function of the risk assessment of the surrounding area.

Thus, advanced technology and volunteers can support this challenging task. Nowadays, remote sensing technologies can support the monitoring of TTCSs and sediment dynamics in the channel network (Cucchiaro, Cazorzi, et al., 2019). Indeed, remote sensing platforms (e.g., satellites and airborne) can provide high-resolution images (time series with resolution down to 0.30 m) and multi-temporal digital elevation models (DEMs) supplying a general overview and of the current situation. Satellite products are valuable pre-screening tools, able to analyse, in general, the structural integrity and coupled with DEMs could also provide an overview of adjacent sediment processes, such as deposition, erosion, streambank failures and in-channel vegetation dynamics. By integrating this data into the monitoring framework, technicians can strategically prioritise efforts to specific inspections, optimising resource utilisation as highlighted also in Cucchiaro et al. (2024).

Moreover, many TTCSs are nestled within rugged and remote valleys, often inaccessible and far to main roads and paths. In this scenario, a UAV-based survey offers a sustainable and reliable solution for acquiring images or light detection and ranging data on watercourse, riparian vegetation and sediment dynamics

(Cislaghi & Bischetti, 2022). UAV surveys provide the opportunity to simultaneously monitor both the structures and the geomorphic changes of the watercourse, supplying all the necessary data to assess the effectiveness not only of individual TTCS unit but also of the entire system of protective measures. Indeed, each structure typically constitutes an integral component of a larger, interconnected and complex system that functions collectively. Unfortunately, these technologies still show some limitations in their use. Factors such as forest cover and high altitude can be relevant obstacles to conduct these observations.

The other challenge for the scientific communities and the authorities is to involve the volunteers in monitoring. The abandonment of higher-elevation human settlements and activities for economic reasons since the middle of the 19th century (Cislaghi et al., 2019; Tasser & Tappeiner, 2002) drastically reduces the invaluable daily monitoring carried out by shepherds, and loggers, who served as primary witnesses to changes in land use and landscape. On this issue, it is essential, nowadays, to enlist volunteers of civil protection, local associations and regular citizens, for the FLI of hydraulic structures (Cortes Arevalo et al., 2014). To assure a certain data quality, researchers, technicians and volunteers must work together to improve the collected observations. Some key recommendations are reported as follows:

i. *Training*: All volunteers must be well-trained, possibly through workshop and field visits, organised by researchers and technicians.
ii. *Quality control*: Technicians must orchestrate quality control campaigns to evaluate the observations of the less expert volunteers, in assessing levels of damages and of functionality of individual structure.
iii. *Collaborative campaigns*: Volunteers, technicians and researchers must share their experience during inspection campaigns conducted together. Technicians and researchers can increase their knowledge about the local stream features, the volunteers can receive constant updates on methodologies and emerging technologies, and the researchers can test advanced solutions.
iv. *Guidelines and accessibility*: Experts and technicians must draw up comprehensive guidelines ensuring they are both informative, complete, accessible, meanwhile user-friendliness (see Appendix SA in Supporting Information Materials).
v. *Updating courses and technical working group*: Researchers must involve technicians in sharing the results of research, in supporting the choice of technological instruments, and in balancing observations quality, time and costs. This could be pursued through training courses, freely available seminars and technical working group.

By uniting technology, community engagement and systematic protocols, this complex approach stands poised to transform the realm of TTCSs monitoring, enhancing the sustainability and efficacy of watershed management practices.

4.4 | Maintenance strategies

In this context, the present study proposed a comprehensive procedure aimed at predicting the service life of the structure in terms of probability, following the experience of those studies that considered the deterioration process as well-defined by the Markov process (e.g., Abdelkader et al., 2019; Jiang & Sinha, 1989; Thomas & Sobanjo, 2016).Indeed, MCM stands out as reliable and robust tool, offering some benefits. First and foremost, the probabilistic nature of MCM mitigates the possibility of unforeseen, premature end-of-service life stemming from extreme events. This probabilistic approach provides more precise guidance compared to some pioneering studies that attempted to find correlations between the structure age and their expected deterioration (or damage). Many authors, in fact, developed simple empirical relationships, almost exclusively for existing check dams, analysing regional or national dataset (Davidescu et al., 2012; Lee et al., 2022). Second, the user-friendliness and flexibility of MCM facilitates customization, implementing diverse priorities and/or strategies. In fact, MCM can provide the prioritisation of interventions on existing structures as other accurate models (Chahrour et al., 2021; Mazzorana et al., 2018), but also the effects of diverse maintenance strategies over time. Third, MCM assumes that the deterioration state can be linked to the past state, recognising that transition probabilities between states can evolve over time (Sobanjo, 2011). Although this fact requests a continuous update of the repository, already filled with comprehensive historical information, it could be precious to assess the impacts of climate change on structural deterioration. Finally, for the future perspective, MCM can emerge as a support-decision tool, potentially in combination with other simple economic models, for formulating comprehensive intervention programs, encompassing repair types, for conducting cost–benefit analyses, comparing investments and maintenance expenses with direct and indirect losses (Bründl et al., 2009).

5 | CONCLUSIONS

Monitoring and maintenance emerge as crucial activities to ensure the operational functionality of TCSs. This study underscores the significance of the FLIs in providing dependable qualitative indicators (countable and discrete states) that delineate the deterioration of individual elements of TCSs and the decline of the overall performance. A detailed monitoring protocol yields a comprehensive dataset that serves as the basis for characterising the degradation and deterioration of TTCSs over time. Moreover, the developed repository facilitates the implementation of a dynamic deterioration model. The proposed MCM furnishes valuable insights into the potential trajectories of structure degradation and deterioration, offering a crucial tool for informed decision-making and resource allocation in the realm of watercourse management. In addition, MCM enables the simulation of the deterioration process for new and existing structures under different maintenance strategies. The outcome aids in identifying the most suitable approach and balancing investments with risk assessment considerations. Ultimately, this study marks a significant milestone in the development of decision-making support tools. It underscores the necessity of forecasting investments for the monitoring and maintenance of both existing and new structures. This point complements the conventional design procedures that typically focus on regulatory compliance and hydraulic-static requisites.

ACKNOWLEDGEMENTS

This research is part of Return (multi-risk science for resilient communities under a changing climate)—Piccoli Bacini (new approaches for assessing hydraulic hazard in small mountain catchments) and granted by the collaboration agreement between the Lombardy Region (Italy) and the Department of Agricultural and Environmental Sciences (DiSAA) of the University of Milan. The authors wish to thank Mauro Visconti, Mario Domenico Zaffaroni, Nadia Chinaglia, Mauro Orlandi, Paolo Castellini, Roberto Malaspina, and Federico Taroni (Lombardy Region) for the logistic support, and the Lorenzo Spedo, Pietro Mascherpa, Brian Bertani and Pietro Bonaiti Pedroni (students at University of Milan) for supporting the field activities.

DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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REFERENCES

Abdelkader, E. M., Zayed, T., & Marzouk, M. (2019). Modelling the deterioration of bridge decks based on semi-Markov decision process. *International Journal of Strategic Decision Sciences*, *10*(1), 23–45. https://doi.org/10.4018/IJSDS.2019010103

Akita, H., Kitahara, H., & Ono, H. (2014). Effect of climate and structure on the progression of wooden check dam decay. *Journal of Forest Research*, *19*(5), 450–460. https://doi.org/10.1007/s10310-013-0434-x

Armanini, A., Dellagiacoma, F., & Ferrari, L. (1991). From the check dam to the development of functional check dams. In A. Armanini & G. Di Silvio (Eds.), *Fluvial hydraulics of mountain regions* (Vol. 37, pp. 331–344). Springer. https://doi.org/10.1007/BFb0011200

Baggio, T., & D'Agostino, V. (2021). Simulating the effect of check dam collapse in a debris-flow channel. *Science of the Total Environment*, *816*, 151660. https://doi.org/10.1016/j.scitotenv.2021.151660

Biondini, F., Camnasio, E., & Titi, A. (2015). Seismic resilience of concrete structures under corrosion: Seismic resilience of concrete structures under corrosion. *Earthquake Engineering & Structural Dynamics*, *44*(14), 2445–2466. https://doi.org/10.1002/eqe.2591

Blahut, J., Poretti, I., De Amicis, M., & Sterlacchini, S. (2012). Database of geo-hydrological disasters for civil protection purposes. *Natural Hazards*, *60*(3), 1065–1083. https://doi.org/10.1007/s11069-011-9893-6

Blasi, C., Capotorti, G., Copiz, R., Guida, D., Mollo, B., Smiraglia, D., & Zavattero, L. (2014). Classification and mapping of the ecoregions of Italy. *Plant Biosystems—An International Journal Dealing with all Aspects of Plant Biology*, *148*(6), 1255–1345. https://doi.org/10.1080/11263504.2014.985756

Bogdanoff, J. L. (1978). A new cumulative damage model: Part 1. *Journal of Applied Mechanics*, *45*(2), 246–250. https://doi.org/10.1115/1.3424282

Boix-Fayos, C., de Vente, J., Martínez-Mena, M., Barberá, G. G., & Castillo, V. (2008). The impact of land use change and check-dams on catchment sediment yield. *Hydrological Processes*, *22*(25), 4922–4935. https://doi.org/10.1002/hyp.7115

Bombino, G., Gurnell, A. M., Tamburino, V., Zema, D. A., & Zimbone, S. M. (2008). Sediment size variation in torrents with check dams: Effects on riparian vegetation. *Ecological Engineering*, *32*(2), 166–177. https://doi.org/10.1016/j.ecoleng.2007.10.011

Bründl, M., Romang, H. E., Bischof, N., & Rheinberger, C. M. (2009). The risk concept and its application in natural hazard risk management in Switzerland. *Natural Hazards and Earth System Sciences*, *9*(3), 801–813. https://doi.org/10.5194/nhess-9-801-2009

Cesare, M. A., Santamarina, C., Turkstra, C., & Vanmarcke, E. H. (1992). Modeling bridge deterioration with Markov chains. *Journal of Transportation Engineering*, *118*(6), 820–833. https://doi.org/10.1061/(ASCE)0733-947X(1992)118:6(820)

Chahrour, N., Nasr, M., Tacnet, J.-M., & Bérenguer, C. (2021). Deterioration modeling and maintenance assessment using physics-informed stochastic petri nets: Application to torrent protection structures. *Reliability Engineering & System Safety*, *210*, 107524. https://doi.org/10.1016/j.ress.2021.107524

Cislaghi, A., & Bischetti, G. B. (2019). Source areas, connectivity, and delivery rate of sediments in mountainous-forested hillslopes: A probabilistic approach. *Science of the Total Environment*, *652*, 1168–1186. https://doi.org/10.1016/j.scitotenv.2018.10.318

Cislaghi, A., & Bischetti, G. B. (2022). Best practices in post-flood surveys: The study case of Pioverna torrent. *Journal of Agricultural Engineering*, *53*(2), 1312. https://doi.org/10.4081/jae.2022.1312

Cislaghi, A., Giupponi, L., Tamburini, A., Giorgi, A., & Bischetti, G. B. (2019). The effects of mountain grazing abandonment on plant community, forage value and soil properties: Observations and field measurements in an alpine area. *Catena*, *181*, 104086. https://doi.org/10.1016/j.catena.2019.104086

Clinciu, I., Petriţan, I.-C., & Niţă, M.-D. (2010). Monitoring of the hydrotechnical torrent control structures: A statistical approach. *Environmental Engineering and Management Journal*, *9*(12), 1693–1701.

Comiti, F. (2012). How natural are alpine mountain rivers? Evidence from the Italian Alps? *Earth Surface Processes and Landforms*, *37*(7), 693–707. https://doi.org/10.1002/esp.2267

Cortes Arevalo, V. J., Charrière, M., Bossi, G., Frigerio, S., Schenato, L., Bogaard, T., Bianchizza, C., Pasuto, A., & Sterlacchini, S. (2014). Evaluating data quality collected by volunteers for first-level inspection of hydraulic structures in mountain catchments. *Natural Hazards and Earth System Sciences*, *14*(10), 2681–2698. https://doi.org/10.5194/nhess-14-2681-2014

Cortes Arevalo, V. J., Sterlacchini, S., Bogaard, T. A., Junier, S., & Van De Giesen, N. (2016). Decision support method to systematically evaluate first-level inspections of the functional status of check dams. *Structure and Infrastructure Engineering*, *12*, 1487–1504. https://doi.org/10.1080/15732479.2016.1144619

Cucchiaro, S., Cavalli, M., Vericat, D., Crema, S., Llena, M., Beinat, A., Marchi, L., & Cazorzi, F. (2019). Geomorphic effectiveness of check dams in a debris-flow catchment using multi-temporal topographic surveys. *Catena*, *174*, 73–83. https://doi.org/10.1016/j.catena.2018.11.004

Cucchiaro, S., Cazorzi, F., Marchi, L., Crema, S., Beinat, A., & Cavalli, M. (2019). Multi-temporal analysis of the role of check dams in a debris-flow channel: Linking structural and functional connectivity. *Geomorphology*, *345*, 106844. https://doi.org/10.1016/j.geomorph.2019.106844

Cucchiaro, S., Martini, L., Maset, E., Pellegrini, G., Eliana Poli, M., Beinat, A., Cazorzi, F., & Picco, L. (2024). Multi-temporal analysis to support the management of torrent control structures. *Catena*, *235*, 107599. https://doi.org/10.1016/j.catena.2023.107599

Davidescu, Ş. O., Clinciu, I., Tudose, N. C., & Ungurean, C. (2012). An evaluating methodology for hydrotechnical torrent-control structures condition. *Annals of Forest Research*, *55*(1), 125–143.

Decò, A., Bocchini, P., & Frangopol, D. M. (2013). A probabilistic approach for the prediction of seismic resilience of bridges. *Earthquake Engineering & Structural Dynamics*, *42*(10), 1469–1487. https://doi.org/10.1002/eqe.2282

Dell'Agnese, A., Mazzorana, B., Comiti, F., Von Maravic, P., & D'Agostino, V. (2013). Assessing the physical vulnerability of check dams through an empirical damage index. *Journal of Agricultural Engineering*, *43*(4), 9–16. https://doi.org/10.4081/jae.2013.e2

Dell'Oca, A., Guadagnini, A., & Riva, M. (2023). Probabilistic assessment of failure of infiltration structures under model and parametric uncertainty. *Journal of Environmental Management*, *344*, 118466. https://doi.org/10.1016/j.jenvman.2023.118466

Frangopol, D. M., Kallen, M.-J., & van Noortwijk, J. M. (2004). Probabilistic models for life-cycle performance of deteriorating structures: Review and future directions. *Progress in Structural Engineering and Materials*, *6*(4), 197–212. https://doi.org/10.1002/pse.180

Frangopol, D. M., & Neves, L. C. (2003). Probabilistic performance prediction of deteriorating structures under different maintenance strategies: Condition, safety and cost. In D. M. F. E. Brühwiler, M. H. Faber, & B. Adey (Eds.), *Life-cycle performance of deteriorating structures* (pp. 9–18). American Society of Civil Engineers. https://doi.org/10.1061/40707(240)2

Huebl, J., & Fiebiger, G. (2005). Debris-flow mitigation measures. In J. Matthias & H. Oldrich (Eds.), *Debris-flow hazards and related phenomena* (pp. 445–487). Springer. https://doi.org/10.1007/3-540-27129-5_18

Jiang, Y., & Sinha, K. C. (1989). Bridge service life prediction model using the Markov chain. *Transportation Research Record*, *1223*, 24–30.

Kostadinov, S., & Dragovic, N. (2010). Check dams in the torrent control practice in small mountainous catchments. In C. C. García & M. A. Lenzi (Eds.), *Check dams, morphological adjustments and erosion control in torrential streams*. Nova Science Publishers, Inc.

Lee, J.-H., Sameen, M. I., Pradhan, B., & Park, H.-J. (2018). Modeling landslide susceptibility in data-scarce environments using optimized data mining and statistical methods. *Geomorphology*, *303*, 284–298. https://doi.org/10.1016/j.geomorph.2017.12.007

Lee, K.-H., Ewane, E. B., Uchida, T., & Woo, C.-S. (2022). Damage types and deterioration characteristics of check dams built on mountain streams in Southeast Korea. *Frontiers in Earth Science*, *9*, 788029. https://doi.org/10.3389/feart.2021.788029

Li, L., Li, F., Chen, Z., & Sun, L. (2016). Use of Markov chain model based on actual repair status to predict bridge deterioration in Shanghai, China. *Transportation Research Record: Journal of the Transportation Research Board*, *2550*(1), 106–114. https://doi.org/10.3141/2550-14

Li, N., Xie, W.-C., & Haas, R. (1996). Reliability-based processing of Markov chains for modeling pavement network deterioration. *Transportation Research Record*, *1524*(1), 203–213.

Lin, M., Gong, C., Huang, H., & Yang, D. (2023). Damage model and the influence factors of mitigation engineering against glacial debris flow in the Parlung River basin, SE Tibetan Plateau. *Water*, *15*(6), 1098. https://doi.org/10.3390/w15061098

Lucas-Borja, M. E., Piton, G., Yu, Y., Castillo, C., & Antonio Zema, D. (2021). Check dams worldwide: Objectives, functions, effectiveness and undesired effects. *Catena*, *204*, 105390. https://doi.org/10.1016/j.catena.2021.105390

Luino, F. (2005). Sequence of instability processes triggered by heavy rainfall in the northern Italy. *Geomorphology*, *66*(1–4), 13–39. https://doi.org/10.1016/j.geomorph.2004.09.010

Marchi, L., Comiti, F., Crema, S., & Cavalli, M. (2019). Channel control works and sediment connectivity in the European Alps. *Science of the Total Environment*, *668*, 389–399. https://doi.org/10.1016/j.scitotenv.2019.02.416

Mazzorana, B., & Fuchs, S. (2010). Fuzzy formative scenario analysis for woody material transport related risks in mountain torrents. *Environmental Modelling & Software*, *25*(10), 1208–1224. https://doi.org/10.1016/j.envsoft.2010.03.030

Mazzorana, B., Scherer, C., & Marangoni, N. (2008). Additional torrent control strategies on debris flow alluvial fans with extremely high vulnerable settlements. *Proceedings of the 4th Biennial Meeting of iEMSs: International Congress on Environmental Modelling and Software*.

Mazzorana, B., Trenkwalder-Platzer, H. J., Fuchs, S., & Hübl, J. (2014). The susceptibility of consolidation check dams as a key factor for maintenance planning. *Österreichische Wasser-und Abfallwirtschaft*, *66*(5–6), 214–216. https://doi.org/10.1007/s00506-014-0160-4

Mazzorana, B., Trenkwalder-Platzer, H. J., Heiser, M., & Hübl, J. (2018). Quantifying the damage susceptibility to extreme events of mountain stream check dams using rough set analysis. *Journal of Flood Risk Management*, *11*(4), e12333. https://doi.org/10.1111/jfr3.12333

Micevski, T., Kuczera, G., & Coombes, P. (2002). Markov model for storm water pipe deterioration. *Journal of Infrastructure Systems*, *8*(2), 49–56. https://doi.org/10.1061/(ASCE)1076-0342(2002)8:2(49)

Mihalache, A.-L., Marin, M., Davidescu, S. O., Ungurean, C., Adorjani, A., Tudose, N. C., Davidescu, A. A., & Clinciu, I. (2020). Physical status of torrent control structures in Romania. *Environmental Engineering and Management Journal*, *19*(5), 861–872. https://doi.org/10.30638/eemj.2020.081

Mizuyama, T. (1979). Survey of disaster check dam. *Journal of Japan Society of Erosion Control Engineering*, *4*, 26–30. https://doi.org/10.11475/sabo1973.31.4_26

Morcous, G. (2006). Performance prediction of bridge deck systems using Markov chains. *Journal of Performance of Constructed Facilities*, *20*(2), 146–155. https://doi.org/10.1061/(ASCE)0887-3828(2006)20:2(146)

Morcous, G., & Hatami, A. (2011). *Developing deterioration models for Nebraska bridges* (SPR-P1(11) M302). University of Nebraska-Lincoln.

Morcous, G., Rivard, H., & Hanna, A. M. (2002). Modeling bridge deterioration using case-based reasoning. *Journal of Infrastructure Systems*, *8*(3), 86–95. https://doi.org/10.1061/(ASCE)1076-0342(2002)8:3(86)

Ng, S.-K., & Moses, F. (1998). Bridge deterioration modeling using semi-Markov theory. In N. Shiraishi, M. Shinozuka, & Y. K. Wen (Eds.), *Structural safety and reliability* (pp. 113–120). Balkema.

Norris, J. R. (1998). *Markov chains (Fascicolo 2)*. Cambridge University Press.

Ogasawara, K., & Kambara, J. (2015). Efforts in maintenance of Sabo facilities in Nagano prefecture. *Journal of Japan Society of Erosion Control Engineering*, *68*, 47–51. https://doi.org/10.11475/sabo.68.4_47

Paratscha, R., Strauss, A., Smutny, R., Lampalzer, T., Rauch, H. P., & von der Thannen, M. (2019). Probabilistic performance prediction model for Austrian torrent control infrastructure. *Structure and Infrastructure Engineering*, *15*(2), 170–179. https://doi.org/10.1080/15732479.2018.1526195

Piton, G., Carladous, S., Recking, A., Tacnet, J. M., Liébault, F., Kuss, D., Quefféléan, Y., & Marco, O. (2017). Why do we build check dams in alpine streams? An historical perspective from the French experience: A review of the subtle knowledge of 19th century torrent-control-engineers. *Earth Surface Processes and Landforms*, *42*(1), 91–108. https://doi.org/10.1002/esp.3967

Previati, M., Canone, D., Bevilacqua, I., Boetto, G., Pognant, D., & Ferraris, S. (2012). Evaluation of wood degradation for timber check dams using time domain reflectometry water content measurements. *Ecological Engineering*, *44*, 259–268. https://doi.org/10.1016/j.ecoleng.2012.03.004

Quiñonero-Rubio, J. M., Nadeu, E., Boix-Fayos, C., & de Vente, J. (2016). Evaluation of the effectiveness of forest restoration and check dams to reduce catchment sediment yield. *Land Degradation & Development*, *27*(4), 1018–1031. https://doi.org/10.1002/ldr.2331

Sobanjo, J. O. (2011). State transition probabilities in bridge deterioration based on Weibull sojourn times. *Structure and Infrastructure Engineering*, *7*(10), 747–764. https://doi.org/10.1080/15732470902917028

Srikanth, I., & Arockiasamy, M. (2020). Deterioration models for prediction of remaining useful life of timber and concrete bridges: A review. *Journal of Traffic and Transportation Engineering*, *7*(2), 152–173. https://doi.org/10.1016/j.jtte.2019.09.005

Suda, J., & Rudolf-Miklau, F. (2009). Rund um den Lebenszyklus von Schutzbauwerken: Schadenshäufigkeit, Zustandsbewertung und Dauerhaftigkeit. *Wildbach-und Lawinenverbau*, *163*, 102–115.

Tacnet, J.-M., Curt, C., Benjamin, R., & Richard, D. (2012). Efficiency assessment for torrent protection works. *Proceedings of the 12th Congress INTERPRAEVENT 2012*.

Tasser, E., & Tappeiner, U. (2002). Impact of land use changes on mountain vegetation. *Applied Vegetation Science*, *5*(2), 173–184.

Tesileanu, R., Davidescu, S., & Tudose, N. C. (2015). A structural state index for torrent control protection works and its relation to specific characteristics of the torrent catchment area. *Forestry and Hunting Journal*, *20*, 90–96.

Thomas, O., & Sobanjo, J. (2016). Semi-Markov models for the deterioration of bridge elements. *Journal of Infrastructure Systems*, *22*(3), 04016010. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000298

Xiong, C., Huang, J., & Lu, X. (2020). Framework for city-scale building seismic resilience simulation and repair scheduling with labor constraints driven by time–history analysis. *Computer-Aided Civil and Infrastructure Engineering*, *35*(4), 322–341. https://doi.org/10.1111/mice.12496

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Cislaghi, A., Morlotti, E., Cucchiaro, S., Morando, P., & Bischetti, G. B. (2024). Monitoring of torrent control structures: An integrated approach from first-level inspections to maintenance strategies. *Journal of Flood Risk Management*, e13011. https://doi.org/10.1111/jfr3.13011