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Exploring innovative techniques for damage control during natural disasters

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ABSTRACT

The study critically examines the principles, mechanisms, and effectiveness of different damage control techniques in dealing with natural disasters, emphasizing their pivotal role in minimizing casualties and economic losses. Each of these damage control techniques is mapped based on their applications and relevance in the key areas of natural disaster management. By utilizing various real-world instances, the present study shows that the effective implementation of various innovative techniques is shaping the space of natural disaster management in a global context. The integration of different innovative techniques into the existing natural disaster management system has improved the survival rate, economic performance, and sustainable development. The study finds that innovative disaster financing models, clear strategies, and creating awareness among communities can improve the overall efficiency of innovative techniques that are currently used for damage control during natural disaster events. Despite the substantial advantages of these creative strategies, the study acknowledges challenges such as financial constraints, unclear policy goals, and community adaptation requirements. The study also indicates that in the future, automatic damage restoration, quick prototyping, and additive engineering will play a vital role in controlling damage from catastrophic events, while it acknowledges limitations in temporal scope, generalizability, and financial constraints.

1. Introduction

Natural disasters inflict profound destruction [1], leaving enduring traces of injuries, fatalities, livestock loss, property damage, and economic harm long after their occurrence. According to Statista 2023,[1] in the year 2022, approximately 31,000 deaths occurred due to 421 natural disaster events worldwide. It causes a global economic loss of about 313 billion United States Dollars as estimated. Natural disaster events may result from different natural processes, such as earthquakes, hurricanes (storms), tsunamis, floods, droughts, landslides, heatwaves, volcanic eruptions, and wildfires. Numbers show that the impact of natural disasters varies widely in different countries globally. In 2022, the greatest number of natural disasters occurred in these five countries in sequence: the United States of America, Indonesia, Colombia, China, and Brazil. The greatest fatalities due to natural catastrophes during 2022 are heatwaves in Europe, drought in Uganda, and floods in India.[2] The Philippines, followed by India, topped the global disaster risk index of 2022. The impact of natural catastrophes results in a complex relationship between structural damages and society [2].

The timeline for the evolution of various control techniques for damage control during natural disasters is very interesting, as shown in Fig. 1. During the early 1950–1960 emergency response plans such as “duck and cover”[3] were used as civil defense tactics for fallout shelters and evacuation during nuclear emergencies. The establishment of earthquake-resistant structures was encouraged during 1970–1980, especially in seismically active regions [3]. In addition, hazard maps have been developed to identify flood- and landslide-prone areas for better land use planning and management [4]. In the 1990s, to enhance evacuation planning, real-time traffic flow models were introduced to reduce congestion [5]. During 2000, advanced technologies were used for better natural disaster management. Remote sensing [6], ICT (information and communication technology) [7], and drone technology

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1 https://www.statista.com/statistics/510952/number-of-deaths-from-natural-disasters-globally/ accessed on 04th July 2023
2 https://www.statista.com/statistics/273893/natural-disasters-claiming-the-most-fatalities/ accessed on 04th July 2023
3 https://www.britannica.com/topic/duck-and-cover accessed on 5th July 2023

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are used for rescue operations, damage assessment, and recovery [8]. Thereafter, a dominance in the use of technology for damage control during natural disasters has been observed [9]. Now artificial intelligence (AI) is heavily used for big data analysis to improve natural disaster management [10]. Then currently disruptive technology is also used for creating awareness and preparedness among communities through education and training for emergencies [11]. Since 1950, due to technological revolutions, early warning systems have continuously evolved for accuracy and coverage.

It is essential to explore various innovative techniques to control damage during natural catastrophic events due to several reasons as discussed below. First, life is important, and natural disasters often lead to significant losses of human, livestock, plants, organisms, and other entities' lifespans. The development and implementation of innovative techniques for damage control can minimize the number of casualties, and provide a shield of life expectancy [12]. These could include early warning systems, well-designed evacuation measures, and resilient infrastructure plans to withstand the impact of disasters. Second, the economic loss associated with natural disasters is very expensive [13]. It can cause widespread damage to residential, industrial, and agricultural zones respectively, and can take years to mend. Innovative damage control techniques can help minimize economic losses by realizing disaster-resistant construction techniques, active emergency response systems, and retrieval plans. Third, the development of advanced damage control techniques can foster disaster preparedness through extensive planning. It includes the creation of more advanced forecasting models, and the design of more realistic emergency protocols to address natural catastrophic events. More informed or prepared communities can respond more efficiently to any natural disasters, curtailing the number of casualties and decreasing overall economic damage [14].

In the quest for sustainable development goals, the implementation of innovative techniques for damage control during natural disasters has emerged as a crucial strategy [15,16]. These catastrophic events often underscore vulnerabilities in existing structures, presenting invaluable opportunities to integrate sustainable practices during the recovery process. This integration extends to the adoption of green structure designs and the incorporation of green energy innovations, aimed at mitigating the impacts of climate change and fostering environmental resilience. Furthermore, embracing technological innovation is imperative in the pursuit of reducing damage caused by natural catastrophes [9,17,18]. The continuous evolution of technology has led to efficient and cost-effective solutions that enhance disaster preparedness and response. For example, advanced monitoring systems, the creation of disaster-resistant structures fortified by state-of-the-art engineering, and the application of advanced data analytics together could help in predicting disasters and minimizing their impacts. It is essential to acknowledge that the exploration and advancement of such innovative techniques for disaster-related damage control extend their application beyond immediate disaster management. It also fosters technological modernization across various important other fields. Overall, it helps ensure the safety and well-being of communities in the face of natural disasters and simultaneously boosts overall progress in the community and economy. Therefore, delving into modern approaches for damage control during natural disasters is not only a way to reduce casualties and minimize economic losses but also a pathway to improve disaster preparedness, promote sustainability, and foster robust technological growth in the economy. The interconnected nature of these objectives accentuates the significance of ongoing research and rapid progress in the field by emphasizing its far-reaching impact on societal well-being and advancement.

Based on the above premises, the present study attempts to explore various innovative techniques for damage control during natural disasters. There are multiple contributions of this study to the existing literature. The primary objective is to identify and explore key innovative techniques for damage control during natural disasters. Then, label the key areas where innovative techniques can make a significant impact during natural disasters. It also discusses the possible integration of innovative techniques into existing disaster management contexts. Finally, this study provides an agenda for future studies. This article is divided into the following subsections: Literature review (Section 2), key innovative techniques for damage control (Section 3), and benefits and challenges (Section 4), and follows by the conclusion (Section 5).

2. Literature review

Among the traditional emergency response strategies, "duck and cover" civil defense has been well referenced in previous studies [19,20]. The "duck and cover" strategy goes well with natural disasters such as earthquakes and storms. It can provide limited protection from flying debris and structural collapse. However, it is not suitable for tackling massive destruction resulting from floods, wildfires, or hurricanes due to physical limitations [21]. During the 1970s, different guidelines were issued for the establishment of earthquake-resistant infrastructures, especially in the earthquake-prone zones, to minimize enormous casualties [3]. Thereafter, across the world, various studies have been conducted that confirm enhanced infrastructural design in buildings, and transportation is useful for withstanding earthquakes [22,23]. Moreover, studies have confirmed that good structural designs are necessary to minimize the impact of natural disasters [24].

Subsequently, hazard mapping techniques have been introduced to identify the risk-prone zones for floods, earthquakes, landslides, droughts, and other risky zones for risk assessments [4]. Hazard maps have certain advantages, such as providing useful information on potential risks as early warning systems and evacuation plans during emergencies [25,26]. Hazard maps are also helpful in decision-making and land use planning. Several studies have also highlighted its drawbacks, such as hazard maps are difficult to interpret, validations, and the danger of mapping multiple hazard maps [27,28]. To overcome the

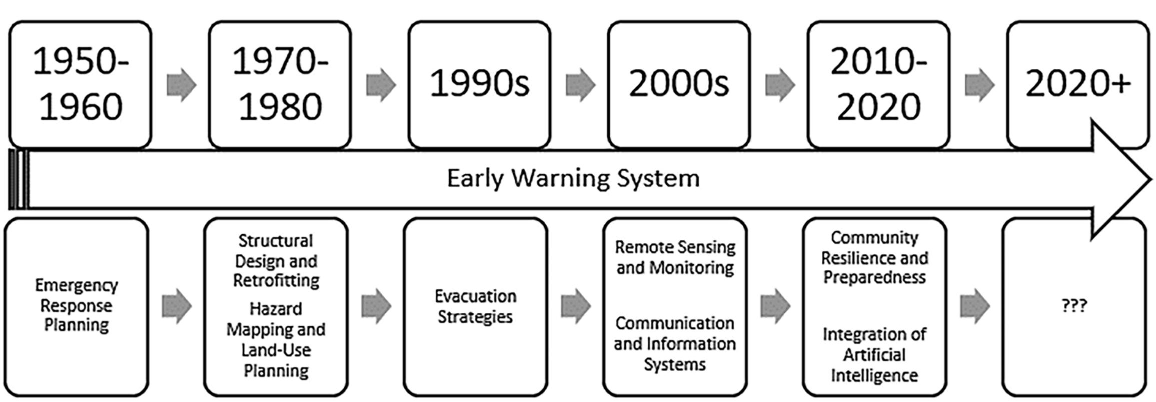

Fig. 1. Evolution of different control techniques for damage control during natural disasters.

obstacles associated with hazard maps, various advancements and innovations have been proposed, such as nature-based solutions [29], soft risk maps [30], analytic hierarchy processes [31], geographic information systems (GIS) [32,33], information technology [34], remote sensing [35], and satellite data [36,37]. Similarly, developments and inventions have occurred in emergency evacuation plans since the 1990s. To enhance transportation congestion and improve mobility during emergencies, various innovative real-time algorithms and digital twin models have been proposed [38–43].

Since the beginning of the twenty-first century, technological innovations have driven natural disaster management practices. Technologies like remote sensing and GIS disclose the crucial information obtained from spatial data. This includes complex information on catastrophic movement, environment, urban planning, land use, socio-economic, emergency relief resources, and others [44]. Although remote sensing and GIS are powerful technologies, they have several drawbacks, such as deficiencies in early fire detection and advanced image processing systems [45,46]. The issue associated with the application of remote sensing is the usage of light detection and ranging (LIDAR) to detect flood depths. The integration of remote sensing with GIS can achieve greater efficiency [33,35]. Similarly, the integration of social media with remote sensing data can yield better decisions for natural disaster management [47]. There is also a drawback in the application of remote sensing techniques in mountain hazard mapping [48] and information extraction in terrestrial biospheres [49]. A recent study shows that a combination of remote sensing and AI would be useful for real-time mapping of earthquake-induced building damage [50,51].

The advancement of ICT is a boom for rapid communication and coordination during natural disasters to reduce vulnerabilities [52]. It is helpful to extend relief and reach out to rural communities in response to natural catastrophes [53,54]. The combination of ICT and drone technology offers numerous utilities during natural disasters, such as surveillance [55], health care [56,57], logistics [58,59], security [60], and others. A recent study shows that the union of drone technology with AI could be useful for efficiently combating natural disasters in the future [61]. There is no doubt that the application of disruptive technologies has enhanced the overall process of prevailing natural disaster management [9]. Big data analytics and AI models are continuously improving the framework for natural disaster administration [10,51]. Big data analytics is useful in informed decision-making during emergencies [62,63], forecasting [64], and predictions of socioeconomic consequences [65]. Advanced AI models utilize data from various sources (geospatial, social media, and sensors), analyze the data, and provide more accurate information necessary for natural disaster management. Multi-lingual social media insights on natural disasters can be extracted from well-designed decision support systems with AI for comparison, analysis, and decision making [66–68]. Technology plays a vital role in transferring knowledge to create awareness, drill, and prepare communities for catastrophes to minimize fatalities [11]. Early warning systems (EWSs) have evolved since the 1950s. The EWS was initially designed to monitor earthquake activities to control damage. Due to technological advancements, more precise EWSs are currently available that utilize real-time data obtained from social media, IoT, sensors, remote sensing, and other mediums for decision-making [69]. Today, due to the boom of technologies, the automation of natural disaster management has become possible [70]. Thus, exploring innovative techniques for damage control during natural disasters can protect communities and build resilience. Table 1 highlights the key insights from the literature review.

3. Key innovative techniques for damage control

Due to the frequent occurrence of natural disasters, damage control in the face of natural disasters becomes a major concern for the state level and local level governments. The advent of various innovative techniques has significantly helped in mitigating or controlling the damage caused by natural disasters. Among the various innovative techniques, the most popular are drone technology [71], remote sensing and GIS [44], IoT [72], AI [67], 3D printing technology, self-healing materials [73,74], blockchain [75], digital twin models [76,77], and disasters financing [78,79]. These techniques have helped in a new era of disaster management by enabling state/local authorities to provide proactive and effective responses to natural disasters.

Table 1
Emerging trends in natural disaster management: key literature insights.

Trends	Description
Emergency Response Strategies	"Duck and cover" civil defense is effective in earthquakes and storms but has limitations in floods, wildfires, or hurricanes
Infrastructure Design for Earthquake Resistance	Guidelines since the 1970s emphasize earthquake-resistant infrastructure for minimized casualties
Hazard Mapping Techniques	Hazard mapping aids risk identification but faces challenges; proposed solutions include GIS, remote sensing, and nature-based solutions
Innovations in Emergency Evacuation Plans	Developments since the 1990s include real-time algorithms and digital twin models for improved mobility during emergencies
Technological Innovations in the 21st Century	Remote sensing, GIS, and AI enhance disaster mapping; challenges include early fire detection deficiencies, addressed by LIDAR integration and AI application
Information and Communication Technology (ICT) and Drones	ICT advancements and drone technology integration benefit communication, surveillance, healthcare, logistics, and security. Disruptive technologies, big data analytics, and AI models improve disaster administration
Evolution of Early Warning Systems (EWS)	EWS, evolving since the 1950s, now utilizes real-time data from various sources for precise decision-making and automation in disaster management
Innovative Techniques for Damage Control	The application of innovative techniques protects communities, builds resilience, and leverages automation for efficient response and recovery

Source: Authors' own analysis.

For example, drone technology and remote sensing, combined with GIS, have emerged as powerful tools for real-time information gathering and mapping in disaster-affected areas [80–82]. Nowadays, Drones are equipped with advanced cameras and sensors, which help in rapidly surveying large regions [83]. This process aids in damage assessment, survivor location, hazard identification, etc. Furthermore, remote sensing integrated with GIS could enable the mapping of affected areas, assessment of damage, and identification of vulnerable regions, thereby supporting decision-making processes [44]. In addition, low Earth orbit (LEO) satellites provide global coverage by generating high-resolution images and supplying near real-time data [46,84]. It also provides weather information and communication channels that could enhance situational awareness and global coordination, thereby improving disaster response efforts. Additionally, digital twin models also facilitate real-time monitoring, simulation, and analysis of disaster-affected areas, which aids in impact assessment, response strategy testing, and recovery optimization [76,77].

IoT plays an important role in disaster management. It interconnects devices and systems, thereby, enabling the collection and sharing of critical data. IoT devices can also monitor environmental conditions, infrastructure stability, and emergency response systems [85]. This allows for the development of early warning systems, optimized evacuation processes, and, most importantly, efficient resource allocation. Additionally, AI can analyze vast amounts of real-time data to support faster decision-making processes in disaster management. AI algorithms help in predicting disaster paths, simulating scenarios, optimizing resource allocation and providing real-time assistance [86]. It could also automate any process and thereby help streamline logistics, reducing response time, and enhancing the efficiency of emergency services.

In addition to the aforementioned advancements, other cutting-edge technologies, such as 3D printing, are emerging as transformative tools in disaster response and recovery efforts. The inherent rapid and flexible manufacturing capabilities of 3D printing provide a revolutionary approach to producing critical items swiftly and efficiently. This technology proves invaluable in the creation of emergency shelters and essential medical supplies by leveraging digital designs [87]. The ability to rapidly deploy these items in the aftermath of a disaster contributes significantly to addressing immediate needs, ensuring that affected communities have access to shelter and medical resources promptly. Furthermore, the integration of self-healing materials represents a remarkable stride in mitigating the long-term effects of disasters due to their unique ability to automatically repair damage caused by disasters, thereby enhancing structural resilience over time. Moreover, the self-healing properties of these materials contribute to sustainable solutions to the challenges posed by natural disasters by autonomously repairing damage and therefore increasing the durability and longevity of the built infrastructure. Self-healing materials accelerate the entire process of recovery and reconstruction by reducing ongoing maintenance requirements and the assurance of the built environment's durability. Furthermore, these materials work with 3D printing to create durable buildings that can withstand time and self-repair after natural disasters. 3D printing speeds up the manufacturing of essential devices such as emergency shelters and medical supplies. Consequently, the utilization of contemporary technologies such as 3D printing and self-healing materials amplifies the efficiency and effectiveness of overall disaster response and recovery efforts and fosters sustainable and resilient communities in the long run. As these technologies continue to advance rapidly, their widespread adoption in disaster-prone regions may redefine the landscape of disaster preparedness and post-disaster recovery and thereby contribute to building more robust and adaptive societies.

In the context of disaster management, the integration of blockchain technology is crucial because it brings transparency and increases efficiency to the management of relief funds, supply chains, and aid distribution [75]. The decentralized and tamper-resistant ledger system of blockchain ensures that every transaction related to relief efforts is recorded transparently and securely and thereby, minimizes the risk of fraud, and fosters trust among stakeholders such as donors, relief organizations, and the affected communities. The immutable nature of blockchain technology helps in tracing the allocation and utilization of relief funds and thereby creates a level of accountability in crucial crisis times. Furthermore, innovative financing mechanisms have also emerged as major contributors to effective disaster management. For instance, financial tools such as microinsurance and catastrophe bonds make it easier to shift risks to the financial market and guarantee quick access to recovery money [78]. For areas impacted by predetermined disasters, catastrophe bonds particularly work as a form of disaster insurance, proactively guaranteeing the availability of financial resources in the wake of the event. In addition to ensuring that finances are available during disasters, this proactive financial strategy expedites the entire response and recovery process. Additionally, microinsurance, a specially designed insurance product to meet the needs and risks of small communities, helps to lessen the financial impact of calamities and thereby promotes community resilience and expedites recovery by distributing risk and financial obligation. Together, these tactics and technologies have the power to completely transform disaster management techniques, resulting in more responsive, transparent, and resilient systems that benefit people worldwide. When combined, these cutting-edge techniques have completely changed the way that disasters are managed and have been instrumental in reducing damage caused by natural disasters. They have empowered stakeholders with timely information, optimized response strategies, efficient resource allocation, and long-term recovery and resilience. We discuss the principles, mechanisms, and effectiveness of each technique in Table 2.

3.1. Key disaster management areas and application of these techniques

The current study undertakes a comprehensive categorization of innovative techniques in disaster management, presenting a summarized overview in Table 3. Disaster management encompasses pivotal areas crucial for the effective response and mitigation of natural calamities, including early warning systems, resilient infrastructure, evacuation procedures, disaster preparedness/planning, search and rescue operations, communication and connectivity, data analytics and decision support, postdisaster recovery and reconstruction, community resilience and empowerment, and sustainability goals [88,89]. In subsequent sections, the article meticulously examines each domain, elucidating how cutting-edge technologies, such as drone technology, remote sensing and GIS, IoT, AI, 3D printing technology, self-healing materials, blockchain, digital twin models, and disaster financing, can be strategically employed to enhance disaster management efforts. By harnessing the power of these cutting-edge technologies, disaster management can be revolutionized, resulting in more resilient, sustainable, and safer communities in the face of natural disasters [90].

Early warning systems, which are critical for damage control, benefit from the real-time information gathered by drone technology and the mapping capabilities of remote sensing and GIS technologies [91]. LEO satellites further contribute by providing communication channels and high-resolution imagery, enhancing early warning capabilities [92]. Resilient infrastructure relies on 3D printing for rapid on-site production of essential components, reducing the risks associated with external supply chains, while self-healing materials automatically repair infrastructure damage, ensuring durability with minimal human intervention [93–95].

Efficient evacuation procedures leverage drones for situation assessment and route identification, IoT devices for monitoring conditions, and AI algorithms for route optimization and automated decision-making [96–98]. Disaster preparedness and planning rely on remote sensing, GIS, and AI for data collection, analysis, and informed decision-making, with blockchain ensuring transparency and efficiency and digital twin models optimizing response strategies [99,100]. Search and rescue operations benefit from drones' real-time visual data, complemented by the mapping and identification capabilities of remote sensing, GIS, and AI [101,102].

Communication and connectivity during disaster response and recovery are ensured by LEO satellites, IoT devices, and blockchain technology for global communication, data sharing, and secure and transparent communication, respectively [103,104]. Data analytics and decision support rely on remote sensing, GIS, and AI for geospatial data analysis, while digital twin models provide real-time monitoring and analysis throughout the disaster management process [67,99,105]. Post-disaster recovery and reconstruction are expedited by 3D printing technology, which is supported by blockchain for resource allocation and financial transactions, and digital twin models for monitoring and optimizing recovery processes [106,107]. Community resilience and empowerment are bolstered by digital twin models and blockchain, which enhance community preparedness through real-time monitoring and secure digital identities for seamless access to aid and resources [106,107]. Sustainability goals are supported by drone technology and IoT devices, offering essential environmental impact data, while 3D printing and self-healing materials promote sustainable practices by reducing waste and reliance on external supply chains [108–109].

Therefore, the integration of these innovative techniques has revolutionized disaster management, facilitating efficient responses, fostering resilience, and aligning with sustainability goals. The real-time data and insights provided by these technologies enhance situational awareness, enabling better coordination among response teams and stakeholders. As technology evolves, there is potential for further refinement and expansion of these techniques, which is promising for

Table 2
Principles, mechanisms, and effectiveness of each technique.

Technology	Principles	Mechanisms	Effectiveness
Drone Technology	Unmanned aerial vehicles (UAVs) equipped with cameras and sensors	Real-time visual data, damage assessment, search, and rescue	Situational awareness, mapping, resource allocation
Remote Sensing and GIS	Data collection, GIS integration	Mapping, damage assessment, decision-making	Mapping affected areas, vulnerability assessment, decision-making
LEO Satellites	Low Earth Orbit, global coverage	Real-time data, imagery, and communication capabilities	Situational awareness, global coordination, data acquisition
Internet of Things (IoT)	Interconnected devices, data collection and sharing	Environmental monitoring, data-driven decision-making	Early warning systems, optimized evacuation, resource allocation
Artificial Intelligence (AI)	Data analysis, prediction, automation	Data analysis, scenario simulation, and decision support	Predicting disasters, optimizing resource allocation
3D Printing Technology	Additive manufacturing, rapid prototyping	On-demand production, customized solutions	Rapid production, localized resilience, reduced logistical challenges
Self-healing Materials	Automatic damage repair, enhanced resilience	Self-repair, durability improvement	Maintaining structural integrity, long-term cost savings
Blockchain	Decentralized and transparent ledger technology	Transparent transactions, data sharing, accountability	Efficient resource management, secure transactions
Digital Twin Models	Virtual replicas, real-time monitoring	Monitoring, simulation, recovery optimization	Real-time monitoring, optimized response strategies
Disasters Financing	Innovative financial mechanisms	Catastrophe bonds, microinsurance, risk-sharing	Timely funding, financial resilience, post-disaster recovery

Source: Authors' own analysis.

Table 3
Significant impact areas: innovative techniques for natural disaster management.

Key Areas	Drone Technology	Remote Sensing & GIS	LEO Satellites	IoT	AI	3D Printing Technology	Self-healing Materials	Blockchain	Digital Twin Models	Disasters Financing
Early Warning Systems	✓	✓	✓	✓	✓					
Resilient Infrastructure						✓	✓			
Evacuation Procedures	✓			✓	✓					
Disaster Preparedness/ Planning		✓			✓			✓	✓	
Search and Rescue Operations	✓	✓			✓					
Communication & Connectivity			✓	✓				✓		
Data Analytics & Decision Support		✓			✓				✓	
Post-Disaster Recovery & Reconstruction						✓	✓			✓
Community Resilience & Empowerment								✓	✓	✓
Sustainability Goals	✓			✓		✓	✓			✓

Source: Authors' own analysis.

unlocking greater capabilities for disaster resilience and recovery. The continuous advancement and integration of these technologies holds promise for creating more resilient and safer communities in the face of future natural disasters.

3.2. *Case studies to highlight the successful implementation of innovative techniques*

In Table 4, we present case studies and real-world examples that highlight the successful implementation of innovative techniques in disaster management. These use cases demonstrate how drone technology, remote sensing, GIS, IoT, AI, 3D printing technology, self-healing materials, blockchain, digital twin models, and disaster financing are being used in real-world scenarios. We present these case studies in tabular format to provide a clear and organized summary, showing how each technology has been applied to improve disaster response, resilience, and sustainability in diverse real-world circumstances. These case studies demonstrate how these cutting-edge solutions can successfully reduce the effects of natural disasters and improve disaster management procedures.

4. Benefits and challenges

4.1. *Potential benefits*

Embracing state-of-the-art methods in catastrophe management holds a multitude of potential advantages, each playing a crucial role in fortifying disaster response capabilities. Drone technology, for instance, empowers first responders with swift assessments and precise mapping of affected areas, significantly enhancing overall safety measures. The integration of remote sensing and GIS with LEO satellites further amplifies these benefits, providing real-time information crucial for informed decision-making [44,84]. The IoT takes disaster management a step further by enabling real-time monitoring of environmental conditions, resource distribution, and infrastructure stability, thereby facilitating proactive response actions and bolstering community resilience [110].

In the realm of data analysis, AI algorithms and automation play a pivotal role. These technologies sift through vast datasets, offering decision support and optimizing resource allocation. The predictive capabilities of AI, particularly in forecasting disaster paths and intensity, streamline operational procedures and significantly enhance response efficiency [111–113]. Additionally, the on-site manufacturing

Table 4
Case studies that describe the successful implementation of these advanced techniques.

Technology	Description
Drone Technology	In the aftermath of Hurricane Harvey in 2017, drones were used for damage assessment and search and rescue operations. Real-time aerial imagery provided by drones aided in identifying trapped individuals and assessing the extent of the disaster, expediting response efforts.
Remote Sensing and GIS	During the 2018 Camp Fire in California, remote sensing and GIS played a vital role in mapping and assessing the fire's impact. High-resolution imagery from LEO satellites and other remote sensing platforms helped identify burned areas, damaged infrastructure, and affected communities.
Internet of Things (IoT)	In Barcelona, Spain, an IoT-based early warning system was implemented to monitor the structural health of buildings during seismic events. Real-time data collected from sensors embedded in buildings enabled authorities to assess structural integrity, make informed evacuation decisions, and prioritize emergency response.
Artificial Intelligence (AI)	AI-powered algorithms and automation in flood forecasting and response have been successful in the Netherlands. AI analyzes weather data, water levels, and historical flood patterns to predict and automate flood response measures, enabling timely warnings, activation of flood control systems, and optimized emergency responses.
3D Printing Technology	Following the earthquake in Nepal in 2015, 3D printing technology was used to rapidly construct emergency shelters. On-site production using locally available materials reduced dependency on traditional methods, and accelerated housing provision. Additionally, self-healing materials, such as self-healing concrete, increase infrastructure resilience to seismic events.
Blockchain	The United Nations World Food Programme (WFP) utilizes blockchain technology in refugee camps for aid distribution, and transaction management. Blockchain ensures transparent and secure records, facilitating efficient and accountable aid distribution while empowering refugees through secure digital identities.
Digital Twin Models	Singapore implements digital twin models for urban planning, and disaster management. These models integrate real-time data from various sources, including sensors and satellite imagery, to monitor infrastructure systems. Digital twin models aid in predicting, and simulating disaster scenarios, optimizing response strategies, and enhancing overall resilience.
Disasters Financing	The Caribbean Catastrophe Risk Insurance Facility (CCRIF) utilizes catastrophe bonds for financial protection against hurricanes, and earthquakes. This mechanism ensures rapid access to funds for immediate response, and recovery efforts, supporting affected countries in managing the financial impacts of disasters.

Source: Authors' own analysis.

capabilities of 3D printing technology and the automatic repair features of self-healing materials contribute significantly to disaster resilience by ensuring the rapid production of critical items and the autonomous repair of infrastructure damage [87,93].

The transparent and secure nature of blockchain technology has revolutionized the management of relief funds, aid allocation, and supply chain processes. These factors foster trust among stakeholders and streamline these critical processes efficiently [100]. Digital twin models, on the other hand, offer real-time monitoring and simulation capabilities, optimizing response strategies and aiding in the planning of recovery and reconstruction efforts [77]. Furthermore, as mentioned before, innovative financing products such as catastrophe bonds and microinsurance play a pivotal role in providing timely financial support and risk transfer while empowering communities to invest in preparedness and effective recovery measures [78].

In essence, incorporating these cutting-edge methods gives stakeholders access to real-time data, which enhances decision-making, facilitates resource allocation, builds community resilience, streamlines operational procedures, and prompts financial assistance.

4.2. Positive impacts

As was previously stated, introducing novel approaches to the process of managing disasters produces numerous advantages by having a large impact on different facets of response and recovery activities. For example, the deployment of sophisticated early warning systems, made possible by the complex interactions between drone technology, remote sensing, GIS, and the Internet of Things, can significantly reduce the number of human casualties. This device provides communities timely warnings that eventually save lives and lower the number of casualties by giving them vital information for preventative evacuation planning. Additionally, the integration of drone technology, AI, and digital twin models improves the effectiveness of disaster response and search and rescue operations, raising the possibility of finding and saving people in dire circumstances [8,101,102].

From an economic standpoint, the rapid evaluation of damage, made possible by drone technology, remote sensing, GIS, and digital twin models, hastens the assessment process and accelerates the processing of insurance claims. This expedited response allows for targeted resource allocation and effective post-disaster recovery planning, ultimately reducing economic losses [114]. The incorporation of 3D printing technology and self-healing materials has emerged as a cost-effective solution for the repair and reconstruction of critical infrastructure, thereby reducing economic disruptions and downtime [109]. Additionally, optimizing resource allocation through AI, automation, and blockchain ensures the effective distribution of aid, supplies, and manpower, minimizing waste and maximizing their impact on mitigating economic losses [98].

Looking beyond immediate impacts, the adoption of innovative techniques plays a pivotal role in fostering sustainable development. Sustainable construction practices, facilitated by 3D printing technology and self-healing materials, contribute to waste reduction, utilization of locally available resources, and enhanced infrastructure durability in disaster-prone regions [109]. Empowering communities through digital twin models, secure identities via blockchain, and disaster financing mechanisms not only cultivates resilience but also facilitates effective disaster recovery [106,107]. Moreover, environmental monitoring and planning, supported by remote sensing, GIS technologies, and IoT, contribute to sustainable land use, ecosystem preservation, and effective natural resource management in disaster-affected areas [67,99,105]. This comprehensive integration of innovative techniques underscores their transformative potential in not only addressing immediate challenges but also fostering long-term sustainable development in disaster-prone regions.

4.3. Addressing challenges

Despite the substantial benefits offered by innovative techniques in disaster management, their widespread adoption encounters significant challenges. Foremost among these challenges are financial constraints, as the implementation of advanced technologies and infrastructure upgrades necessitates substantial investment [115]. Efficient resource allocation and strategic planning are crucial in tackling technological challenges such as an adequately trained workforce, data infrastructure requirements, and smooth technology integration [116]. Highlighting the need for putting policies into action is crucial to ensure that new ways of handling disasters work well. To use these technologies smoothly, we need flexible and regularly updated rules that address concerns about the security, privacy, and ethical use of data. Involving the public and gaining their trust is crucial for these strategies to work, as people should be ready to accept and adopt them. To overcome any possible resistance to the adoption and implementation of new disaster management methods, policymakers should conduct awareness campaigns, promote disaster management-related education programs, and directly engage with communities.

Successful collaboration among the public and private sectors, research institutions, communities, and governments is also crucial for understanding various aspects of these methods and assessing potential negative impacts. Global partnerships and international cooperation at the government level for the sharing of information and resources could further enhance the development of a more responsive and resilient global community in the field of disaster management.

5. Conclusion

This study attempts to explore the evolution of various natural disaster control techniques. It highlights the crucial role of innovative techniques in minimizing casualties and economic losses caused by disasters. It also underscores the integration of sustainable practices and highlights the interconnected objectives of fostering environmental resilience and technological modernization in the field of disaster management. This study explains each approach's principles, mechanisms, and effectiveness in dealing with disasters. We present case studies and real-world examples to illustrate the benefits of the successful implementation of advanced disaster management approaches.

By acknowledging the substantial benefits of creative strategies during disasters, this study recognizes potential challenges such as financial budget constraints, unclear policy goals, and community adaptation requirements. We also discuss ways to address these challenges through the development of innovative financing models and collaborative efforts from global stakeholders. Future research may explore sustainable techniques for rapid prototyping and additive manufacturing to bolster resilience.

While this study provides valuable insights into the evolution of damage control techniques since 1950 and their impact on disaster management, certain limitations should be acknowledged. The temporal scope may not fully encompass the latest technological advancements, and the generalizability of findings could be influenced by the selected case studies. Financial constraints pose a notable barrier to the implementation of innovative techniques, especially in resource-constrained regions. Although the study touches on challenges like policy ambiguity and community adaptation, a more in-depth exploration of these complexities is warranted. Future research should address these limitations by examining recent innovations, considering contextual factors, and providing a more detailed analysis of financial and policy challenges to enhance the understanding of integrating innovative techniques into disaster management frameworks.

Ethics statement

Not applicable because this work does not involve the use of animal or human subjects.

CRediT authorship contribution statement

Moinak Maiti: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Formal analysis, Conceptualization. **Parthajit Kayal:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis.

Declaration of competing interest

There is no conflict of interest.

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