Springer Theses
Recognizing Outstanding Ph.D. Research

Martin Klose

Landslide Databases as Tools for Integrated Assessment of Landslide Risk

Springer

Martin Klose

Landslide Databases as Tools for Integrated Assessment of Landslide Risk

Doctoral Thesis accepted by
the University of Vechta, Germany

Springer

Author
Dr. Martin Klose
Applied Physical Geography
University of Vechta
Vechta
Germany

Supervisor
Prof. Bodo Damm
Applied Physical Geography
University of Vechta
Vechta
Germany

ISSN 2190-5053 ISSN 2190-5061 (electronic)
Springer Theses
ISBN 978-3-319-20402-4 ISBN 978-3-319-20403-1 (eBook)
DOI 10.1007/978-3-319-20403-1

Library of Congress Control Number: 2015942627

Springer Cham Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media
(www.springer.com)

Springer Theses

Recognizing Outstanding Ph.D. Research

Aims and Scope

The series "Springer Theses" brings together a selection of the very best Ph.D. theses from around the world and across the physical sciences. Nominated and endorsed by two recognized specialists, each published volume has been selected for its scientific excellence and the high impact of its contents for the pertinent field of research. For greater accessibility to non-specialists, the published versions include an extended introduction, as well as a foreword by the student's supervisor explaining the special relevance of the work for the field. As a whole, the series will provide a valuable resource both for newcomers to the research fields described, and for other scientists seeking detailed background information on special questions. Finally, it provides an accredited documentation of the valuable contributions made by today's younger generation of scientists.

Theses are accepted into the series by invited nomination only and must fulfill all of the following criteria

- They must be written in good English.
- The topic should fall within the confines of Chemistry, Physics, Earth Sciences, Engineering and related interdisciplinary fields such as Materials, Nanoscience, Chemical Engineering, Complex Systems and Biophysics.
- The work reported in the thesis must represent a significant scientific advance.
- If the thesis includes previously published material, permission to reproduce this must be gained from the respective copyright holder.
- They must have been examined and passed during the 12 months prior to nomination.
- Each thesis should include a foreword by the supervisor outlining the significance of its content.
- The theses should have a clearly defined structure including an introduction accessible to scientists not expert in that particular field.

More information about this series at http://www.springer.com/series/8790

Parts of this thesis have been published in the following journal articles:

Damm, B., Klose, M., 2014. Landslide Database for the Federal Republic of Germany: A Tool for Analysis of Mass Movement Processes and Impacts. In: Sassa, K., Canuti, P., Yin, Y. (Eds.), Landslide Science for a Safer Geoenvironment, Volume 2: Methods of Landslide Studies. Springer, Berlin, pp. 787–792.

Klose, M., Damm, B., Gerold, G., 2012. Analysis of Landslide Activity and Soil Moisture in Hillslope Sediments using a Landslide Database and a Soil Water Balance Model. GEO-ÖKO 33(3-4), 204–231.

Klose, M., Damm, B., Terhorst, B., 2015. Landslide Cost Modeling for Transportation Infrastructures: A Methodological Approach. Landslides 12, 321–334.

Klose, M., Gruber, D., Damm, B., Gerold, G., 2014. Landslide Susceptibility Modeling on Regional Scales: The Case of Lower Saxony, NW Germany. In: Sassa, K., Canuti, P., Yin, Y. (Eds.), Landslide Science for a Safer Geoenvironment, Volume 2: Methods of Landslide Studies. Springer, Berlin, pp. 437–442.

Klose, M., Gruber, D., Damm, B., Gerold, G., 2014. Spatial Databases and GIS as Tools for Regional Landslide Susceptibility Modeling. Zeitschrift für Geomorphologie NF 58(1), 1–36.

Klose, M., Highland, L., Damm, B., Terhorst, B., 2014. Estimation of Direct Landslide Costs in Industrialized Countries: Challenges, Concepts, and Case Study. In: Sassa, K., Canuti, P., Yin, Y. (Eds.), Landslide Science for a Safer Geoenvironment, Volume 2: Methods of Landslide Studies. Springer, Berlin, pp. 661–667.

Risk varies inversely with knowledge

Irving Fisher, *The Theory of Interest,* 1930

Supervisor's Foreword

Landslide risk is a pressing societal issue that is still poorly understood. A major challenge of risk assessment originates from the difficulty of quantifying risk considering the wide range of landslide types and processes and the various cost factors independent of size or magnitude. Recent studies stress the importance of integrated approaches that use damage statistics and data on societal risk acceptance to explore landslide risk in all its facets. A key to these new approaches are landslide databases that store geospatial and impact-related information on past and current landslides. The availability of Geographic Information Systems (GIS) in recent years has made landslide databases an important tool for spatial inventory and hazard mapping. The full scientific potentials of databases in risk assessment, however, go far beyond the scope of GIS applications, but are still widely underestimated. This relates to a lack of approaches capable of searching database contents for damage or cost information and to derive risk by the systematic fusion of complex data sets from multiple sources. The development of innovative tools for knowledge discovery in landslide databases is critical for assessing landslide risk in integrated perspective.

This doctoral thesis written by Martin Klose is a pioneering research work that makes an excellent contribution to fundamental understanding of landslide risk. The study introduces an analytical framework for integrated risk assessment and new approaches to data integration, modeling, and visualization tailored for use with data sets extracted from landslide databases. "From physical process to economic cost" is the principle of method development in this research work, with the goal of bridging the gap between the analysis of landslide hazard and impact. A key role is played by a landslide susceptibility model that enables to identify and delineate areas at risk of landslides and to assess infrastructure exposure. Temporal landslide hazard is derived from landslide frequency statistics and a hydrological simulation approach to estimate triggering thresholds. These methods are integrated into a powerful toolset for cost survey and modeling that uses historical data to compile, model, and extrapolate damage costs on different spatial scales over time. The combination of this toolset with techniques to analyze fiscal cost impacts supports integrated risk assessment by exploring the economic relevance of landslide losses.

Martin Klose presents in his doctoral thesis a novel approach to landslide risk assessment that constitutes a major scientific advance in a research field critical to global society. The thesis is a brilliant example of cross-cutting and societally relevant Ph.D. research in the Earth Sciences and neighboring disciplines. It is to expect that the thesis will make a global impact, which is already reflected by the attention paid to the journal articles accompanying this research work. Martin Klose has written the thesis with the experience of a four-month research visit at the U.S. Geological Survey in Golden (CO), USA. The cooperative research he made at this world-leading research institute was funded by a scholarship of the German Academic Exchange Service. Martin Klose initiated this partnership with colleagues from the Landslide Hazards Program and is actively participating in global scientific exchange and the consulting of decision makers. The results of this cooperative research and further projects found their way into his doctoral thesis and provide an international perspective on landslide risk. This makes the present thesis a top-level research work of high scientific excellence. It is therefore a great pleasure to nominate Martin Klose for a Springer Thesis Prize.

Vechta
April 2015

Prof. Bodo Damm

Acknowledgments

This doctoral thesis in Applied Physical Geography was prepared at the University of Vechta under the supervision of Professor Bodo Damm. I am grateful to the scientific advice he gave to me in all stages of the Ph.D. research. His mentoring over the past 3 years together with the responsibility he delegated to me has been a great personal benefit. Thanks are also due to Professor Birgit Terhorst who co-supervised the thesis and without her help this research would have never been possible. Professor Jörg Grunert is thanked for his scientific support and for acting as external examiner. I would also like to thank Lynn Highland for her great hospitality during a research visit at the USGS Geologic Hazards Science Center and her valuable assistance in scientific writing and communication.

The doctoral thesis was an essential part of the research project *Identification and Spatial Modeling of Hazard Potentials from Landslides in Lower Saxony* (MWK Niedersachsen 11.2-76202-10-1/07). Much of this Ph.D. research has also been conducted in the framework of the project *Landslide Database for the Federal Republic of Germany* funded by the German Research Foundation (DFG DA 452/6-1). A further part of the research work benefited from a scholarship given by the German Academic Exchange Service for studying in the USA (DAAD D/12/45096). Travel grants were also provided by the Universitätsbund Göttingen e.V. and the University of Vechta. The financial support and research funding of these institutions is gratefully acknowledged.

This Ph.D. research benefited from the scientific and technical assistance from Bachelor and Master students at the Universities of Vechta and Göttingen. I owe special thanks to Daniel Gruber and Philipp Maurischat for their support in conducting the studies. For the pleasant collaboration during my time at the University of Göttingen, I would like to thank Professor Gerhard Gerold, Dorothea Röckl, and Ingrid Kohlrautz-Weinrich. Thanks are also due to Susanne Döhler, Claudia Dornieden, Annette Janßen, and Monika Kolbeck who were great colleagues at the University of Vechta. This doctoral thesis would have never been possible without the support of my parents and brother to whom I am particularly grateful.

Contents

Chapter 1
Introduction

1.1 Landslides—Why So Complex Phenomena?

Landslides are among the world's most frequent geohazards and pose serious risks to human activity on slopes across the globe (e.g., Brabb 1991; Dilley et al. 2005; Nadim et al. 2006; Hong et al. 2007; Kirschbaum et al. 2010; Petley 2012). As simply defined, a landslide is "the movement of a mass of rock, earth or debris down a slope" (Cruden 1991), with gravity and often water as well being the major driving factors of this geomorphic process (e.g., Sidle and Ochiai 2006; Lu and Godt 2013). The diversity of landslide types is large, ranging from slides in a strict sense to types of movement such as flows, falls, topples, spreads, and complex landslides, a combination of at least two of these movement types (cf. Varnes 1958, 1978; Nemčok et al. 1972; Cruden and Varnes 1996; Dikau et al. 1996; Hungr et al. 2014). Each landslide represents a specific state of activity in a much broader concept of slope stability. The stability of slopes is usually understood as a "physical system that develops in time through several stages", including besides the landslide itself (slope failure), complex pre- and post-failure process mechanisms (Hungr et al. 2014; see also Terzaghi 1950; Vaunat et al. 1994; D'Elia et al. 1998). Various states of landslide activity (active, dormant, reactivated, etc.) can be differentiated (e.g., WP/WLI 1993), and within the broad stability spectrum of slopes, the shift from stable to unstable conditions over time is controlled by predisposition, preparatory, and triggering factors (cf. Crozier 1986; Glade and Crozier 2005a).

The causes and triggers of landslides are diverse (e.g., Wieczorek 1996), varying between the different regions of the world, but with intense or prolonged rainfall (e.g., Guzzetti et al. 2008; Kirschbaum et al. 2012), earthquake shaking (e.g., Keefer 2002; Ugai et al. 2013), and human activity (e.g., Sidle et al. 1985; Nadim et al. 2011) being globally the most widespread causative factors. Rapid urbanization of the world's hillsides today increasingly involves settlement in areas susceptible to landslides while often intensifying landslide susceptibility by slope disturbance itself (cf. Alexander 1989; Pike et al. 2003; Schuster and Highland 2007). Both their close dependency on human activity and the variety of their types and processes make landslides an everyday hazard in many areas worldwide

M. Klose, *Landslide Databases as Tools for Integrated Assessment of Landslide Risk*, Springer Theses, DOI 10.1007/978-3-319-20403-1_1

(Klose et al. 2014a). This distinguishes landslides from related geohazards (earthquakes, storm events, etc.) of which they are a frequent secondary effect (e.g., Harp et al. 2009; Marano et al. 2010), with their losses increasing that of the triggering event significantly (cf. Budimir et al. 2014).

Landslides more than any other geohazard are characterized by a complex distribution in space and time (Fig. 1.1). Each year thousands of landslides occur worldwide, not only in high or low mountain areas (e.g., Korup 2012), but also in parts of the world with little topographic relief (cf. Brabb and Harrod 1989), including the shorelines of oceans (e.g., Lee and Clark 2002; Iadanza et al. 2009), artificial landscapes in lowland areas (e.g., Wichter 2007), and even continental shelves undersea (e.g., Hampton et al. 1996; Masson et al. 2006). The diversity of distribution areas is only one aspect in the complexity of landslide risk; more important, however, are the spatiotemporal patterns in landslide occurrence, especially at local and regional level. Five different spatial and/or temporal patterns of landslide activity are generally identifiable: (i) event-based clustering (Fig. 1.1; see also Cardinali et al. 2000), (ii) seasonal clustering (e.g., monsoon cycle; Petley et al. 2007), (iii) geofactor-oriented clustering (relief, lithology, etc.; cf. Sect. 5.1), (iv) continuous (or episodic) landsliding (slope creep over broad areas; e.g., Hilley et al. 2004), and (v) land use-related distribution (dispersed or clustered; see also Fig. 1.1). Although not with a strict focus to risk analysis, spatiotemporal patterns in landslide occurrence have already been described in related studies as well, including, amongst others, Witt et al. (2010), Rossi et al. (2010), and Tonini et al. (2013).

A unique feature of landslides is their large spectrum of sizes, velocities, and lifetimes (e.g., Malamud et al. 2004; Guthrie and Evans 2007; Crozier 2010). From a global perspective, the size spectrum of a single landslide spans at least nine (areal extent) to more than twelve (volume) orders of magnitude (Guzzetti 2005; Guzzetti et al. 2012). Landslides in their extremes are thus either discrete points in space or large regional phenomena whose deposits cover tens or hundreds of square kilometers (cf. Glade and Crozier 2005b). Alternatively, the velocity of landslides ranges from slow (mm/year) to extremely rapid (m/s) movement, whereby velocity and distribution of activity is often varying within a single landslide (e.g., Cruden and Varnes 1996). Landslides result in landforms that show long persistence in the geomorphic landscape (cf. Guthrie and Evans 2007), with ages of landslide features and deposits reaching up to thousands of years in many cases (e.g., González Díez et al. 1996; Terhorst 2001). The long lifetime of landslides together with their nature to create rough and unstable terrain often makes areas affected by landslides inhabitable for decades or even centuries (e.g., Burke et al. 2002; Van Den Eeckhaut et al. 2010).

Landslide impact in physical terms involves damage to people or property located on a slide mass or in its pathway by burial, collision, and displacement (direct impact). Besides these on-site impacts, there are also impacts experienced off-site (indirect impact), including damage from landslide-induced secondary hazards. The impact of a landslide is either temporally coinciding with its occurrence (instant impact) or emerges in its aftermath (delayed impact) (cf. Glade and Crozier 2005a; Crozier et al. 2013). The degree of landslide impact (landslide intensity) is highly variable and largely depends on the type of landslide, its magnitude, and the vulnerability

Fig. 1.1 Examples of landslide triggering events with a complex distribution of landslides in space and time. **a** Widespread landslide activity on highly developed slopes in southern California (USA) as result of severe winter storms in January and February 2005 (*Photo* J. Godt, USGS). **b** Land use as key factor for causing thousands of landslides during the February 2004 rainstorm on southern North Island, New Zealand (*Photo* G. Hancox, GNS Science)

of the element at risk (building, road, etc.) (e.g., Alexander 1986; Flageollet 1999; Pitilakis et al. 2011). Landslide intensity as "the destructive power of a landslide" (Corominas et al. 2014) is generally difficult to define due to unique problems in parameterization, measurement, and scaling of landslide magnitude (cf. Guzzetti 2005). This is mainly because landslides show significant impact as both: fast-moving

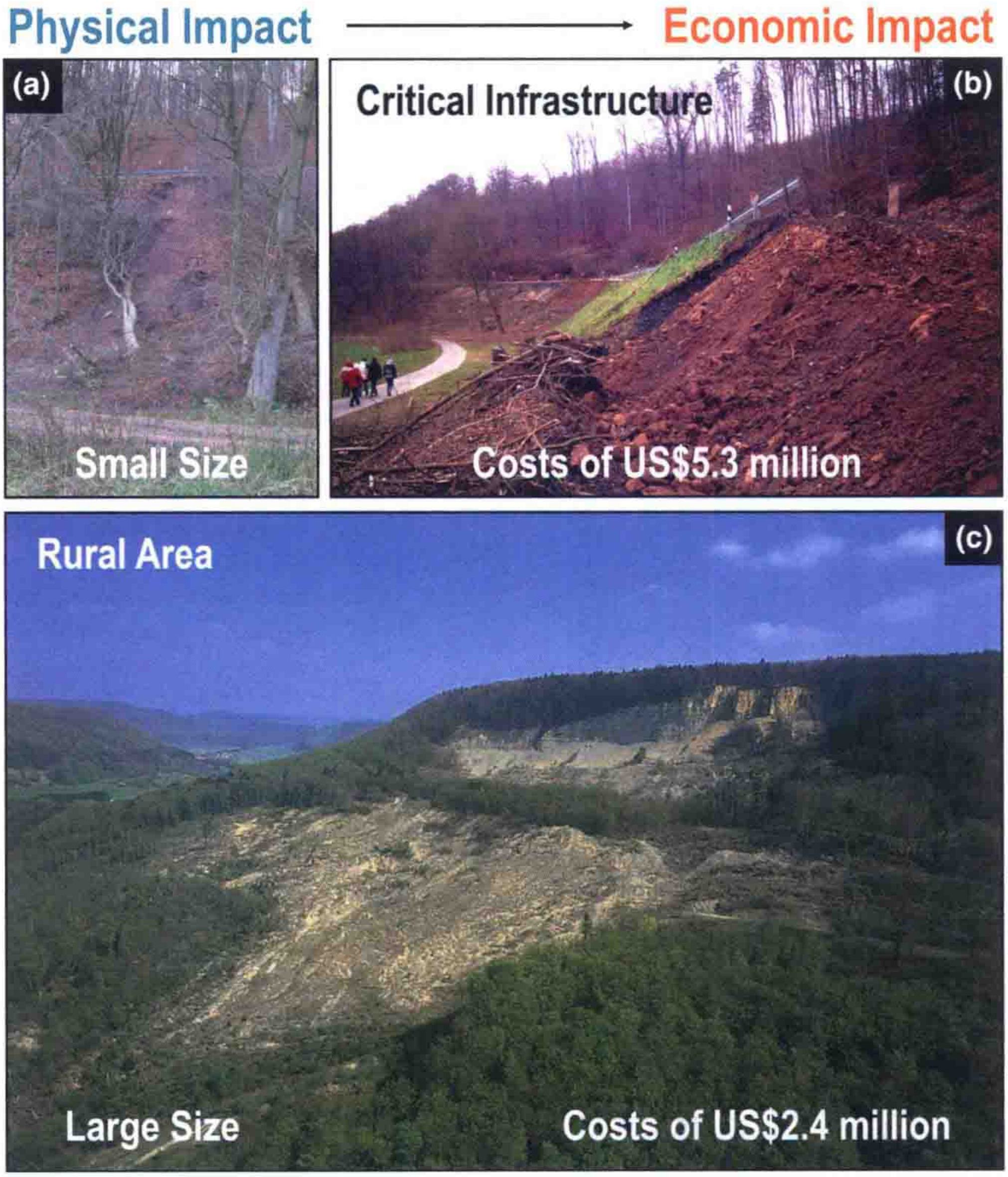

Fig. 1.2 Illustration of the complex relationship between physical landslide processes and the economic impact of landslides. As the examples from NW and SW Germany show, the costs of landslide damage are sometimes independent from landslide magnitude, while cost factors such as landslide location and type of affected infrastructure are often playing an important role: **a**, **b** Landslide damage and repair of highway B 80 or B 3 north of the city of Hann. Münden, Lower Saxony, after repeated landslide damage in the mid-2000s (*Photo* M. Klose; Database B. Damm); **c** the 1983 Mössingen landslide at the Swabian Jurassic escarpment, Baden-Wuerttemberg (*Photo* A. Dieter; cf. Munich Re 1999)

landslides (high magnitude) with large associated damage, and slow-moving landslides (low magnitude) that result in large damage over time as well (e.g., Cruden and Varnes 1996; Urciuoli and Picarelli 2008; Mansour et al. 2011; Antronico et al. 2014).

The relationship between physical landslide impact and economic costs depends on a variety of factors often independent from landslide magnitude (cf. Klose et al. 2014a, b). Most types of landslides result in specific kinds of damage whose translation into monetary losses is beyond simple expression through linear magnitude–damage–cost relationships. A characteristic feature of landslide impact is that there is no strict rule that the larger landslide magnitude, the higher landslide costs (Fig. 1.2; see also Sect. 5.3.1). Thus, even shallow soil slides or small rockfalls affecting highways may result in large costs, while the losses of major landslides in remote rural areas are not necessarily large. Severity of economic impact (direct or indirect) first relates to landslide location (urban or rural) and the question whether critical infrastructure is affected or not (Fig. 1.2; e.g., Blaschke et al. 2000; Geertsema et al. 2009). A second main driver of landslide costs, as case studies indicate (e.g., Cornforth 2005; Hearn et al. 2011; Highland 2012), are the types and methods of post-disaster mitigation, whereas a correlation between direct costs and the damage to or the value of elements at risk is often hard to find (cf. Sect. 5.3.1). These cost factors related to landslide repair and prevention are partly controlled by the level of public and individual risk acceptance and thus the underlying societal conditions (e.g., Fell 1994; Finlay and Fell 1997; Bell et al. 2006; Winter and Bromhead 2012). As a result of disparities in technical and adaptive standards, coping with landslides differs throughout the world. This also causes their impacts and costs to vary geographically, specifically as a function of the region`s level of economic development (cf. Klose et al. 2014a).

1.2 Overview of Global Landslide Impact

Statistics on the death toll and economic losses of landslides are rare to find for above reasons, but those few that are available at national or continental scale clearly illustrate the global significance of landslide impact (Table 1.1; see also Alcántara-Ayala 2014). According to a study from Dilley et al. (2005), an area corresponding to 2.5 % of the world's land surface is prone to landslides. The study states further that 300 million people (5 % of world population) across the globe are living in areas exposed to significant landslide risk. Furthermore, Petley (2012) has found that between 2004 and 2010 landslides claimed more than 30,000 lives, with a strong concentration of landslide fatalities in E- and SE-Asia, the Himalayas, and Central America (Fig. 1.3). These regional clusters of fatal landslides are often considered as global landslide hotspots (Nadim et al. 2006). By referring to data from the Centre of Research for the Epidemiology of Disasters (CRED), Kjekstad and Highland (2009) report that 17 % of the fatalities from natural hazards are due to landslides. Few additional studies illustrate the societal relevance of loss of live from landslides at national level. In their time series of landslide fatalities in Italy, Salvati et al. (2010), for instance, record a total of more