An adaptive multi-hazard framework for climate-resilient management of national road networks

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INTRODUCTION

Extreme hydro-geological events are increasingly challenging the resilience of transportation networks. Climate change alters the frequency, magnitude and spatial distribution of extreme rainfalls, floods and landslides with direct consequences for the safety and functionality of road infrastructure (IPCC, 2023; European Commission, 2021a, 2021b). These impacts are particularly critical where strategic road corridors cross mountainous areas, coastal sectors and alluvial sites, because the disruption of a single link may propagate across wider transport systems and affect mobility, logistics and emergency response.

Road administrations have traditionally addressed geo-hydrological hazards through local protection works, scheduled maintenance and post-event emergency interventions. These approaches remain necessary, but they are not sufficient when hazard conditions evolve rapidly and when multiple processes may occur simultaneously or sequentially. Recent disaster risk reduction and climate adaptation policies therefore emphasize the need to integrate climate resilience, infrastructure management and emergency planning within common decision-support procedures (UNDRR, 2015; European Commission, 2021a, 2021b; Ministero dell'Ambiente e della Sicurezza Energetica, 2023).

A substantial body of research has addressed landslide susceptibility, hazard mapping, infrastructure vulnerability and multi-hazard risk assessment (Kappes et al., 2012; Gill and Malamud, 2014). Similarly, the resilience of critical infrastructures and transportation systems has received increasing attention in engineering and risk analysis literature (Bruneau et al., 2003; Ayyub, 2014; Pant et al., 2016; Pregnolato et al., 2017). However, many available methodologies remain focused on individual hazards, single assets or local case studies. National road managers require operational approaches capable of prioritizing interventions over thousands of kilometers of infrastructure, while also supporting real-time decisions during emergencies and incorporating new information after disruptive events.

The Italian national road network managed by ANAS provides a relevant context for testing such an approach. The network includes approximately 33,000 km of roads, more than 18,700 bridges and viaducts and over 2,150 tunnels distributed across highly heterogeneous geological, geomorphological and climatic environments. Preliminary national assessments indicate that about 5,191 km of road network intersect landslide-prone areas and about 6,491 km intersect flood-prone areas, demonstrating the scale of the exposure problem at national level. Recent events have also shown the operational consequences of these hazards: during the May 2023 Emilia-Romagna emergency, ANAS managed 968 events, including 151 classified as natural disasters, while more than 350 km of national road network within the region were affected by closures, restrictions or critical conditions. In April 2026, the Petacciato landslide simultaneously affected the SS16 Adriatica, the Bologna–Bari high-speed and freight railway and the A14 motorway, highlighting the systemic vulnerability of interconnected transport corridors.

This paper presents an adaptive multi-hazard decision-support approach developed for the climate-resilient management of national road networks. The methodology integrates hazard inventories, GIS-based infrastructure databases, operational information, monitoring systems and post-event analyses into a continuously updated workflow. Its objective is not only to support long-term investment prioritisation, but also to connect prevention, emergency management, monitoring and

recovery within the same adaptive process. The approach is illustrated through representative applications covering debris-flow prevention on the national road SS51 in Veneto, emergency management during the Emilia-Romagna 2023 event, monitoring and recovery after the SS47 and SS52 bis rock falls, and systemic transport disruption caused by the Petacciato landslide.

ADAPTIVE MULTI-HAZARD FRAMEWORK

The proposed methodology was developed to support the management of large road networks exposed to multiple geo-hydrological hazards under changing climatic conditions. It adopts a network-scale perspective in which hazard assessment, infrastructure vulnerability, operational management and post-event learning are integrated into a single adaptive decision-support process. The approach is designed to overcome the limitations of static risk inventories by continuously incorporating new information from monitoring systems, emergency response activities, field surveys and completed mitigation works.

The methodology is organized into five interconnected components: multi-hazard knowledge base, infrastructure assessment, priority assessment, operational implementation and feedback updating.

The first component is the construction of a multi-hazard knowledge base. This includes official hazard inventories, landslide and flood hazard maps, geological and geomorphological datasets, climate information, infrastructure inventories, traffic data, historical disruption records and monitoring information. These datasets are integrated within a common GIS environment, allowing geo-hydrological processes and infrastructure elements to be analysed consistently at network scale. The knowledge base is not conceived as a static repository, but as a continuously updated operational platform.

The second component is infrastructure assessment. Hazard information is spatially combined with the road network inventory to identify infrastructure elements potentially affected by landslides, floods or hydraulic criticalities. The assessment considers both the physical interaction between hazards and road assets and the functional role of each road section within the wider transport system. This distinction is essential because the consequences of a geo-hydrological event depend not only on the expected physical damage, but also on the strategic importance of the affected link, the availability of alternative routes and the potential duration of traffic disruption.

The third component is priority assessment. Intervention priorities are defined by combining hazard conditions, infrastructure vulnerability and operational consequences. In this way, the ranking process does not simply identify the most hazardous locations, but the road sections where geo-hydrological processes may generate the greatest impact on network functionality. Traffic levels, previous service interruptions, strategic corridor relevance and socio-territorial functions are therefore incorporated into the decision process. This principle is formalized in the NACT — Network Analysis for Critical Transport Infrastructure project, which introduces a Social-Territorial Relevance indicator combining transport relevance, served population, traffic demand and access to strategic attractors and essential services. Its rationale is that the criticality of a road section does not depend only on its physical condition or exposure to hazards, but also on the role it plays in connecting population, essential services, productive areas, logistic nodes and emergency functions: under equal hazard or structural conditions, sections with higher territorial relevance may require higher intervention priority. This allows hazard or structural criticality to be weighted by the territorial consequences of road unavailability, directing limited resources towards interventions with the highest expected benefit in terms of safety, service continuity and resilience.

The fourth component is operational implementation. Depending on the characteristics of each priority section, the methodology supports the selection of structural and non-structural measures. Structural measures include slope stabilization, debris-flow control works, rock-fall protection systems, hydraulic works and bridge protection measures. Non-structural measures include

monitoring systems, early-warning procedures, traffic management strategies, emergency plans and targeted inspection protocols. The approach, therefore, links long-term investment planning with short-term operational management.
The fifth component is feedback updating. Information produced during inspections, monitoring campaigns, emergency response and post-event recovery is systematically reintroduced into the knowledge base. This feedback loop allows the assessment to evolve over time as new hazards are detected, infrastructure conditions change, mitigation works are completed or climate-related stressors become more evident. Climate resilience is then interpreted as a dynamic management capability, rather than as a fixed property of individual infrastructure assets.
Overall, the methodology supports a transition from reactive management of geo-hydrological events towards adaptive management of national road networks. Its main contribution lies in connecting prevention, monitoring, emergency response and recovery within the same operational workflow, thereby enabling road authorities to update priorities and decisions as knowledge improves.

IMPLEMENTATION ON THE ITALIAN NATIONAL ROAD NETWORK

The methodology was implemented on the road network managed by ANAS through the development of a national geo-hydrological risk mitigation plan. The objective was to transform heterogeneous territorial, infrastructural and operational data into a consistent decision-support system, able to identify critical road sections, to define intervention priorities and to support subsequent updates of the planning process.
The first implementation level consists of a national screening of road sections potentially affected by geo-hydrological hazards. The analysis combines the ANAS network graph with official hazard maps and institutional datasets, including PAI landslide and flood hazard areas, IFFI landslide inventory data, ISPRA information and other territorial open data (Trigila et al., 2010; ISPRA, 2021, 2025). This step identifies road sections intersecting areas classified as potentially affected by landslides or floods and provides the spatial basis for subsequent prioritisation. The same planning documentation reports 6,491 km of road infrastructure potentially affected by flood events and 5,191 km potentially affected by landslides. The network inventory used in the plan includes 32,744 km of ANAS roads, 2,157 tunnels, 18,720 bridges and viaducts, 3,276 overpasses and 1,140 km of service roads.
The second implementation level defines intervention priorities. The Italian national model does not rank road sections exclusively according to hazard classes. Instead, static hazard information is combined with dynamic operational indicators describing traffic relevance and previous service disruptions. For landslide-related criticalities, the priority level combines a landslide hazard index derived from PAI mapping with a partial priority index based on traffic levels and recorded network unavailability due to past landslide or flood events. For hydraulic criticalities, the model similarly combines flood hazard information with traffic, disruption records and hydraulic vulnerability indicators, including bridge-related vulnerability where relevant.
This structure allows the prioritisation process to distinguish between locations that are hazardous in geomorphological terms and locations where a geo-hydrological event would produce major consequences for road serviceability. A road section with moderate hazard but high traffic demand, limited redundancy and a history of repeated disruptions may therefore receive a higher implementation priority than an isolated section with more severe local hazard but lower systemic consequences. This distinction is essential for national-scale planning, where investment decisions must account for both physical risk and network functionality. As noted above, the NACT project's Socio-Territorial Relevance indicator can also be combined with hazard or bridge/viaduct attention classes to obtain normalised risk classes and decision-support priorities. The application of the model produces classes of intervention priority and supports the definition of operational programmes. In the 2024 mitigation planning process, the model identified 987 interventions classified from high-

priority to necessary, corresponding to an estimated investment of approximately EUR 8.439 billion, excluding completion works. The same documentation further subdivides highly priority interventions into operational subclasses, allowing funding strategies to be directed first towards the most critical corridors and intervention clusters.

National implementation therefore provides more than a static vulnerability map. It establishes an operational planning workflow in which official hazard information, infrastructure inventories, traffic data and historical disruption records are translated into an intervention programme. The same structure also allows subsequent updating: new hazard maps, monitoring results, field inspections, emergency observations and completed works can be incorporated into the database and used to revise both the hazard assessment and the intervention priorities.

In this sense, the Italian implementation represents the operational core of the proposed adaptive approach. It connects the national-scale identification of geo-hydrological exposure with investment planning, monitoring needs and emergency preparedness, while maintaining a structure that can be progressively updated as new information becomes available.

OPERATIONAL VALIDATION

The national implementation described above was progressively tested through operational applications developed under different geo-hydrological conditions and management phases. These applications are not intended as isolated case studies, but as complementary validations of the adaptive approach. Each one represents a specific phase of the risk-management cycle: prevention, emergency management, monitoring-based recovery and systemic resilience of interconnected transport corridors (Figure 1, Table 1).



Fig. 1 ANAS network and location of applications.
1 SS51 “di Alemagna”; 2 SS47 “Valsugana”; 3 Emilia-Romagna; 4 Petacciato

Tab. 1 Operational validation of the adaptive methodology

Application	Main hazard	Management phase	Validated component
1 SS51 “di Alemagna”	Debris flows, shallow landslides	Prevention	Monitoring, rainfall-based warning and proactive traffic management
2 SS47 “Valsugana”	Rock fall	Recovery	Monitoring-supported reopening and residual-risk management
3 Emilia-Romagna	Floods, landslides	Emergency management	GIS-based operational coordination and post-event updating
4 Petacciato	Deep-seated landslide	Systemic resilience	Multi-network corridor management and adaptive prioritization

Prevention and early warning: SS51 “di Alemagna”

The SS51 “di Alemagna” represents a strategic Alpine corridor connecting the Veneto Region with the Dolomites Mountain area. The road crosses sectors affected by recurrent debris-flow and shallow-landslide processes, with several phenomena already documented in the IFFI inventory and potentially interfering with the infrastructure during intense rainfall events. The corridor is particularly relevant because of its role in the accessibility of the touristic venue of Cortina d’Ampezzo recently a seat of the Milano–Cortina 2026 Winter Olympic Games.

Within the proposed methodology, the SS51 application validates the preventive component of the adaptive workflow. The management strategy does not rely exclusively on structural mitigation works, but combines protection measures with monitoring, rainfall nowcasting and early-warning procedures. Experimental systems based on high-resolution rainfall estimation and short-term prediction have been developed to support the detection of critical rainfall conditions potentially capable of triggering debris flows. These systems are integrated with local warning devices and traffic-management procedures, allowing the road manager to move from a purely reactive response to a more proactive operational model.

The SS51 experience demonstrates that, for debris-flow-prone corridors, resilience depends not only on reducing hazard intensity through engineering works, but also on improving the capacity to anticipate hazardous conditions and manage traffic before the landslide reaches the road. In the framework, this information becomes part of the knowledge base and supports the periodic revision of priorities, thresholds and operational procedures.

Monitoring-based recovery: SS47 “Valsugana”

The SS47 “Valsugana” rock fall of 12 January 2024 represents a validation of the framework during post-event recovery and infrastructure reopening. A portion of dolostone slope detached and affected both the road bridge and the adjacent railway corridor, producing a critical condition for two strategic transport infrastructures. Inspections documented structural damage to the bridge and a transversal displacement of the deck, while geological assessment indicated the persistence of residual instability conditions on the slope.

The recovery strategy required coordination between different infrastructure operators, rapid slope stabilisation works, bridge assessment and continuous monitoring. A Ground-Based Synthetic Aperture Radar system was installed on the opposite slope to monitor deformation in near real time and support decisions concerning safety, works execution and reopening. The monitoring campaign provided millimetric displacement information and helped distinguish relevant slope movements from cyclic thermal effects and non-critical local variations.

In this case, the value of the methodology lies in the integration of monitoring within the decision process. Monitoring is not treated as a separate technical activity, but as a component of the adaptive workflow: it reduces uncertainty during emergency response, supports safe reopening and produces new data for future hazard assessment. The SS47 case also shows that geo-hydrological events affecting road infrastructure may involve interdependent systems, such as road and rail corridors, requiring coordinated recovery strategies.

Emergency management: Emilia-Romagna floods and landslides, May 2023

The May 2023 Emilia-Romagna emergency provides a regional-scale validation of the methodology under conditions of widespread and simultaneous disruption. The event affected a complex road network exposed to flooding, landslides, and bridge-related criticalities. ANAS managed 968 events during the emergency period, including 151 classified as natural disasters. The main phase of 16–17 May involved 87 major events and affected approximately 358 km of road connections, corresponding to about 18.5% of the regional ANAS network. Road serviceability was compromised by both flooding and landslide-related closures or restrictions.

The emergency required the rapid integration of multiple information streams: road closures, field inspections, bridge surveys, landslide observations, hydraulic criticalities, drone surveys, terrestrial laser scanning, satellite observations and operational communications between territorial units and control rooms. The GIS environment became the common operational platform for maintaining a synoptic representation of the affected network while preserving the detail of each individual event.

The inventory of May 2023 landslide phenomena included about 80,000 newly activated landslides in Emilia-Romagna. By intersecting this inventory with the ANAS road graph, 79 landslides were identified as directly interfering with the road network within a 14 m buffer, while 134 were identified as interfering or potentially interfering within a 54 m buffer. Additional GIS-based refinement supported the identification of intervention needs and the preliminary estimation of associated costs.

This application validates two central aspects of the adaptive approach. First, the same database structure used for planning can support emergency management when many disruptions occur simultaneously. Second, post-event information can be transformed into updated knowledge for design, prioritisation and future mitigation planning. The emergency therefore becomes part of the learning cycle rather than remaining an isolated operational episode.

Systemic resilience: Petacciato landslide, April 2026

The Petacciato landslide represents the most recent and systemic application considered in this paper. The event affected the Adriatic transport corridor in Molise Region, simultaneously involving the SS16 “Adriatica”, the Bologna–Bari railway and the A14 motorway. The landslide can be interpreted as a complex landslide mechanism according to established landslide classification schemes (Varnes, 1978; Hungr et al., 2014), with deformation extending from the coastal sector towards the sea and retrogressive effects towards the inland area.

Unlike the previous applications, Petacciato cannot be interpreted only as a road-infrastructure problem. The event demonstrated that a single geo-hydrological process may compromise several transport systems at the same time, producing effects that exceed the management capacity of an individual asset owner if not addressed through coordinated corridor-scale planning. In this sense, the case validates the need to extend infrastructure resilience from the asset scale to the interconnected transport-system scale.

The preliminary post-event reconnaissance in Molise identified a large number of restoration and mitigation needs across the ANAS network, with 94 interventions planned and an estimated total amount of approximately EUR 47.4 million. This illustrates how a major geo-hydrological event can rapidly generate a broad programme of emergency, restoration and risk-reduction actions, requiring prioritisation criteria consistent with the national planning framework.

Petacciato therefore provides a critical validation of the adaptive methodology. It shows that network resilience cannot be assessed only by overlaying hazard maps and road assets. It requires the capacity to understand functional interdependencies, identify corridor-scale consequences, coordinate with

other infrastructure managers and update priorities after major events. This case strongly supports the transition from road protection towards integrated management of critical transport corridors.
The four applications validate different components of the proposed methodology. The SS51 demonstrates the role of prevention, monitoring and early warning in debris-flow-prone corridors. The Emilia-Romagna emergency demonstrates the capability of the approach to manage widespread and simultaneous disruptions at regional scale. The SS47 case validates the integration of monitoring into recovery and reopening decisions. Petacciato extends the methodology to systemic resilience, where roads, railways and motorways are affected by the same geo-hydrological process.
Collectively, these applications show that the methodology is not limited to ex-ante risk mapping. It operates across the full management cycle, linking prevention, emergency response, monitoring, recovery and planning updates. This is the central validation outcome: the same adaptive structure can support both strategic national-scale prioritisation and operational decisions during real geo-hydrological events.
The operational cases also indicate the need for decision-support indicators capable of ranking not only hazardous assets, but also road sections whose unavailability would generate disproportionate socio-territorial impacts. Tools such as NACT provide a possible extension of the proposed methodology by combining hazard or structural attention classes with network relevance indicators.

CONCLUSIONS

Geo-hydrological hazards are increasingly affecting the safety, functionality and continuity of road networks. Under changing climatic conditions, road administrations cannot rely only on static hazard maps, isolated protection works or post-event emergency response. They require adaptive management procedures capable of integrating prevention, monitoring, emergency operations, recovery and long-term investment planning within the same decision-support process.
This paper presented an adaptive multi-hazard methodology developed for the climate-resilient management of national road networks in Italy. The approach combines official hazard inventories, infrastructure databases, traffic and disruption records, monitoring systems and post-event observations within a continuously updated geo-spatial knowledge base. Its main objective is to transform heterogeneous information into operational priorities, allowing road managers to identify critical sections, select appropriate structural and non-structural measures and update decisions as new evidence becomes available.
The implementation on the Italian national road network demonstrates the applicability of the methodology at national scale. The approach was used to assess thousands of kilometres of infrastructure exposed to geo-hydrological processes, and to support the definition of intervention priorities based not only on hazard conditions, but also on infrastructure vulnerability and network functionality.
The operational applications confirm that the methodology is not limited to ex-ante planning. The SS51 case validates its use for prevention and early warning in debris-flow-prone corridors. The Emilia-Romagna 2023 emergency demonstrates its value for managing widespread and simultaneous disruptions through GIS-based operational coordination. The SS47 case shows how monitoring can support recovery and safe reopening after a rockfall event. Finally, the Petacciato landslide highlights the need to extend road-infrastructure management towards the resilience of interconnected transport corridors, where roads, railways and motorways may be affected by the same geo-hydrological process.
The principal contribution of the proposed approach is therefore the integration of strategic planning and operational management into a single adaptive cycle. Each event, inspection, monitoring campaign or completed mitigation work becomes new information for improving future decisions. In this perspective, climate resilience is not treated as a fixed property of individual assets, but as the

capacity of the management system to learn, update priorities and maintain network functionality under evolving hazard conditions.

Although developed for the Italian national road network, the methodology is transferable to other road administrations facing similar exposure to multiple geo-hydrological hazards. Future developments should focus on the integration of high-resolution climate projections, automated data flows from monitoring systems and quantitative performance indicators for measuring the effectiveness of adaptation measures over time.

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Keywords: climate resilience; road infrastructure; multi-hazard; decision support; adaptation.