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Review Article

The use of UAVs for landslide disaster risk research and disaster risk management: a literature review

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Abstract: On a global scale, from 2005 to 2019, there were 275 high-magnitude, low-frequency disasters that involved 14,172 fatalities and four million affected people. Similar patterns have taken place during longer periods of time in recent decades. This paper aims to analyse the contribution of the international landslide research community to disaster risk reduction and disaster risk management in reference to the use of Unmanned Aerial Vehicles (UAVs) in a literature review. The first section notes the relevance of disaster risk research contributions for the implementation of initiatives and strategies concerning disaster risk management. The second section highlights background information and current applications of drones in the field of hazards and risk. The methodology, which included a systematic peer review of journals in the ISI Web of Science and SCOPUS, was presented in the third section, where the results include analyses of the considered data. This study concludes that most current scholarly efforts remain rooted in hazards and post-disaster evaluation and response. Future landslide disaster risk research should be transdisciplinary in order to strengthen participation of the various relevant stakeholders in contributing to integrated disaster risk management at local, subnational, national, regional and global levels.

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1 Introduction

1.1 Impact of disasters associated with landslides

Owing to the growing impact of disasters on society, the scientific community has been committed to reducing disaster risk and strengthening disaster risk management, particularly in the last two decades (Lavell and Maskrey 2014; Briceño 2015; Cutter et al. 2015; Alcántara-Ayala et al. 2015; Oliver-Smith et al. 2016). As a result of current population growth and urbanization, areas highly susceptible to landslides are increasingly sites for human settlement, thus causing frequent modification of hillslopes. As a result, there has been an increase in the number of landslide-related disasters.

Notwithstanding the contributions of landslide research, local studies and recommendations made through various policies aimed at disaster risk reduction, landslide disaster events have increased in recent years as confirmed by EM DAT records. Accordingly, from 2005 to 2019 there were 275 high-magnitude, low-frequency disasters that involved 14,172 deaths and nearly four million affected people (EM-DAT database) (Fig. 1).

At the regional level, the highest number of recorded events was in Asia with 64.4%, followed by the Americas (18.2%), Africa (13.8%), Oceania (2.2%) and Europe (1.5%). As far as individual countries are concerned, China had the highest number of events with 38 (14.2%), followed by Indonesia (*N*=29, 10.5%), Afghanistan (*N*=18, 6.5%), India (*N*=14, 5.1%), Nepal (*N*=12, 4.4%), Colombia (*N*=11, 4%), Pakistan (*N*=11, 4%), Myanmar (*N*=10, 3.6%) and Philippines (*N*=10, 3.6%) (EM-DAT database) (Fig. 1).

Out of the total number of fatalities, 66% (*N*=9,350) were concentrated in Asia, 18.4% (*N*=2,608) in Africa, 14.6% (*N*=2,076) in the Americas and the remaining 0.8% (*N*=114) and 0.2 % (*N*=24) in Oceania and Europe, respectively. Countries with highest number of human losses were China, with approximately one fifth of the total (23.8%, *N*=3,374), followed by Philippines with 9.1% (*N*=1,283), 7.9% in Sierra Leone (*N*=1,118), 7.0% in Indonesia (*N*=998), 6.3% in Afghanistan (*N*=886), 5.3% in Colombia (*N*=758) and 4.6% in India (*N*=657) (EM-DAT database) (Fig. 1).

Single events with highest number of losses occurred in China (August 8, 2010: 1,471 fatalities), Philippines (February 2006: 1,126 fatalities in the disaster of Leyte), Sierra Leone (August 2017: 1,102 deaths) and Uganda (March 2010: 388 fatalities and in 2015, there were 350 deaths in the El Cambray II landslide) (EM-DAT database) (Fig. 1).

1.2 Science, technology and policymaking

Historical and contemporary consequences of disasters provide a sound evidence base for disaster risk reduction. Thereby, strategies should be directed towards integrated disaster risk management, alongside integrated disaster risk research. Thus, moving towards integrated research on disaster risk has allowed the establishment of transdisciplinary

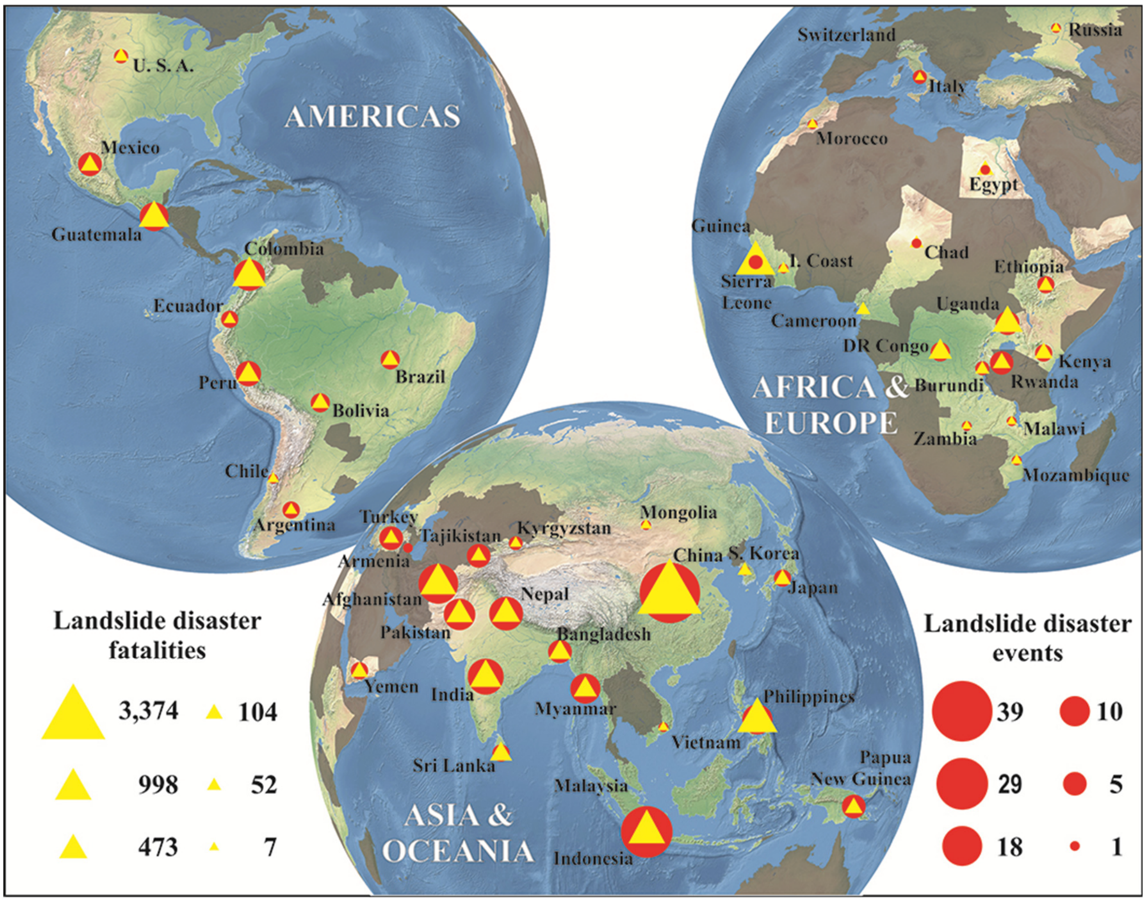

Fig. 1 Number of high-magnitude, low-frequency landslide disasters and associated fatalities around the globe from 2005 to 2019. **Source:** EM-DAT database.

alliances at different scales, including all relevant stakeholders, from grassroots to policymakers, to address the challenges publicised by international agendas such as the Sendai Framework for Disaster Risk Reduction (SFDRR) (UNISDR 2015), the Sustainable Development Goals (UN 2015) and the Climate Change Agreement (UNFCC 2015).

Among the four priorities of the SFDRR, the first priority, understanding disaster risk, stresses that disaster risk management policies and practices should be based on an understanding of disaster risk in all its spheres of vulnerability, capacity, exposure of persons and assets, hazard characteristics and the environment (UNISDR 2015). Therefore, at the national and local levels, disaster risk information should be provided periodically and on a real-time basis, with the support of geospatial information technology to enhance measurement, collection, analysis and dissemination of data. Location-based disaster risk information, including risk maps, should be available for decision makers, the general public and communities at risk through use of geospatial information technology. On the global and regional levels, such endeavours should also identify research and technology gaps and provide recommendation priority areas for research in disaster risk reduction (UNISDR 2015).

Along these lines, landslide and other types of hazards and disaster risk research have immensely benefited from geospatial information technology such as popular Geographical Information Systems (GIS) and remote sensing techniques. Various techniques have been applied to improve our understanding of landslide dynamics, provide key instrumentation and monitoring data, assess landslide hazards and risks and map areas affected by landslide disasters (Dai and Lee 2002; Berardino et al. 2003; Canuti et al. 2004; Cheng et al. 2004; Ayalew and Yamagishi 2005; Bai et al. 2009; Pradhan 2010; Niethammer et al. 2012; Kosolapov et al. 2018; Bilasco et al. 2019; Borrelli et al. 2019; Melis et al. 2020; Eker and Aydin 2021).

Central to this task, the 21st century has witnessed the progressive incorporation of Unmanned Aerial Vehicles (UAVs), commonly known as drones, as one of the major low-cost tools to gain a better understanding of hazards dynamics but also to address significant issues of disaster risk and disaster response. Landslide research has been no exception. Consequently, this paper aims to analyse the use of UAVs by the international landslide research community for disaster risk reduction and disaster risk management through a systematic literature review.

In an attempt to recognise the evolution of the use of UAVs for landslide disaster risk research and disaster risk management on a global scale and to identify research gaps, this systematic literature review examines related peer-reviewed published literature. This endeavour is not intended as a comprehensive analysis of the techniques and use of UAVs for landslide hazard assessment per se but rather as a recognition of the contribution of drones to the different dimensions of landslide disaster risk research and disaster risk management.

The paper begins by noting the relevance of disaster risk research contributions for the implementation of initiatives and strategies concerning disaster risk management. It will then provide background information and current applications of drones in the field of hazards and risk. The third section is concerned with the method, which included a systematic peer-review literature of journals within the ISI Web of Science and SCOPUS. The final section, where results are presented, reflects on the extent to which existing publications of UAVs have contributed to landslide disaster risk research.

2 Unmanned Aerial Vehicles (UAV): Background information

2.1 Origins and significance

Technological advancement of UAV has made impressive progress in recent years, nonetheless, this cannot be regarded as a new development, as it resulted from the evolution of certain technologies being experimented with throughout the 20th century (Colomina and Molina 2014). According to Valavanis (2007), UAVs appeared in 1917 during World War I, where they were put to military uses. However, he posited that UAVs had their origins approximately 2,500 years ago, when humans, by imitating birds, sought to create the first objects that could fly. Therefore, in a sense, the birth of UAVs can be tied to the developments within the field of aeronautics.

Colomina and Molina (2014) suggested that this technology dates back specifically to 1916, with the Wright Brothers and their flying machine, and their initial prototype was modified and advanced by the military actions that arose around 1930. Significant progress was made regarding the use of drones for espionage, terrain recognition and mapping. Likewise, Nonami et al. (2010) highlighted the relevance of the Vietnam War, the Cold War and the Gulf War in adding to the development of UAVs, increasing their use in military tactical operations.

Undoubtedly, the technological makeup of UAV equipment during the first half of the 20th century was not nearly as complex as the drones we are familiar with today. Currently there are various versions of UAVs whose use depends to a large extent on the objectives assigned to it. UAVs have the ability to acquire aerial images that can then be useful for spatial analysis of broad swathes of territory through geospatial techniques. As a result, UAVs are included within the field of remote sensing. Indeed, UAV equipment for military use remains the most advanced in terms of technology, particularly the time of autonomy and the ability to carry large sensors.

UAVs and associated data collection have become great assets for the general population along with the use of GIS. They are put to everyday uses to collect, manage, analyse and map compiled information. This has given a greater significance to geospatial studies, such as photogrammetry and remote sensing, increasing the possibility of developing studies with a different spatial-temporal basis (Colomina and Molina, 2014). Nonetheless, there are a series of advantages and limitations that should be considered when using UAVs (Table 1).

With regard to their applications, UAVs have been widely studied in various fields of knowledge, geosciences being among the most prominent. Numerous studies have found UAVs to be a useful tool for data acquisition in areas such as agriculture, forestry, architecture, archaeology, civil engineering, photogrammetry, environmental studies, geophysics, geology, geomorphology, geography and urban studies (Eisenbeiss 2009; Colomina and Molina 2014; Cigna 2018; Singh 2018 and Niedzielski 2018).

In the specific area of disaster response, several investigations have determined that the use of UAVs is fundamental not only for post-disaster analysis but for assessing pre-disaster conditions, in other words, for predicting and describing disaster risk (Giordan et al. 2017; Nikolakopoulos and Koukouvelas 2017; Giordan 2018). In this regard, the primary value of UAV technology has been its efficiency in recording aerial images for the generation of cartographic products that can be used, well in advance, in the analysis of hazards, exposure, and vulnerability, in addition to the assessment of disaster impact.

2.2 Classification

For Dalamagkidis (2015) UAV is an unmanned

Table 1 Advantages and limitations of the use of UAVs for hazard and disaster risk research

Advantages	Sources	Limitations	Sources
UAVs can be used under high-risk circumstances without endangering human life in remote areas	Boccali et al. 2017; Nikolakopoulos et al. 2018	There is limited UAV sensor payload in weight and dimension	Carvajal et al. 2011; Nikolakopoulos and Koukouvelas 2017
UAVs can be used in areas where access is difficult and where no manned aircraft are allowed	Danzi et al. 2013; Bouali et al. 2017; Afif et al. 2019	UAVs need to acquire a higher number of images in order to obtain the same image coverage and comparable image resolution to those derived from large-format cameras	Buill et al. 2016; Fiorucci et al. 2018
UAVs can be used with multiple sensors	Stoll 2013; Koschitzki et al. 2017; Themistocleous 2018; Yaprak et al. 2018	UAVs cannot be used in cloudy and rainy weather conditions	Chou et al. 2010; Koschitzki et al. 2017; Ardi et al. 2018; Fiorucci et al. 2018
UAVs possess real-time capabilities and the ability for fast data acquisition	Ahmad et al. 2013; Barrile et al. 2017	Low-cost UAVs sensors are normally less stable than high-end sensors	Lazar et al. 2018; Ghorbanzadeh et al. 2019
UAVs are less expensive and have lower operating costs than manned aircrafts	Akcay 2015; Barlow et al. 2017; Afif et al. 2019	Low-cost UAVs are normally equipped with less powerful engines, limiting the reachable altitude	Danzi et al. 2013; Sun et al. 2019
		Low-cost UAVs are not equipped with air traffic communication equipment	Van der Sluijs et al. 2018; Menegoni et al. 2019

aircraft supported by a remote-control system. Nonetheless, different terms are used to describe UAVs. UAVs have also been referred to UAS (Unmanned Aerial System), RPV (Remotely Piloted Vehicle), RPAS (Remotely Piloted Aircraft System) or simply as 'drones'. Such terms are strongly associated with requirements and concepts used in the military or civil field. For example, the U.S. Air Force uses the acronym 'RPA' to describe the aircraft and the pilot, while 'RPAS' is used in the UK, and the Federal Aviation Administration recognizes the term 'UAS' (Dalamagkidis 2015). Moreover, it has also been pointed out that the term 'UAV' is widely used in the fields of artificial intelligence and robotics, computational science and in photogrammetry and remote sensing. Along the same lines, the term 'RPV' was first used in 1970 by the United States Department of Defense, whereas today the National Aeronautics and Space Administration (NASA) uses 'ROA' and 'RPA' (Eisenbeiss 2009). Certainly, the use of the concept, in legal terms, will depend largely on the aeronautical authorities of each country, as well as the regulations and laws established for each case.

There are several types of UAV classifications. These vary according to factors such as shape, weight, operational altitude, type of airspace used, autonomy, military use and others. Valavanis (2015) suggested that the primary classification pertains to the weight of the aircraft (see Table 2). According to this classification, most of the equipment used for scientific research is classified into the *micro* or *mini* categories, since very often equipment heavier than 25 kg requires specific permits for use, along with an operator's license.

Additionally, equipment used in the scientific field includes UAVs with rotors (4 or 8 motors) or fixed wings; both versions possess well-defined qualities for their use, which will depend largely on the objectives of the investigation.

UAVs are also classified in terms of take-off and landing configuration: Horizontal Take-off landing (HTOL) and Vertical Take-off landing (VTOL) (Hassanalian et al. 2017). VTOL posse an advantage over the HTOLs when it comes to the aircraft floating or staying stable in flight, however, it also presents limitations as cruising speed is lower than HTOL, and therefore, they are not considered for long distance missions in which higher speed is required. VTOL equipment is widely used due to its ability to take off vertically. Development of equipment combining the capabilities of both types has been sought. Thus, various configurations have been created depending on the size of the UAV equipment. In equipment heavier than 2 kg, 4 hybrid configurations are available, namely tilt-rotor, tilt-wing, tilt-body and ducted fan UAV.

For most commercial equipment of the type of micro drones, which are characterised by less than 2 kg of weight, configurations include fixed-wing, flapping wing, tilt-rotor, ducted fan and rotary wing. The latter, among the best known and used internationally, are also subdivided according to the number of engines, for example, twincopter, tricopter, quadrotor, hexacopter, octocopter, etc.

In the analysis carried out in this work, it was observed that the use of commercial, VTOL equipment with a rotary wing configuration predominated.

2.3 Characteristics and sensors

As mentioned earlier, commonly used equipment for scientific investigations is classified as micro or mini, since most UAVs involved in these investigations have an average weight between 1 and 25 kg, a range less than 10 km and a flight ceiling close to 500 m (Van Blyenburgh 2006). The autonomy time of the equipment can vary between 15 to 90 min depending on batteries, as well as type of equipment being used. A good example of maximum

Table 2 UAV categorization for differentiation of existing systems. Source: Van Blyenburgh (2006).

Type	Mass (kg)	Range (km)	Flight alt. (m)	Endurance (h)
Micro	< 5	< 10	≤ 500	≤ 1
Mini	< 20-150[a]	< 10	150-300 [a]	≤ 2
Tactical				
Close range (CR)	25-150	10–30	3,000	2-4
Short range (SR)	50-250	30-70	3,000	3-6
Medium range (MR)	150-500	70-200	3,000	6-10
Low altitude long endurance (LALE)	500-1,500	> 500	3,000	> 24
Medium altitude long endurance (MALE)	1,000-1,500	> 500	3,000	24-48

Note: a = varies according to the legislation of each country flight time is fixed-wing SenseFly eBee X RTK. This type of equipment, with various degrees of flight autonomy, has been used in several studies where flight missions covering very large areas are required (Dall'Asta et al. 2016; Harder et al. 2016; Kraaijenbrink et al. 2016; Lambiel et al. 2017).

Similarly, the choice of equipment depends on the area to be examined and the scale of work. Fixed-wing equipment allows for coverage of larger areas, unlike the propeller-based models. Nonetheless, the latter can obtain better-quality oblique images.

The types of sensors also vary. They can be optical (DJI equipment, EVO, Yuneec, SenseFly eBee), multispectral (MAPIR Camera, Parrot SEQUOIA), radar, LiDAR (RIEGL Vux - 1UAV, VelosUAV, OnyxStar Xena) or those that include thermal cameras (FLIR Duo Pro R, DJI Zenmuse XT, Workswell WIRIS® Pro). Efforts are currently being made to add other types of sensors in order to extract more information about different phenomena.

2.4 Applications

UAVs are used in a diverse array of research studies and in many different disciplines. UAVs have been the subject of studies on agriculture (Tekin and Fornale 2019), forestry and fires (Merino et al. 2015), archaeology and cultural heritage (Themistocleous et al. 2017), environmental sciences (Jayaweera et al. 2019), wildlife (Zmarz et al. 2018), geomorphology, geology and geophysics (Walter et al. 2018).

Within the natural hazards field, there are several studies developed to address the characteristics and dynamics of floods (Murphy et al. 2016; Serban et al. 2016; Izumida et al. 2017; Cescutti et al. 2018; Langhammer and Vackova 2018; Yalcin 2018; Leal-Alves et al. 2020), earthquakes and tsunamis (Li et al. 2011; Nedjati et al. 2016; Vollgger and Cruden 2016; Dominici et al. 2017; Valkaniotis et al. 2018; Mavroulis et al. 2019; Koukouvelas et al. 2020), fires (Merino et al. 2012), volcanic processes (Mori et al. 2016; Thiele et al. 2017; Darmawan et al. 2018; Favalli et al. 2018; De Beni et al. 2019; Kazahaya et al. 2019) and landslides, which are the object of the present study (Stumpf et al. 2013; Lucieer et al. 2014; Barlow et al. 2017; Tanteri et al. 2017; Chang et al. 2018; Comert et al. 2018).

Some of the reasons that justify the use of UAVs in studies within the field of Earth sciences include rapid image accessibility (post-disaster events), low-cost compared with satellite imagery, access to difficult areas or under high-risk circumstances, best option to acquire images of small areas with higher pixel resolution, easy operation, possibility of mounting different types of sensors, transportation convenience without the need for large vehicles, among some other aspects.

3 Methodology

A systematic search approach was used to seek out published, peer-reviewed investigations focused on the use of UAVs for landslide research on a global scale (Fig. 2).

Originally the search strategy was to review 20 years of literature, although in the end, our focus was limited to the period between 2000 and 2019. However, since the major publications on this topic started in 2005, the timeframe was set up as 2005 to 2019. Aiming at analysing consistent peer-reviewed studies, only publications in English were considered. Owing to the systematic nature and comprehensiveness of databases, searches were undertaken in the main bibliographic repositories 'ISI Web of Science' and 'SCOPUS'. Initial results were screened to fit into this study's research plan in two phases: first, title and abstract, and second, full text. Articles that met the inclusion criteria in the first phase were reviewed at the full text phase (Fig. 2).

Inclusion criteria of the papers analysed included peer-reviewed publications during the period January 2005 and December 2019, with a global geographic scope and containing the terms 'UAV', 'RASP', 'drone' and 'unmanned', in addition to 'landslide', 'mass movement', 'slope failure', 'mass wasting', 'slope instability', 'slope processes', 'unstable slope', 'avalanche', 'rock-fall' and 'rock-slide'. Landslide-related terms were added to exclude all publications concerning study by use of UAVs related to other types of hazards such as earthquakes, floods, forest fires, etc. (Fig. 2).

Based on the search strategy and inclusion criteria, 333 publications were identified within the ISI Web of Science, whereas in SCOPUS 398 articles met the conditions. After manual and automatic deduplication, a total of 241 publications (191 ISI Web of Science and 50 SCOPUS) were included in this study (Fig. 2).

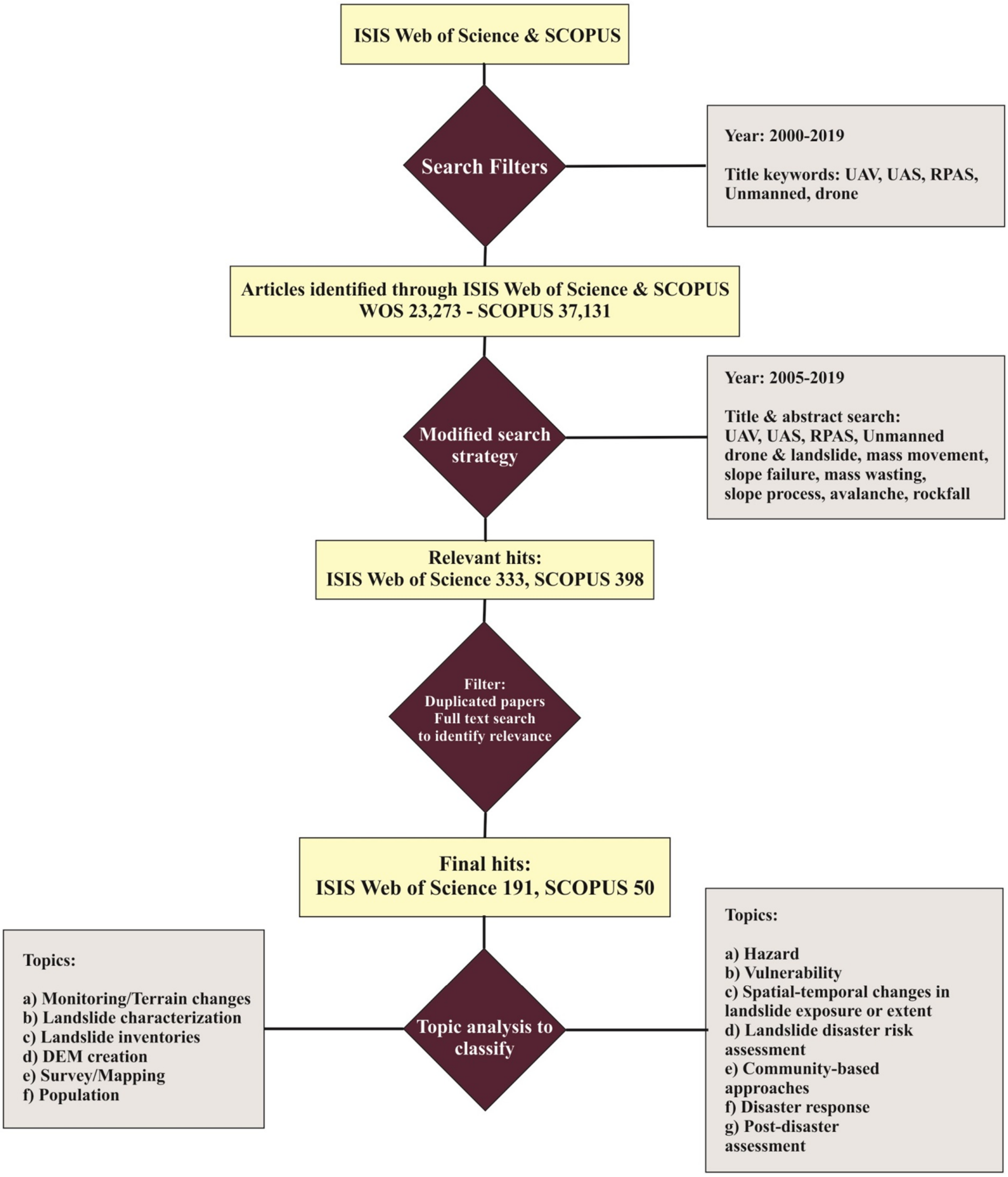

Fig. 2 Systematic mapping procedure.

The following general categories of variables were extracted from the articles to create a structured matrix of information for further analysis of knowledge gaps and knowledge clusters: (1) year of publication; (2) type of publication (journals or books); (3) Global Citation Score (for ISI Web of Science); (4) list of authors; (5) main scientific field; (6) list of institutions; (7) countries; (8) country where research was carried out; (9) topics of the research (hazard, vulnerability, risk assessment, response and post-disaster assessment); and (10) method of analysis (monitoring, landslide inventory, DEM, landslide characterization and survey/ mapping).

4 Results

4.1 General description

Results from the search process showed that 241 publications were selected, out of which 191 were included in the ISI Web of Science and 50 in SCOPUS. Identified as selection factors were number of publications per year, the publication's influence, a focus on disaster risk research, countries of publication and disciplines studying the use of UAVs for landslide disaster risk research and management. The same procedure was followed by those publications included in SCOPUS by using Excel, except in the case of the Global Citation Score of authors.

Of the total number of publications (*N*=241), 24 were published from 2005 to 2014 and 217 between 2015 and 2019. Despite the fact that there were no records for the years 2006, 2007 and 2008, there was a noticeable development in these investigations starting in 2015 (*N*=14) showing an ascending trend until 2019 when 29% of the total publications were produced (*N*=70) (Fig. 3).

At the regional level, authors from European countries published 62.2% of the total articles (37.2% in collaboration with institutions from the same continent and 25% from other regions), while those from Asia participated in 48.1% (35.1% with institutions from the same region and 13% with the participation of authors from other continents). Authorship from the Americas accounted for 17.8% (12.9% in association with institutions from the same region and 4.9% from other geographical areas), while Oceania and Africa published 1.7% and 0.8%, respectively, in partnership with institutions from other global regions.

Literature analysed from the period 2005 to 2019 was shown to include 153 journal articles (63.5%), 87 conference proceeding papers (36.1%) and one review paper (0.4%). The largest number of studies were published in the journal *Landslides* (*N*=29), followed by the *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* (ISPRS Archives) (*N*=15), *Remote Sensing* (*N*=11), *Natural Hazards and Earth System Sciences* (*N*=9) and *Engineering Geology* (*N*=8). All of them included records published from 2015 to 2019 (Table 3).

Fields of research associated with the publications included civil engineering (*N*=35), geology (*N*=34), earth sciences (*N*=28) and geography (*N*=22). Most of these studies are from geosciences, environment-related disciplines and geospatial information science and new technologies (Fig. 4). It is worth mentioning that among these disciplinary areas, hazard evaluation approaches predominate.

Of the total number of publications, 81.3% (*N*=196) were focused on hazards, 17% on post-disaster assessment (*N*=41), 0.8% on disaster response activities (*N*=2), 0.4% on community-based approaches (*N*=1) and 0.4% on spatial-temporal changes in landslide exposure or extent (*N*=1). No publications were concerned with vulnerability-related aspects or landslide disaster risk assessment (Table 4).

4.2 Hazards

Out of the 241 publications reviewed, 81% (*N*=195) had studies on the use of UAVs to carry out

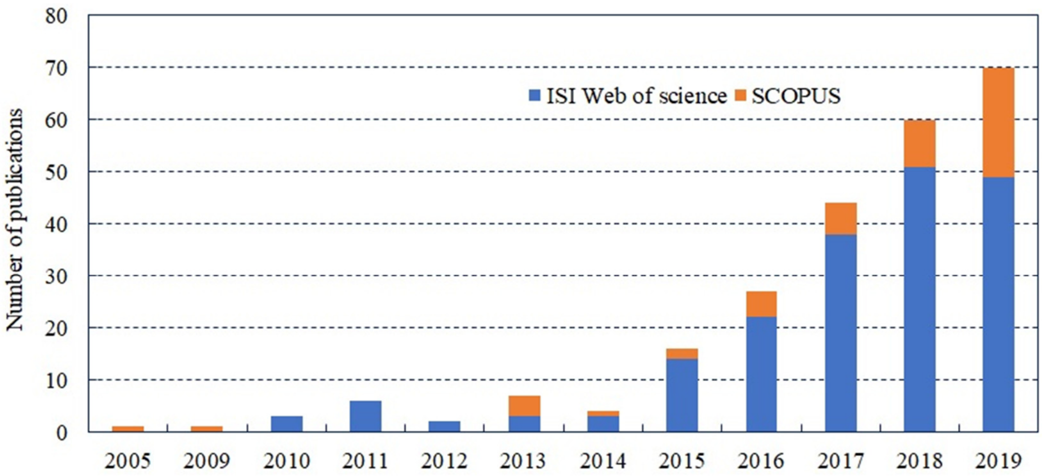

Fig. 3 Temporal distribution of published investigations.

Table 3 Publications with the most articles issued

Journal	Number of records
Landslides	29
International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences (ISPRS Archives)	15
Remote Sensing	11
Natural Hazards and Earth System Sciences	9
Engineering Geology	8
ISPRS International Journal of Geo-Information	6
Journal of Mountain Science	6
Geomorphology	5
Geosciences	5
Bulletin of Engineering Geology and the Environment	4
Environmental Earth Sciences	4
Geomatics Natural Hazards & Risk	4
Advancing Culture of Living with Landslides, vol 2: Advances in Landslide Science	3
International Conference on Unmanned Aerial Vehicle in Geomatics (UAV-G)	3
International Journal of Remote Sensing	3
IOP Conference Series: Earth and Environmental Science	3
ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences	3
Journal of Applied Remote Sensing	3
Landslides and Engineered Slopes: Experience, Theory and Practice, vols 1-3	3
Earth Resources and Environmental Remote Sensing/GIS Applications IX	2
Earth Surface Dynamics	2
Earthquake Spectra	2
Engineering Geology for Society and Territory, vol 2: Landslide Processes	2
First Break	2
Geoenvironmental Disasters	2
IGARSS 2018 - 2018 IEEE International Geoscience and Remote Sensing Symposium	2
MATEC Web of Conferences	2
Natural Hazards	2
Progress in Earth and Planetary Science	2
Sensors	2
XXIII ISPRS Congress, Commission V	2
Journals with 1 Publication	90
Total	241

aerial photographic surveys to produce orthophotos (Afif et al. 2019; Cardenal et al. 2019; Nikolakopoulos et al. 2019) which identified geomorphological and morphometric attributes of mass movement processes as well as symptoms of hillslope instability such as ground deformation, cracks, formation of escarpments and changes in the morphology of the terrain or in the volume of displaced or moving masses (Rothmund et al. 2015; Busa et al. 2019; Karantanellis et al. 2019). Oblique photos, video and point cloud generation records were also among the main topics of this type of application (Francioni et al. 2015; Rossi et al. 2016; Pfeiffer et al. 2019).

In the study of aerial images produced by UAVs, 48.5% of the publications (*N*=117) emphasized landslide characterisation: area, length, slope and volume were noted from the images and information obtained in the field (Shi et al. 2015; Chang et al. 2018; Chudy et al. 2019). A total of 51% (*N*=122) of the publications studied UAVs in relation to digital terrain models for morphometric and susceptibility analyses and for monitoring changes or the landslide dynamics of active processes (Tanteri et al. 2017; Yeh et al. 2018; Sun et al. 2019). These models were both digital su rface models (DSM) and terrain models (DTM) with pixel sizes smaller than one meter. They were also used to produce high-resolution 3D views of the sites investigated.

Publications that addressed issues such as monitoring (or changes in the terrain) and inventory creation only accounted for 27.4% (*N*=66) and 1.7% (*N*=4) of the total. In the first case, studies were mainly focused on monitoring landslide dynamics (Stumpf et al. 2013; Barlow et al. 2017; Obanawa and Hayakawa 2018), the evolution of landforms (Lucieer et al. 2014; Rau et al. 2014; Hsieh et al. 2016; Comert et al. 2018; Ghorbanzadeh et al. 2019; Horacio et al. 2019; Li et al. 2019), as well as the processes of removal and accumulation of soil or rock, characterisation of joints, identification and dynamics

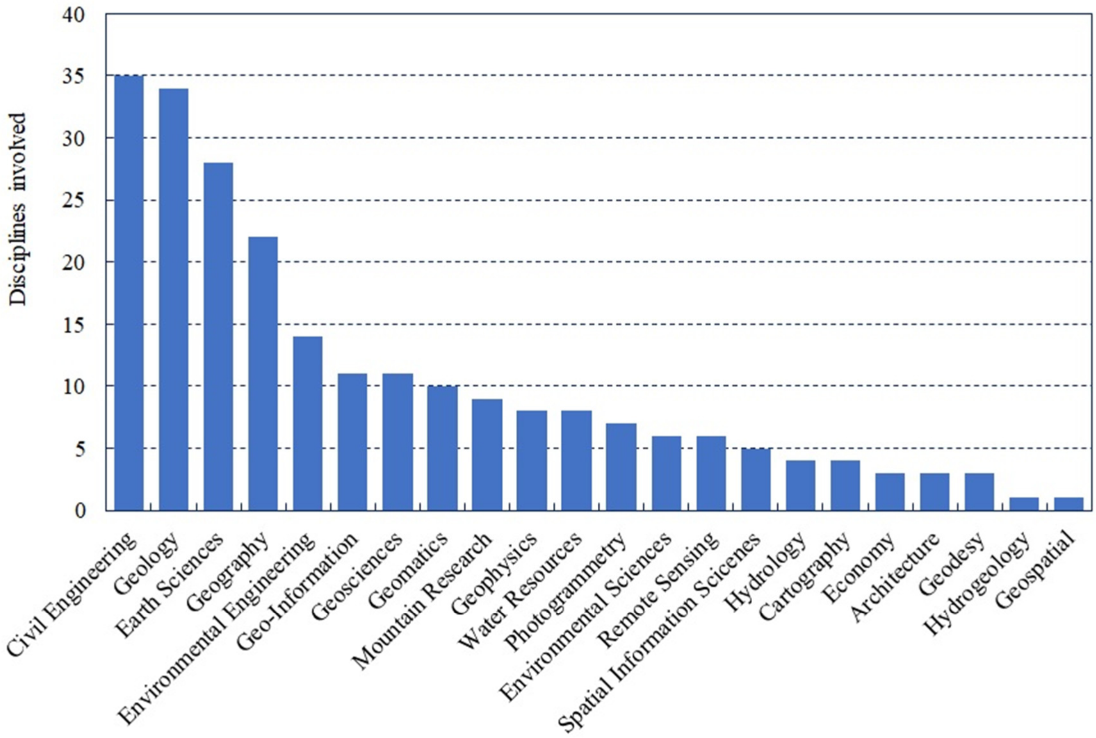

Fig. 4 Disciplines engaged in landslide disaster risk research using UAVs.

Table 4 Methodological approaches and landslide-related research focus of publications

Methodological approach/ topics of research	Hazard	Vulnerability	Spatial-temporal changes in landslide exposure or extent	Landslide disaster risk assessment	Community based approaches	Disaster response	Post-disaster assessment
Monitoring, terrain changes	67	0	0	0	0	1	5
Landslide characterization	117	0	1	0	0	2	29
Landslide inventories	4	0	0	0	0	1	11
DEM	122	0	0	0	0	1	21
Surveying, mapping	197	0	1	0	1	2	39
Population	0	0	0	0	0	0	0

of fault fractures, fissures and scarps and changes in the relief in comparison with elevation models or point clouds (Stumpf et al. 2013; Francioni et al. 2015; Letortu et al. 2018). In most cases, the work was done by combining different types of spatial data (satellite images, LIDAR, digital elevation models, historical photographic records, etc.) with UAV images.

From the total papers reviewed, 224 (92.9%) of studies used only one drone to carry out the related research, while the remaining 17 (7.1%), reported the use of more than one drone. Out of the 185 types of UAVs that were included in the analysed literature, 164 were micro, 20 were mini and only one was a medium UAV.

Publications featuring models of UAVs were only reported in 62.2% of the contributions. DJI Phantom equipment was the most used (Table 5). RGB cameras were adapted to the drones in 95% of the cases, followed by LIDAR (3%), multispectral cameras (1.5%) and a magnetometer.

4.3 Vulnerability

Despite the term 'vulnerability' frequently being used in landslide disaster risk context to refer to physical fragility of buildings, this study, much like Alcántara-Ayala (2021), understands the notion of vulnerability as the set of socioeconomic, cultural,

Table 5 Models of UAVs used in the reviewed publications

UAVs models	Percentage (%)
DJI Phantom 4 pro	11.8
DJI Phantom 2	8.7
DJI Phantom 3 Pro	8.1
DJI Phantom 3 Adv	6.2
Asctec Falcon 8	5.6
DJI phantom 4	5.0
SenseFly eBee	3.7
DJI Mavic pro	2.5
F1000 Feima Robotics	2.5
DJI Phantom 3 Standard	2.5
DJI S1000	1.9
DJI Inspire 1	1.9
Mikrokopter Okto XL	1.9
DJI Inspire 2	1.9
Quest 300	1.9
DST drone Saturn	1.9
Other models (42)	32.3

political, institutional and environmental conditions or processes which increase the likelihood of individuals, groups of people/communities, assets or systems of being negatively impacted by landslides. Therefore, owing to the evident linkages of vulnerability studies with the social conditions of the exposed population to the potential occurrence of landslides, this issue has not yet been addressed from the perspective of UAV use.

4.4 Spatial-temporal changes in landslide exposure or extent

Only one publication focused on evaluating urban growth and associated spatial-temporal exposure of buildings and people in a mountainous area highly susceptible to landslides (Garnica and Alcántara 2017).

4.5 Landslide disaster risk assessment

Owing to the positioning of landslide disaster risk in the interface between societies and the environment, on the edge of socio-environmental processes within specific territorial contexts, landslide disaster risk assessment involves qualitative and/or quantitative approaches to identify the multidimensional nature of disaster risk including landsliding characterisation and estimating conditions of exposure and vulnerability. When combined, these conditions could negatively affect communities, livelihoods, assets and the environment (Alcántara-Ayala 2016). This conceptual approach to integrated landslide disaster risk research has not been widely represented in the scientific literature, which is not surprising given the lack of publications that include the use of UAVs related to this kind of approach.

4.6 Community-based approaches

Lin et al. (2019) is the only article suggesting the possibility of using UAV images to encourage education and community mapping in regions affected by landslides.

4.7 Disaster response

Two articles were found regarding the use of UAVs in disaster response. De Cubber et al. (2014) deployed a UAV in the Balkans in spring 2014 to work with traditional relief workers in damage assessment, area mapping, visual inspection and re-localizing the still dangerous remains of military ordnance that shifted during flooding and landslides. Likewise, in order to support decision making regarding reopening a main road, investigations of an earthquake-triggered rockfall in central Italy were carried out by Santangelo et al. (2019).

4.8 Post-disaster assessment

A total of 41 publications (17%) that covered topics of post-disaster evaluations using UAV were identified (Wen et al. 2011). These included the impact of landslide disasters along with the characterisation of landslide processes (Coe et al. 2016; Dang et al. 2016; Catane et al. 2019). Of particular relevance were 11 studies (N=4.6%) in which landslide inventories generating spatial distribution maps were developed (Yang et al. 2015; Zekkos et al. 2017; Chen et al. 2018; Saito et al. 2018).

These investigations were mostly directed towards the creation of aerial photography surveys to subsequently produce maps, orthophotos and digital elevation models. Characteristics of the landslide processes, and to a lesser extent damage or impacts on populations or roads, were also considered. Based on such experience, several authors agreed that UAVs could be regarded as very good tools for monitoring, surveys and mapping in terms of immediate response and economic thrift but also considered that lack of autonomy time, since it ranged from 15 to 45 min depending on the type of equipment used, is the most significant disadvantage, as it prevents the UAV from operating in a wide geographical area.

5 Discussion

Aligned with the SFDRR, the science and technology communities are committed to reinforcing strategies to leverage innovation and technology development for disaster risk management (UNISDR 2015), particularly through scientific assessments, synthesis of policy-relevant scientific evidence, scientific advice to decision makers and monitoring and review, along with the cross-cutting capabilities of communication and engagement and capacity development (Aitsi-Selmi et al. 2015).

The goal of this review was to gather the available evidence regarding the progress of the use of UAVs for landslide disaster risk research and disaster risk management on a global scale and to identify research gaps. We identified 241 peer-reviewed articles that investigated such outcomes: 12% of these were published in the *Landslides* journal.

This paper began by presenting the significance of landslide disasters on societies around the globe. From a technical perspective there are advantages and limitations regarding the use of UAVs for hazard and disaster risk research and disaster response (Table 1). In broad terms, it can be said that UAVs are inexpensive equipment able to reach remote sites, and in so doing, they reduce the chance of people being exposed to harm, particularly during or after a disaster. Despite being capable of producing high-resolution images, workload and time invested in the generation of cartographic products can be substantial. Nonetheless, recent investigations on their various applications suggest their unlimited potential for use in Integrated Landslide Disaster Risk Management (Alcántara-Ayala 2021).

This review showed that literature on the use of UAVs for Disaster Risk Reduction (DRR) and Disaster Risk Management (DRM), while making technological advances, deals particularly with landslide dynamics and disaster response. Among the various topics, five relatively distinctive foci were found (Table 4). Most of the studies reviewed focused on landslide hazards (81.3%), followed by post-disaster assessment (17%). Quite clearly, social aspects related to vulnerability dimensions have not been privileged so far in this type of research.

Methodologies involved included five major steps: (1) mission planning; (2) flight survey; (3) post-processing (ground control points, images) by using Structure from Motion (SfM) techniques using diverse software (Agisoft, Pix4D, Photomodeler, Contextcapture, Trimble business); (4) UAV-derived products (point clouds, orthoimages, DSM/DTM, 3D models); and (5) main areas of analysis (landslide inventories, participatory mapping, assessing losses, landslide monitoring, extraction of landslide geometrical and geomorphological features, elements exposed to landslides, emergency and early warning systems, landslide post-disaster impact analysis, landslide susceptibility mapping, landslide simulation and augmented reality).

From a natural hazards perspective, the main research contributions of published papers were mostly focused on mapping geometric or geomorphologic features (28.2%); landslide monitoring (27.4%); multitemporal analysis of landslides to analyse morphology, displacement, volumes and development of cracks (10%); landslide susceptibility in terms of hazard or risk (8.7%); landslide inventories (5.4%); landslide simulation (3.7%); reconstruction of topography (2.5) and landslide dynamics (1.7%).

According to the papers included in the review, the use of UAVs in landslide studies was considered a good alternative to traditional techniques as UAVs are inexpensive, lightweight, compact, and capable of reaching difficult-to-access areas, integrating different sensors and producing high-resolution imagery suitable for temporal surveys and post-disaster emergencies. Among the principal drawbacks of UAVs are the lack of operability under particular weather conditions (wind, rainfall), they only have a limited area of coverage and a short flight range, do not perform well in dense vegetation, have a limited autonomy time and are hampered by aerial flight regulations.

Given the technical nature of UAVs and their capabilities for survey and mapping, it is not surprising that a great percentage of the published literature deals with identifying hazards and disaster response. Additionally, one potential reason for such an outcome could be the prevalence of hazard-centric research undertaken mostly from mono-disciplinary perspectives. Likewise, despite the encouraging results of how the SFDRR takes care of its main priorities, there is still a wide misunderstanding of the notion of disaster risk; yet often, disaster risk and disasters are seen as synonymous with hazards, lacking a comprehensive understanding of the processes involved in the social construction of risk (Lavell and Maskrey 2014; Oliver-Smith et al. 2016; Satake et al. 2018). Undoubtedly, "Governance arrangements, risk assessments, early warning systems, and other institutional and technical capacities still concentrate on natural hazards" (Briceño 2015). In the same vein, efforts remain unbalanced as disaster risk governance still focuses on disaster response and recovery (Lavell and Maskrey 2014; Briceño 2015).

6 Concluding Remarks

Although the use of drones in DRR is a relatively new field of study and the literature available is limited, results from this systematic review map focused on the application of UAVs in landslide disaster risk research. Disaster risk management on a global scale revealed that there have been increasing numbers of publications on the subject in the last fifteen years, but especially in the last lustrum.

Evidence for the identification of several knowledge gaps was found. Geographical representation is not well balanced. At a regional level, research has been conducted mostly in Europe and by developed countries, while most of the articles were published in China, Italy and the United States. Mapped literature has also shown the current state of the DRR landslide research base and the wide range of disciplines involved.

The existing evidence to date suggests that although several studies have focused on landslide hazards and response, it would be desirable to conduct further research to address topics associated with vulnerability, exposure and disaster risk assessment and also to further strengthen collaborations among countries and regions.

While we concur with many of these studies about the need to promote real-time access to reliable data, as that produced by UAVs after, for example, a landslide or a disaster occurs, in situ information regarding communities and property/assets at risk is also needed for analysis and dissemination of data to be used by different stakeholders to reduce disaster risk.

The role of science and technology in the DRR policy arena is still insufficient, and more detailed and cost-effective research is needed to identify key lessons and policy challenges, as well as strengthening capacity building at a local level. Based on the analysis presented here, it was found that research related to the use of UAVs for disaster risk reduction can be considered a cost-effective approach whose future progress will have the utmost relevance in developing nations where funding available for science is limited.

The understanding of landslide disaster risk and the contributions provided by landslide research are highly valuable for strengthening disaster risk reduction initiatives. Owing to the complexity of landslides, efforts should be made to address all aspects of disaster risk. Therefore, this study advocates for more partnerships between the natural and social sciences in the coming years, as well as other stakeholders, including communities at risk. There needs to be greater consideration of potential synergies in integrated landslide disaster risk research using UAVs, including improved understanding of disaster risk by considering hazards, vulnerability and exposure. Failure to include such approaches precludes subsequent analysis and hampers the efficacy of landslide disaster risk research for guiding DRR policy and practice.

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