International Journal of Disaster Risk Reduction 84 (2023) 103440

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: www.elsevier.com/locate/ijdrr

Insights gained into geo-hydrological disaster management 25 years after the catastrophic landslides of 1998 in southern Italy

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ARTICLE INFO

Keywords:
Sarno
Landslide
Emergency response
Risk reduction
Prevention measures
Resilience

ABSTRACT

Understanding how natural processes may turn into disasters represents a key aspect to the implementation of effective risk reduction strategies. Within this framework, the current study aimed to document positive and negative experiences related to one of the deadliest landslide disasters in Italy, in which 160 people lost their lives, 115 were injured, and 1210 became homeless. The disaster took place on May 5, 1998, after nine days of continuous rainfall, in five towns of the Campania region (southern Italy) which were struck by hundreds of shallow landslides that evolved into rapid and extremely rapid debris/hyperconcentrated flows. Our analysis focused on the early response phase of the disaster, and highlighted numerous human shortcomings which amplified the impact on the population. The human loss was relatively contained by a reactive behavior of many citizens that as soon after the first flows, occurred in the afternoon of May 5, left their houses.We also provided a summary of non-structural prevention measures prompted by the disaster that were realized at the national scale during the next 23 years, together with useful findings for evaluating their effectiveness. Some criticisms affecting the policies in effect were also discussed. Information and examples reported in the current study may assist with the development and implementation of geo-hydrological risk mitigation strategies in other parts of the world, since landslide disasters similar to the one described in this article continue to occur worldwide.

1. Introduction

In disaster risk science, past events are often considered as lessons that can be more or less valuable, depending on our capacity to understand what they "say" to us [1] and on whether learning from them can be achieved which will endure at a societal level over time [2,3]. Each disaster provides experience that can inform and improve future performance in prevention and response activities, based on the assumption that analyzing positive and negative examples from past events (e.g. Ref. [4]) can help with learning and implementing changes that cope better with future events [5]. To enhance the resilience of communities, Leroy et al. [6] emphasized the importance of knowing, understanding, communicating, and learning lessons from past disasters at several scales, starting from individuals and families up to national governments. According to Hoffmann and Muttarak [7], educational activities can assist in strengthening communities, especially those with prior disaster experience. In such communities, narratives of events and storytelling by eyewitnesses and affected people provide valuable resources for enhancing public awareness and preparedness [8,9], as well as for verifying whether past experiences have been properly considered in the risk mitigation process [10].

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https://doi.org/10.1016/j.ijdrr.2022.103440
Received 19 June 2022; Received in revised form 7 November 2022; Accepted 8 November 2022
Available online 11 November 2022
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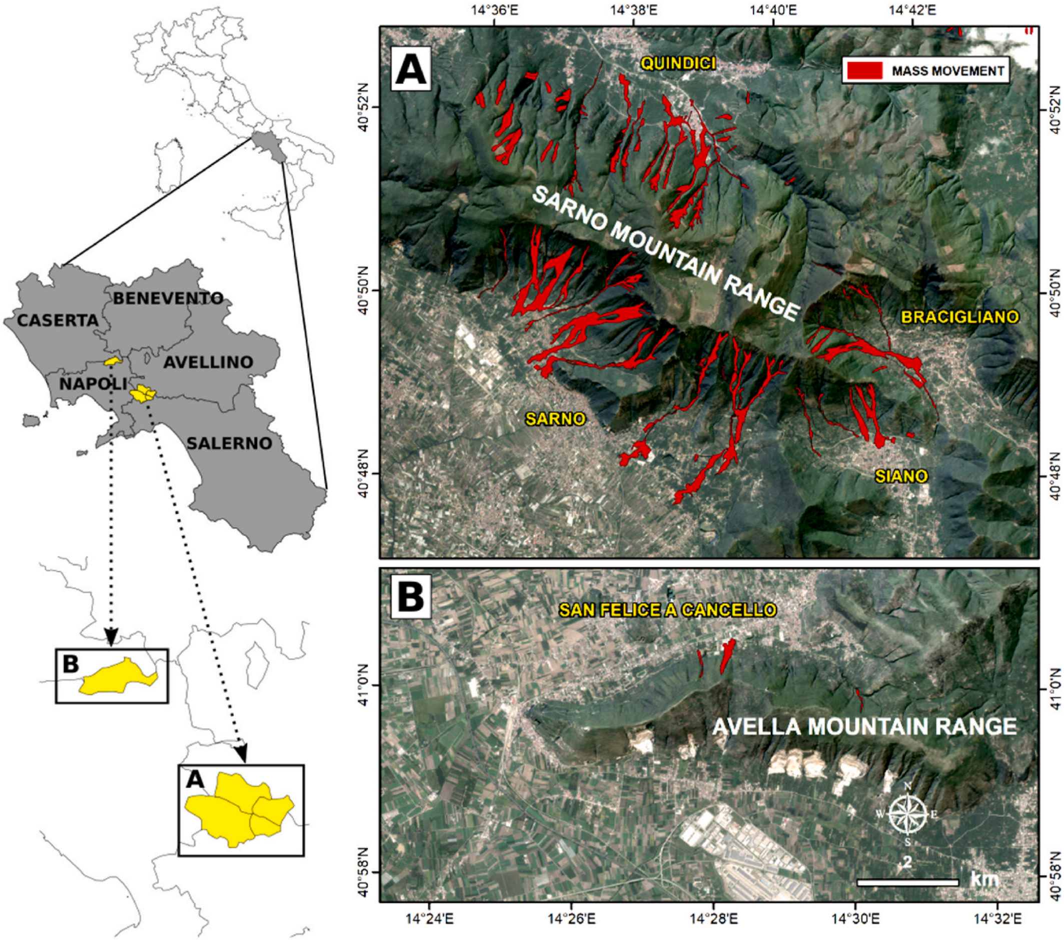
With specific reference to lessons learned from disasters caused by landslides, most literature focuses on specific aspects related to pre-event hazard and vulnerability conditions [11–14], as well as on risk perception developed in the aftermath of such events [15–19]. Besides this, research on response actions [20–24] deserves a particular interest for understanding how decision makers and citizens react during landslide events, helping identify which are the recurrent weak points that could result in human loss [25]. To speed up risk mitigation policies and resilience of communities to future scenarios, it is essential in fact to bridge the gap between scientific analysis of landslide disaster responses and human and societal behaviors, providing a transfer from research to practice [26]. This prompted us to perform a critical analysis of one of the deadliest landslide disasters in Italy, now approaching its 25th anniversary, by addressing the crucial aspects of the early response phase and the effectiveness of national scale measures and regulations established in the aftermath to reduce the human impact of future, similar events.

The analyzed disaster occurred over a 12 h period from the early afternoon of May 5, 1998 until the early morning of May 6. A large area of the Campania region (southern Italy) was struck by hundreds of rainfall-triggered shallow landslides that evolved into rapid debris/hyperconcentrated flows, which overwhelmed several neighborhoods in the towns of Bracigliano, Quindici, San Felice a Cancello, Sarno, and Siano (Fig. 1). During the event, 160 people lost their lives, 115 were injured, and 1210 became homeless, along with severe damage to buildings and economic activities totaling more than 30 million euros [27]. Starting on the May 6, the Italian



TOWN	MOUNTAIN RANGE	PREFECTURE	AREA (km²)	RESIDENTS (Istat 1991)	DENSITY (people/km²)
SAN FELICE A CANCELLO	AVELLA	CASERTA	27.2	16771	616.6
SIANO	SARNO	SALERNO	8.6	9265	1077.3
BRACIGLIANO	SARNO	SALERNO	14.4	5105	354.5
QUINDICI	SARNO	AVELLINO	24	3023	125.9
SARNO	SARNO	SALERNO	40	31509	787.7

Fig. 1. Location of the study sites (the gray and yellow colors highlight the Campania region and the affected towns, respectively, with the prefectures indicated by name), properties of the affected towns, and spatial distribution of mass movements during the 1998 disaster, as mapped by the Italian Landslide Inventory Project (IFFI, Inventario dei Fenomeni Franosi) available at: http://www.difesa.suolo.regione.campania.it/content/view/64/28/. Aerial images in the background were gathered from web map services available at: http://www.pcn.minambiente.it/mattm/en/view-service-wms/.

Department of Civil Protection required scientific support from the Italian research community to optimize the management of the emergency response phase [28]. This generated a significant improvement in existing knowledge of hillslope instability processes in this geographical area that, until 1998, was quite inadequate, although similar events have occurred through the centuries [29,30]. According to Guadagno et al. [31], more than 200 scientific articles focusing on the geological aspects of this event were published in journals and conference proceedings up to 2010. Further literature also refers to the societal and economic impacts of the event [32–34]. On the other hand, issues explaining how the disaster took place on May 5, 1998, and how it was managed, did not receive sufficient scientific attention. Providing responses to these questions is essential in understanding why this event resulted in such loss of lives and property for a developed country like Italy, and why the five towns were impacted so differently. Thus, this study describes a valuable learning experience with the intention of recognizing and preventing errors or shortcomings that generate disasters in urban settings hit by rapid geo-hydrological processes. Such deficiencies are still evident worldwide, as demonstrated by recent events in early 2022 (e.g., Petrópolis, Brazil).

Besides providing new insights about the 1998 disaster evolution and impacts, this study also aims to understand whether non-structural measures implemented at national scale in the period 1998–2021 are contributing to the geo-hydrological disaster risk reduction. For this purpose, the temporal variations of the average landslide and flood mortality rates were analyzed, and some critical key points which require further efforts and improvements were pointed out.

2. Description of the sites

The disaster described here occurred in a mountainous sector of the Southern Apennines, approximately 30 km east of the city of Naples. As shown in Fig. 1, the towns affected by disastrous mass movements were Bracigliano, Quindici, San Felice a Cancello, Sarno, and Siano, which fall under the administration of three separate prefectures (i.e., local branches of the central government). Sarno is the most populated town and has the largest territory [35]. In the 1970s and the first half of the 1980s, rapid and uncontrolled urban expansion took place in the foothills over areas exposed to high landslide and debris flow hazards.

From a geological point of view, all these towns are located at the base of mountain ranges (namely Sarno and Avella) formed by Mesozoic carbonate rocks that, since the late Quaternary, were repeatedly mantled by pyroclastic airfall deposits as a result of the explosive activity of the nearby Somma-Vesuvius volcanic complex [36,37]. The pyroclastic cover laid on the intensely fractured carbonate bedrock consists of alternating layers of pumice (with a grain size that is dominantly gravelly sand) and buried soil horizons (silty sand), which are characterized by different hydraulic and mechanical properties with negligible cohesion [38–41]. Accordingly, the shear strength of the cover is mostly controlled by matric suction [42].

The thickness of the pyroclastic cover is quite variable (4–7 m according to De Vita et al. [41]), becoming progressively thinner on the steepest slopes at the highest altitudes. Both the Sarno and Avella mountain ranges (highest altitude of about 1000 m a.s.l.) are characterized by steep slopes, with gradients in the order of 35°–50°. In the foothills, towns lie at altitudes varying between 30 and 250 m a.s.l., with slope gradients in the order of 5°–15°. Vegetation covering the two mountain ranges consists of woods formed mainly by deciduous chestnuts, oaks, and beeches, alternating with Mediterranean scrub, which is fed by a Mediterranean climate. This climate is characterized by hot, dry summers and moderately cool, rainy winters, with rainfall of approximately 1000 mm/year in the foothills, and 1400–1500 mm/year at the summits.

Historically, the described geo-environmental conditions characterizing both the study area and neighboring mountain ranges allowed the occurrence of shallow landslides that transformed into rapid flows downstream. Most events before 1998 resulted in severe damage and the loss of human lives, as reported by many studies [29,43–45].

3. The May 1998 landslide disaster

3.1. Characteristics of rainfall and mass movements

From a meteorological point of view, the disaster occurred at the end of the rainy season after nine days of continuous rainfall associated with a low-pressure system centered over the Tyrrhenian Sea [46]. On 4 and May 5, 1998, the system shifted towards the coast of the Campania region, resulting in more abundant orographically enhanced precipitation. During these two days, the rain gauge at Lauro (nearest to Quindici), the closest to the landslide initiation areas, recorded a total rainfall of 173.6 mm [47]. The rain gauge at Sarno recorded a total of 120 mm at the toe of the slope [48]. Several authors remarked that, on an annual scale, the overall rainfall of May 4 and 5 was not exceptional because it was characterized by a moderate return period and low intensity [30,46,49]. Cascini [28], however, argued that such rainfall was almost twice as much as the May average, and nine consecutive rainy days occurred only twice in the period 1917–1998, with much lower cumulative rainfall. Capparelli and Versace [49] also found that the monthly and maximum daily rainfall values observed in April and May 1998 were significantly higher than those recorded during 1967–1997.

This volume of rainwater was sufficient to increase infiltration that weakened the local stability conditions of the pyroclastic sediments by increasing pore-water pressure and reducing suction accordingly. Consequently, beginning on the afternoon of May 5, a series of shallow landslides occurred progressively at the highest altitudes (between 600 and 900 m a.s.l.). Most of the source areas corresponded to morphological discontinuities represented by natural scarps and road cuts, interrupting the spatial continuity of the pyroclastic deposits [47,50]. Both natural and man-made cuts were among the most important predisposing factors controlling the initial failures during both the 1998 and other similar events occurring in the region [51]. Morphological conditions also controlled the evolution of the instability processes downslope. In most cases, initial debris slides [52] evolved into debris avalanches [53] before being channelized into narrow gullies or channels, in which the mobilized mass transformed into rapid and extremely rapid debris or hyperconcentrated flows [48,50,52,54]. In addition to topography, this evolution was also controlled by the liquefaction of the displaced mass, a likely phenomenon in saturated granular deposits such as those mantling the carbonate massifs in the study region [55].

Velocities of flows in the foothills were estimated to be in the range of 5–20 m/s [56], with runout distances ranging from a few hundred meters to more than 2 km [57]. Many flows grew in volume during their propagation downstream because of the entrainment of additional material eroded from the channels, reaching total values estimated to be up to 500,000 m^3 in the Sarno area [58]. In the deposition zones (urbanized areas), the average height of the fronts of the flows was estimated as 6–8 m.

Overall, approximately 2,000,000 m^3 of pyroclastic sediments and carbonate rocks was displaced during the entire event [48].

3.2. The spatio-temporal distribution of phenomena and related impacts

This section was developed by means of a detailed analysis of the information collected from: 1) books and newspaper articles; 2) videos reporting stories of both affected people and rescue teams interviewed by journalists during and soon after the event; and, 3) political and legal proceedings. All the references related to the analyzed data sources were included within Appendix A.

3.2.1. Timeline of the distress phase

The first flows, which did not cause fatalities, were recorded on May 5, 1998 in the town of Quindici, between 12:00 and 12:30 p.m. [30]. Such preliminary phenomena induced the mayor to alert the Prefecture of Avellino to the need for additional rescue teams, and to warn the population by communicating the possible occurrence of further damaging flows in the afternoon, suggesting the evacuation of buildings at risk. This action was undertaken by the mayor together with first responders based on prompt observation of the critical situation in the field, in terms of damage and flow magnitude, as well as on the knowledge that similar processes had already occurred in Quindici and surrounding areas before 1998, with known human impact (e.g., in January 1997 [59]). Many residents followed the mayor's advice and evacuated their homes, whereas others decided to stay indoors.

At approximately 4:00 p.m. (Fig. 2), further flows overwhelmed Quindici, swamping some rescue vehicles intervened shortly before, and causing the first five deaths among people staying on the ground floor of the affected buildings. Consequently, the upstream part of the town, exposed at the highest risk of being affected by further flows, was inaccessible to relief teams, and several people remained trapped within their homes. At about the same time, other flows occurred in the town of Bracigliano causing the loss of six lives and several injuries, after which the mayor informed the prefecture of Salerno about the ongoing events. The town of Sarno was also affected by the first flows that interrupted some roads, without consequences for people.

Approximately 1 h later (i.e., 5:00 p.m.), rapid flows hit the town of Siano, overwhelming dozens of buildings and causing the death of four women staying on the ground floors of two buildings. A young girl staying on the upper floor of one of these buildings was rescued by relief teams many hours later. Between 5:00 and 5:30 p.m., a woman died in her house in the town of San Felice a Cancello as a consequence of the impact of one of the debris flows [60].

At around 6:00 p.m., further high-magnitude flows destroyed another part of Quindici, killing six more people, while another death occurred in Siano and three in Sarno. In the latter town, these first fatalities preceded a further 134 deaths which occurred later at three specific times: 8:00 p.m., 10:00 p.m., and 12:00 a.m. on May 6 (Fig. 2). The flows that occurred at approximately 8:00 p.m. caused 44 fatalities, those at 10:00 p.m. caused four fatalities, whereas the flows at about 12:00 a.m. on May 6 resulted in the major loss of 86 people, including those staying within a hospital (Figs. 3 and 4). Sarno was the town with the most damage and the highest number of fatalities (Table 1). Here, most of the bodies were found in collapsed buildings (e.g., Figs. 3 and 4) that were built since the 1970s. These buildings were close to artificial channels realized during the Bourbons' kingdom in the 16th century to convey water and sediments from the hillslopes towards dedicated basins downstream. During the 1998 event, these channels (as the one shown in Fig. 4) functioned as preferential paths for rapid flows to reach and overwhelm the urbanized areas. Decades of poor maintenance and an advanced state of abandonment resulted in the filling of many sections with sediments, vegetation, and waste. This had

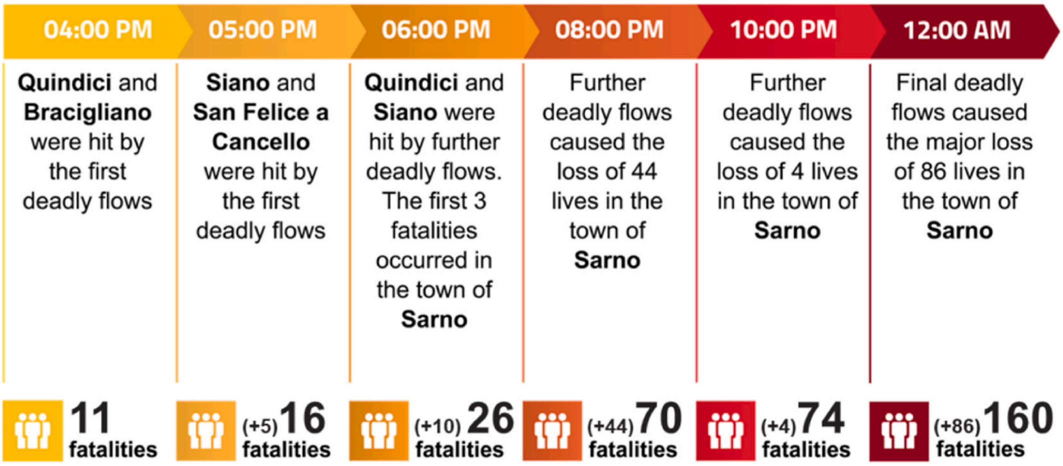


Fig. 2. Timeline showing evolution of the death toll on May 5, 1998. For each estimated time step, both the relative and cumulative numbers of fatalities are provided.

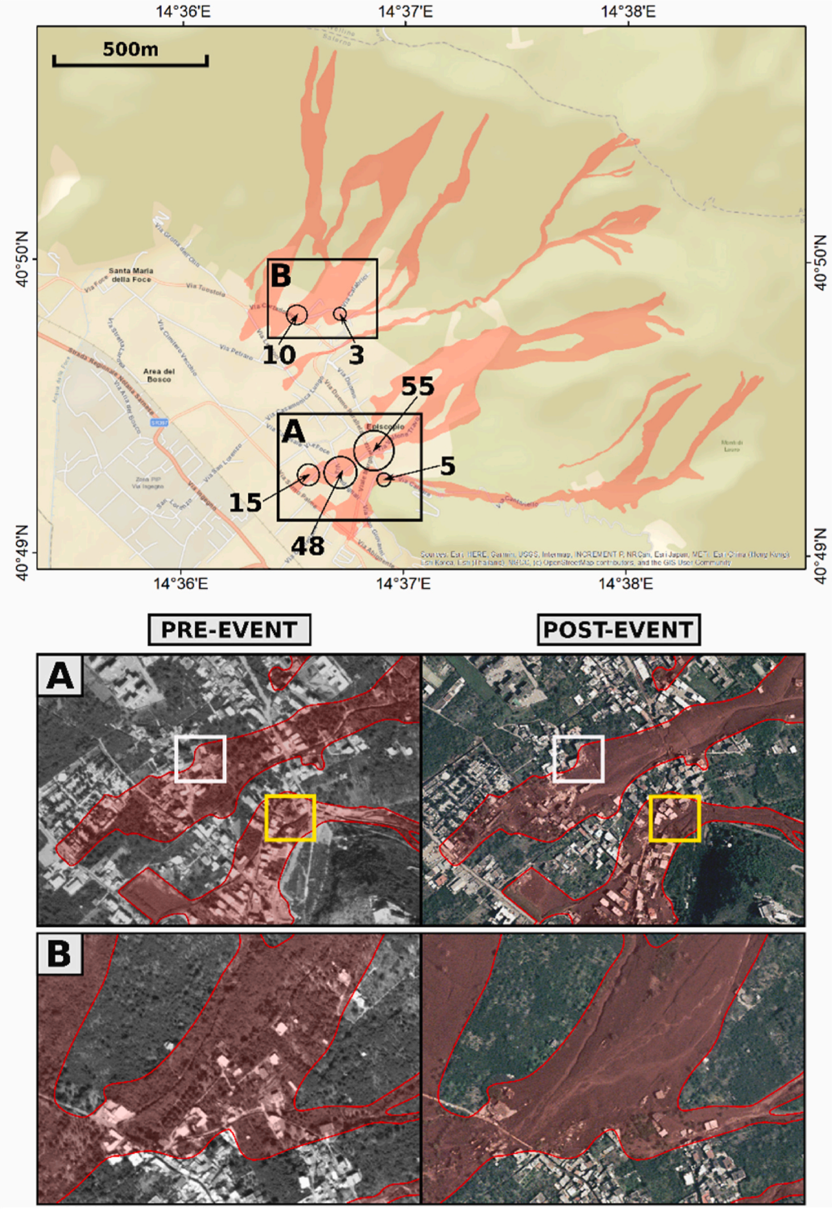


Fig. 3. The map shows the most damaged area of Sarno town. Red polygons represent the mass movements also displayed in Fig. 1; the numbers outside the circles indicate the death tolls corresponding to the affected zones. Rectangles A and B refer to the aerial images acquired before and after the disaster, shown in the panel below. Images on the left (pre-event) were taken in July 1988 whereas images on the right (post-event) were taken on May 9, 1998. Both datasets are available as a web map service at: http://www.pcn.minambiente.it/mattm/servizio-wms/. The white and yellow squares locate the position of the hospital and an artificial drainage channel, shown respectively in Fig. 4. The transparent shaded areas mark perimeters of the inundated zones in both pre- and post-event aerial images.

compromised their functionality, facilitating the spread of mud and debris in built-up areas.

3.2.2. Impact on people and economic damage

Overall, 160 people lost their lives during the 1998 disaster (Table 1); 88 (55%) were males and 72 (45%) females. A total of 57 fatalities were over 60 years old, while other age groups included children (20), teenagers (17), young adults (29), and adults (37) (Fig. 5).

According to healthcare authorities, in the town of Sarno, most people lost their lives as a consequence of suffocation caused by rapid burial beneath mud and debris (72%); 18% were affected by head trauma; 6% by injuries to internal organs, and 4% perished because of severe mutilation. Narratives from interviews given by survivors and rescue operators to local news agencies (Appendix A) enabled us to identify the circumstances which led to fatalities in terms of condition, context, or location [61]. Generally, the majority (119, 74%) died indoors at home or within other buildings (i.e., hospital or shops), whereas a few people (30, 19%) were dragged by

Fig. 4. Photographs showing the collapsed part of the hospital (left), and a building penetrated by mud and debris that overflowed from the abandoned drainage channel (right) (credits: www.vigilfuoco.it). Location of these buildings is indicated by squares in Fig. 3, according to the corresponding colors here displayed.

Table 1
Death tolls and displaced people in the affected towns [27].

TOWN	FATALITIES	DISPLACED
SAN FELICE A CANCELLO	1	84
SIANO	5	500
BRACIGLIANO	6	70
QUINDICI	11	120
SARNO	137	436

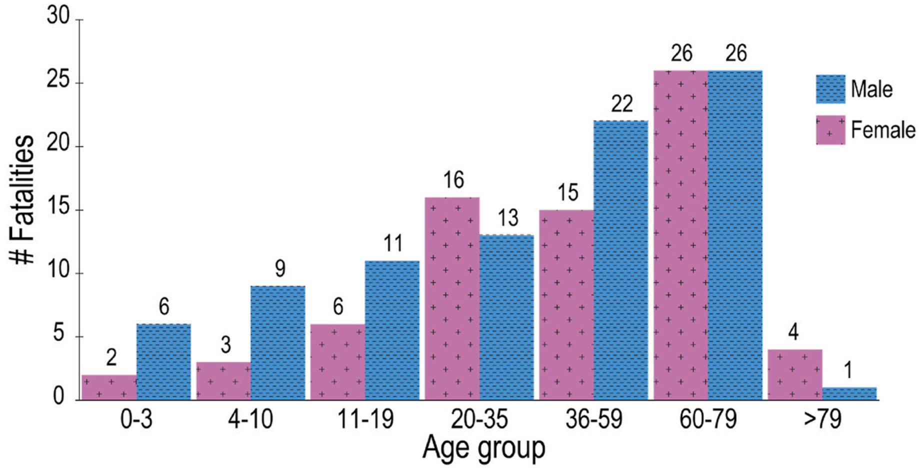


Fig. 5. Number of fatalities grouped by gender and age.

turbulent flows while they were outdoors, within the proximity of their homes or inside vehicles while attempting to escape (Fig. 6). For 11 people (7%), it was not possible to determine where they lost their lives. The data shown in Fig. 6 highlight that no gender differences were found among people who perished indoors, while people who died outdoors were mostly males because they also included some rescuers as well as men attempting to escape in vehicles.

Data from the Italian Department of Civil Protection related to the five towns [27] indicated that 154 buildings were completely destroyed, 397 were severely damaged to be inaccessible, and 126 were partially accessible. Economic damage to the houses was estimated at € 25.56 million, and the loss related to the manufacturing and industrial sector amounted to approximately € 8.52 million.

The magnitude of the event, and the dramatic consequences, marked it as exceptional in the long history of geo-hydrological disasters in Italy.

3.3. *Emergency response management and legal consequences*

Before describing how local authorities responded to the ongoing disaster on May 5, it is important to note that in 1998, technological knowledge in the field of landslide monitoring and early warning systems, as well as in civil protection organization and risk

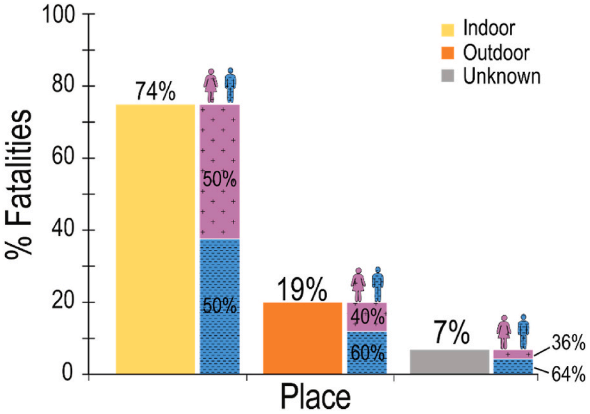


Fig. 6. Percentage of fatalities in the 1998 event calculated according to gender and location.

communication, were in their infancy in Italy. The Italian civil protection system was regulated by Law 225 (February 24, 1992), which established civil protection as a public service managed by central and local authorities, and operated by means of public corps (such as firefighters and police) and voluntary institutions. This law identified the mayor as the first responsible coordinator of civil protection at the municipal scale for all phases of the disaster management cycle. In case of emergencies involving multiple municipalities, management was the responsibility of the prefecture which had to coordinate the relief operations and find all the necessary resources to guarantee emergency response activities. In the case of emergencies requiring exceptional aid, these were provided and managed by the central government in collaboration with local authorities. Even though Law 225 introduced several novelties representing the backbone of the civil protection system, it was characterized also by a series of limitations that had to be overcome following the 1998 event, as described in the following sections.

With regard to the disaster, on May 2, 1998, the Italian Department of Civil Protection issued a weather warning at the synoptic scale, reporting the worsening of weather conditions, with intense rainfall and strong winds expected over the ensuing 72 h. Similar warnings were issued on May 3 and 4. It is important to note that in 1998, these warnings were based on meteorological forecasts performed at low spatial and temporal resolutions, without specific indications of possible geo-hydrological scenarios. Furthermore, they were shared with local authorities only and not publicly conveyed to citizens.

In the afternoon of May 5, 1998, the first flows interrupted road networks, power supplies, and communication systems, isolating entire neighborhoods that became inaccessible to rescue teams. These first phenomena, however, served as an “alert” for the population, and many people decided to leave their homes for safety. It is important to emphasize that this self-evacuation was not managed by local authorities but was mainly autonomous, with each person or household deciding whether to evacuate, where to go, and by which means. In the towns of Quindici, Siano, and Bracigliano, useful communication to encourage people to leave their homes was provided door-to-door and with megaphones by mayors, together with firefighters and police. Such efforts saved many people in these three towns before the occurrence of successive flows in the late afternoon of May 5, approximately two or 3 h after the first flows.

In the town of Sarno, the evolution of the disaster was quite different. The numerous flows affected a larger territory and occurred over a longer time span (8 h from 4:00 p.m. to 12:00 a.m.). In this interval, the flows hit the upstream settlements closest to the mountains first, whereas those located downstream were hit later in the evening. After the first flows, unlike in the other towns, the mayor recommended that citizens (about 5000 people) stay at home and not evacuate, since the main roads were invaded by flows and outdoor conditions were thus unsafe. As in the other towns, some people decided to stay at home, but many others escaped because of fear and personal awareness of similar but less impactful past events. According to the judges who analyzed the management of the disaster in the ensuing trial, the behavior of the Sarno Mayor was a clear indicator of general unpreparedness in managing the ongoing situation and promptly evacuation [62]. This led to his penal conviction in 2013 (15 years later) to 5 years in prison and interdiction from public office, for contributing to the death of 137 people, some of whom consisted of personnel and patients in the hospital (white square in Figs. 3 and 4) that collapsed at approximately 12:00 a.m. as a consequence of the impact of the final high-magnitude flows. Besides the Mayor of Sarno, the Italian Court of Appeal sentenced also the negligent behavior of the Prefecture of Salerno, for managing the emergency response with long delays in the provision of necessary aid to the three towns (i.e., Sarno, Siano, Bracigliano; Fig. 1). This resulted in a civil conviction for both the Minister of the Interior and Presidency of the Council of Ministers, represented locally by the Prefecture of Salerno. Neither the Prefect nor others in his staff were penally convicted.

4. Non-structural measures prompted by the disaster

In addition to countermeasures already in effect in 1998, the disaster prompted the Italian government to develop further non-structural measures to improve geo-hydrological risk reduction across the whole country. The strategy to consider mostly non-structural rather than structural measures was driven by the presence of many urban settlements in landslide- or flood-prone areas that could not be relocated or protected by means of structural interventions that required prohibitively expensive economic resources.

The first national-scale measure introduced after the 1998 disaster was Law 267, promulgated on August 3, 1998. Most of the actions established in this law had been anticipated in a previous law, 183/1989, which suffered from insufficient resources and delays due to a relatively novel risk prevention and protection framework [63]. This shortcoming prompted Law 267/1998 to be promulgated three months after the disaster. It consists of the following key points:

1) to map all areas prone to geo-hydrological hazards and to classify the urbanized territory according to four risk levels (i.e., from R1 “low” to R4 “very high”);
2) to provide guidelines and restrictions in terms of urban and territorial planning according to risk zoning;
3) to recruit technicians able to improve the efficiency of public administrations involved in environmental and civil protection at both national and regional levels;
4) to define criteria for relocating manufacturing activities and healthcare facilities built in areas at risk;
5) to assign the financial resources necessary to realize both these national activities and the first interventions in areas affected by the 1998 disaster.

As with many other regulations aimed at mitigating environmental risks in Italy, Law 267/1998 can be considered as “disaster-driven” because it was approved in a so-called window of opportunity for policy change created by the disaster [64]. This relates to a historical tendency to neglect prevention activities in the absence of large disasters until the next event raises the issue again. The implementation of actions provided in Law 267/1998 was, in fact, quite slow until the next disaster in 2000 which was a flood that killed 13 people in the Calabria region [65]; following this flood, the Italian government ratified Law 365/2000. This law accelerated the hazard and risk zoning established previously, and improved the rain gauge and radar networks for hydrological monitoring. Moreover, this law introduced the so-called functional multi-hazard centers (FMCs) that monitor weather and ground conditions constantly all year around. These centers were developed in almost all Italian regions to support local civil protection authorities in their decision-making processes and early warning procedures. As described by Martelloni et al. [66], the FMCs process environmental data in real time, so that the achievement of event-specific thresholds (e.g., rainfall and ground displacement for landslide risk) leads to the issuing of alerts calibrated on possible geo-hydrological scenarios. This allows mayors to be aware of the consequent risk and to take charge of predisposing necessary prevention measures (e.g., evacuation, roads closure) that will respond effectively to potential landslides and flooding processes. In these cases, mayors can alert the citizens with specific messages published on websites and social networks.

Besides this, Law 365/2000 identified a series of scientific institutions (e.g., universities and research centers) that can support civil protection in both risk management and emergency response through advancing knowledge and understanding of natural risks.

All these measures converged within the national alert system for geo-hydrological risk prevention, which was organized by means of the Decree of the Italian President of the Council of Ministers (DPCM) of February 27, 2004. This decree also clarified the procedures, roles, and responsibilities of all relevant authorities, and introduced the subdivision of Italian territory into alert zones [67], allowing the optimization of both hydrometeorological forecasts and warning operations.

In 2007, the European Commission provided inputs to improve the efforts devoted to geo-hydrological risk reduction, and introduced the EU Floods Directive (2007/60/EC). In Italy, the directive was implemented by means of Legislative Decree 49/2010. However, it is important to note that this European directive did not consider the risk of landslide and debris flows in mountain

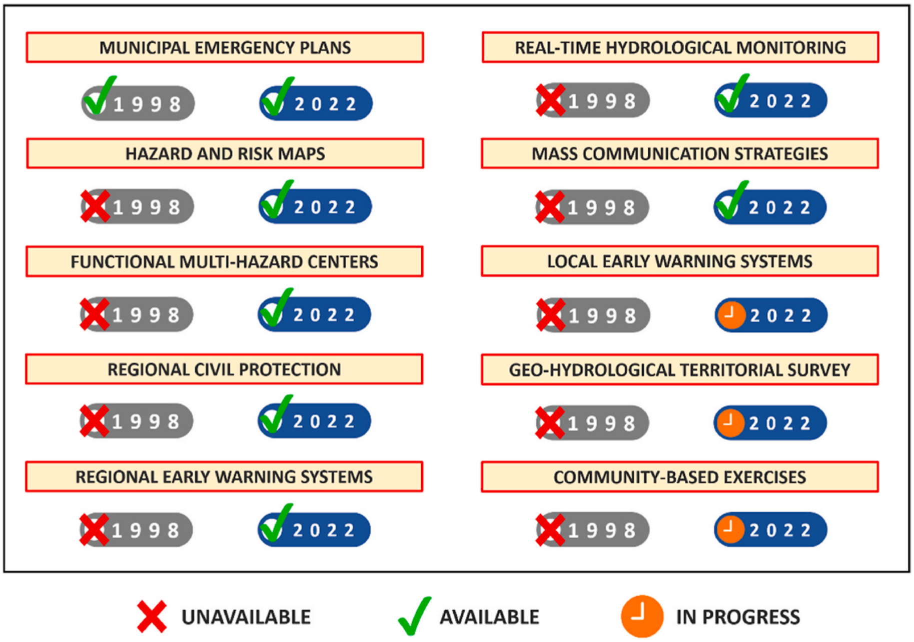


Fig. 7. Summary of non-structural measures aimed at reducing the geo-hydrological risk in Italy, comparing availability in 1998 and 2022.

torrents, leaving a legislative gap that has not yet been overcome.

In addition to all these measures related to geo-hydrological risk, it is important to underline that the 1998 disaster provided a significant catalyst for additional legislation dealing with the civil protection system. Specifically, remarkable advances were made in terms of emergency planning, risk communication, and community participation in the preparedness phase. The 2001 reform of Title V of the Italian Constitution (Constitutional Law 3/2001) was one such advance; this reform transferred all important functions of the civil protection organization from the state to the regional level. In this way, regional administrations became responsible for operational tasks related to both prevention and response activities, as well as taking responsibility for related financial resources. They also play a key role in supporting the mayors and municipal civil protection structures. This optimized the entire management chain, increasing the effectiveness of all operations within each phase of the disaster management cycle.

In 2018, Legislative Decree 1/2018 introduced the Civil Protection Code that improved Law 225/1992 and organized all related legislation enacted in the previous 20 years. This decree reiterates that all Italian municipalities must have operational emergency plans, with periodic updates, and that these plans should include public preparedness exercises. The participation of citizens in civil protection activities is an important aspect of the Code, because specific articles are devoted to the dissemination of civil protection culture and knowledge as well as to activities aimed at informing the population on how to prepare for risk scenarios.

The DPCM - April 30, 2021 was the most recent regulation aimed at improving the organization of the civil protection system at the national scale. Specifically, this decree provided guidelines on the contents of emergency planning, introducing a new operational scale consisting of a group of neighboring municipalities that cooperate by sharing healthcare facilities, firefighter stations, road connections, and other infrastructure and resources that may be essential during emergency responses. It is worth noting that this new scale was introduced to also manage prevention and preparedness activities aimed at reducing the impact of future natural or anthropogenic hazards.

Fig. 7 summarizes the main differences between the current situation (year 2022) and that in 1998 in terms of non-structural measures aimed at geo-hydrological risk prevention. The first point is represented by municipal emergency plans and is the only measure present in both 1998 and 2022. As mentioned previously, the emergency plans were improved over the years in terms of risk zoning, alert procedures and responsibilities, resources, communication systems, so that for this reason the more recent plans are more effective than those used in 1998. Further measures shown in the scheme in Fig. 7 include those ranging from hazard and risk assessment through to monitoring, up to communication strategies aimed at increasing risk awareness and public participation in disaster prevention. All improvements are supported by technological advances in prediction and monitoring activities, communication systems, and relief operations.

The last three measures shown in Fig. 7 (right hand column) are critical because, despite their relevance, they are still in progress. The early warning systems [68] operating at local scale, i.e., over a basin or a municipality, are common in areas already struck by disasters (see Refs. [69,70] and references therein) compared to the rest of Italy, where they are lacking. These systems should be coupled to geo-hydrological territorial surveys (i.e., multi-disciplinary teams of experts, such as geologists and engineers supporting authorities in risk management) that were introduced in the aftermath of the 1998 disaster [28,71]; however, thus far, few regional and municipal governments have set up these despite playing a significant role also during emergency responses. Training exercises involving citizens are relatively uncommon in all the country, even though such drills are among the most important tools for preparing people to face emergency situations and respond effectively with correctly behaviors [72–74].

5. Usefulness of the adopted measures for risk reduction

To evaluate whether the non-structural measures described previously have effectively contributed to reducing the geo-hydrological risk in Italy, we examined two experiences related to recent geo-hydrological events. These cover different spatial scales (i.e., municipal and regional), and refer to processes with magnitudes comparable to those recorded in previous events affecting the same areas but with more serious human consequences. In addition, we compared the mortality rates related to floods and landslides calculated in two time intervals (1976–1998 and 1999–2021).

5.1. Event 1: San Martino Valle Caudina (2019)

On December 21, 2019, mass movements similar to those that occurred in 1998 (described in section 3.1), occurred along the Partenio Mountain Range, located 18 km far from Quindici. At approximately 7.30 p.m. the town of San Martino Valle Caudina was hit by a debris flow triggered by a shallow landslide that mobilized 10,000 m^3 of pyroclastic deposits [75]. The landslide occurred after rainfall of about 280 mm in three days, supplying a flow that carried mud, boulders, and tree trunks within the stream crossing the town, blocking it, and causing heavy damage to roads and buildings close to the city hall [75]. The key points in terms of prevention and emergency management related to this event are as follows.

1) Alert issued: Before the event, on December 20, 2019 at 12:05 p.m., the regional authority of Civil Protection issued alert no. 067/2019 to all mayors and authorities involved in the civil protection system of the entire Campania Region (e.g., prefectures, firefighters, police, volunteers), declaring the possible occurrence of geo-hydrological processes with impacts on urban areas. Simultaneously, the alert was published on the Civil Protection website and disseminated through social networks. The alert was at level 2 on a severity scale ranging from 1 (low) to 3 (high), indicating that the loss of human life was possible. Level 2 was selected on the basis of rainfall estimates with meteorological models and rainfall observations from previous days and weeks, performed by the local FMC.

2) Emergency management: The event was managed by the mayor using a recent emergency plan ratified on July 25, 2018 by the town council and financed with funds from the regional administration.
3) Evacuation: The mayor issued a mandatory evacuation of 300 people just after the flow reached the urban center, before complete destruction of the road network and flooding of buildings caused by stream obstruction and the heavy rain which continued throughout the night.
4) Citizens' behavior: Citizens were already aware of possible flow processes impacting the urban center, since in 1999, there was a similar situation [76,77]. This facilitated the timely evacuation of residents through both autonomous and mayor-issued evacuation orders.

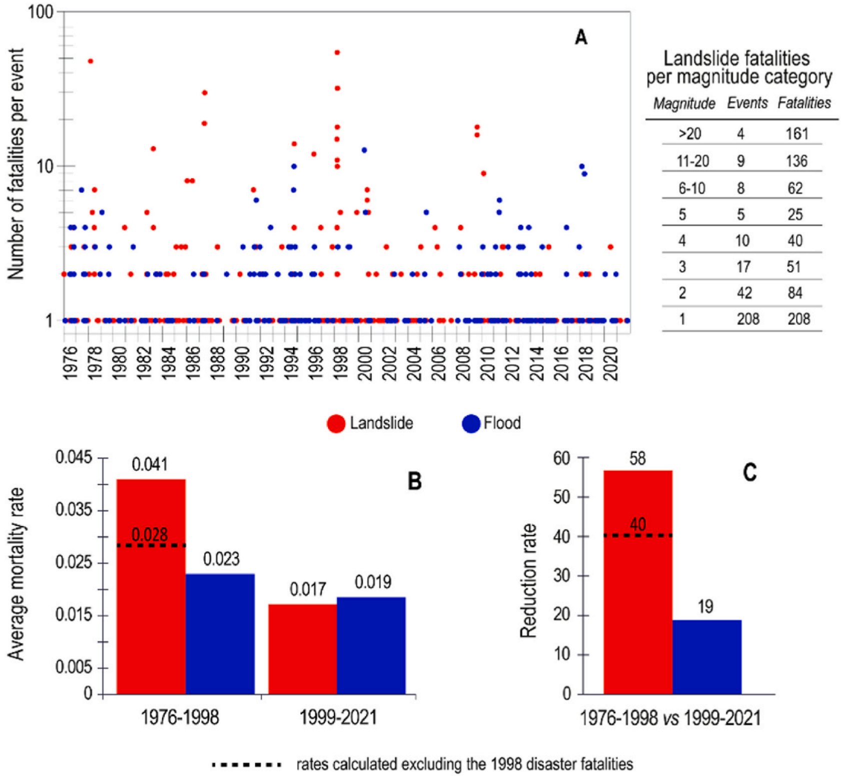
On the same day, other landslides hit mountainous areas close the town of San Martino Valle Caudina and the Amalfi coast causing serious damage to the road networks, but with little human consequence.

5.2. *Event 2: Piedmont (2020)*

On 2 and October 3, 2020, the north-western part of Italy and southern France were struck by Storm "Alex". Many rain gauges in the Piedmont Region recorded more than 50% of the average annual rainfall, with return periods higher than 200 years (with reference to durations of 12 and 24 h). At some stations, rainfall reached unprecedented amounts, quantified at almost 600 mm in 24 h [78]. In the past century, the Piedmont Region has been affected by several geo-hydrological disasters. The most important events occurred in 1994 and 2000, when 71 and 34 people lost their lives, respectively. A comparison between the rainfall properties of the 1994, 2000, and 2020 events performed by ARPA [78] showed that the 2020 event was characterized by the shortest duration and highest intensity. As a result, many urban centers were affected by devastating floods and landslides, which resulted in three fatalities in Italy.

The key points in terms of prevention and emergency management related to this event are as follows.

1) Alert issued: Before the event (on October 1, 2020), the regional authority of Civil Protection issued alert no. 275/2020 to all mayors and authorities involved in the civil protection system. In this case, the alert was at Level 2 for many parts of the Piedmont region. It was published on the Civil Protection website and disseminated via social networks.
2) Emergency management: Relevant support for emergency management was provided by the local FMC with real-time monitoring of meteorological systems, performed with weather radar and satellite observations, along with a dense network of sensors in the field (rain and stream gauges) to monitor hydrologic conditions in terms of soil saturation and flooding response of watersheds.



Landslide fatalities per magnitude category

Magnitude	*Events*	*Fatalities*
>20	4	161
11-20	9	136
6-10	8	62
5	5	25
4	10	40
3	17	51
2	42	84
1	208	208

Fig. 8. (A) Number of fatalities per flood (blue) and landslide (red) events during 1976–2021 reported by Salvati et al. [80,81]; the table on the right indicates the amount of landslide events and total fatalities per each magnitude category. The count of fatalities related to the 1998 disaster is split per single landslide process. (B) Average mortality rates, expressed as the number of fatalities per 100,000 people per year, associated with flood and landslide events during two selected time periods (1976–1998, 1999–2021). (C) Reduction of mortality rates as a percentage. The dashed lines indicate rates calculated without the 160 fatalities of the 1998 disaster.

These data were also used by the FMC to feed numerical models that were able to predict which sectors of the drainage network could have been affected by critical levels, reporting the approximate occurrence times and expected severity levels. Throughout the event, teams of volunteers and experts coordinated by the mayors monitored critical points in the field for prevention purposes (e.g., bridges, roads and settlements at risk).

3) Evacuation: Dispatches published on news websites and collected during the event reported that, in several urban centers of the region, mayors evacuated about 500 people.
4) Citizens' behavior: Citizens who had experienced the events of 1994 and 2000 [11,79] were already aware of the possibility that floods and landslides could impact urban centers. In addition, the exceedance of rainfall and stream level thresholds was shared frequently by the FMC with both local authorities and citizens through different communication systems, including social networks, SMS, and email. Probably, this led to many people to adopt self-protection behaviors (e.g., to avoid dangerous roads or to stay away from unstable slopes).

5.3. *Evolution of mortality rates*

The available data on landslide and flood fatalities in Italy [80–83] enabled some temporal trends to be portrayed. Fig. 8A shows the number of fatalities per event with reference to both landslides and floods occurred in the considered time span, such as 1976–2021.

On one hand, Fig. 8A shows that very low-magnitude events, with one fatality, occurred almost constantly over time; on the other hand, it is also evident a lack of high-magnitude (≥20 fatalities) landslide events after 1998.

Available data on landslide and flood fatalities per year, and information on the size of the population collected from national censuses, were used to calculate the annual mortality rates, defined here as the number of fatalities per 100,000 inhabitants per year [84,85]. The annual rates were then averaged according to two selected sub-periods, such as 1976–1998 and 1999–2021, to verify the potential occurrence of some remarkable differences in the average mortality rates across the 1998 disaster. In particular, average of the landslide mortality rate related to the sub-period 1976–1998 was calculated in two different ways: the first includes the 1998 disaster fatalities (160), whereas the second one excludes such fatalities to avoid a data skewness.

Fig. 8B shows the average mortality rates calculated for the two equal 23-year periods. Comparing the two periods, the average landslide mortality rate decreased from 0.041 to 0.017 (58%), whereas the flood mortality rate decreased from 0.023 to 0.019 (19%) as shown in Fig. 8C. The average landslide mortality rate calculated without fatalities of the 1998 disaster (reported with a dashed line in Fig. 8B) is equal to 0.028. The reduction rate (Fig. 8C), however, remains noteworthy (40%). This decreasing behavior is in line with previous findings that compared the landslide average mortality rates in different periods, starting from 1861, in different physiographic areas of Italy [86].

Therefore, these outcomes highlight as the progressive implementation of the described countermeasures was associated with a progressive reduction in flood and landslide mortality rates.

6. Discussion points

6.1. *Remarks about disaster management in the 1998 event*

The first point that deserves analysis is the combination of natural and human factors which led to a severe toll in terms of fatalities (i.e., 160) during the 1998 disaster. On the afternoon of May 5, 1998, the rapid occurrence of multiple mass movements caused an unprecedented disaster in all the affected towns, which was too complex to be managed by mayors and relief teams. Generally, in order to understand what this disaster "says" to us [1] and to extrapolate learnings useful for improving future prevention and response actions, we believe it is important to note a series of weak points which hampered emergency response across the entire area. All the following points were inferred from information reported in section 3 and a detailed analysis of the used data sources, including the legal proceedings listed in Appendix A. Weaknesses related to human factors are as follows: 1) lack of suitable scientific knowledge

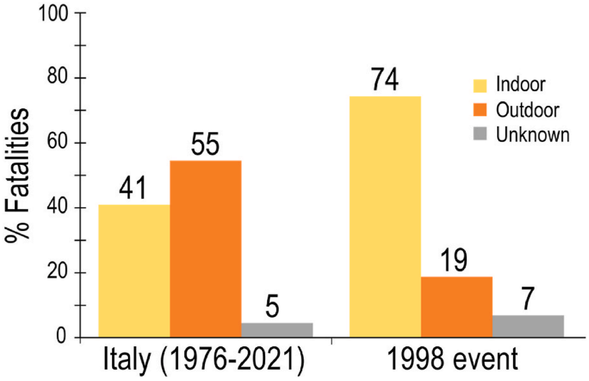


Fig. 9. Comparison between the percentage of fatalities caused by landslides in Italy during 1976–2021 [80,81], and those recorded in the 1998 event calculated according to the death place.

about landslides and debris flow phenomena in pyroclastic deposits; 2) lack of local experts supporting both municipalities and prefectures; 3) lack of efficient emergency plans; 4) unpreparedness among citizens and institutions; 5) errors in communication strategies; and 6) limited resources in terms of personnel and equipment to respond, as well as limitations in emergency communication systems. These human shortcomings should be coupled with natural factors, such as: 7) complex geological setting; 8) rapid progression of phenomena; 9) long runout of flows (i.e., more than 2 km) that impacted areas believed to be safe, interrupting some escape routes; and 10) low visibility due to electricity blackouts, heavy rain, and fog, which impeded the intervention of helicopters. In the smaller towns of Quindici, Bracigliano, and Siano, distress was partially controlled by the mayors with the support of firefighters and police, who facilitated the evacuation of many residents after the first flows, before the successive flows two to 3 h later. In the town of Sarno, after the first flows, the mayor recommended that citizens not to leave their houses. The different instructions and behavior, associated with the different geographical properties of the affected areas (Fig. 1), combined with the characteristics of mass movements, had an inevitable impact on the death toll recorded in each town (Table 1). In the town of Sarno, many people followed the mayor's advice to stay indoors; moreover, there was no mandatory evacuation order, leading to both doctors and patients remaining inside the hospital (Fig. 4), where they died at approximately 12:00 a.m. as a consequence of the final high-magnitude flows. The result was that 74% of the victims died indoors, in contrast with data at the national scale [87], which shows that most people (55%) who have died as a consequence of landslide and debris flow processes were outdoors (Fig. 9). The human loss affected mostly the elderly population, which was the most vulnerable due to physical difficulties in escaping or being evacuated quickly, as some of them were also disabled. This represents a paradox if one thinks that older people had more knowledge and experience of past events than the younger ones.

According to the judges who analyzed several stages of the event with the support of consultant geologists, if the Mayor of Sarno had issued a mandatory evacuation before 8:00 p.m., at least 100 people could have been saved. However, no one will ever know if a complete evacuation of at least 5000 people could have been performed with the available resources and in safe conditions before that time.

6.2. *Inferences for post-event measures*

The 1998 landslide disaster represents a benchmark for geo-hydrological risk reduction in Italy. The relevant impact on people and urban settings, as well as unprecedented legal consequences for local and central decision-makers, provided a strong motivation to understand how this risk could have been mitigated to avoid future disasters. As previously stated, several non-structural measures were promoted and actuated in the aftermath. More than twenty years were necessary (i.e., 1998–2021) to implement most of them because of the complexity of political decisions, recovery of economic resources [88], and limited interactions between central and local administrations. Among the completed measures, it is important to highlight all those activities aimed at assessing hazard and risk conditions throughout the country, as well as those that enabled the construction of an advanced civil protection system based on defined tasks and roles, providing the means to manage different natural hazards (e.g., volcanic processes and wildfires). Further measures are still in progress, particularly those involving citizens and local technicians (Fig. 7). It is thus important to note that participation of the public in various phases of the disaster management cycle is a difficult issue worldwide [89]. Achieving satisfactory levels of awareness and participation according to bottom-up approaches often depends on deep cultural changes and effective communication strategies that require time to change or develop fully. In Italy, information about natural risks and self-protection measures is provided mostly by the mass media, public meetings and campaigns, or scientific disclosures by research centers. On the other hand, training exercises are often carried out without citizens, providing them little opportunity to learn proper procedures through direct experience. This is crucial for educating people on how to react in case of an alert or ongoing event; the need for practical emergency drills is also recommended in the Priority 4 key point of the Sendai Framework [90]. Therefore, it is important to note that during the 1998 disaster, many people who were aware of the impact of past mass movements in the area, left their houses in a timely way and without hesitation, saving their lives. This circumstance indicates that knowledge is essential for adopting safety behaviors and increasing community resilience.

As shown in Section 5.3, data reported in the Italian catalogue of landslide and flood fatalities [80,81] highlight a considerable reduction in mortality rates after 1998, namely 58% (or 40% net of the 1998 disaster fatalities) and 19% for landslides and floods, respectively. This is in contrast with an increase in geo-hydrological processes documented only in some Italian regions thus far [91–93]. It is very likely that the non-structural measures implemented after 1998, as summarized in Fig. 7, are significantly contributing to reduce such rates. The recent events of San Martino Valle Caudina (2019) and Piedmont (2020), described in Section 5, demonstrated that these measures were applied successfully, reducing the severity of consequences in the affected communities. The decreasing in the number of fatalities and, consequently, in the mortality rates cannot be solely related with the adoption of non-structural mitigation measures, but also to the combination of multiple factors (e.g. socio-economic conditions, implementation of structural mitigation measures, improvement of construction techniques), and not last, variations in the triggering factors. Gariano and Guzzetti [94] and Rossi et al. [95] argued that the reduced trend of high-magnitude landslide impacts, as shown in Fig. 8, is largely due to improved monitoring and warning systems, risk zoning, enforcement of landslide mitigation strategies, and increased availability of information on landslides and their consequences. All of these measures have contributed to reducing the vulnerability of individuals and communities. However, it is worth considering that high-magnitude landslides often depend on other natural processes characterized by recurrence times in the order of centuries, such as specific meteorological conditions leading to long-lasting rainfall or severe earthquakes that can trigger seismic-induced landslides. The data in Fig. 8 also show that events characterized by only one fatality occurred almost constantly in the considered time span, and this trend was observed for both landslide and flood phenomena. As estimated by Rossi et al. [95], low magnitude landslides (i.e., those causing 1–2 fatalities) were expected with a low return period, and a consequently large temporal frequency, corresponding to a predicted average return period $T \leq 27$ years over a large area of Italy. At the same time, a high frequency of low magnitude flood events was documented by Salvati et al. [96]. Available information [80,85] emphasizes that most of these events are caused by (i) convective precipitation leading to shallow landslides, debris flows, and flash floods in small watersheds [97–99], as well as by (ii) localized rock failures, such as in the Italian Alps [100,101]. It is more likely that, besides non-structural measures listed before and financial resources spent by the Italian Government in the last decades to realize local structural interventions [88], death tolls associated with such low-magnitude events may be considered as part of a tolerable risk that the community is inclined to accept, since further reduction is currently not feasible with regard to the cost to the individual or public, or because the solution is impractical to implement; this is encapsulated by the 'as low as reasonably practicable' (ALARP) principle [102,103].

6.3. Future challenges

On a global scale, geo-hydrological events similar to the one described here, in terms of the type of mass movements and effects on the population, continue to occur with variable magnitudes and impacts. Among those that occurred in the recent past, it is important to highlight the following: 1) the event of July 3, 2021, in Atami (Japan), where 25 people died and two people remained missing [104]; 2) debris flows in 2010 that killed 42 people on Madeira Island [105]; and 3) lahars that occurred in 2009 along the northern flank of San Vicente Volcano (El Salvador), which inundated neighborhoods in five municipalities (Guadalupe, Verapaz, Tepetitán, San Cayetano Istepeque, and San Vicente), killing more than 250 people and destroying 130–200 homes [106]. In addition, during the writing of this paper, there was news footage documenting landslides and debris flows dragging vehicles and people in Petrópolis, Brazil [107] where, according to the authorities, more than 230 people have died (Fig. 10). Shortly before this event in Brazil, similar processes had affected the La Gasca suburb of Quito in Ecuador [108], with a death toll of approximately 30 people. In the early October 2022, almost a hundred people died in the Las Tejerías landslide disaster, in Venezuela.

All these events highlight that more efforts are still necessary to reduce risk conditions on a global scale. Worldwide, there are many urban settings with similar conditions as the five towns affected by the 1998 disaster (Fig. 10). According to the Sendai Framework [90], developing countries have the most severe risk conditions and suffer the highest mortality and economic losses. This was confirmed by several studies addressing fatal landslides and debris flows at global scale [109–112]. Many developing nations in fact do not possess adequate resources, capacity, or the necessary technical skills to carry out required landslide risk reduction measures [103]. International cooperation, already pursued by several programs and initiatives (e.g. Refs. [113–116]), should be a means to enhance the resilience of such communities. The Italian experience together with those of other developed countries (e.g., in Europe [117–120]) may offer effective opportunities to implement disaster risk reduction policies in the countries where these are still at the beginning stage.

At the national scale, due to hundreds of deadly geo-hydrological events that have occurred in the past, the Italian Civil Protection gathered relevant experience in emergency response and management, as well as developed both structural and non-structural measures for risk mitigation. However, some problems still need to be addressed to improve resilience across the entire country. Updating hazard maps and risk evaluations should be a primary concern, as highlighted by Donnini et al. [121], along with the implementation of monitoring and early warning systems at the municipal or basin scale. The latter, together with a geo-hydrological territorial survey, would have been useful during the event in San Martino Valle Caudina (Section 5.1) enabling evacuations before the impact of flows with the urban center, as well as in the disaster occurred on September 15, 2022 in the Marche region, during the writing of this paper, where many settlements were struck by landslides and flooding processes causing 13 fatalities. The lack of geo-hydrological territorial surveys in some Italian regions means that when civil protection authorities issue severe alerts, many urban areas are not monitored on the ground by experts who are able to detect hazardous situations early enough. Preparedness for response and recovery should also be strengthened by enhancing training activities that focus on self-protecting actions. Implementation of these measures should also be useful in reducing the mortality associated with small-scale events, as underlined in the previous section (Fig. 8).

With reference to the area struck by the 1998 disaster, in 2013 Calvello et al. [15] analyzed landslide risk perception in the town of

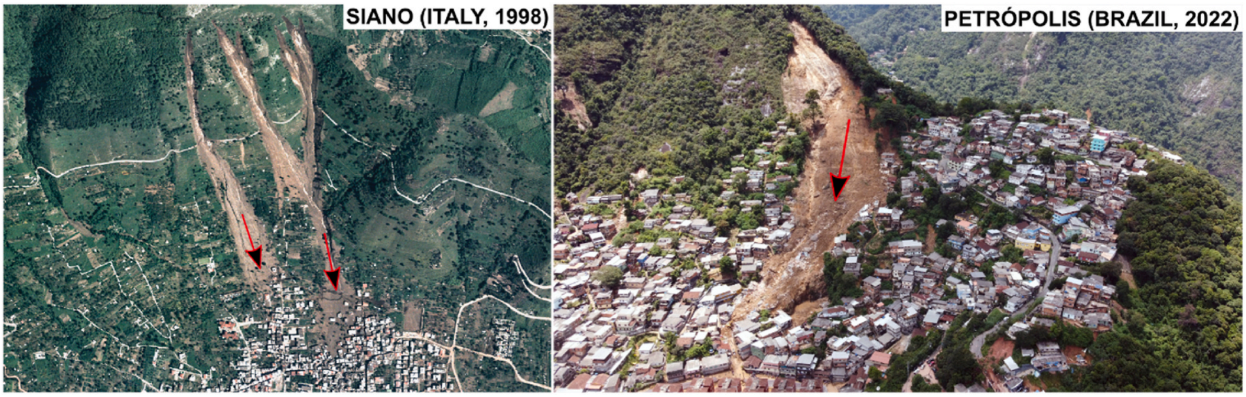


Fig. 10. Two aerial pictures representing similar landslide scours and damage within the urbanized areas of Siano (Italy, 1998; credits: http://www.pcn.minambiente.it/mattm/servizio-wms/) and Petrópolis (Brazil, 2022; credits: https://www.reuters.com/).

Sarno. They found that, despite the recent event, residents were relatively unaware of the existence of a residual risk, highlighting a clear lack of information. At the same time, residents demonstrated a wish to participate in risk management activities and to benefit from more reliable communication. The widespread participation of citizens in training exercises may help mitigate these situations, enhancing communication practices since, as underlined by Scolobig [62], shortcomings in risk and crisis communication can also lead to legal liability for disaster managers and public authorities, as evident after the 1998 event.

7. Conclusions

Analysis of disasters that have occurred in the past provides important knowledge for improving both prevention and response activities aimed at mitigating the impact of future events. Understanding both natural and human factors that can turn natural phenomena into disasters is essential for increasing societal awareness and implementing proper countermeasures to enhance the resilience of communities. In the light of this framework, this study provides an in-depth analysis of the landslide disaster that occurred in Southern Italy on May 5, 1998, resulting in 160 human losses, 115 injuries, and 1210 displacements. Specifically, the work focused on the management of the early response phase and any shortcomings, as well as on the effects of non-structural measures implemented at the national scale in the aftermath of the disaster over a time span of more than 20 years (i.e., 1998–2021). Key points from the study are listed below:

- A general unpreparedness and a lack of awareness among both decision-makers and citizens contributed to a severe death toll. However, the collected chronicles and storytelling demonstrated that people who *were* aware of past landslides in the area decided to evacuate after the first flows, saving their lives.
- The relevant losses and social impact of this event prompted the Italian government to implement a national program for geo-hydrological risk mitigation, mostly based on non-structural measures.
- According to data reported within the Italian catalogue of landslide and flood fatalities, during the time span 1999–2021 the mortality rates related to landslide events decreased at least 40%, compared with the previous time span 1976–1998. Mortality rates related to flood events decreased from 0.023 to 0.019 (19%). These figures suggest that non-structural measures effectively contributed to the reduction in fatalities after the 1998 event, as highlighted by the recent events of San Martino Valle Caudina (2019) and Piedmont (2020).
- The primary challenge to further enhance geo-hydrological risk mitigation in Italy is the participation of citizens in various phases of the disaster management cycle. This should be realized through effective communication strategies and training exercises aimed at improving self-protection measures, which should be useful during ongoing events when the intervention of rescue teams could be impeded, as demonstrated in the analyzed disaster.
- At the global scale, disasters like the one described here continue to be a issue (e.g., Petrópolis, Brazil, 2022), demonstrating that many urban settlements worldwide have similar conditions to the five Italian towns affected in 1998. Therefore, outcomes of this study may represent a reference for other countries that are planning to advance the geo-hydrological disaster risk reduction by implementing policies, strategies and coping capacities of local communities.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2022.103440.

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