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THEMATIC ISSUE

The use of digital technologies for landslide disaster risk research and disaster risk management: progress and prospects

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Abstract
In the past few decades, digital technologies have played a more and more important role in landslide disaster risk management. To identify the progress and future directions with regard to the use of digital technologies in landslide disaster risk management, a systematic review of journal papers in the ISI Web of Science is conducted in this study. Findings indicate that in the early phase, landslide risk management research mainly focused on hazard evaluation and zonation. Then, studies about the spatial predictions of landslides and landslide susceptibility appeared. The research scale of landslides is developing from large scale to fine scale. The use of digital technologies in landslides has been widely discussed since 2009. The use of digital technologies has been developing in the directions of deep learning and artificial intelligence. The monitoring means has been gradually developing from high altitude to low altitude and to ground sensors. Processing technologies are the most widely used in landslide disaster risk research, followed by sensing technologies. Different types of digital technologies play different roles in landslide disaster management. Digital technologies account for a low proportion in the mitigation phase, but contribute the most in the disaster preparation phase. In the future, digital technologies can further strengthen mitigation for and responses to landslide disasters. The application of digital technologies in landslide disaster management should gradually adapt to the needs of the vulnerable group. The government should implement differentiated landslide disaster management according to the regional level of economic development and digital technology development. This study not only reviews the state of the latest technology, but also addresses the future trend of research and provides support for scientists and decision-makers involved in landslide disaster management.

Keywords Landslide · Digital technologies · Systematic review · Disaster risk

Introduction

Landslides are the downward sliding of rock and soil along a weak part of a slope under the action of natural or human activities, which are great threats to human life and property (Brenning 2005; Mei et al. 2020). Due to rapid population growth, hill-slopes in areas susceptible to landslides are increasingly modified for residential and agricultural proposes. Thus, landslide-related geological disasters are more common. According to Georeferenced Emergency Events Database (EM DAT) records, more than 216 serious landslides occurred from 2015 to 2021, which involved large numbers of deaths and affected many people (https://www.emdat.be/). In addition, numerous moderate and minor landslides occur frequently (Khan et al. 2020). Landslide disasters have continual and increasing impact on humanity and world economics (Shoaib et al. 2021). The scientific community and world governments have been committed

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to reducing landslide disaster risk and strengthening risk management, particularly in the last 2 decades (Lavell and Maskrey 2014; Briceño 2015; Alcántara-Ayala 2021).

In the past 2 decades, digital technologies have been widely adopted by scholars and managers, and have an increasingly important role in landslide disaster risk research and management. Digital technology is a science and technology associated with computers or other electronic equipment (Berkhout and Hertin 2004; Baliga et al. 2019). Modern digital technologies mainly include four types: sensing, communication, processing, and actuation (Aceto et al. 2018; Lember et al. 2019). Sensing technology refers to collecting various forms of information related to landslides with sensors, such as that of rainfall, mountain deformation, or pressure (Chai et al. 2020; Hermle et al. 2021; Qi et al. 2021). The sensors used for landslide risk management include underground and remote sensors (Zhao and Zhong 2018). Underground sensors include extensometers, piezometers, tilt meters, and accelerometers, which are used to monitor deformation and underground pressure. Remote sensing refers to non-contact, long-distance detection technology, which include optical remote sensing, Synthetic Aperture Radar (SAR), light detection, etc. (Zhao and Zhong 2018). The advantages of remote sensors lie in their large-scale monitoring and low cost, whereas those of underground sensors are more accurate and real-time.

Communication technology refers to the transmission of data in the form of electromagnetic, acoustic, or light waves from a field collection system to an intelligent analysis platform (Bennett and Davey 1965). It creates new opportunities for people to interact with data, from machine-to-machine communication and wireless networks to social media (Gracchi et al. 2019; Kumar et al. 2020; Menon et al. 2021). For example, a three-level wireless early warning transmission network of county-township-village has been established in China for areas threatened by geological disasters, based on communication technologies (Mei et al. 2020). Actuation technology is represented as robotics, virtual reality, 3D visualization, and 3D printing. It provides various technologies to reconstruct past scenes and simulate future developments (Heitzler et al. 2016; Lember et al. 2019; Meechang et al. 2020). The data of mountains, rivers, landforms, and villages can be reproduced through virtual reality technology to help training people to respond to disasters. Processing technology is used to mine potential information from environmental data and previous landslides, which is widely used in landslide hazard susceptibility assessment.

Processing technologies developed on landslide susceptibility assessments mainly includes seven categories: heuristic approaches, physically based methods, statistical approaches, geostatistical methods, machine-learning models, and deep learning algorithms (Chalkias et al. 2014; Van Dao et al. 2020; Azarafza et al. 2021; Nanehkaran et al. 2021; Habumugisha et al. 2022). These individual approaches have their advantages and limitations, as shown in Table 1 (Reichenbach et al. 2018; Merghadi et al. 2020; Yong et al. 2022).

The four phases of the landslide disaster risk management life cycle are mitigation, preparedness, response, and recovery, which are promoted around the world to reduce the negative impacts (Klimeš et al. 2012; Rodriguez-Morata et al. 2019). Digital technologies are used to store, process, and distribute information, which can be useful at every phase of disaster risk management (Dattilo and Spezzano 2003; Pradhan 2012; Lember et al. 2019; Alimohammadlou et al. 2021). First, digital technologies are needed for collecting and analyzing the spatial and geographic information of landslide risk in a mitigation plan. These technologies help determine natural resources, such as the land cover or topography and the appropriateness of the project plan. Second, digital technologies can be used to simulate exercises and improve strategies and evacuation plans for landslide preparedness. Third, the response phase requires digital technologies for alerting target groups and providing evacuation plan in affected areas. Finally, digital technologies are needed for damage assessment, development plan evaluation, and activity monitoring.

There are many types of digital technologies, all of which are developing rapidly. Some studies have focused on the use of a certain kind of digital technology in landslide disaster research (Marco et al. 2014; Reichenbach et al. 2018; Zhu et al. 2018; Merghadi et al. 2020). For example, Reichenbach et al. (2018) and Merghadi et al. (2020) summarized the applications of a statistically based model and machine learning in landslide susceptibility assessment, respectively. Garnica-Pena and Alcántara-Ayala (2021) analyzed the contribution of Unmanned Aerial Vehicles (UAVs) to landslide disaster risk research and management. A systematic review to sort out the use of various digital technologies in landslide disaster research and the different stages of landslide management is still lacking. It is necessary to further review the recent international literature and collect information about the exploration, application, and achievements of digital technologies in landslide disaster risk research and management worldwide, to highlight their applicability and key roles as well as to propose the limitations of current research and the main research directions in the future.

This study systematically reviews and summarizes related peer-reviewed published literature in the ISI Web of Science (WoS) to identify research gaps and propose future directions. The contribution of this study could be regarded not only as a review of the state of the latest technology but also an effective method to address future research trend and provide support for scientists and decision-makers involved in landslide disaster management. This paper is organized as follows. The section "Research methodology" introduces the

Table 1 Advantages and limitations of different techniques in landslide susceptibility assessment

Category	Representative method	Advantages	Limitations
Knowledge-based methods (Zhu et al. 2018; Yong et al. 2022)	Fuzzy logic, multi-criteria evaluation	1. Can make use of experts' experiences 2. Nonlinear relationships can be expressed	1. Inapplicable at large scale 2. Relies on the ability of an expert
Heuristic or index-based approaches	Analytic hierarchy process model	1. Ranking and weighting of landslide-causing factors 2. Low computation cost	1. Requirements for understanding instability factors of regional landslides and their occurrence mechanism 2. Only linear relationships can be expressed
Geostatistical methods (Apriyono and Santoso 2022)	Ordinary kriging, Inverse distance weighting method	Consideration of the spatial autocorrelation of landslide occurrence	1. Assumption of stationary second order for the spatial autocorrelation of landslides 2. Large numbers of landslide samples required
Physically-based methods (Nanehkaran et al. 2021)	Simple limit equilibrium models	Applicable to local areas and generally have high prediction accuracy	1. Inapplicable at large scale 2. Require large amounts of detailed landslide and environmental data 3. Strict instability factors of regional landslides and their occurrence mechanism
Statistical approaches (Reichenbach et al. 2018)	Logistic regression, quadratic discriminant analysis	1. Provides robust predictions 2. Widely used 3. Easy to understand	1. Require a normal distribution of environmental factors 2. Only linear relationships can be expressed
Machine-learning models (Merghadi et al. 2020)	Random forest, support vector machine, decision tree	1. High ability to analyze data with more accuracy in landslide susceptibility 2. Robust in noisy environments 3. Nonlinear relationships can be extracted	Local optimization and over fitting
Deep learning algorithms (Huang et al. 2020; Van Dao et al. 2020; Azarafza et al. 2021; Habumugisha et al. 2022)	Artificial neural network, supervised deep neural networks, fully connected sparse autoencoder neural network	1. Automatically learn and extract inherent features from big data 2. Nonlinear relationship can be extracted 3. Can effectively avoid local optimization and over fitting	The model is a black box, which cannot express the internal relationship between landslide impact factors and landslide occurrence

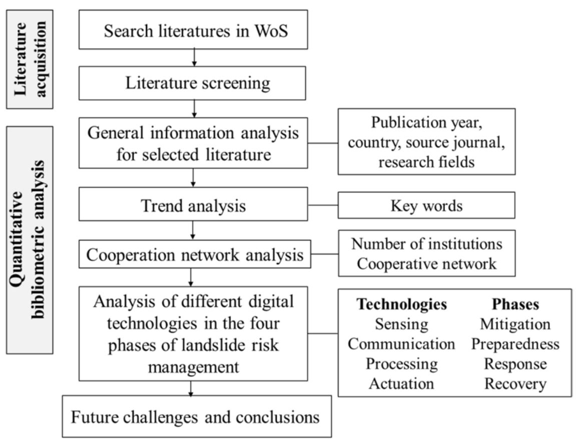

Fig. 1 Overall methodology flowchart for this study

research framework and methodology. The section "Results and key findings" presents the results and key findings of the use of digital technologies for landslide disaster risk research and management. The section "Discussion and future challenges" conducts in-depth discussions to identify research gaps and future directions. The section "Conclusions" presents the conclusions of this study.

Research methodology

The objective of this study was to systematically analyze the use of digital technologies for landslide disaster risk research management. The overall flowchart is shown in Fig. 1. First, related studies were selected through literature searching and screening. Then, a quantitative bibliometric analysis was performed for the selected publications. The following four categories of information were analyzed: (1) general information of the selected publication including the publication year, country, source journal, and main research fields; (2) the trend of digital technologies in landslide disaster risk research management; (3) the institutional cooperation network for the selected publication; and (4) the use of different digital technologies in the four phases of the disaster risk management life cycle (mitigation, preparedness, response, and recovery). Finally, this study discusses the future challenges and development directions of digital technology application in landslide disaster risk research and management.

Literature acquisition scheme

A systematic search approach was used to seek out published, peer-reviewed articles focused on the use of digital technologies in landslide research. The dataset used in this study came from the WoS core collection. The earliest publication year of work related to landslides and technologies in WoS was published in 1991; thus, the timespan was set from 1991 to 2021 (June). The search terms were *landslide* and *digital technologies*, for which 86 publications were collected. Second, considering the classification of digital technologies, our search keywords were broadened to include the following four aspects: sensing, communication, processing, and actuation technologies. The search terms for the application of sensors in landslides were *landslide* combined with *sensors*, *satellite*, *remote sensing*, *Radar*, *LiDAR* (light detection and ranging), or INSAR (interferometric synthetic aperture radar). The search terms for the application of communication technology in landslides were *landslide* combined with *communication equipment*, *mobile device*, *mobile phone*, *telephone*, *Internet*, *wireless network*, *online*, *fiber*, or *social media*. The search terms for the application of processing technologies in landslides were *landslide* combined with *processing technology*, *machine learning*, *deep learning*, *intelligence*, *AI*, *cloud computing*, *big data*, and *GIS*. The search terms for the application of actuation technology in landslides were *landslide* combined with *actuation technology*, *robotics*, *3D* (three-dimensional) *printing*, *3D visualization*, and *virtual reality*.

A total of 5805 publications with no duplication were collected based on the above search strategies. The initial status of all articles was to be confirmed, marked as 0. The suitability of these articles was further confirmed using some inclusion/exclusion criteria during the title, keyword, abstract, and full reading screening phases (Fig. 2). In the title screening, publications unrelated to landslide disaster risk research were excluded based on the titles of the papers and were marked as 1. For example, articles whose titles were related to flood, earthquake, or other disasters were marked as 1.

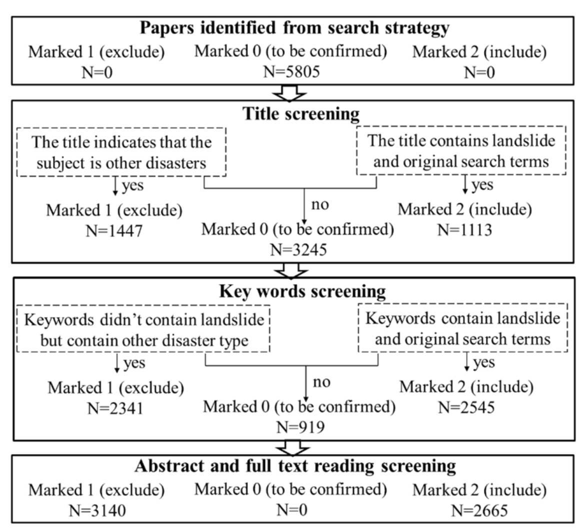

Fig. 2 Search process for identifying publications on the use of digital technologies in landslide disaster risk research management

Articles with landslide and the search terms mentioned above in their titles were marked as 2, indicating that these articles were relevant to this systematic review. Then, we made further judgment based on keywords for the publications that cannot be confirmed through title screening. Articles with keywords containing landslides and the original search terms were marked 2. By contrast, articles with keywords that do not contain landslide but mention other disaster types, such as rock fall, earthquake, and typhoon, were marked as 1. Other papers that could not be identified uniformly would be clarified by reading the abstracts and the text until all papers were marked as 1 or 2. Finally, all the publications marked 2 were randomly selected to ensure that the subjects of the articles meet the requirements of this study by reading their full versions.

Quantitative bibliometric analysis

After artificial filtering, a total of 2665 publications were finally obtained. A quantitative bibliometric analysis was performed for the selected papers based on CiteSpace (Version 5.8). First, general information was analyzed including the number of publications in each year, the authors, the affiliations of the authors, the source journals, and the research fields. Then, the trend of digital technologies applications in landslide disaster risk research and management was explored based on a keyword time-zone map. Third, the institutional cooperation networks of the selected publications were constructed to find the relationships among research institutions. Finally, the uses of different digital technologies in the different phases of disaster risk management were presented and analyzed to investigate their important roles and limitations.

The disaster risk management life cycle consists of four phases: mitigation, preparedness, response, and recovery (Othman and Beydoun 2010; Khan et al. 2020; Meechang et al. 2020). Mitigation refers to long-term mitigation measures to prevent the occurrence of landslide (Chen et al. 2017; Yu et al. 2018). Preparation refers to preparations made to respond to landslides quickly and reduce losses (Meechang et al. 2020). Landslide response focuses on early warning, monitoring, and activities when a landslide occurs, such as evacuating people, saving lives, and protecting property (Mei et al. 2020). Recovery refers to the process of restoring the lives of people and the ecology in the affected area to a normal level after the disaster (Yu et al. 2018).

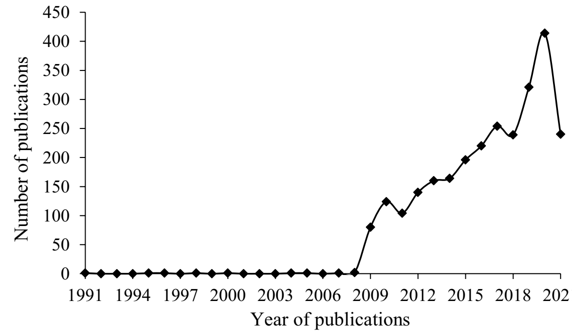

Fig. 3 The number of publications in each year (as of June 2021)

Results and key findings

General information analysis of the selected papers

The variation trend of the number of publications with time can be divided into three phases (Fig. 3). Before 2009, the number of papers relating to digital technologies in landslide disaster risk research and management was small, accounting for only 0.3% of the total number. The number of publications from 2009 to 2020 rose exponentially, with the growth rate in 2018–2020 much higher than that in 2009–2017. It can be seen that after 2009, the use of digital technologies in landslide disaster research began to receive extensive attention. Moreover, with the development of technology, the potential applications of digital technology in landslide disaster management have been increased significantly, so the relevant research shows an increasing trend year by year.

At the continent level (Fig. 4a), authors (all authors in a selected publication, not just the first author) from Asia accounted for nearly half of the total publications, followed by Europe and North America, which accounted for 34.81% and 10.4%, respectively. Other continents accounted for less than 3%. At the country level (Fig. 4b), authors from China published 21.17% of the total papers, whereas those from Italy published 8.61% and the United States published 8.31%. Authorship from India and Iran accounted for 5.42% and 4.88%, respectively. South Korea, Malaysia, Turkey, France, and England each accounted for approximately 3%. The results showed that the regions with more publications are those greatly affected by landslide disasters, such as Asia and Europe. Moreover, as China is experiences frequent landslide disasters, the proportion of relevant publications is the highest among all countries.

Fields of research associated with the publications included geology ($N = 1750$), engineering ($N = 762$), environmental sciences ($N = 691$), water resources ($N = 622$), remote sensing ($N = 513$), imaging science and photographic technology ($N = 394$), meteorology and atmospheric sciences

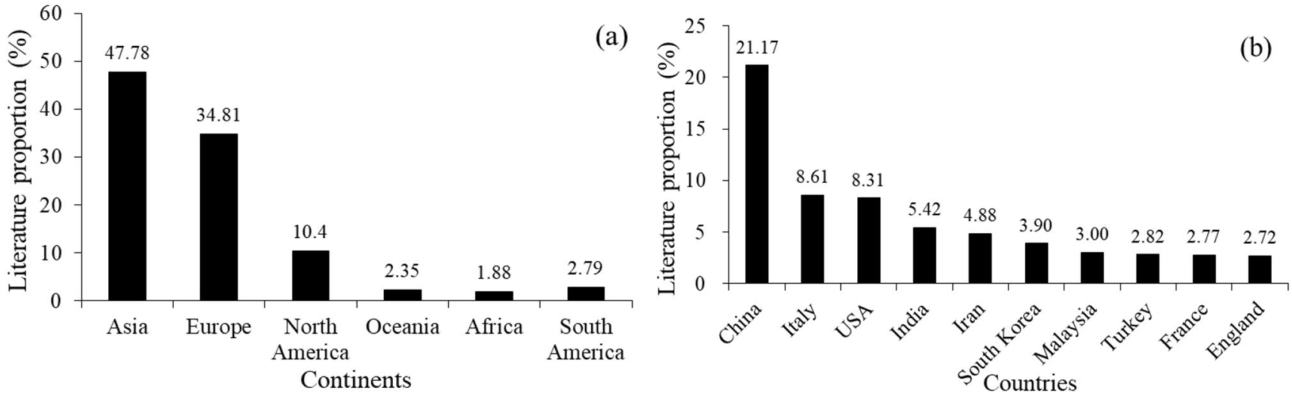

Fig. 4 Proportions of literature published in different regions (**a**) and countries (**b**)

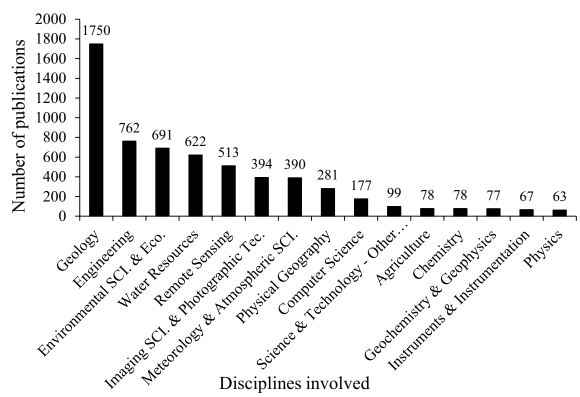

Fig. 5 The main disciplines involved in the selected publications

(*N* = 390), physical geography (*N* = 281), and computer science (*N* = 177). The main disciplines are geosciences, remote sensing, environment-related disciplines, and computer-related disciplines (Fig. 5). The research fields and disciplines of the published papers showed that the relevant research mainly focuses on the geological and environmental fields related to landslides, and the technologies involved are mainly remote-sensing technology and computer science. The largest number of studies was published in *Landslides* (*N* = 235), followed by *Remote Sensing* (*N* = 190), *Natural Hazards* (*N* = 156), *Environmental Earth Sciences* (*N* = 146), *Geomorphology* (*N* = 116), *Engineering Geology* (*N* = 98), *Natural Hazards and Earth System Sciences* (*N* = 84),

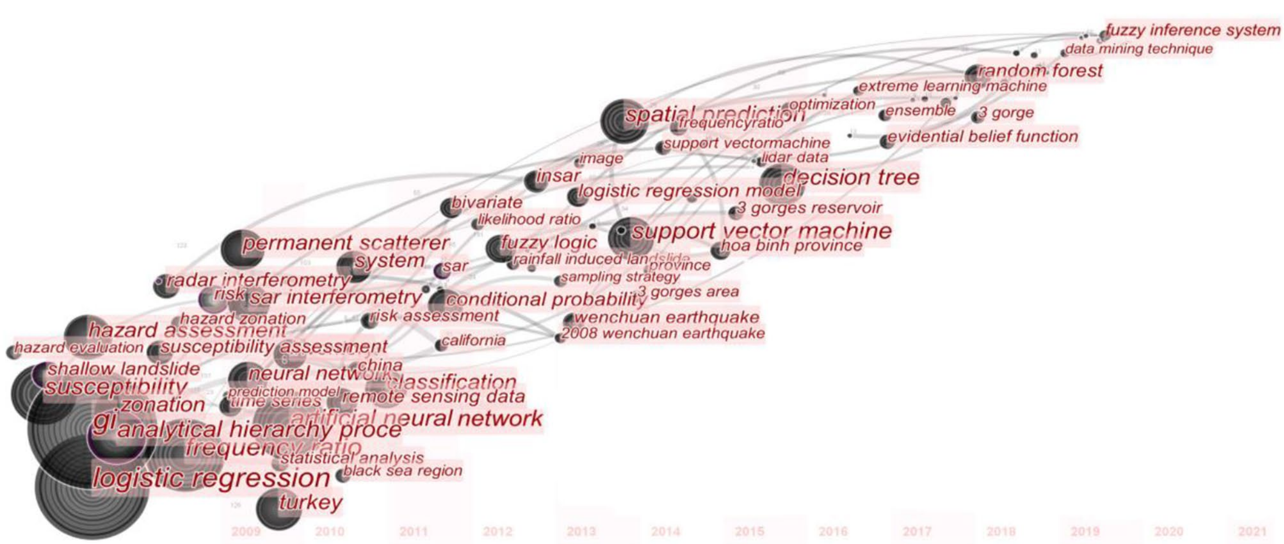

Fig. 6 Keyword time-zone map of selected papers

Geomatics Natural Hazards & Risk ($N=82$), and *Bulletin of Engineering Geology and the Environment* ($N=79$).

Trend analysis of digital technologies in landslide disaster risk research

Figure 6 displays the keyword time-zone map of the selected publications. The keyword map covers the changes over time for the following aspects of keywords: research topic, study area, and digital technology. The research topic development trend demonstrates that landslide disaster risk research mainly focused on landslide susceptibility, risk assessment, and hazard zonation in the early days. Then, keywords such as *rainfall-induced landslide* and *spatial prediction* appeared. The use of digital technology in landslide research has evolved from landslide susceptibility to prediction, which indicates that people's attention over the past 10 years has evolved from exploration of the existing state of potential landslide areas to the prediction of the future state.

The study area development trend indicates that scholars initially paid attention to large-scale regions with frequent landslides, such as the Black Sea region in Turkey, China, and California. Then, the focus gradually shifted to small-scale regions, such as major engineering areas with landslide risk or areas with natural disasters. Therefore, keywords such as *Three Gorges*, *Wenchuan*, and *Himalaya* emerged. The landslide research scale is becoming finer.

The earliest processing technology keywords, such as *GIS*, *physical-based model*, *logistic regression*, *statistical analysis*, *multivariate*, and *artificial neural network*, appeared in 2009. From 2012 to 2015, keywords such as *likelihood ratio*, *time-series*, *support vector machine*, *decision tree*, and *multi-criteria decision* began to appear. After 2015, keywords, such as *random forest*, *extreme learning machine*, *data mining technique*, and *fuzzy inference system*, have occurred frequently. The keyword changes indicate that the use of digital technologies is becoming increasingly in-depth, and developing in the directions of data mining and deep learning.

The earliest sensing technologies were remote sensing, radar interferometry, and SAR interferometry, which appeared in 2009 and 2010. Then, it developed into InSAR, Lidar. In recent years, monitoring technologies, such as UAV (Unmanned Aerial Vehicle) and persistent scattered interferometry, have appeared more frequently. The means of landslide-monitoring is gradually developing from high altitude to low altitude and to ground sensors.

Cooperation network analysis

The institutional cooperation networks are shown in Fig. 7. The top-ranked institution by publication count is the Chinese Academy of Sciences with 131. The second, third, and fourth ones are China University of Geosciences, Universiti Putra Malaysia, and Duy Tan University in Vietnam, with 124, 69, and 69, respectively. As observed, the institutions with large numbers of published articles

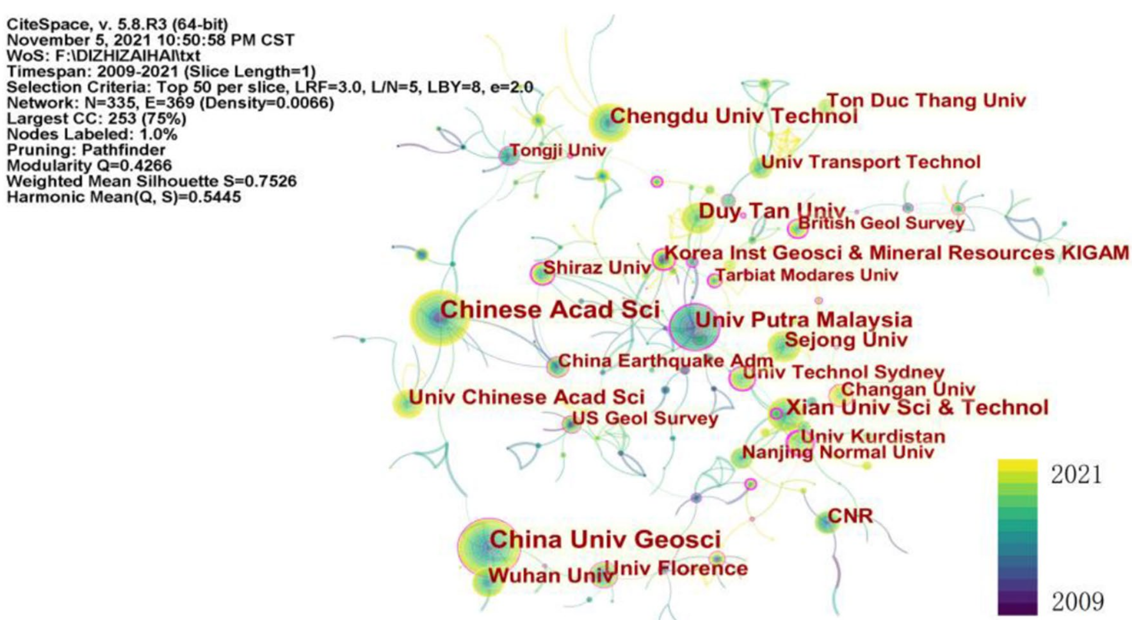

Fig. 7 Institutional cooperation networks

related to landslide disaster risk research are located in Asia. The frequent geological disasters in these areas make scholars pay extra attention to relevant topics.

The top-ranked item by institutional cooperation network centrality is Chengdu University of Technology in China, with a centrality of 23. The second is Research Institute for Geo-Hydrological Protection, National Research Council of Italy, with a centrality of 20. The third is University of Florence in Italy, with a centrality of 19. The first publications of these three organizations all appeared in 2009. The fourth is Shiraz University in Iran with the first publication in 2015 and a centrality of 19. The fifth is the Chinese Academy of Sciences with the first publication in 2009 and a centrality of 19. All of these institutions cooperate closely with other institutions and are important network nodes in the institutional cooperation network.

The use of digital technologies in different management stages of landslides

According to the phases of landslide disaster risk management and the classification of digital technologies, the uses of various digital technologies in each phase and their distribution were extracted, which are listed in Table 2. Overall, the use of digital technologies is very uneven in different phases of landslide disaster management. Digital technologies account for a very low proportion (0.76%, $N=20$) in the mitigation phase of landslide disaster risk management. Engineering governance is the main measure to mitigate landslide hazards, and digital technology is difficult to apply to stabilizing geological conditions at present. Digital technologies contribute the most (75.7%, $N=1998$) in the disaster preparedness phase. A large number of studies have focused on using digital technologies, such as GIS, remote sensing, or statistical models to evaluate and map the vulnerability of regions to landslides to provide support for landslide management. Digital technologies also play an important role in the recovery phase after landslide disasters, descriptions of which account for 18.48% ($N=488$). The use of digital technologies in landslide disaster response accounts for 5.07% ($N=134$), which is mainly for disaster warning and other related research. The response to landslides requires real-time, fast action. Digital technology is an indispensable means for this, which has great potential in the landslide response stage in the future.

Sensing technologies in landslide disaster risk research and management

Of the total number of publications in landslide disaster risk research, 35.91% ($N=948$) focused on the use of sensing technologies. Among them, only 0.23% ($N=6$) focused on the mitigation phase of landslide disaster management. Much attention has been paid to the contribution of sensing technologies to landslide preparedness, which accounts for 22.08% ($N=583$) of the total number. The use of sensing technologies in the recovery and response phases of landslides accounts for 11.21% ($N=296$) and 2.39% ($N=63$), respectively.

Sensing technology is seldom used in landslide mitigation, because mitigation mostly takes place by implementing remedial works. A few studies exist on the directly use of sensing technologies in landslide mitigation. Related studies used remote sensing to evaluate the slope stability and effectiveness of remedial works (Smedley et al. 2009; Miller 2012; Liu et al. 2020). For example, Liu et al. (2020) investigated the effectiveness of large-scale governmental risk mitigation programs based on the InSAR. Smedley et al. (2009) discussed the possibility of remote-sensing techniques to evaluate and plan future maintenance and stabilization interventions. Government engineering measures are still the main means to mitigate landslides. Sensing technologies can contribute to mitigation by evaluating engineering treatment measures. Such research should receive further attention in the future to provide guidance for the implementation of government engineering measures.

Sensing technologies are widely used in the preparedness phase of landslide disaster risk management, accounting for 22.08% ($N=583$) of the total publications and 61.5% of sensing-related landslide publications. The sensing technologies involved in the landslide preparedness phase mainly include optical remote sensing, InSAR, LiDAR, and terrestrial laser scanning. Optical remote sensing includes high-spatial-resolution Ziyuan-3 (ZY-3) and Gaofen-1 (GF-1) satellite imagery and time-series remote-sensing images from Landsat Thematic Mapper/Enhanced Thematic Mapper (TM/ETM), Systeme Probatoire d'Observation de la

Table 2 Distribution of digital technologies in landslide disaster risk management

	Sensing	Communication	Processing	Actuation	Total
Mitigation	6 (0.23%)	1 (0.04%)	10 (0.38%)	3 (0.11%)	20 (0.76%)
Preparedness	583 (22.08%)	76 (2.88%)	1258 (47.65%)	81 (3.07%)	1998 (75.7%)
Response	63 (2.39%)	28 (1.06%)	41 (1.55%)	2 (0.08%)	134 (5.07%)
Recovery	296 (11.21%)	21 (0.8%)	153 (5.8%)	18 (0.68%)	488 (18.48%)
Total	948 (35.91%)	126 (4.77%)	1458 (55.23%)	104 (3.94%)	2640 (100%)

Terre (SPOT), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Indian Remote Sensing Satellite-1C (IRS-1C), and RapidEye, which are applied in generating landslide susceptibility/risk maps or landslide hazard zones through image interpretation (Liu et al. 2013; Chen et al. 2015; Duan et al. 2020; Guo et al. 2021). InSAR and LiDAR usually obtain the 3D geomorphologic characterization by generating a digital elevation model and identifying surface deformation (Edward et al. 2018). Terrestrial laser scanning has been widely applied to landslide characterization and monitoring, especially for rockslides (Marco et al. 2014; Macciotta and Hendry 2021).

Only 2.39% ($N=63$) of the total identified publications focus on the use of sensing technologies in the response phase of landslide disaster risk management. Landslide early warning based on underground sensors and the Internet of Things (IoT) are the subjects of these studies (Casagli et al. 2010; Liao et al. 2010; Atzeni et al. 2015; Uchimura et al. 2015). The IoT obtains dynamic landslide information in real time through various sensors, global positioning systems, and laser scanners, and transmits it through the network, so that managers can activate early warnings of landslides. The IoT is an important technical means for future rapid landslide response. In addition, in-situ ground-based monitoring technology can monitor landslides, and provide early warning information by observing slope displacement, precipitation, and soil hydrological data to assist decision-makers in responding to landslides.

The use of sensing technology in landslide disaster recovery accounted for 11.21% with 296 publications. Related studies mainly include two categories. The first is post-disaster assessment that includes mountain deformation and disaster damages or losses using InSAR and optical satellite imagery (Greif and Vlcko 2012; Dai et al. 2019; Qu et al. 2020). InSAR can be used to track the temporal evolution of a failure process and assess the slope restoration after a landslide. Optical satellite imagery can be used to evaluate vegetation recovery. The second is landslide mapping and inventory using optical imagery after landslide occurrence (Bianchini et al. 2017; Martha et al. 2019; Ye et al. 2019).

The use of sensing technologies in landslide disaster management has unique advantages. Sensing technology can be widely used for the acquisition of field information with the advantage of large-scale monitoring area and low cost. However, the different sensing technologies also have their own limitations. The use of optical images for landslide disaster risk management has strong dependency on meteorological and illumination conditions. Optical sensing technologies are difficult to be used in monitoring and responding to landslides caused by rainfall. InSAR techniques have potential for monitoring slow-moving landslides because of their ability to measure millimeter-scale deformations. However, due to the limitations of topography and signal-processing technology, InSAR is difficult to be used effectively in practice. Some scholars pay attention to the use of ground-based sensors in landslide disasters. Ground-based sensors generally contain a rain gauge and a displacement gauge, which can be used to acquire rainfall and hillside deformation data in real time (Marco et al. 2014). The disadvantage is that the monitoring area of such sensors is limited. Realizing the complementary advantages of various sensors and establishing a landslide-monitoring network of space, sky, and ground monitoring should be important directions of sensing technology applications in landslide disaster risk management in the future.

Communication technologies in landslide disaster risk management

Only 4.77% ($N=126$) of the publications found were about communication technologies in landslide disaster risk management. More than half of these focused on the preparedness phase. Publications on landslide disaster response and recovery are also reported. Only one publication is concerned with the use of communication technologies in landslide mitigation management (Edward et al. 2018). Edward et al. (2018) used crowdsourcing to enhance the mitigation and management of landslides based on a smartphone application, which is an administrative interface and database. At present, communication technology does not play a major role in landslide mitigation, and can only be used as an auxiliary means.

Communication technologies are widely used in the preparedness and response phase of landslide disaster risk management. In these two phases, research focuses on the use of optical fiber, wireless sensor networks, and other communication technologies for landslide-monitoring (Benoit et al. 2015; Zhang et al. 2016; Damian et al. 2018; Zheng et al. 2018) and early warning (Hong et al. 2011; Pei et al. 2011; Hemalatha et al. 2019). Relevant research in the recovery phase mainly includes landslide inventories based on web data or open-source software (Mantovani et al. 2010; Battistini et al. 2013; Juang et al. 2019), an assessment of community social awareness of, and engagement around, landslides via a web platform (Bignami et al. 2018), and a survey of rock-slope failures after landslides (Voumard et al. 2017). For example, many organizations have developed online engagement tools to collect volunteer information. In addition, the Internet and media technology can play an important role in social assistance in the post-disaster recovery phase.

Communication technologies give people opportunities to prevent and respond to landslide disasters effectively and quickly. Landslide-related information about disaster details and responses can be shared through text messages, voice calling, or social media. However, the digital divide may lead to inequitable information transmission. Some residents, especially the elderly, often fail to respond in time, because they cannot receive transmitted disaster information, and their lives are threatened. Therefore, addressing the digital divide and ensuring the comprehensive accessibility of information are challenges for the wide application of communication technologies. Given that landslide disasters are sudden and destructive, efficient information transmission is important. 5G technology, which has been extensively developed and commercially applied in recent years, has great potential for improving the efficiency of information transmission with the advantages of large data flow, short delay, high rate of information transmission, and high reliability. The organic combination of 5G technology, sensors, and cloud computing should be explored in the future to significantly improve the efficiency of landslide disaster response.

Processing technologies in landslide disaster risk management

Processing technologies are the most widely used technologies in landslide disaster risk management, accounting for 55.23% ($N = 1458$) of the total publications. Among them, 47.65% ($N = 1258$) focused on the preparedness phase, 5.8% ($N = 153$) on the recovery phase, 1.55% ($N = 41$) on the response phase, and only 0.38% ($N = 10$) on the mitigation phase.

For the mitigation of landslide disaster risk management, digital techniques such as computer simulation and machine learning mainly played a role in two aspects. One is to evaluate the effectiveness of landslide protection works or facilities (Asch 2005; Mao et al. 2012; Dang et al. 2016). For example, Mao et al. (2012) evaluated the effect of vegetation in protecting artificial and natural slopes against shallow landslides. Sassa et al. (2012) tested the function of undrained dynamic-loading ring shear in landslides. The other is to optimize the design of landslide mitigation engineering (Liang et al. 2019; Vali 2021). For example, Vali (2021) evaluated the effects of a water table on the behavior of a geogrid-reinforced soil-footing system in marine soft soil layers and recommended the optimum specification of the reinforced soil-footing system. Adil Hassan et al. (2022) simulated the development of pore pressures and water content in the dike's upstream and downstream slopes in physical experimental tests, and found that appropriate dike design and maintenance are dependent on surrounding hydraulic conditions, dimensions, and soil types. Non-cohesive materials with fine particles were preferable.

Processing technologies are most used in the preparedness of landslide disaster risk management, which mainly include the following three aspects. The first is landslide disaster susceptibility assessment using different processing models, such as logistic regression, machine learning, artificial neural networks, and GIS (Azarafza et al. 2018; Akinci and Zeybek 2021; Rahman 2021). Such studies account for more than half of the research on processing technologies in landslide disaster risk management. Among them, machine-learning methods, including random forest, decision tree, neural network, hybrid support vector, and Bayesian model, have been widely used in recent years. The second is landslide spatial probability prediction using machine learning, deep learning, or GIS (Wu et al. 2014; Wang et al. 2020; Nguyen and Kim 2021). The third is landslide unstable factors identification causing landslide based on numerical modeling (Dou et al. 2015; Shoaib et al. 2021).

Research on processing technologies in the landslide response phase mainly focuses on the development of early warning models or systems and on the decision support system (Sassa et al. 2010; Chae et al. 2017; Ahmed et al. 2018; Park et al. 2019; Thirugnanam et al. 2020). The key to processing technology applications in landslide response lies in the timely processing of real-time data. Thus, most of these studies are combined with sensing or communication technology application (Atzeni et al. 2015; Hemalatha et al. 2019). The combination of various digital technologies is an important requirement for efficient landslide response.

Studies of processing technologies in the landslide recovery phase mainly pay attention to landslide hazard mapping using GIS and machine-learning methods (Prabu and Ramakrishnan 2009; Chong et al. 2012). In addition, a few studies focus on vegetation rehabilitation after landslide disasters based on the Markov chain model or GIS-based methods (Chuang et al. 2010; Bugday and Ozel 2020). The multiple layer geotechnical model of the soil has been applied in the recovery phase, which is the basis for defining the remediation measures that finally lead to stabilizing landslide motions (Marschallinger et al. 2009).

Processing technology is indispensable for landslide disaster management. Risk assessments and early warning systems of landslides generally involve a large quantity of spatiotemporal data. Mining valuable information from these data for landslide disaster management must rely on processing technology. In addition, timeliness is a key indicator of the early warning system. Thus, real-time, large-scale processing capability with high accuracy and intelligence in landslide data mining is necessary in the future. Moreover, the identification of landslide disaster-causing factors based on big data has become an important aspect in landslide prevention. Deep learning and AI algorithms for massive and real-time data still need to be further developed for landslide-monitoring and prediction.

Actuation technologies in landslide disaster risk management

The proportion of actuation technologies applied to landslide disaster risk management is only 3.94% ($N = 104$). Among them, only three studies focus on the use of actuation technologies in the mitigation phase of landslide disaster risk management. The first study developed a 3D ground model to obtain a detailed understanding of the structure and lithology of a complex landslide system (Merritt et al. 2013). The second assessed stabilization measures using an optical–mechanical crack gauge (Klimes et al. 2012). The third described a 3D numerical simulation of landslide reinforced by discrete piles (Kanagasabai et al. 2011).

A total of 81 papers are related to the use of actuation technologies in the landslide preparedness phase, which account for approximately 3.07% of the total publications. These studies mainly focus on numerical simulations of landslide processes based on a 3D model, which can provide support for landslide prediction and sensitivity evaluations (Hungr 2009; Hungr and Mcdougall 2009; Hess et al. 2017). Two papers explored the use of actuation technologies for the response to a landslide disaster. Huang et al. (2016) developed an early warning system based on 3D technology and WebGIS. Crosta et al. (2017) employed early warning criteria for complex rockslides by setting up a virtual monitoring network using ground-based radar interferometry.

For the recovery phase, virtual earth and smoothed particle hydrodynamics are applied in 3D terrain modeling to the visual analysis of real landslide events (Yu et al. 2011, 2016). In addition, a 3D numerical model is used to investigate the deformation mechanisms leading to a landslide and the long-term evolution of a slope combined with pre- and post-failure remote sensing data (Donati et al. 2020). Actuation technology is still in its infancy and is the least used digital technology in landslide disaster management at present.

Discussion and future challenges

With the development of digital technology and increased attention on landslide disaster management, many new digital technologies have emerged in landslide risk management, especially for landslide assessment mapping. One of the new technologies for landslide assessment is the deep-learning-based algorithm. For example, Huang et al. (2020) proposed a fully connected sparse autoencoder neural network (FC-SAE) method and Van Dao et al. (2020) proposed a spatially explicit neural network model for landslide susceptibility prediction. These methods can extract the optimal nonlinear features from environmental factors and have better performance than some traditional machine-learning methods.

Another new technology is the hybridized model, which combines multiple models for landslide assessment. Panahi et al. (2022) developed a group method of data handling (GMDH) and a hybridized model of GMDH based on different metaheuristic algorithms for landslide susceptibility mapping, which had better predictive performance than both random forest and boosted regression trees. Nanehkaran et al. (2021) developed a fuzzy-logic-based multi-criteria decision-making method containing analytic hierarchy process (AHP), multiple-criteria decision-making, and fuzzy logic for landslide susceptibility analysis, and achieved accurate results. Azarafza et al. (2018) developed a combinatorial method containing multi-criteria decision-making, likelihood ratio, and fuzzy logic theory for the risk assessment of landslide occurrences. These models make up for the defects of a single model by combining different models to obtain better results, which mirrors the inevitable trend of landslide prediction toward more and more accuracy.

In addition, in terms of landslide management, some new technologies have also emerged. The Internet of Things (IoT), as a new generation of information integration technology, has also begun to receive extensive attention in landslide disaster management studies, which promotes more sophisticated and dynamic perception and management of landslide disasters to achieve a state of wisdom (Mei et al. 2020). People have begun to use the game platform to enact various scenarios in disaster events to enhance users' awareness and educate people for disaster response in an engaging way (Meechang et al. 2020). Other technologies, such as Weibo, TikTok, robotics technology, intelligent computing, etc., are also gaining an important role in disaster management.

In recent years, many studies had reviewed the use of certain kinds of digital technologies in landslide disaster management or natural disaster management (Reichenbach et al. 2018; Mei et al. 2020; Merghadi et al. 2020). Reichenbach et al. (2018) reviewed the use of statistical methods for landslide susceptibility modeling. The Reichenbach et al.'s (2018) study found that the statistical methods for landslide susceptibility modeling had an increasing preference toward machine learning in recent years and a clear geographical bias in susceptibility study locations, with many studies in countries most threatened by landslides, such as China, India, and Italy. These findings are consistent with our study. Several previous studies have found that some new digital technologies or new data are widely used in natural disaster management, such as crowdsourcing, robotics, and mobile global positioning system (GPS) data (Park et al. 2017; Yu et al. 2018). From our results, these new data or new technologies have not been widely used in landslide disaster management. In the future, we can further explore how to use these new technologies to reduce the risk of landslide disaster, especially the application of robotics in landslide early warning and rescue. Previous studies have also found that social media plays a significant role in disaster monitoring and detection and post-disaster coordination and response in natural disaster management, such as for flood and earthquakes (Yu et al. 2018; Dargin et al. 2021). Our research showed that social media has not played such an important role in landslide disasters, but it has great potential for the future. In addition, based on the research results of this work, the use of digital technology in landslide disaster risk management still faces challenges, described in what follows.

Strengthening the use of digital technologies in weak phases

Most digital technologies are applied in the preparation and response phases of landslide disaster risk management, while only a few studies focus on the mitigation and response phases (Uchimura et al. 2015; Mclennan et al. 2016). How to strengthen the use of digital technologies in these weak phases is a challenge that needs to be addressed. Our study found that the uses of digital technologies in the landslide mitigation phase are the least common, accounting for only 0.76% of all the searched literature. The main reason may be that digital technologies are difficult to use to mitigate landslides directly. Engineering measures are still the main mitigation measures at present, which include drainage engineering measures to reduce or eliminate the harm of water, mountain stabilization engineering to maintain the mechanical balance, and physical and chemical methods to improve the soil and rock properties of the sliding zone (Asch et al. 2009; Singh 2010; Hostettler et al. 2019). A small quantity of research has involved the support of digital technologies for these engineering measures (Asch et al. 2009; Sassa et al. 2012; Ha et al. 2020). Further strengthening can be considered from the following aspects. First, scenario simulations of water diversion projects in the rainy season based on digital technologies are worthy of further exploration. For example, simulations of surface-water flow under different terrain conditions and different rainfall events using 3D digital terrain technology can be used to determine the best drainage direction, location, and quantity of drainage ditches to obtain the best effect with the lowest project cost (Anderson et al. 2011). Second, more attention should be paid to monitoring the changing stress distribution in rocks under external loads, pore pressure fluctuations, temperature gradients, and hydrochemical exchanges based on ground sensors, so as to arrange timely protective engineering measures (Asch et al. 2007). In the future, we can also deeply explore how to use virtual reality and other technologies to simulate the long-term and short-term effects of different engineering measures and determine the optimal combination for preventing landslides.

The proportion of digital technology use in the landslide disaster response phase is about 5.07%, which mainly focuses on landslide early warning systems (Casagli et al. 2010; Atzeni et al. 2015; Huang et al. 2016). More accurate monitoring and early warning of landslide disasters will remain the focus of attention in the future by combining multiple technologies. The IoT integrated with communication technologies like 5G; processing techniques like cloud computing, deep learning, and big data analytics; as well as sensors, provide potential solutions for early warning of landslide disasters (Montori et al. 2018; Mei et al. 2020; Menon et al. 2021). Additionally, establishing a landslide-monitoring network system trinity of space, sky, and ground and combining communication and processing technologies to realize comprehensive landslide management should also be an important future direction (Marco et al. 2014; Garnica-Pena and Alcántara-Ayala 2021).

Vulnerable groups in digital landslide disaster management

The trend analysis of digital technologies in landslide disaster risk research indicated that digital technologies are developing in depth, complexity, and diversification. However, digital technologies ultimately serve people. Overly complex technologies are not conducive to widespread use by people, especially for digitally vulnerable groups (Dargin et al. 2021). Most of the digitally vulnerable are elderly, who lag in the acquisition, possession, and use of digital resources. They may also have little education. It is difficult for them to accept and adapt to the constantly updated digital technologies. These residents often cannot receive early warning information in time, resulting in threats to their lives and properties. In addition, vulnerable groups also include residents of remote mountainous areas where landslides occur frequently. These areas have low network penetration and fewer people with electronic devices due to poverty. These vulnerable groups have brought great challenges to the digital management of landslide disasters (Dargin et al. 2021).

To solve the problems faced by vulnerable groups, the use of digital technologies in landslide disaster management should gradually adapt to vulnerable populations (Hargittai et al. 2019). For example, the corresponding optimization design of public terminals can be carried out for vulnerable groups and an elderly friendly interface with information that is easy to distinguish and find can be launched. Conversely, public welfare organizations, volunteers, Internet enterprises, and other social forces can be mobilized to provide services to improve digital knowledge, literacy, and skills of vulnerable groups. Meanwhile, traditional management methods, such as radio broadcast, should also be kept for alternatives.

Construction of resilient communities assisted by digital technologies

People have recognized the importance of landslide disaster risk management, and made great efforts to reduce landslide occurrence. However, the immediate risk stemming from frequent, unpredictable hazards and thus more severe consequences highlights the need for alternative landslide disaster risk management strategies, such as resilience (Ma et al. 2020). A resilient community has strong ability to resume functionality in the wake of a crisis, which is an efficient system for human beings to adapt to future natural disasters (Ma et al. 2020; Mcclymont et al. 2020; Chan et al. 2022). At present, there is little research on resilient communities facing landslide disasters.

The rapid development of digital technologies has great potential to promote the formation of resilient communities. However, the research on the use of digital technologies in landslide disaster management is mostly to provide support for government departments (Alam and Ray-Bennett 2021). Residents in areas threatened by geological disasters have little understanding of other digital technologies beyond mobile phones and the Internet. Digital technologies should also be rooted in the community, directly serve the residents facing geological disasters, and give them early warnings before disasters occur (Ramakrishnan et al. 2022). Digital technologies should be understood and mastered by residents at the community level, so that communities threatened by landslide disasters can independently deal with the whole cycle of landslide disaster management and gradually achieve peaceful coexistence between man and nature. In the future, it will be urgent to explore the formation mechanism and theoretical framework of resilient communities facing landslide disaster with the support of digital technologies and government departments (Santos et al. 2020).

Ethical issues in digital landslide disaster risk management

Our results showed that digital technologies, especially social media, play an important role in the recovery phase of landslides. The popularity of social media means that landslide disasters not only no longer involve only the suffering residents, but also develop into a public topic in connection with other communities (Lovari and Bowen 2020). To date, social media use by landslide or other disaster response agencies has been relatively ad hoc (Hayes and Jackson 2020; Lovari and Bowen 2020). The media's reports on landslide disasters do not always have a positive effect, but are accompanied by some ethical disputes, including anger, accusations, and abuse, causing secondary harm to the affected people. Therefore, it is necessary to further explore the ethical and proper use of social media in landslide disaster risk management (Hayes and Jackson 2020). For example, in the process of conveying the disaster situation, the media could truthfully inform about the disaster situation and focus on conveying the needs of the affected areas and people, rather than relying on incitement to attract attention.

In addition, with the development of digital technologies, people in disaster affected areas can receive volunteer help and charitable aid from around the world (Santos et al. 2020). Affected areas truly need the help of the entire society. However, the needs of affected people are the biggest obstacles to post-disaster reconstruction. If charity is taken for granted and the disaster is taken as a reason for asking, the lack of gratitude may exacerbate the negative impact of the disaster on mankind. Disaster-stricken groups should abide by certain ethical norms in disasters, enhance the awareness of actively changing roles, and take the initiative to resist disasters, all of which play important roles in effective disaster prevention and reduction. Thus, digital technologies bring convenience to disaster management; the ethical thinking of affected residents and external public opinion are also key issues that need to be attended to in the future (Hayes and Jackson 2020).

Governmental implication of classified management of landslide disasters

Digital technologies are widely used in landslide disaster management in most regions of the world. Due to the differences of technical conditions and economic levels in different regions, the digitization degree of landslide disaster risk management is normally different. The government should implement differentiated classified controls according to the existing regional characteristics (Alam and Ray-Bennett 2021). For regions with better economic conditions and higher degrees of digitization, the government should focus on the full coverage of digitization, that is, pay attention to the improvement of digital technologies for vulnerable groups. Concurrently, the government should gradually infiltrate digital technologies into the grass-roots management of communities and promote the transition from traditional communities to resilient communities facing geological disasters with the help of digital technologies. For areas with general economic conditions and digitization degrees, landslide disaster management combining traditional and digitization modes should be adopted in the short term. In terms of digitization, the application of low-cost digital technologies such as remote sensing and the Internet can be strengthened in landslide disaster management. Meanwhile, the government should increase capital investment, build a digital platform, and implement monitoring and early warning as soon as possible on the basis of absorbing the experience and lessons of other regions. For areas with very poor digital management, attention should be paid to the role of the masses in geological disaster management. The government should equip communities or residents with basic digital equipment, such as mobile phones and networks, and start the digitization development as soon as possible.

Conclusions

Digital technologies have been widely studied by scholars and managers, and have gradually played a more and more important role in landslide disaster risk research and management in the past decades. However, there is still a lack of systematic review to sort out the use of various types of digital technologies in landslide disaster research and different stages of landslide management. To highlight the applicability and key roles of different technologies in different stages of landslide management and to propose the limitations of current research and the main research directions in the future, this study systematically reviewed and summarized related peer-reviewed published literature in the ISI Web of Science (WoS). A quantitative bibliometric analysis was performed for the selected papers, including general information analysis, trend analysis, and cooperation network analysis. The uses of digital technologies are also mapped on the four phases of landslide disaster risk management. The results showed that digital technologies are widely used in landslide disaster risk research with 2665 identified publications. After 2009, the use of digital technologies in landslide disaster management began to receive extensive attention. With the development of technology, the publications related to the use of digital technology in landslide management increased year by year. Asia, where landslide disasters are serious, has published nearly half of the total articles, followed by Europe and North America, which account for 34.81% and 10.4%, respectively. The proportion of relevant publications in China is the highest among all countries. The main disciplines are geosciences, remote sensing, environmental, and computer-related disciplines. The main journals include *Landslides*, *Remote Sensing*, *Natural Hazards*, *Environmental Earth Sciences*, and *Geomorphology*.

The use of digital technology as a landslide research topic has evolved from landslide susceptibility to landslide prediction, which indicates that people's attention over the past 10 years has evolved from the exploration of the existing states of potential landslide areas to the prediction of their future states. The research scale of landslides is developing from large scale to finer scale. The use of digital technologies is becoming increasingly in depth and is developing in the directions of data mining, deep learning, and AI. Landslide monitoring is gradually developing from high altitude to low altitude and to ground sensors. Different types of digital technologies play different roles in landslide management. Sensing technologies are mainly used for the acquisition of field information. Processing technologies are mainly used for mining the potential information based on the massive landslide data. Communication technologies can be mainly used for emergency response because of their timeliness and rapid propagation. Actuation technologies mainly focus on the numerical simulation of the landslide process, which can provide support for landslide prediction and sensitivity evaluation.

The use of digital technologies is uneven in different phases of landslide disaster management, with low proportions in the mitigation and response phases and high proportions in the preparation and recovery phases. In the future, the use of digital technologies in the weak phases of landslide disaster risk research needs to be strengthened. Realizing the complementary advantages of various sensors and establishing a landslide-monitoring network system trinity of space, sky, and ground should be important directions for applying sensing technologies in landslide disaster risk research. It is also urgent to explore the formation mechanism and theoretical framework of resilient communities facing landslide disasters with the help of digital technologies. Moreover, the use of digital technologies in landslide disaster risk research should gradually adapt to the elderly and the vulnerable. The government should implement differentiated landslide disaster management according to regional economic level and digital adoption degree.

This paper is a systematic review of the use of digital technology in landslide disaster risk management. The contribution of this study can be regarded not only as a review of the state of the latest technology, but also an effective method to address future research trend and provide support for scientists and decision-makers involved in landslide disaster management. In this study, we classify digital technologies into four categories. However, due to the large number of fields and publications involved, some new but less-applied digital technologies are less discussed. Some details of the use of a certain type of technology may also be ignored. Digital technology has great potential in all phases of landslide disaster risk management, which is worthy of further exploration by scholars in the future.

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Declarations

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