

Article

Bridging Knowledge, Protection and Development Gaps Through an Interdisciplinary Multi-Stakeholder Approach to Natural Hazards Risk Management

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Abstract: The escalation of climate-induced disasters underscores how climatic variability has become a main question in designing risk-sensitive policies in advanced and developing countries. The macroeconomic implications of Natural Hazards (NHs) are extremely significant, as they can compromise financial stability and long-term prosperity. To mitigate risks and close the knowledge, protection, and development gaps can free resources, speeding up reconstruction of infrastructure, recovering from disruption of supply chains, and returning to pre-disaster levels of activities. This is not a simple task involving different steps of a “ladder approach”, sharing the burden of cost and responsibilities across the relevant stakeholders and reducing moral hazard. This approach rests on Public–Private Partnerships (PPPs) and technological R&D public investments able to crowd private ones in and establish useful Public–Private Insurance Schemes enhancing the disaster risk management role of the state. This paper proposes leveraging innovation technology both to enhance risk assessment and reduce uncertainty for climate-related NHs such as landslides. It is an important interdisciplinary question; in fact, despite the unequivocal acknowledgment of the global warming system, the precise ramifications of global warming and associated climatic shifts on NHs like landslides remain still elusive. The advanced modeling technique implemented by our interdisciplinary PPP contributes to geographically circumscribe the areas eventually subjected to landslides and constantly monitor the vulnerability of their structures, infrastructures, economic activities, and hence population. The reliable data that we can produce through remote sensing acquisition systems are necessary inputs to contain risk exposure both physically and financially.

Keywords: climate change; natural hazards; resilience; risk management; economic development; innovation technology



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1. Introduction

Engagement in Public–Private Partnerships (PPPs) addresses the largest and most complex risks modern societies are facing. As evidenced by the Geneva Association [1], this approach can tackle even the Changing Risk Landscape due to tangible risks as climate-induced Natural Hazards (NHs). Technological advancements such as richer datasets and sophisticated modeling may improve the risk insurability.

Our interdisciplinary multi-stakeholder approach precisely fits this evidence, focusing its attention on climate-induced NHs, specifically landslides and floods, leveraging new advanced physical-based modeling and reliable data that will be obtained through a new generation of remote sensing monitoring systems. The whole contribution of our PPP in terms of innovation technology and macro-financial literacy will sustain the new de-risking role of the state through its practical consequences on insurance policies and pricing useful

to address in a financially sustainable way the intense phenomena of such climate-induced NHs that can severely compromise economic growth.

Among climate-induced NHs, Lin et al. [2] showed that despite the unequivocal acknowledgment by the Fifth Assessment of the Intergovernmental Panel on Climate Change (IPCC) of the warming global climate system, the precise ramifications of global warming and associated climatic shifts on landslides are still elusive. Marín Rodríguez et al. [3] analyzed the global trends and structures of landslide risk and economic loss research from 2002 to 2023 using scient-metric techniques such as co-authorship, co-word, co-citation, cluster analysis, and trend topics, among others. Thus, analysis of 92 studies gathered from Scopus and Web of Science databases reveals a continuous growth in environmental, social, and quantitative research topics, even if predominant contributions come mainly from China and Italy.

Defining risk management in the case of hydrogeological hazards linked to climate change, such as floods and landslides, requires a dynamic susceptibility assessment to circumscribe, from time to time, subjected areas, structures, and infrastructure, and hence populations and their environmental and economic exposure. Moreover, if these hydrogeological hazards occur in seismic and volcanic areas, the continuous happening of events produces a progressive negative impact on structures and infrastructure, increasing the vulnerability and catastrophic impact of each following event. This problem is very complex in the Eurozone because of its crumbling structures and infrastructure, the result of decades of austerity and underinvestment, in an era of extremely severe emergencies such as climate change and aggressive global competition. This is even far more engaging in Italy, as it involves cultural and historical sites that are very difficult to protect from NHs while maintaining their priceless values.

In the case of the Eurozone, the opportunity of a new financial strategy to increase the resilience of society from NHs is suggested by the coexistence of the private savings glut of the rich and the strict fiscal rules. Adopting a crowding-in approach in partnership with big finance governments can give rise to a new age of infrastructure, generating steady returns for investors and asset managers who look after pensions and insurance schemes and unlocking trillions now devoted to welfare states. But, for the big finance to accept to be a partner of such a PPP, governments must take on the task of de-risking return profiles.

This paper refers to the role of financial institutions and technological innovation in Natural Hazard Risk Management (Section 2). The Discussion Section highlights the role of interdisciplinary research and the need for cooperation between the public and private sectors through Public–Private Partnerships (PPPs) (Section 2.1). In Section 3, it is presented the Italian Smart Climate Risk Protection Policy, evidencing European comparisons and concluding about how it is possible to improve insurance affordability and the behavior towards risk. Section 4 summarizes the risk assessment methodology. Section 5 explains how to refine risk assessment to increase resilience. The advantages of refining risk assessment and future perspectives are evidenced in Section 6.

2. The Role of Financial Institutions and Technological Innovation in Natural Hazard Risk Management

In macroeconomics and finance literature, the de-risking approach is everything but new. The de-risking role of financial institutions as the Central Bank is well described in making efficient financial markets and safe assets to satisfy “Liquidity Preference as Behavior Towards Risk” (Tobin) [4] and the need for money capital in the firm [5]. Different components of risk can then be managed, not only financial risk but even operative and technical ones [6].

In a speech at Lloyd’s of London given by Carney [7], the former Chairman of the Financial Stability Board and Governor of the Bank of England, on 29 September 2015, the UK insurance industry was invited to reflect on how urgent it was to take into much more serious account the threat of climate change posed to financial stability and hence long-term prosperity. Since the 1980s, the number of registered weather-related loss events has tripled,

and NatCatSERVICE of Munich Re has evidenced the extraordinary increase in inflation-adjusted insurance losses from these events. It was precisely then that Carney's "Tragedy of the Horizon" gave the start to a new point of view going well beyond the traditional horizon. Most actors used not to look further than a business cycle, a political cycle, a credit cycle, and a technocratic mandate in the case of monetary policy, while climate change and its consequences became a matter of financial stability that the current generation had to fix to give a future to next generations. The speech even clarified the extreme importance of better information to assess risks and to produce new insurance and re-insurance profitable products and remembered that "an old adage is that which is measured can be managed" and that "supply creates demand", as recited in macroeconomics by Say's Law. It is just following this point of view that it is possible to understand the very important role of innovation technology and technical information to correctly define realistic consequences of NHs and effects of climate change. This enables us to reduce uncertainty in the risk-return profiles of whatever physical, economic, and financial investment, therefore enhancing the chances for more resilient and sustainable economic growth.

More recently, "the soft budget constraint syndrome has penetrated capitalism" (Kornai) [8] and "de-risking" regimes involving PPPs have become hegemonic [9] with respect to state-led planning that, as well evidenced by Kornai [8], may suffer from inconsistency and be less reliable, especially in a context of the very high uncertainty of the NHs.

2.1. A Path to Sustainable Financial Protection

In de-risking regimes, multiple stakeholders must be effectively involved through Public–Private Partnerships (PPPs) and Public–Private Insurance Programs (PPIPs). As evidenced in "High-Level Framework for Public–Private Insurance Programs" presented in May, at G7 Italia 2024 [10], global financial markets and particularly insurance markets can accomplish the extremely important role of absorbing damages and losses from NHs.

According to OECD [11] "Recommendation on Building Financial Resilience to Disaster Risks", for sustainable development to be guaranteed, it is necessary to prevent new disaster risks, reduce the existing ones, and manage the residual ones. All this must be carried out, even "leveraging technology in insurance to enhance risk assessment and policyholder risk reduction" and "Enhancing Financial Protection Against Catastrophe Risks" through "the Role of Catastrophe Risk Insurance Programs" [12]. The International Association of Insurance Supervisors, then, underlies in its report "a call to action" and "the role of insurance supervisors in addressing natural catastrophe protection gaps" [13]. It is evident in this context the extremely effective role of technology and innovation to measure the effects and reduce uncertainty for whatever NH and degree of climate change. This is to some extent what is achieved by Aladdin (BlackRock), where the biggest example in the new era of investment management tech is cited. Aladdin is a tech platform that unifies the insurance investment management processes; the software enables us to manage portfolios across both public and private market investments. Aladdin Climate, then, helps to understand and act upon the effect of climate change on investments and quantify climate risks in financial terms, arriving at climate-adjusted valuations and risk metrics through climate science, policy scenarios, asset data, and financial models. Our PPP, a networking cooperation between universities and enterprises, fits precisely into this area to create spill-over effects as catalysts for economic and social development at the local level and strengthen universities' entrepreneurial capacity, supporting innovation and even research commercialization.

3. The Italian Smart Climate Risk Protection Policy and European Comparisons

Draghi [14,15] evidenced the opportunity to issue guidelines for EU Pension Plans and fix capital adequacy rules for insurance companies established in the Eurozone, as the existing fragmented regulatory framework can compromise European economic growth. In fact, EIOPA [16] reports, for example, that in France the coverage of NHs was already compulsory in 1982; policies are mandatory, and due to a principle of solidarity among citizens,

insurers charge an extra premium for the NHs coverage, which is set by the law as a fixed percentage on the property and causality insurance premiums of the underlying contracts.

As far as the Italian approach to the regulation of the insurance industry, on 31 December 2024 it is going to start a new Smart Climate Risk Protection Policy specifically implemented for catastrophic damages characterized by a compulsory scheme, circumscribed, by now, to a limited target of policyholders made of enterprises and households. We will refer to the last Italian Budget Law [17] to describe its perimeter and the role of each stakeholder involved in it, namely the Italian government, the insurance industry and its Supervisory Authority (IVASS), the Italian insurance financial group directly controlled by the Ministry of Economy and Finance (SACE), and the national reference price comparison site for the insurance sector (Facile.it). In this paper, the Italian approach will be briefly compared to a Lloyd's catastrophe insurance policy in The Netherlands (Section 3.2.4) as referred to in the EIOPA's Report [16].

3.1. Bridging Protection Gaps

Climate change and NHs can rapidly and severely hit the financial stability of economies. Due to scarce information and awareness on their impact on the economies and a lack of financial literacy, the effective demand for insurance may be scarce, and public and private finance may end up being extremely exposed. Thus, financial "protection gaps", happening whenever those who may be directly or indirectly injured by the NHs cannot rapidly recover from a disaster due to the absence of insurance coverage and other financial protection, can be very far to be closed through a genuine demand for insurance protection. This can justify the choice of the Italian de-risking government to adopt a compulsory coverage as that introduced by the last Italian Budget Law [17].

Starting from 31 December 2024, the Italian Budget Law introduces the obligation to stipulate insurance contracts to cover damages to their tangible fixed assets, such as lands and buildings, plants and machinery, and industrial and commercial equipment, caused by natural disasters and catastrophic events that occurred on the national territory, for companies registered in Italy and abroad but operating in Italy through an establishment, excluding agricultural companies.

This is a novelty in the Italian insurance panorama (within which the perimeter of compulsory insurance coverage was limited to a few activities, the main one being that relating to the circulation of vehicles), whose purpose would appear to be that of replacing the public system with the private one, relieving the public sector from the burden of paying compensation in case of calamitous and catastrophic events, and inducing the private system to seek conditions of mutuality that allow the restoration of economic and productive conditions more rapidly than state intervention.

Any failure to stipulate insurance coverage will determine the exclusion for the uninsured party from the assignment of contributions, subsidies, and financial benefits to be drawn from public resources, also with reference to those provided for in the event of calamitous and/or catastrophic events (paragraph 102 of [17]).

3.2. Regulation and Re-Insurance

3.2.1. Businesses

With reference to the hazards to be covered, pending the detailed indications that the Ministers of Economy and Finance and of Enterprise and Made in Italy, in agreement with the IVASS, the current list (i.e., earthquakes, floods, landslides, inundations, and overflows) is merely exemplary.

Similarly to civil liability arising from the circulation of vehicles and vessels, insurance companies will not be able to avoid the obligation to contract under penalty of applying an administrative pecuniary sanction ranging between EUR 100,000 and EUR 500,000.

Given the nature of the insurance commitment that they will have to assume, paragraph 103 of article 1 of [17] allows insurance companies not only to directly underwrite the risk, having the financial capacity to do so, but also to act in co-insurance or by establishing

consortia with other insurance companies; the latter must, however, be registered and approved by IVASS, which will evaluate their stability.

Acting as a public reinsurer, then, SACE will ensure that the obligations undertaken by the insurance companies are fulfilled, indemnifying the private insurance and reinsurance companies up to 50% of the compensation paid by the latter, for an amount not exceeding 5000 million Euro for the year 2024 and, for each of the years 2025 and 2026, not exceeding the greater amount between 5000 million Euro and the free resources at December 31 of the immediately preceding year, not used for the payment of compensation in the reference year.

To further ensure the overall solvency of the system, it is expected that the obligations assumed by SACE will be guaranteed on first demand and without the possibility of recourse by the state as insurer of last resort. The state guarantee is explicit, unconditional, and irrevocable (paragraph 109 of article 1 of [17]).

The eventual expansion of the scope of insured risks will also influence the verification of the solvency conditions of companies by IVASS; it cannot be excluded that, in order to meet the obligations to contract imposed by the provisions mentioned above, companies will seek greater diversification of the risks present in their portfolio and, possibly, alternative forms of reinsurance. In the next future, it will also be interesting to see how the pricing of coverage and its tax treatment are declined, since different areas of the country correspond to a more or less marked exposure to calamitous and/or catastrophic events.

3.2.2. Real Estate Sector

With specific reference to the real estate sector, the legislator also intended to extend the range of those subjected to mandatory insurance. In this regard, in fact, on 27 February 2024, Italian Law [18] was published in the *Official Journal*, converting Legislative Decree No. 212 of 29 December 2023, according to which all those who have benefited from the tax benefits under the so-called “superbonus” (see Art. 119, paragraph 8-ter, [19]), in relation to expenses for interventions started after 30 December 2023, are also obliged to obtain insurance to cover damage caused to the related properties (including, therefore, even residential properties) by natural disasters and catastrophic events, all within one year of the conclusion of the works subjected to the benefits of the “superbonus”. The beneficiaries of the “superbonus”, therefore, could find themselves in a delicate position: while, on the one hand, they are entitled to the enjoyment of specific tax breaks, on the other, they will now be required to take out additional insurance policies, representing a further financial burden for them.

3.2.3. Online Platforms

On 4 July 2024, SACE [20], in partnership with Facile.it, launched Smart Climate Risk Protection, a catastrophic damage policy for micro-enterprises. The partnership between SACE and Facile.it marks an important point in the world of insurance, and, for the first time, two leading companies join to allow micro-enterprises to obtain maximum benefits with the best technology available on the market. The aim of the agreement is to make Smart Climate Risk Protection accessible in a simple and fast way, with a direct link to MySACE.it, the Facile.it platform.

With this initiative, SACE extends its commitment to serving micro-enterprises, providing them with tailor-made products and digital promotion channels, while Facile.it confirms itself as a point of reference in savings not only for end consumers but also for the B2B sector.

3.2.4. Improving Insurance Affordability and Behavior Towards Risk

It was the European Insurance and Occupational Pensions Authority (EIOPA), a European Union financial regulatory institution, that introduced the concept of “Impact Underwriting”, which is “the development of new insurance products and the engagement

with public authorities, without disregard for actuarial risk-based principles of risk selection and pricing” [16,21].

The compulsory regime chosen by the de-risking Italian government can be mitigated by big data and technologies, useful to better adapt the insurance products or services to customers’ needs but even to prevent NHs and their consequences. Reflecting the actual risk a policyholder is exposed to, risk-based pricing as premiums and deductibles can produce safer behavior, helping climate change adaptation and mitigation of the risks. This then reflects a reduction in risk, less money to afford losses, and decreasing premiums. For example, a Lloyd’s catastrophe insurance policy in the Netherlands allowed purchasing coverage for flood damage, earthquake, and terrorism risks. As far as flood risk, policyholders received premium discounts if they took measures to “floodproof” their home. They found flood risk information on the insurer’s website, on which they could enter their zip code to extract information about flood probabilities, potential water levels, the quality of flood protection, and the risk-based insurance premium. Four different measures allow each a 5% premium discount: (1) installing electrical equipment; (2) the central heating installation above the ground floor level; (3) having flood shields available; and (4) having a waterproof floor on the ground floor level, such as tiles [16].

Similar approaches have already been adopted even in Italy through the DERRIS (Disaster Risk Reduction InSurance) Pilot Project [22] by UNIPOLSAI (a multi-line insurance company belonging to the Unipol group, which is a leader in the Italian non-life sector). DERRIS is a project (2015–2018) co-funded by the European LIFE program and involves the leadership of the Unipol Group alongside partners including the City of Turin, Cineas, ANCI, Coordinamento Agende 21, and UnipolSai. The project aims to test and implement an innovative form of PPP between insurance companies, municipalities, and businesses to enhance the resilience of Italian Small and Medium Enterprises (SMEs) to climate change. It provides them with a simple and free tool linked to their zip code (the CRAM tool; <https://cram.derris.eu/>; accessed on 9 July 2024) for the assessment, prevention, and management of risks related to NHs, considering five hazards: flood, lightning, rain, hail, landslide, wind, and temperature. The goal of the DERRIS project is to assess the impact of climate change on risk factors and to forecast adaptation strategies that will be the subject of actions on both a large scale (urban or hydrographic district) and on the local scale of individual companies. The approach taken in the project is essentially empirical, using reference scenarios found in the Intergovernmental Panel on Climate Change (IPCC) climate reports [23] and in the Italian Institute for Environmental Protection and Research (ISPRA) report [24]. It starts with a simplified assessment of the effects of NHs without analyzing the causes and physical mechanisms of natural phenomena but directly evaluating qualitatively the consequences on the territory.

For example, regarding the risk of landslides, a simplified methodology has been referenced, based on the National Geological Map of the ISPRA [25] and the Italian Landslide Inventory (IFFI) [26]. The assessment of the hazard considers simply that the increase in precipitation associated with climate change may trigger only shallow landslides among the documented landslides. The assessment of vulnerability is based on the CRAM tool for self-assessment by companies, with the construction of a risk class matrix. The definition and pricing of the policy will be linked to the eventual adoption of a series of intervention strategies. The CRAM tool was set up to automatically generate the Company Adaptation Action Plan (CAAP), a company road map of actions for adaptation that the SMEs have to follow based on the information provided by the companies themselves. Different stakeholders at the local level were then involved in the realization of the Integrated District Adaptation Plan (IDAP) as trade organizations, representatives of businesses, and the different departments of the local public administration (environment, urban planning, civil protection, urbanization and requalification of public space, mobility, management of green areas, public works, communication, and social services). Unipol Banca was involved in developing a financial instrument (a loan ranging from a minimum of EUR 10,000 to a

maximum of EUR 100,000) to support the SMEs participating in the pilot experiment to implement the action in their CAAPs.

The examples cited above of the Lloyd's catastrophe insurance policy in the Netherlands and the Italian Derris pilot project offer us the occasion to stress the importance of our contribution. Firstly, the climate change effect may produce dynamic extreme tail events that very simplified and static systems of evaluation are not able to detect. Secondly, the risk assessment based on a zip code identification rests on an extremely simplified territorial schematization (Section 4). Finally, a contest of changing climate, expectedly growing climate-related losses, and increasing premiums justify the intervention of public re-insurances and PPIPs to contain the "protection gap". The unaffordability for the policyholders on the one hand and a crowding of the private insurances and re-insurances out of the market due to their inability to remain profitable were, in fact, other sources of long-term financial instability for economies.

4. Risk Assessment Methodology

Our working methodology is based on a critical analysis of the weaknesses discussed earlier for the Derris Pilot Project in Turin (Italy). Indeed, as highlighted in [27], there is no universally accepted methodology to define the landslide risk assessment in a changing climate.

The data sources of the Italian pilot project to define the landslide risk assessment are the Geological Maps of ISPRA [25] and the Inventory of Landslides in Italy [26].

The methodology they use to calculate risk and its evolution induced by climate change is based on the estimation of hazard (IFFI landslide inventory) and vulnerability (CRAMTool and zip code).

It is a very reliable starting point of analysis, but assuming the estimation of vulnerability is valid, even if based on self-assessment, the technical weak point where our PPP can intervene to improve the methodology is the assessment of hazards at a more detailed scale.

In fact, the IFFI on landslides suffers from a series of problems inherent in the methodology used for mapping landslides:

- The national territory is described by collecting heterogeneous data obtained with different mapping and interpretation techniques.
- The scale adopted for mapping of landslides (1:10,000 or 1:25,000) is too broad to allow for a correct assessment.
- Although the inventory contains 614,799 landslides, the coverage of the national territory is still partial.
- The periodic updating of the maps is carried out in a heterogeneous manner across the national territory.

Considering all that has been discussed and intending to apply the same working methodology, the next paragraphs outline actions to be taken to enhance the risk assessment.

5. Refining Risk Assessment to Increase Resilience

The probability of a catastrophic event is related to the system's ability to counteract it, depending on the mechanical and geometric characteristics of the natural and built system in question. Therefore, the calculation of the probability of occurrence is more accurate the more precise the definition of the models capable of following the underlying physical phenomenon and the related physical parameters is. Hence, the probability of occurrence is closely tied to the uncertainties inherent in the definition of behavioral models and the related physical parameters. The techniques available in the engineering field for handling uncertainties have been discussed in [28–30]. Each source of uncertainty must be adequately considered and addressed. Epistemic uncertainty can be overcome as it is linked to a lack of knowledge that can be refined through in-depth investigations. As discussed earlier, one of the main sources of epistemic and aleatory uncertainty in risk assessment for landslides lies in the quality of the data and the scale to which they refer. For example, in

modeling landslide phenomena, a scale of analysis with insufficient level of detail induces not only epistemic errors with serious repercussions on the geological and geotechnical models used but also errors with high aleatory uncertainties due to greater data dispersion resulting from an excessively broad scale of analysis. Thus, having a detailed analysis of the geotechnical model through a combination of conventional monitoring systems and innovative instruments, along with continuous data acquisition, results in a significant reduction in both epistemic uncertainty (allowing previously unavailable information to be obtained) and aleatory uncertainty (availability of a large quantity of high-quality data) [31]. For each level of uncertainty (the level of information between complete absence of information and total knowledge), there is an optimal model to be used. A low level of information only permits deterministic analyses, while as the level of information increases, it is possible to achieve a more accurate frequency distribution of each given variable and thus a statistical treatment of it. In fact, statistical analyses with inaccurate and/or scarce data can lead to unreliable and often misleading results, impacting risk assessment.

Our PPP therefore works in the direction of producing information for accurate calculation of the probability of occurrence of catastrophic events and managing the related uncertainties to reduce risk and improve resilience. Moreover, as previously discussed, the huge quantity and quality of data that will be disposable can be useful to train AI algorithms to refine the precision of the forecasts with further significant implications even for the insurance and reinsurance industries by providing more accurate risk calculations. Clearly, the distribution of the population, strategic and non-strategic civil and military structures and infrastructures, as well as productive activities across the territory, can provide guidance on the priority scale to adopt and the level of detail to reduce uncertainty.

In the following, the attention is devoted exclusively to NHs related to climate-induced landslides. In fact, the landslide risk assessment can be effectively supported by our PPP, as it includes even the expertise to develop advanced models to simulate the effects of climate change and, on the other hand, the creation of innovative investigation and monitoring systems.

6. Advantages of Refining Risk Assessment and Future Perspectives

The application of the refining assessment just described is presented for three cases where the Derris approach would have been unreliable due to the extreme complexity of hydrological, geological, and geotechnical characteristics of the sites as generally found throughout the Italian territory. Different approaches have been developed depending on the characteristics of soil deposits and the type of landslide.

In the case of rainfall-induced landslides in shallow pyroclastic deposits of the Campania Region (Figure 1), ref. [32] proposed a multidisciplinary approach that involves the expertise of hydrologists, meteorologists, computational mechanics experts, economists, and geotechnical engineers for landslide risk management, which significantly impacts the epistemic component of uncertainty. In the territories under consideration, a supplementary investigation program was developed, which included the redaction of thematic maps at detailed scales (1:1000 and 1:2000) and the execution of in situ and laboratory tests for the mechanical characterization of soils. Furthermore, complex monitoring systems with continuous data acquisition and remote management were installed in the study areas. A framework (Figure 2) was proposed for the assessment of landslide evolution under a simplified hypothesis, which can be used to create a Decision Support System [33] for stakeholders involved in land management and the protection of areas at risk.

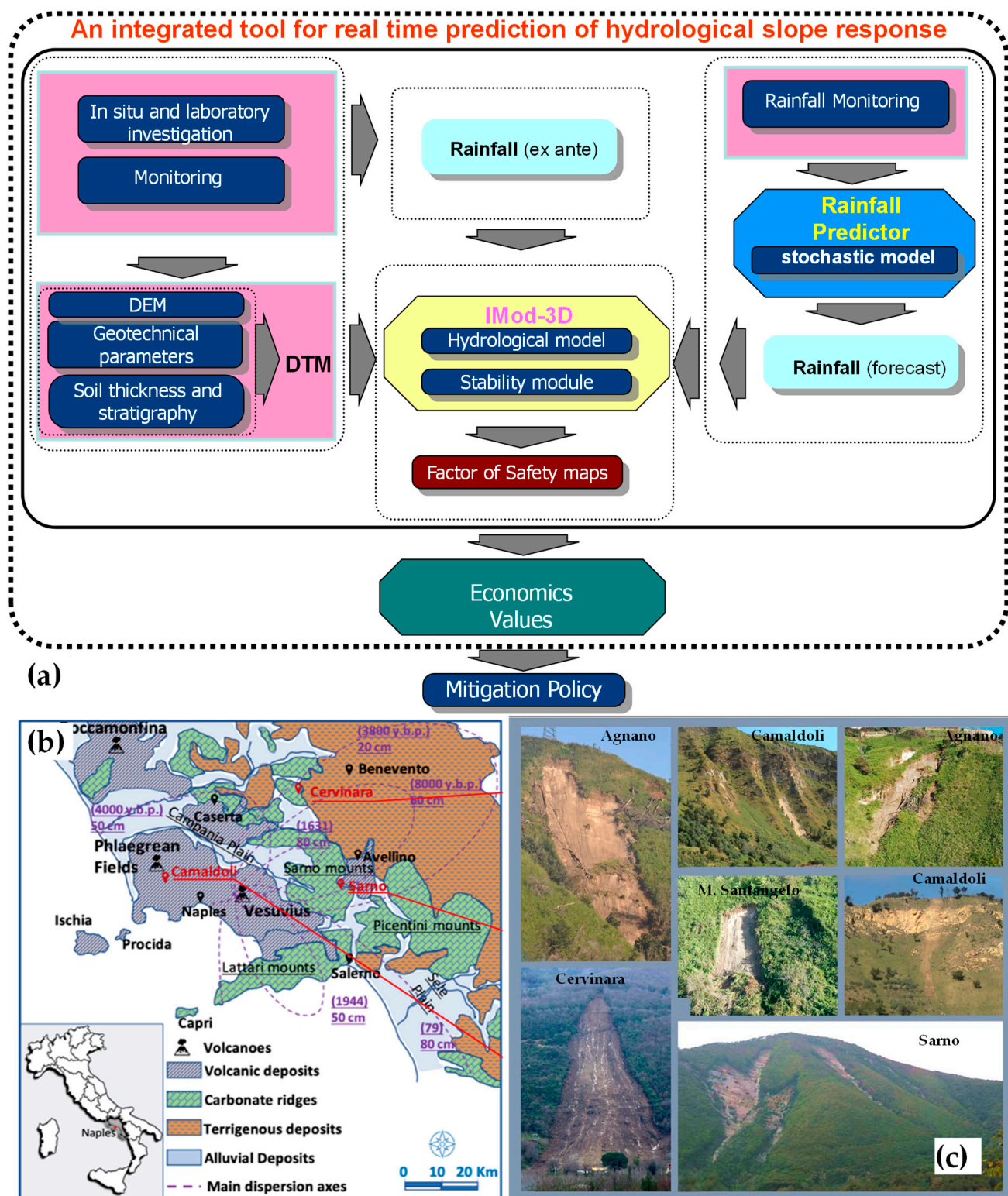


Figure 1. (a) Flow chart of the Decision Support System (DSS). (b) Geomorphological contexts of the pyroclastic deposits in Campania, Italy. (c) Landslide case history.

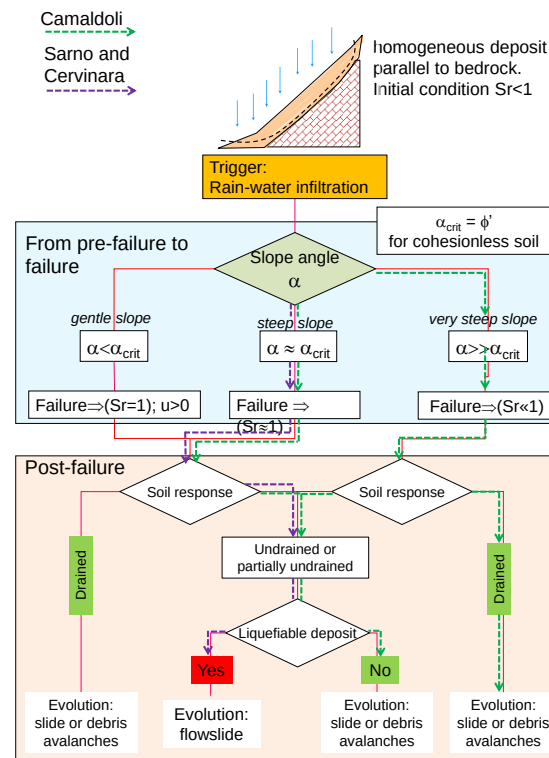


Figure 2. Flow chart for simplified assessment of the post-failure evolution of landslides.

This also led [34] to the creation of a soil database for hydro-geotechnical models for volcanic soil deposits. The database contains all the data needed to define advanced constitutive relationships to be implemented in a physically based model to capture landslide failure under weather rainfall forecasts (such as those caused by climate change). The data contained in the soil database represents the essential input for initializing AI algorithms, while the monitoring data serve to train the AI.

Moreover, since 2019, research has been implementing technological innovation and advanced expertise in defining advanced monitoring systems both for the study of the effects of landslides and earthquakes and for Structural Health Monitoring and Reinforcement (SHMR) [35]. This research activity led to the realization of the New Smart Hybrid Transducer (NSHT) (Figure 3) and the registration of industrial property patents [36]. In Figure 3a, there is a schematic representation of an application of NSHT as a landslide Early Warning System (EWS) and as an SHMR system by a single acquisition system (Figure 3c). The proposed monitoring system is constituted by distributed strain and temperature NSHTs based on optical fiber sensing technology. The NSHT (Figure 3b) is constituted by a mono-mode optical fiber for communication embedded in a composite support material connected to an interrogation system (Figure 3c).

This NSHT can be remotely interrogated with different techniques (Brillouin scattering and Rayleigh backscattering), and each part of the fiber acts as a sensor. In static acquisition, a system including the NSHT is capable of continuously monitoring strains and temperatures along the transducer, covering 1 km up to 50 km with a spatial resolution of up to 20 cm and spatial sampling of 5 cm. In dynamic acquisition, it can monitor sections from 20 m to 100 m with a sampling frequency of 20 to 50 Hz and sub-centimeter spatial resolution and sampling. Applying NSHTs (described by the yellow line in Figure 3a) in adherence to the structures of buildings, tunnels, viaducts, and landslides (as a Smart Estenso Inclinometer), it is possible to continuously remotely monitor the strains induced and highlight in real time the occurrence of a failure (the strain peaks detected by the red curve in Figure 3a).

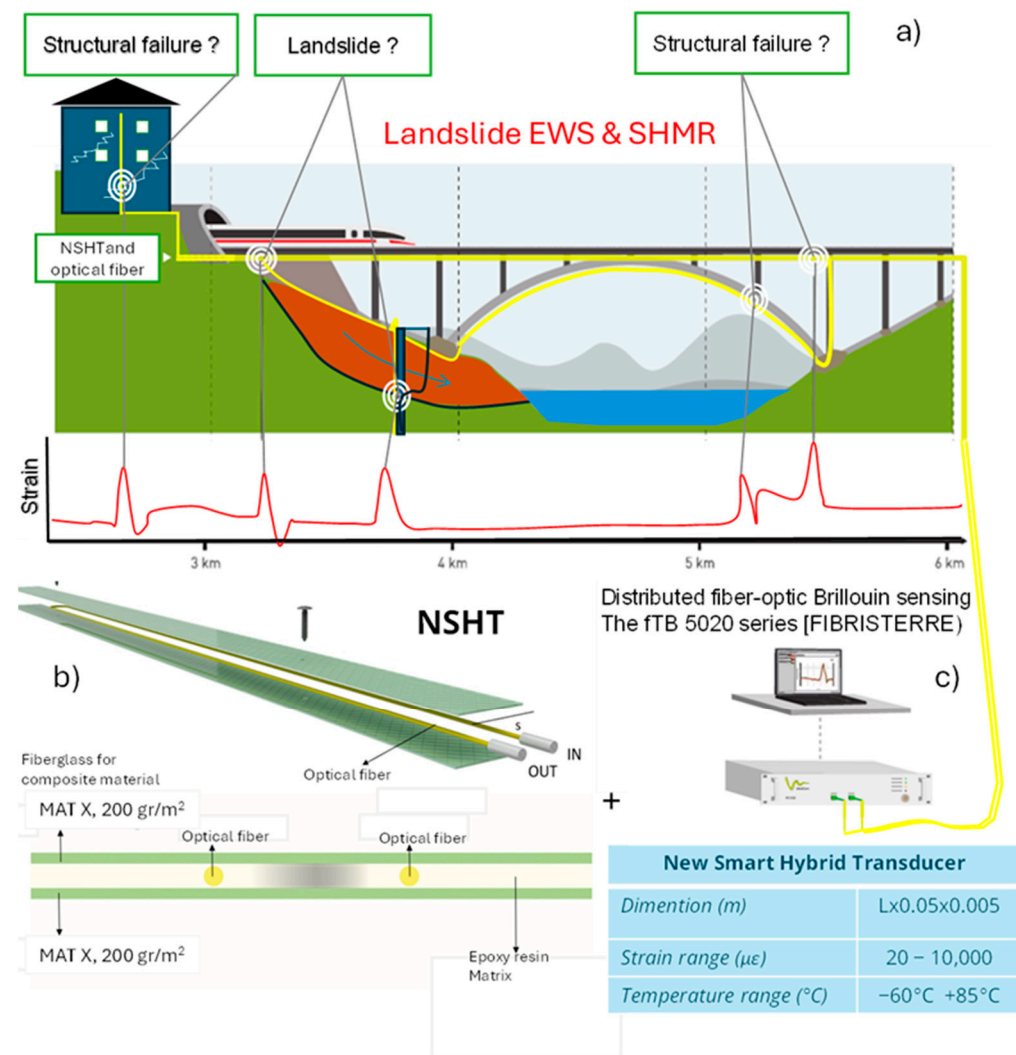


Figure 3. (a) Schematic representation of Landslide EWS and SHMR; (b) implementing the NSHT as a strain and temperature-distributed transducer; and (c) the interrogation system of FIBRISTERRE for optical fiber sensors.

As a final example, NSHT has been implemented by CUGRI (inter-University Consortium, named the Research Center for prevision prediction and prevention of the Great Risks) and Centola Municipality in the case of deep clay shales landslides as a smart estenso-inclinometer, with the complex monitoring system installed in Cilento Geopark (southern Italy) [37]. This complex monitoring system has been providing practically continuous information on weather and subsoil variables since 2021. This enables us to identify the link between rainfall, pore water pressure, the underground strain profiles of deposits, and the reactivation of landslides (Figure 4).

NSHT can be used in the static and dynamic fields, even to test wind turbine blades. Applications on pile foundations and bridge piers are ongoing. For further research, we suggest that NSHT might be used even to constantly monitor the strain of underground along very long distances (up to 50 km) (e.g., the monitoring of the effects of bradyseism such as that recently seen in Campi Flegrei, in southern Italy).

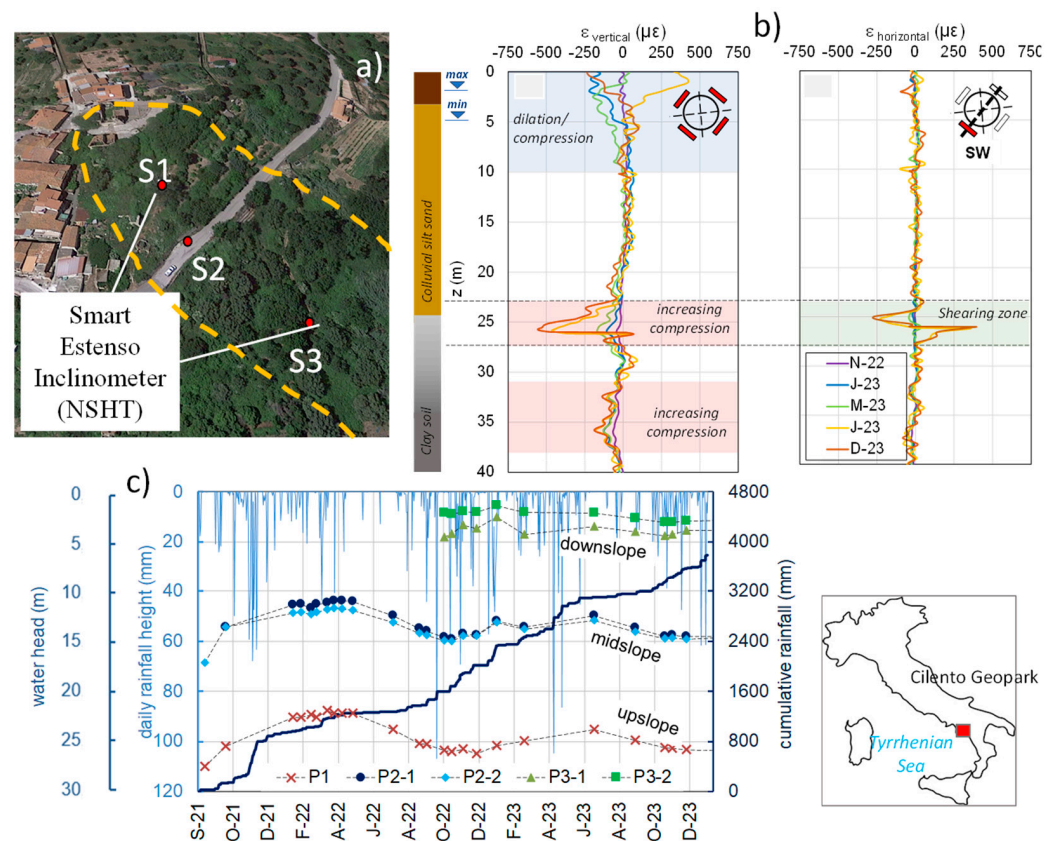


Figure 4. (a) San Nicola experimental field: location of the three monitored sites (S1, S2, and S3); (b) daily and cumulative rainfall and groundwater fluctuations at the three sites; and (c) identification of landslide activation by Smart Estenso Incliner strain profiles.

7. Conclusions

The current paper presents an interdisciplinary multi-stakeholder approach to NH risk management that exploits the expertise of meteorologists, geologists, engineers, and economists of public institutions such as universities, knowledge transfer management, interuniversity centers for prediction and prevention, municipalities, academic spinoffs, and enterprises.

The approach has proposed to leverage innovation technology both to enhance risk assessment and reduce uncertainty for landslides. The advanced modeling technique presented contributes to geographically circumscribe the areas eventually subjected to landslides and constantly monitor the vulnerability of their structures, infrastructures, economic activities, and hence population.

This helps bridge protection gaps, encouraging behavior towards risk, increasing the affordability of the policies, and increasing the capability of businesses to stay on the market, hence boosting socioeconomic resilience, financial stability, and long-term prosperity.

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