ICL Contribution to Landslide Disaster Risk Reduction

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Editors

Understanding and Reducing Landslide Disaster Risk

Volume 1 Sendai Landslide Partnerships and Kyoto Landslide Commitment

Springer

ICL Contribution to Landslide Disaster Risk Reduction

Series Editor

Kyoji Sassa, The International Consortium on Landslides, ICL, Kyoto, Japan

The ICL Contribution to Landslide Disaster Risk Reduction book-series publishes integrated research on all aspects of landslides. The volumes present summaries on the progress of landslide sciences, disaster mitigation and risk preparation. The contributions include landslide dynamics, mechanisms and processes; volcanic, urban, marine and reservoir landslides; related tsunamis and seiches; hazard assessment and mapping; modeling, monitoring, GIS techniques; remedial or preventive measures; early warning and evacuation and a global landslide database.

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ISSN 2662-1894 ISSN 2662-1908 (electronic)
ICL Contribution to Landslide Disaster Risk Reduction
ISBN 978-3-030-60195-9 ISBN 978-3-030-60196-6 (eBook)
https://doi.org/10.1007/978-3-030-60196-6

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

ICL and Springer created a new book series “ICL Contribution to Landslide Disaster Risk Reduction” in 2019 which is registered as ISSN 2662-1894 (print version) and ISSN 2662-1908 (electronic version). The first books in this series are six volume of books “Understanding and Reducing Landslide Disaster Risk” containing the recent progress of landslide science and technologies from 2017 to 2020.

Organizational Structure of the Fifth World Landslide Forum

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International Consortium on Landslides (ICL)
Global Promotion Committee of International Programme on Landslides (IPL-GPC), including: United Nations Educational, Scientific and Cultural Organization (UNESCO), World Meteorological Organization (WMO), Food and Agriculture Organization (FAO), United Nations Office for Disaster Risk Reduction (UNDRR), United Nations University (UNU), International Science Council (ISC), World Federation of Engineering Organizations (WFEO), International Union of Geological Sciences (IUGS), International Union of Geodesy and Geophysics (IUGG)
Kyoto University (KU), Japan Landslide Society (JLS), Japanese Geotechnical Society (JGS), Japan Society for Natural Disaster Science (JSNDS) and Japan Association for Slope Disaster Management (JASDiM)

Co-sponsors

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Foreword by Mami Mizutori

More landslides can be expected as climate change exacerbates rainfall intensity. The long-term trend of the last 40 years has seen the number of major recorded extreme weather events almost double, notably floods, storms, landslides, and wildfires.

Landslides are a serious geological hazard. Among the host of natural triggers are intense rainfall, flooding, earthquakes or volcanic eruption, and coastal erosion caused by storms that are all too often tied to the El Niño phenomenon. Human triggers including deforestation, irrigation or pipe leakage, and mine tailings, or stream and ocean current alteration can also spark landslides. Landslides can also generate tsunamis, as Indonesia experienced in 2018.

Globally, landslides cause significant economic loss and many deaths and injuries each year. Therefore, it is important to understand the science of landslides: why they occur, what factors trigger them, the geology associated with them, and where they are likely to happen.

Landslides with high death tolls are often a result of failures in risk governance, poverty reduction, environmental protection, land use and the implementation of building codes. Understanding the interrelationships between earth surface processes, ecological systems, and human activity is the key to reducing landslide risk.

The Sendai Framework for Disaster Risk Reduction, the global plan to reduce disaster losses adopted in 2015, emphasizes the importance of tackling these risk drivers through improved governance and a better understanding of disaster risk.

One important vehicle for doing that is the Sendai Landslide Partnerships 2015–2025 for global promotion of understanding and reduction of landslide risk facilitated by the International Consortium on Landslides (ICL) and signed by the leaders of 22 global stakeholders, including the UN Office for Disaster Risk Reduction (UNDRR), during the Third UN World Conference on Disaster Risk Reduction in Sendai, Japan.

The Sendai Landslide Partnerships—featured on the Sendai Framework Voluntary Commitments online platform—helps to provide practical solutions and tools, education, and capacity building, to reduce landslide risks.

The work done by the Sendai Partnerships can be of value to many stakeholders including civil protection, planning, development and transportation authorities, utility managers, agricultural and forest agencies, and the scientific community.

UNDRR fully supports the work of the Sendai Landslide Partnerships and ICL and looks forward to an action-oriented outcome from the 5th World Landslide Forum to be held in November 2020 in Kyoto, Japan. Successful efforts to reduce disaster losses are a major contribution to achieving the overall 2030 Agenda for Sustainable Development.

Mami Mizutori
United Nations Special Representative of the
Secretary-General for Disaster Risk Reduction

Foreword by the Assistant Director-General for the Natural Sciences Sector of UNESCO for the Book of the 5th *World Landslide Forum*

As the world slowly recovers from the COVID-19 global pandemic, and looking back at the way this crisis developed, it becomes evident that as a global community we were not prepared for an event of this scale. Although not commonly perceived as such, biological hazards such as epidemics are included in the Sendai Framework for Disaster Risk Reduction 2015–2030. In that sense, the preparedness approach for a pandemic is very similar to that of a geophysical natural hazard such as landslides.

Although natural hazards are naturally occurring phenomena, the likelihood of their occurrence and of associated disasters is rising. Climate change, urban pressure, under-development and poverty and lack of preparedness are increasingly transforming these natural hazards into life-threatening disasters with severe economic impacts. Therefore, Disaster Risk Reduction (DRR) is gaining momentum on the agenda of the UN system of Organizations including UNESCO. While the Sendai Framework for Disaster Risk Reduction 2015–2030 is the roadmap for DRR, other global agendas including the Sustainable Development Goals, the Paris Climate Agreement and the New Urban Agenda have targets which cannot be attained without DRR.

In shaping its contribution to those global agendas, UNESCO is fully committed in supporting its Member States in risk management, between its different mandates and disciplines and with relevant partners. The International Consortium on Landslides (ICL) is UNESCO's key partner in the field of landslide science. The Organization's support to the Consortium is unwavering. Since ICL was established in 2002, the two organizations have a long history of cooperation and partnership and UNESCO has been associated with almost all of ICL activities. I am very glad that ICL and UNESCO are mutually benefitting from their collaboration.

The 5th World Landslide Forum (WLF5) is expected to represent a milestone in the history of landslide science particularly for scientists and practitioners. One of the major outcomes of WLF5 will be the Kyoto 2020 Commitment for global promotion of understanding and reducing landslide disaster risk (KLC2020). This commitment is expected to strengthen and expand the activities of the Sendai Landslide Partnership 2015–2025. With UNESCO already engaged as a partner, the adoption of this international commitment will raise global awareness on landslide risk and mobilize wider partnerships that draw together stakeholders from all levels of society, across different regions, sectors and disciplines.

It is my great pleasure to congratulate the organizers for holding this event and assure you that UNESCO is fully committed in contributing to its success. As part of that contribution, our Organization is proud to host a session on landslides and hazard assessment at UNESCO-designated sites such as natural World Heritage sites, biosphere reserves and UNESCO Global Geoparks. This session aims to assess landslide impacts on our shared cultural and natural heritage, providing the best opportunity to generate public awareness and capacity development for landslide disaster reduction.

I am confident that WLF5 will contribute to further advance the knowledge of both scientists and practitioners regarding landslide disaster risk reduction. This book paves the way for the science, knowledge and know-how which will feature in the deliberations of the Forum. UNESCO commends all of the contributors to this publication. I look forward to an enhanced collaboration between UNESCO and ICL in future activities and undertakings.

Shamila Nair-Bedouelle
Assistant Director-General for Natural Sciences
UNESCO

Preface

Understanding and Reducing Landslide Disaster Risk

Book Series: ICL Contribution to Landslide Disaster Risk

The International Consortium on Landslides (ICL) was established in pursuance of the 2002 Kyoto Declaration "Establishment of an International Consortium on Landslides," with its Statutes adopted in January 2002. The Statutes define the General Assembly of ICL as follows: in order to report and disseminate the activities and achievements of the Consortium, a General Assembly shall be convened every 3 years by inviting Members of the International Consortium on Landslides, individual members within those organizations, and all levels of cooperating organizations and individual researchers, engineers, and administrators. The General Assembly developed gradually prior to, during and after its first meeting in 2005. In the light of the 2006 Tokyo Action Plan, the Assembly was further facilitated at, and following the First World Landslide Forum held in November 2008. On the occasion of each of its triennial forums, ICL publishes the latest progress of landslide science and technology for the benefit of the whole landslide community including scientists, engineers, and practitioners in an understandable form. Full color photos of landslides and full color maps are readily appreciated by those from different disciplines. We have published full color books on landslides at each forum. In 2019, ICL created a new book series "ICL Contribution to Landslide Disaster Risk Reduction" ISSN 2662-1894 (print version) and ISSN 2662-1908 (electronic version). Six volumes of full color books *Understanding and Reducing Landslide Disaster Risk* will be published in 2020 as the first group of books of this series.

The Letter of Intent 2005 and the First General Assembly 2005

The United Nations World Conference on Disaster Reduction (WCDR) was held in Kobe, Japan, 18–22 January 2005. At this Conference, ICL organized session 3.8 "New international Initiatives for Research and Risk Mitigation of Floods (IFI) and Landslides (IPL)" on 19 January 2005 and adopted a "Letter of Intent" aimed at providing a platform for a holistic approach in research and learning on 'Integrated Earth System Risk Analysis and Sustainable Disaster Management'. This Letter was agreed upon and signed, during the first semester of 2005, by heads of seven global stakeholders including the United Nations Educational, Scientific and Cultural Organization (UNESCO), the World Meteorological Organization (WMO), the Food and Agriculture Organization of the United Nations (FAO), the United Nations International Strategy for Disaster Risk Reduction (UNISDR-currently UNDRR), the United Nations University (UNU), the International Council for Science (ICSU-Currently ISC), and the World Federation of Engineering Organizations (WFEO).

The first General Assembly of ICL was held at the Keck Center of the National Academy of Sciences in Washington D.C., USA, on 12–14 October 2005. It was organized after the aforementioned 2005 World Conference on Disaster Reduction (WCDR). ICL published the

first full color book reporting on Consortium activities for the initial 3 years, 2002–2005 titled "Landslides-Risk analysis and sustainable disaster management". In the preface of this book, the Letter of Intent for Integrated Earth System Risk Analysis and Sustainable Disaster Management was introduced. Results of the initial projects of the International Programme on Landslides (IPL) including IPL C101-1 Landslide investigation in Machu Picchu World Heritage, Cusco, Peru and previous agreements and MoU between UNESCO, ICL and the Disaster Prevention Research Institute of Kyoto University including UNESCO/KU/ICL UNITWIN Cooperation programme were published as well in this book.

The 2006 Tokyo Action Plan and the First World Landslide Forum 2008

Based on the Letter of Intent, the 2006 Tokyo Round-Table Discussion—"Strengthening Research and Learning on Earth System Risk Analysis and Sustainable Disaster Management within UN-ISDR as Regards Landslides"—towards a dynamic global network of the International Programme on Landslides (IPL) was held at the United Nations University, Tokyo, on 18–20 January 2006. The 2006 Tokyo Action Plan—Strengthening research and learning on landslides and related earth system disasters for global risk preparedness—was adopted. The ICL exchanged Memoranda of Understanding (MoUs) concerning strengthening cooperation in research and learning on earth system risk analysis and sustainable disaster management within the framework of the United Nations International Strategy for Disaster Reduction regarding the implementation of the 2006 Tokyo action plan on landslides with UNESCO, WMO, FAO, UNISDR (UNDRR), UNU, ICSU (ISC) and WFEO, respectively in 2006. A set of these MoUs established the International Programme on Landslides (IPL) as a programme of the ICL, the Global Promotion Committee of IPL to manage the IPL, and the triennial World Landslide Forum (WLF), as well as the concept of the World Centres of Excellence on Landslide Risk Reduction (WCoE).

The First World Landslide Forum (WLF1) was held at the Headquarters of the United Nations University, Tokyo, Japan, on 18–21 November 2008. 430 persons from 49 countries/regions/UN entities were in attendance. Both Hans van Ginkel, Under Secretary-General of the United Nations/Rector of UNU who served as chairperson of the Independent Panel of Experts to endorse WCoEs, and Salvano Briceno, Director of UNISDR who served as chairperson of the Global Promotion Committee of IPL, participated in this Forum. The success of WLF1 paved the way to the successful second and third World Landslide Forum held in Italy and China respectively.

The Second World Landslide Forum 2011 and the Third World Landslide Forum 2014

The Second World Landslide Forum (WLF2)—Putting Science into Practice—was held at the Headquarters of the Food and Agriculture Organization of the United Nations (FAO) on 3–9 October 2011. It was jointly organized by the IPL Global Promotion Committee (ICL, UNESCO, WMO, FAO, UNDRR, UNU, ISC, WFEO) and two ICL members from Italy: the Italian Institute for Environmental Protection and Research (ISPRA) and the Earth Science Department of the University of Florence with support from the Government of Italy and many Italian landslide-related organizations. It attracted 864 participants from 63 countries.

The Third World Landslide Forum (WLF3) was held at the China National Convention Center, Beijing, China, on 2–6 June 2014. A high-level panel discussion on an initiative to create a safer geoenvironment towards the UN Third World Conference on Disaster Risk Reduction (WCDRR) in 2015 and forward was moderated by Hans van Ginkel, Chair of Independent Panel of Experts for World Centers of Excellence (WCoE). In a special address to this high-level panel discussion, Irina Bokova, Director-General of UNESCO, underlined that

countries should be united to work against natural disasters and expressed commitment that UNESCO would like to further deepen cooperation with ICL. Ms. Bokova awarded certificates to 15 World Centres of Excellence.

The Sendai Landslide Partnerships 2015 and the Fourth World Landslide Forum 2017

The UN Third World Conference on Disaster Risk Reduction (WCDRR) was held in Sendai, Japan, on 14–18 March 2015. ICL organized the Working Session "Underlying Risk Factors" together with UNESCO, the Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT) and other competent organizations. The session adopted ISDR-ICL Sendai Partnerships 2015–2025 (later changed to Sendai Landslide Partnerships) for global promotion of understanding and reducing landslide disaster risk as a Voluntary Commitment to the World Conference on Disaster Risk Reduction, Sendai, Japan, 2015 (later changed to Sendai Framework for Disaster Risk Reduction). After the session on 16 March 2015, the Partnerships was signed by Margareta Wahlström, Special Representative of the UN Secretary-General for Disaster Risk Reduction, Chief of UNISDR (UNDDR), and other representatives from 15 intergovernmental, international, and national organizations. Following the Sendai Landslide Partnerships, the Fourth World Landslide Forum was held in Ljubljana, Slovenia from 29 May to 2 June in 2017. On that occasion, five volumes of full color books were published to disseminate the advances of landslide science and technology. The high-level panel discussion on 30 May and the follow-up round table discussion on 31 May adopted the 2017 Ljubljana Declaration on Landslide Risk Reduction. The Declaration approved the outline of the concept of "Kyoto 2020 Commitment for global promotion of understanding and reducing landslide disaster risk" to be adopted at the Fifth World Landslide Forum in Japan, 2020.

The Fifth World Landslide Forum 2020 and the Kyoto Landslide Commitment 2020

The Fifth World Landslide Forum was planned to be organized on 2–6 November 2020 at the National Kyoto International Conference Center (KICC) and the preparations for this event were successfully ongoing until the COVID-19 pandemic occurred over the world in early 2020. The ICL decided to postpone the actual Forum to 2–6 November 2021 at KICC in Kyoto, Japan. Nevertheless, the publication of six volumes of full color books *Understanding and Reducing Landslide Disaster Risk* including reports on the advances in landslide science and technology from 2017 to 2020 is on schedule. We expect that this book will be useful to the global landslide community.

The Kyoto Landslide Commitment 2020 will be established during the 2020 ICL-IPL Online Conference on 2–6 November 2020 on schedule. Joint signatories of Kyoto Landslide Commitment 2020 are expected to attend a dedicated session of the aforementioned Online Conference, scheduled on 5 November 2020 which will also include and feature the Declaration of the launching of KLC2020. Landslides: Journal of the International Consortium on Landslides is the common platform for KLC2020. All partners may contribute and publish news and reports of their activities such as research, investigation, disaster reduction administration in the category of News/Kyoto Commitment. Online access or/and hard copy of the Journal will be sent to KLC2020 partners to apprise them of the updated information from other partners. As of 21 May 2020, 63 United Nations, International and national organizations have already signed the KLC2020.

Call for Partners of KLC2020

Those who are willing to join KLC2020 and share their achievements related to understanding and reducing landslide disaster risk in their intrinsic missions with other partners are invited to inform the ICL Secretariat, the host of KLC2020 secretariat (secretariat@iclhq.org). The ICL secretariat will send the invitation to the aforementioned meeting of the joint signatories and the declaration of the launching of the KLC2020 on 5 November 2020.

Eligible Organizations to be Partners of the KLC2020

1. ICL member organizations (full members, associate members and supporters)
2. ICL supporting organization from UN, international or national organizations and programmes
3. Government ministries and offices in countries having more than 2 ICL on-going members
4. International associations /societies that contribute to the organization of WLF5 in 2021 and WLF6 in 2023
5. Other organizations having some aspects of activities related to understanding and reducing landslide disaster risk as their intrinsic missions.

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Kyoto, Japan

Appendix: World Landslide Forum Books

WLF	Place/participants	Title	Editors	Publisher/pages
WLF0 (1st General Assembly) 2005	Washington D.C., USA 59 from 17 countries/UNs	Landslides-Risk Analysis and Sustainable Disaster Management	Kyoji Sassa, Hiroshi Fukuoka, Fawu Wang, Goghui Wang	Springer/377 pages ISBN: 978-3-540-2864-6
WLF1 2008	Tokyo, Japan 430 from 49 countries/regions/UNs	Landslides-Disaster Risk Reduction	Kyoji Sassa, Paolo Canuti	Springer/649 pages ISBN: 978-3-540-69966-8
WLF2 2011	Rome, Italy 864 from 63 countries	Landslide Science and Practice Vol. 1 Landslide inventory and Sustainability and Hazard Zoning	Claudia Margottini, Paolo Canuti, Kyoji Sassa	Springer/607 pages ISBN: 978-3-642-31324-0
		Vol. 2 Early Warning, Instrumentation and Monitoring		Springer/685 pages ISBN: 978-3-642-31444-5
		Vol. 3 Spatial Analysis and Modelling		Springer/440 pages ISBN: 978-3-642-31309-7
		Vol. 4 Global Environmental Change		Springer/431 pages ISBN: 978-3-642-31336-3
		Vol. 5 Complex Environment		Springer/354 pages ISBN: 978-3-642-31426-1
		Vol. 6 Risk Assessment, Management and Mitigation		Springer/789 pages ISBN: 978-3-642-31318-9
		Vol. 7 Social and Economic Impact and Policies		Springer/333 pages ISBN: 978-3-642-31312-7
WLF3 2014	Beijing, China 531 from 45 countries/regions/UNs	Landslide Science for a Safer Geoenvironment Vol. 1 The International Programme on Landslides (IPL)	Kyoji Sassa, Paolo Canuti, Yueping Yin	Springer/493 pages ISBN: 978-3-319-04998-4
		Vol. 2 Methods of Landslide Studies		Springer/851 pages ISBN: 978-3-319-05049-2
		Vol. 3 Targeted Landslides		Springer/717 pages ISBN: 978-3-319-04995-3
WLF4 2017	Ljubljana, Slovenia 588 from 59 countries/regions/UNs	Advancing Culture of Living with Landslides Vol. 1 ISDR-ICL Sendai Partnerships 2015-2025	Kyoji Sassa, Matjaž Mikoš, Yueping Yin	Springer/585 pages ISBN: 978-319-53500-5

(continued)

WLF	Place/participants	Title	Editors	Publisher/pages
		Vol. 2 Advances in Landslide Science	Matjaž Mikoš, Binod Tiwari, Yueping Yin, Kyoji Sassa	Springer/1197 pages ISBN: 978-319-53497-8
		Vol. 3 Advances in Landslide Technology	Matjaž Mikoš, Željko Arbanas, Yueping Yin, Kyoji Sassa	Springer/621 pages ISBN: 978-3-319-53486-2
		Vol. 4 Diversity of Landslide Forms	Matjaž Mikoš, Nicola Casagli, Yueping Yin, Kyoji Sassa	Springer/707 pages ISBN: 978-3-319-53484-8
		Vol. 5 Landslides in Different Environments	Matjaž Mikoš,Vít Vilímek,Yueping Yin, Kyoji Sassa	Springer/557 pages ISBN: 978-3-319-53482-4
WLF5	2020 (publication) 2021 (Forum)	Understanding and Reducing Landslide Disaster Risk Vol. 1 Sendai Landslide Partnerships and Kyoto Landslide Commitment	Kyoji Sassa, Matjaž Mikoš, Shinji Sassa, Peter T. Bobrowsky, Kaoru Takara, Khang Dang	Springer In Process
		Vol. 2 From mapping to hazard and risk zonation	Fausto Guzzetti, Snježana Mihalić Arbanas, Paola Reichenbach, Kyoji Sassa, Peter T. Bobrowsky, Kaoru Takara	
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Part I

Forum Lectures and Special Lectures

On the Prediction of Landslides and Their Consequences

Fausto Guzzetti

Abstract

The general assumptions and the most popular methods used to assess landslide hazard and for risk evaluation have not changed significantly in recent decades. Some of these assumptions have conceptual weakness, and the methods have revealed limitations. In this work, I deal with populations of landslides i.e. numerous landslides caused in an area by a single trigger (e.g. a rainstorm, an earthquake, a rapid snowmelt event), or by multiple events in a short or long period. Following an introduction on what we need to predict to assess landslide hazard and risk, I introduce the strategies and the main methods currently used to detect and map landslides, to predict populations of landslides in space and time, and to anticipate the numerosity and size characteristics of the expected landslides. For landslide detection and mapping, I consider traditional methods based on the visual interpretation of aerial photographs, and modern approaches that exploit the visual, semi-automatic or automatic analysis of remotely sensed images. For landslide spatial prediction, I discuss the results of a global review of statistical, classification-based methods for landslide susceptibility assessment. For the temporal prediction, leveraging on a global analysis of geographical landslide forecasting and early warning systems, I discuss short term forecast capabilities and their limitations. Next, I discuss long term landslide projections considering the impact of climate variations on landslide projections. For landslide numerosity and size characteristics, I discuss existing statistics of landslide area and volume obtained from large populations of event-triggered landslides. This is followed by an analysis of the landslide consequences, with emphasis on a spatial-temporal model of societal landslide risk in Italy. I end offering recommendations on what I think we should do to make significant progress in our collective ability to predict the hazard posed by populations of landslides, and to mitigate their risk.

Keywords

Prediction • Maps • Susceptibility • Hazard • Model • Consequences • Risk

Introduction

Landslides are present on all continents and play an important role in the evolution of landscapes (Densmore et al. 1997; Hovius et al. 1997, 2000; Lavé and Burbank 2004; Malamud et al. 2004a; Guzzetti et al. 2009; Chen et al. 2014; Bucci et al. 2016). In many areas, landslides pose a serious threat to people, private and public properties, society, and the environment (Brabb 1989, 1991; Nadim et al. 2006; Kirschbaum et al. 2009; Petley 2012; Guthrie 2013; Dowling and Santi 2014; Pereira et al. 2015, 2017; Badoux et al. 2016; Grahn and Jaldell 2017; Froude and Petley 2018; Herrera et al. 2018; Salvati et al. 2018). It is therefore not surprising that landslide hazard assessment and risk evaluation, at the boundary between science, technology and application (Fig. 1), are increasingly popular among scientists, practitioners, decision makers, and even concerned citizens.

Despite numerous attempts and unquestionable progress, the general assumptions and the most popular methods and techniques used to detect and map landslides, to assess landslide susceptibility and hazard, and for risk evaluation and mitigation, have not changed significantly in recent

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K. Sassa et al. (eds.), *Understanding and Reducing Landslide Disaster Risk*, ICL Contribution to Landslide Disaster Risk Reduction,
https://doi.org/10.1007/978-3-030-60196-6_1

decades. Today, some of these assumptions reveal theoretical weakness, and the adopted methods and techniques show practical and operational limits. The complete spectrum of landslide hazard and risk studies is vast, spanning from the hazard caused by a single landslide or a small portion of a natural or engineered slope, to the risk posed by multiple landslides of different types to the population of a region or nation (Guzzetti 2000; Badoux et al. 2016; Pereira et al. 2017; Salvati et al. 2018; Rossi et al. 2019), to the assessment of the potential occurrence of landslides at the continental (Van Den Eeckhaut et al. 2012a; Broeckx et al. 2018; Wilde et al. 2018) or the global (Nadim et al. 2006) scales.

This paper describes and expands the topics covered in the talk entitled *On the prediction of landslides and their consequences* that I was invited to deliver at the 5th World Landslide Forum (WLF5) in Kyoto, Japan. Based on my competency and personal experience, in the talk and in this work, I do not cover the entire spectrum of landslide hazards and risk. Instead, I concentrate on the hazards and risk posed by populations of landslides, i.e. the occurrence of many landslides that sculpt (literally!) landscapes, and pose serious threats to people, property, and the environment. This is a complex, multi-faceted topic with scientific, technological, and practical aspects (Fig. 1), which I address based on the assumption that our ability to predict landslides and their consequences measures our ability to understand the underlying physical (e.g. geological, geomorphological, hydrological, mechanical, climatic, tectonic) processes that control or condition landslides, as well as their spatial and temporal occurrence. With an important corollary worth mentioning: prediction must be scientifically based (Guzzetti 2015).

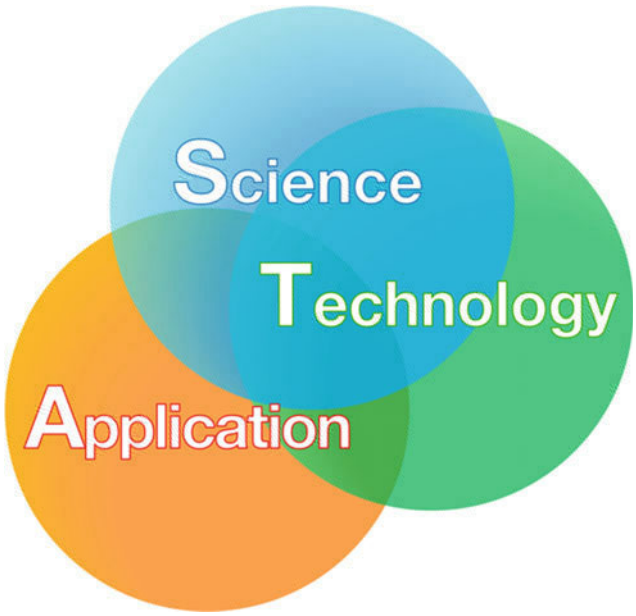

Fig. 1 Conceptual representation of the three realms of science, technology and application, which underpin modern landslide hazard and risk assessment

The article builds upon previous work I have published in the last three decades on (i) landslide detection and mapping (Guzzetti et al. 2012) and the often neglected quantification of the uncertainty associated with landslide mapping (Carrara et al. 1992; Ardizzone et al. 2002) and the quality of landslide maps (Santangelo et al. 2015); (ii) the types, comparison, and use of landslide inventory maps (Guzzetti et al. 2000; Galli et al. 2008; Guzzetti et al. 2012); (iii) the modelling of landslide susceptibility adopting statistical classification methods (Carrara et al. 1991; Guzzetti et al. 1999; Reichenbach et al. 2018), or physically based approaches (Guzzetti et al. 2002a; Alvioli et al. 2014, 2016, 2018; Raia et al. 2014); (iv) the definition and application of a conceptual framework for landslide hazard assessment based on the pioneering work of Varnes and the IAEG Commission on Landslides and other Mass-Movements (1984) (Guzzetti 2005; Guzzetti et al. 2015, 2006a); (v) the objective definition of rainfall thresholds for possible landslide occurrence (Guzzetti et al. 2007, 2008) and the quantification of their related epistemic and aleatory uncertainties (Brunetti et al. 2010; Peruccacci et al. 2012, 2017; Gariano et al. 2015a; Melillo et al. 2015, 2016), and the use of the thresholds for the design and operation of geographical landslide early warning systems (Guzzetti et al. 2020); (vi) the determination and analysis of landslide size statistics obtained from event inventory maps (Guzzetti et al. 2002b, 2009; Malamud et al. 2004b; Brunetti et al. 2009; Stark and Guzzetti 2009; Taylor et al. 2018); (vii) the vulnerability to landslides of various types of elements at risk (Galli and Guzzetti 2007), including the population (Salvati et al. 2018); and on (viii) the definition and quantitative measurement of landslide risk (Cardinali et al. 2002; Reichenbach et al. 2005), with emphasis on the risk to the population (Guzzetti 2000; Guzzetti et al. 2005a; Salvati et al. 2010, 2018), and the perception of landslide risk (Salvati et al. 2014).

The experience gained working, mostly in Italy, with the CNR IRPI Geomorphology Research Group (http://geomorphology.irpi.cnr.it) in Perugia has conditioned my own understanding of landslide processes, and has influenced my ideas and opinions on the methods and techniques best suited to detect and map landslides, to ascertain landslide susceptibility and hazard, and to evaluate landslide vulnerability and risk. I acknowledge that this has somewhat biased the article. However, I maintain that the topics are of interest to a broad audience and the recommendations are general.

The paper is organized as follows. After a brief presentation of the meaning of *landslide prediction*, I discuss key

findings and inherent limitations for the detection and mapping of landslides using remotely sensed imagery (Guzzetti et al. 2012). This is followed by the discussion of some of the results of a review of statistically-based landslide susceptibility methods and models (Reichenbach et al. 2018). Based on two reviews of landslide-climate studies (Gariano and Guzzetti, 2016) and of geographical landslide early warning systems (Guzzetti et al. 2020), I then discuss the temporal prediction of landslides. Next, I present what I consider key results on the prediction of the size and number of landslides. This is followed by a description of landslide vulnerability concepts, and the presentation of a recent spatial-temporal model for the prediction of societal landslide risk to the population of Italy (Rossi et al. 2019). I conclude offering recommendations on what I maintain should be done to advance our collective ability to predict the hazards posed by populations of landslides, and to mitigate the associated risk.

Landslide Prediction

For landslides, like for other natural phenomena that can have harmful consequences or unwanted impacts—e.g. on the environment, population, society, the economy—it is important to clarify what we want (or need) to predict, and what we can (and cannot) predict. In the case of landslides, it is important to clarify the meaning of the term *landslide prediction*. I do so with three examples. First, if I say, *tomorrow there will be a landslide*, I am sure to be right. This is a trivial prediction, because I have not said *where* the landslide is expected, and every day landslides occur somewhere in the world. Second, if I am (slightly) more specific and I say, *tomorrow there will be a landslide in Italy* or in any other region, nation, or landscape dominated by mass-wasting processes, knowing that, for instance, it will be raining hard, I am (almost) certain of being correct. Every year there are thousands of rainfall-induced landslides in Italy, and in landscapes forced by rainfall or other weather-related processes. These two predictions are almost certainly correct, but they are not useful for hazard assessment or for the design or implementation of risk mitigation strategies. Third, if I say, *due to the expected rainfall, in the next 12 h, there will be 50 landslides with a volume larger than 100,000 m^3, in a given area*, I will anticipate *where*, *when*, *how many*, and *how large* we should expect the landslides. The third is a useful prediction, which we presently struggle to do.

Predicting *where*, *when*, *how many*, and *how large* landslides are expected in an area and during a period of time is at the base of landslide hazard assessment (Varnes and the IAEG Commission on Landslides and other Mass-Movements 1984; Guzzetti 2005; Guzzetti et al. 2005a). I maintan that there is nothing in the literature, and in our collective understanding of populations of lanslides, that prevent us to predict *where*, *when*, *how many*, and *how large* landslides are expected, or to predict the consequences of population of landslides. In the next three sections, I discuss the strategies, the methods, and the techniques adopted to determine where landslides occur and where they can be expected, how to predict when or how frequently landslides can occur, and how large and numerous they can be following a triggering event.

Where Landslides Occur and Where They can be Expected

Let me start with *where* landslides occur, and *where* they can be expected. The first topic pertains to the realm of landslide detection and mapping, and the production of landslide inventory maps (Guzzetti et al. 2012), and the second is in the domain of landslide susceptibility modelling and terrain zonation (Reichenbach et al. 2018).

Landslide Detection and Mapping

In 2012, Guzzetti et al. (2012) estimated that less than 1% of the landmasses was covered by landslide maps. Despite new encouraging national efforts (e.g. in Vietnam), and attempts to prepare landslide inventory maps for entire continents (e.g. Africa, Broeckx et al. 2018), the situation has not changed much, and information on past and present landslides remains limited and unsystematic. Even in Italy, a country for which information on landslides is abundant compared to other areas (Trigila et al. 2010; Van Den Eeckhaut et al. 2012b; ISPRA 2018), no effort is underway for the systematic mapping of landslides following major landslide triggering events such as intense or prolonged rainfall periods, rapid snowmelt events, or earthquakes. The lack of accurate and updated landslide information limits the ability to model landslide hazard, evaluate landslide risk, assess the performance of prediction models, and design, implement, and verify adequate landslide mitigation strategies.

Using a combination of landslide mapping methods and techniques, the Italian National and regional geological surveys have collectively mapped more than 620,000 landslides in Italy (Trigila et al. 2010; ISPRA 2018) (Fig. 2). This is a result of the multi-decadal IFFI project (an Italian acronym for *Inventario dei Fenomeni Franosi in Italia*, Italian Landslide Inventory), which, despite some inherent limitation (Van Den Eeckhaut et al. 2012a; Marchesini et al. 2014), is the largest, most advanced, and best organized collection of geographical information on landslides for a

nation. Not counting the large alluvial plains and other flat areas where landslides do not occur, this is an average of about 3.2 landslides per km^2.

At CNR IRPI, in a period of about 30 years, my colleagues mapped more than 124,000 landslides in various parts of Italy covering a total area of 30,285 km^2, 11% of the hills, mountains, and high coastal areas potentially subject to landslides in the country (Fig. 3). This is equivalent to an average density of 4.1 landslides per km^2. The difference between the average landslide density measured by IFFI (3.2 landslides per km^2) (Fig. 2) and the average density measured by our mappings (4.1 landslides per km^2) (Fig. 3) is significant, and highlights the incompleteness of the national inventory, particularly in terms of event and multi-temporal landslide information.

For years, populations of landslides were mapped through the visual interpretation of aerial photographs, with some—typically limited—field checks. Today, satellite images

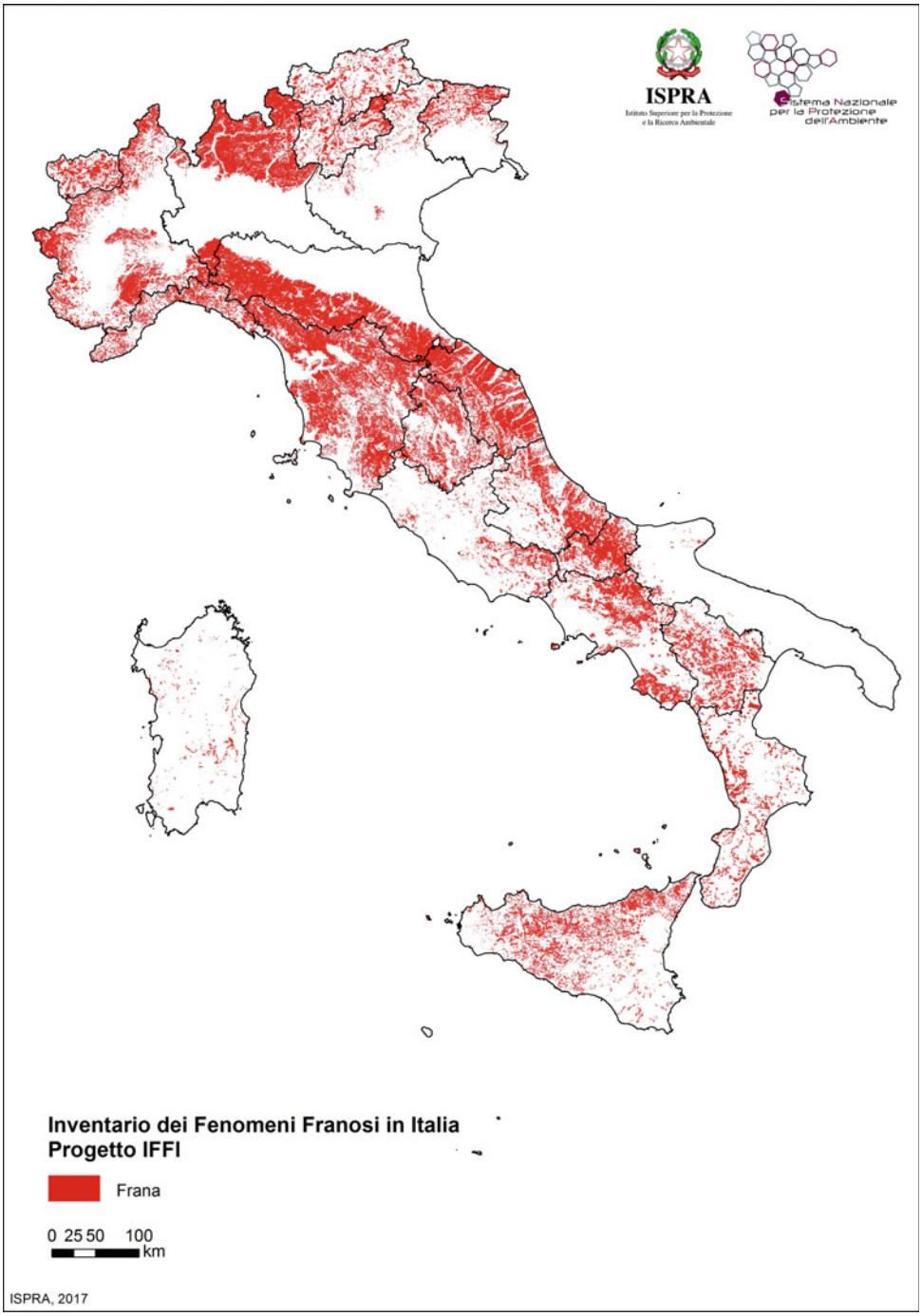

Fig. 2 Landslide inventory for Italy showing more than 620,000 landslides in 302,100 km^2. Map prepared in the framework of the IFFI Italian National project (Trigila et al. 2010). Curtesy of A. Trigila (ISPRA 2018)