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Landslide cost modeling for transportation infrastructures: a methodological approach

Abstract This paper presents a new methodology for ex post assessment of direct landslide costs for transportation infrastructures. The methodology includes tools to compile, model, and extrapolate landslide losses on different spatial scales over time. A landslide susceptibility model enables regional cost extrapolation by means of a cost figure obtained from local cost compilation for a representative case study area. On a local level, cost survey is closely linked with cost modeling, a toolset for cost estimation based on landslide databases. Cost modeling uses landslide disaster management process models (LDMMs) and cost modules to simulate and monetize cost factors for certain types of landslide damage. The landslide susceptibility model provides a regional exposure index and updates the cost figure to a cost index which describes the costs per kilometer of traffic route at risk of landslides. Both indexes enable the regionalization of local landslide losses. The methodology is applied and tested in a cost assessment for highways in the Lower Saxon Uplands, NW Germany, in the period 1980 to 2010. In this 7,400-km² large mountain region, 77km of highway is located in landslide hazard area. Annual average costs of US\$52,000 per km of highway at risk of landslides are identified as cost index for a local case study area. The cost extrapolation results in annual average costs for highways in the Lower Saxon Uplands of US\$4.02 million. This test application as well as a validation of selected modeling tools verifies the functionality of this methodology.

Keywords Landslide losses · Cost modeling · Transportation infrastructures · Landslide susceptibility · Exposure index · Cost extrapolation

Introduction

The world's transportation infrastructure is at risk of landslides in many areas across the globe (cf. Hungr et al. 1999; Prina et al. 2004; Bhandary et al. 2013). Safe and affordable operations of traffic routes are the two main criteria for transportation planning in landslide-prone areas (cf. Saha et al. 2005; Pantha et al. 2008; Hearn 2011). The right balancing of these often conflicting priorities requires, among others, profound knowledge of the direct costs of landslide damage. These costs include capital investments for landslide repair and mitigation as well as operational expenditures for first response and maintenance works (cf. Alimohammadlou et al. 2013). In the present study, all *costs* refer to *direct costs*, and the words *costs*, *losses*, and *prices* are used as synonyms. A number of previous studies show consensus that the transportation sector is probably most affected by the billions of dollars in annual landslide losses worldwide (cf. Schuster and Fleming 1986; Brabb, Harrod 1989; Schuster 1996; Kjekstad and Highland 2009; Trezzini et al. 2013). However, there still remains a large deficit of reliable cost estimates for transportation infrastructures, which mainly relates to the complex nature of landslide impact itself (cf. Guzzetti et al. 2003; Glade and Crozier 2005).

Existing approaches and related methods of landslide cost assessment (i.e., ex post or ex ante approach; cost survey or risk analysis; cf. Meyer et al. 2013) are unable to cope with some characteristic features of landslide impact, including (a) the complex distribution of landslides in space and time (cf. Witt et al. 2010; Malamud et al. 2004) and (b) the problem to reason from landslide intensity and the value and vulnerability of elements at risk to potential costs (i.e., risk estimates ≠ potential costs, vulnerability > 1; cf. Remondo et al. 2008). As a result of strongly variable landslide distribution patterns (i.e., spatiotemporal clustering or dispersion) and wide variations in landslide magnitudes and process mechanisms, the identification, tracking, and documentation of past landslide losses is difficult, which constitutes a crucial problem for cost surveys. Alternatively, case studies show that the costs of landslide damage are rather dependent on the type of landslide repair or mitigation than on the value at risk (cf. Cornforth 2005; Hearn et al. 2011; Highland 2012), as assumed in quantitative risk analysis (cf. Lee and Jones 2004). To improve availability and reliability of landslide loss data, the existing methods of cost assessment need to be optimized to these characteristic features of landslide impact, but this is poorly realized so far.

Most of the early studies of landslide costs for the transportation sector were ex post assessments focused on road networks in the USA, especially the state highway systems (cf. Chassie and Goughnour 1976; Walkinshaw 1992). From a global perspective, there are only few more recent studies dealing with the retrieval and analysis of past landslide losses for traffic routes, and their focus is also primarily on highway infrastructures (cf. Hearn et al. 2008; Public Works Department Malaysia 2008; Negi et al. 2013). The most common method in such transportation-related studies is still cost survey, including expert interviews, questionnaire surveys, and archive studies. This holds true for a large part of today's cross-sector studies not restricted to a certain type of infrastructure (cf. Crovelli and Coe 2009; Rahman et al. 2011; Klose et al. 2012b; Vranken et al. 2013). A majority of such broader-oriented studies from before the year 2000 were focused on cost compilation in local or regional case study areas for periods of increased landslide activity (Fleming and Taylor 1980; Brabb and Harrod 1989; Schuster 1996). By contrast, methodological approaches of systematic cost assessment on large spatial scales have only been developed in few studies so far (cf. Krohn and Slosson 1976). The study of Mathur (1982) was probably the first cost extrapolation for highways. In this study, landslide losses were projected to a national level on the basis of spatial data on landslide susceptibility. Today, the lack of documentation and data transparency is seen as a major drawback of former ex post assessments of landslide losses (cf. Highland 2006).

Since a couple of years, landslide cost assessment experiences a shift from ex post to ex ante, which manifests in an increasing number of studies focused on quantitative risk analysis for traffic routes and related types of public infrastructure (cf. Sterlacchini et al. 2007; Zêzere et al. 2007; Jaiswal et al. 2010; Erener and Düzgün 2013). The uncertainty of cost estimation based on risk analysis, however, is

supposed to be significant (cf. Meyer et al. 2013), as the basic assumption, i.e., cost risks=values at risk, is questionable, given the knowledge about landslide repair and mitigation (cf. Cornforth 2005; Damm 2005; Hearn et al. 2011). Alternatively, quantitative risk-cost-benefit analysis takes empirical cost estimates of mitigation measures into consideration and trades off the costs of landslide mitigation against the risks of landslide hazard, although only on a case-by-case basis (cf. Bründl et al. 2012; Jaiswal and Van Westen 2013). As a consequence, uncertainty involved in ex ante assessment of landslide losses over broad areas is difficult to reduce effectively. Thus, an ex post approach is chosen in this study.

This study presents a new methodology for the estimation and regionalization of past and current landslide losses for transportation infrastructures. Using the example of the Lower Saxon Uplands, NW Germany, the methodological approach is applied to compile, model, and extrapolate the costs of landslide damage to federal highways (i.e., *Bundesstraßen*, below referred to as *highways*; comparable with US routes) in the period 1980–2010. The produced data sets are analyzed regarding cost structure and temporal patterns of landslide losses. This is followed by a validation of the results and a discussion about methodological problems and solutions. All landslide losses provided in this study are given in USD and refer to 2013 values. Loss data published in previous studies are adjusted for inflation by using the US consumer price index (CPI-U, 08-2013).

Study area

This research is based on a local and regional study area, including (a) the Lower Saxon Uplands, NW Germany, and (b) the Upper Weser area, a small part of the Lower Saxon Uplands. The entire region is located at the northern edge of the Central European Uplands and is part of the German Federal State of Lower Saxony (cf. Fig. 1). This mountain area is characterized by low to moderate relief and elevations ranging from 50 to 950 m a.s.l. The total area

of the Lower Saxon Uplands is about 7,400 km², which corresponds to 0.2 % of the total EU-28 territory. Three major physiographic areas can be differentiated in this region (cf. Drozdowski 2003; Heunisch et al. 2007; Reicherter et al. 2008): (a) the Harz Mountains, a compact and strongly dissected Paleozoic basement complex; (b) the Weser-Leine Uplands, where Mesozoic scarps and ridges rise abruptly above their forelands; and (c) the Solling anticline, a gently undulating Triassic sandstone plateau with deeply incised river valleys. The network of highways in the Lower Saxon Uplands has a total length of 1,250 km and thus makes up about 3.1 % of that of entire Germany.

Landslides pose a constant threat to highways in the Lower Saxon Uplands and require repair and mitigation almost every year (cf. Tilch 1999; Damm 2005; Klose et al. 2012b, 2013). This is not only the result of road location in landslide-prone positions but also the consequence of the creation of artificial landslide predispositions, especially through cutting slopes at too steep an angle or the use of unstable soil material for embankment construction (cf. Damm 2000; Krauter et al. 2012). The most frequent types of landslides causing damage to highways are besides small rock fall, shallow to medium deep slide, and/or flow processes on natural and artificial soil or rock slopes. Additionally, slow creeping and deformation processes in fill slopes are a frequent cause of damage to highway embankments. The volumes of most landslides affecting highways usually do not exceed 500 m³. Landslide volumes of up to about 500,000 m³, however, have also been recorded in some cases (cf. Damm 2005; Damm et al. 2010). Many of these landslides are rainfall-induced and occur during or after periods of positive soil moisture anomalies (cf. Klose et al. 2012a).

The Upper Weser area belongs to the southern Solling anticline and covers an area of about 250 km². A landslide susceptibility model for the Lower Saxon Uplands indicates that the spatial patterns of landslide susceptibility in this area are largely similar to those of the entire region (cf. Klose et al. 2013; see “Highway exposure to landslides and regional cost estimate”). As is the case

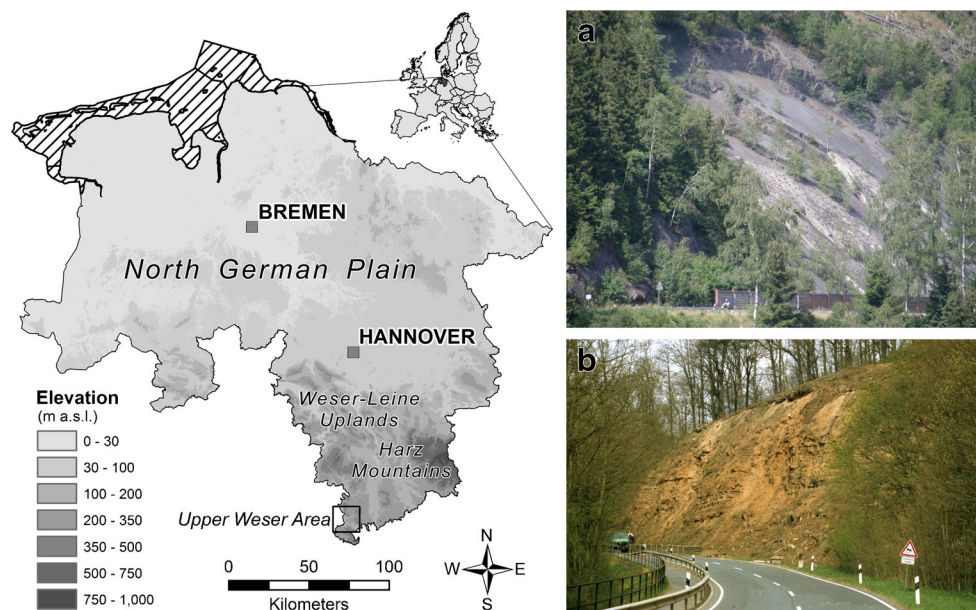


Fig. 1 Location of the Federal State of Lower Saxony, NW Germany. The photos show characteristic landslide sites along highways in **a** the Harz Mountains and **b** the Upper Weser area (Photos: Database B. Damm; base map derived from: ASTER GDEM, a product of METI and NASA)

on a regional level, highways in the Upper Weser area either pass through landslide-prone river valleys or traverse large plateaus with widespread areas that are free of any landslide hazard potential. This spatial distribution of slope instability proves the suitability of the Upper Weser area to serve as a representative case study area for regional cost extrapolation.

Methodology

General framework and workflow architecture

The developed methodology provides a general framework and toolset for estimation and regionalization of landslide costs for transportation infrastructures. To apply the tools provided by this methodology in a regional cost assessment, it is necessary to specify and customize them according to the regional data situation and the sociotechnical conditions of the study area. In this study, the methodology is designed to support regional cost estimation for highways in study areas characterized as follows: (a) high level of societal risk aversion, (b) highly developed highway systems, and (c) advanced coping capacity in both technological and financial terms. The configuration of the tools is based on management practices, mitigation concepts, and cost data from transportation planning, highway maintenance, and engineering in the Central Uplands of Germany.

The workflow architecture of this methodology is defined by a bottom-up approach of cost estimation that pursues the goal to spatially extrapolate past and current landslide losses from a local case study area to regional level (Fig. 2). A reliable time period for cost compilation on a local scale is about the previous 20 to 30 years. The reason for this reference period is to consider cost volatility caused by fluctuating landslide activity. A reference period of 20 to 30 years before the present is also proposed by Walkinshaw (1992). Such an ex post approach is adapted to the spatiotemporal characteristics of landslide impact and increases

the reliability of regional studies. The methodology is composed of two tiers of cost estimation: one on a local and one on a regional level (Fig. 2). Tier 1 provides tools for local cost compilation, and tier 2 is focused on regional cost extrapolation. Both tiers are linked by tools that enable data fusion.

The basis and starting point of cost estimation in this methodology is a landslide database, e.g., the one maintained by our working group (cf. Damm 2013). Most landslide databases store data sets on landslide location and thus provide functionality for landslide susceptibility modeling (cf. Van Den Eeckhaut and Hervás 2012). This is important as a regional landslide susceptibility model is at the heart of this methodology, fulfilling two main tasks: (a) decision support for the selection of a representative case study area for local cost compilation and (b) provision of tools for the regionalization of local landslide losses. In addition to data sets on landslide location, some landslide databases also contain information on landslide impact and types of landslide damage (cf. Van Den Eeckhaut and Hervás 2012). This data is vital for cost compilation in the first tier of this methodology.

The objective of local cost compilation is to create a complete and consistent loss record for the case study area by the application of various techniques to broaden and monetize data sets stored in the underlying landslide database. In this context, the two most important tools are cost survey and cost modeling. The main idea of cost survey is to retrieve first-hand loss data for recent landslides through targeted data mining of official accounting and archive systems. Alternatively, cost modeling is primarily intended for cost estimation of landslide damage older than the last 10 to 15 years, as this is the time period when official accounting and archive systems are electronically available and provide the most detailed loss data. The basic principle of cost modeling is to classify the landslide damage events documented in the landslide database to the following modeling concepts: (a) landslide disaster management process models (LDMM) that provide the costs involved in coping with landslide hazards over the full disaster cycle or (b) cost categories of the total costs of certain types of landslide damage. The result of local cost compilation is a cost figure that gives the annual average costs per kilometer of highway in the case study area.

In the second tier, the regionalization of local landslide losses is realized by GIS-based cost extrapolation using a landslide susceptibility model. The purposes of the landslide susceptibility model in cost extrapolation are as follows: (a) to identify sections of the highway network exposed to landslide hazards, (b) to support the development of a local and regional exposure index, and (c) to update the local cost figure to a cost index. These indexes show the capacity for cost extrapolation because supporting data fusion to realize the connection between the two tiers of this methodology. The basic assumption behind the concept of cost extrapolation is that hazard areas on a regional level probably experience similar annual costs per kilometer of highway as comparable areas at risk on a local level. This enables cost extrapolation to a regional level by simple operations on the basis of the local cost index and the regional exposure index.

Landslide database

The landslide database used in this study is a regional subset of a database system for landslides in the Federal Republic of Germany (cf. Damm 2013). This regional landslide database includes a

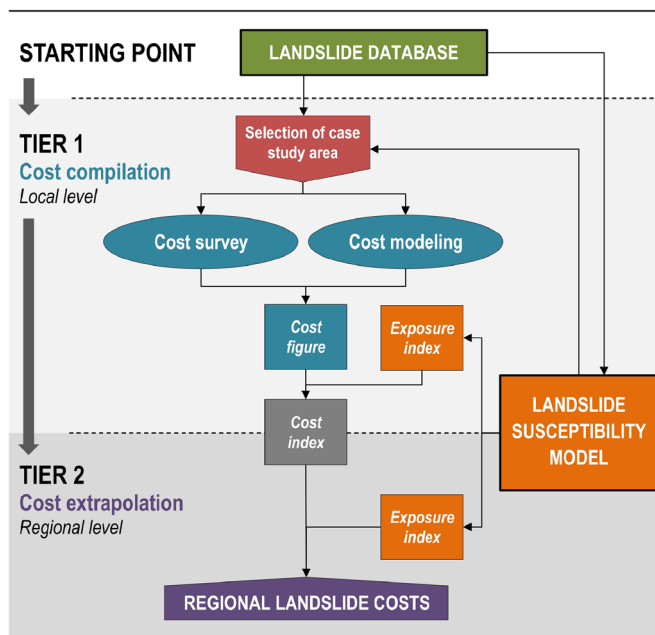


Fig. 2 Workflow architecture and tools of the methodology for landslide cost assessment

spatial landslide inventory and a specialized database with various thematic data sets. To facilitate data embedding in landslide susceptibility modeling and cost tabulation, both data archives are extracted to and managed in ArcGIS® or Microsoft (MS) Excel® format. The main function of these two parts of the underlying landslide database is to provide a data pool for cost modeling and spatial data sets of landslide occurrence for landslide susceptibility modeling and cost extrapolation. Most of the data stored in the specialized database originates from information sources with a high degree of reliability, e.g., scientific publications, agency records, and geotechnical and emergency reports as well as field data. The specialized database includes the following data tables of relevance for cost modeling: (a) general landslide documentation (e.g., location, date, site description), (b) process parameters (e.g., movement type, volume, extent, slip surface), (c) impact and damage (e.g., type of damage, damage severity, first response), and (d) repair and mitigation (e.g., type of repair or mitigation, technical details, costs). This data archive stores a consistent record of such thematic data sets for 33 landslides at highways in the Upper Weser area between 1980 and 2010. Alternatively, the spatial landslide inventory contains the geographic coordinates of 889 landslide sites in the Lower Saxon Uplands and adjacent areas (i.e., northern Hesse, eastern Westphalia). An important data source of this inventory is the landslide distribution map of Schunke (1971). Landslides are represented in the inventory as point objects geocoded based on the spatial reference of the main scarp or the top of the displaced mass.

Local cost compilation

Cost survey

A cost survey was conducted at the Regional Office Gandersheim of the Lower Saxony Department of Transportation (NLStBV). This cost survey enabled the acquisition of data on landslide costs for highways in the Upper Weser area between 2001 and 2010. The obtained loss data exclusively refer to landslides that are already recorded in the landslide database. The costs of these most recent landslides are well-documented in the Project Information and Management System (PRIMAS) operated by the NLStBV Regional Office Gandersheim. This system is a MS Excel® database for accounting and controlling of the business processes during one fiscal year. PRIMAS records for construction and maintenance projects with costs >US\$70,000 of all payment transactions, internal labor costs, and a brief specification of services. The financing of landslide repair below these minimum costs is based on fixed maintenance budgets that hamper cost itemization. PRIMAS cost data are used for the evaluation of seven (21 %) major projects of landslide repair and mitigation. A key advantage of cost survey based on PRIMAS is that this system provides a large part of the actual landslide costs. Only costs associated with road closure are often included in maintenance budgets and must be evaluated by cost modeling. This also is the case for the costs of first response that are usually ignored in PRIMAS. The only prerequisite for data retrieval in PRIMAS is the difficult task of identifying the right project ID for the relevant landslide damage.

Cost modeling

LDMMs are used for database-driven cost modeling of recorded landslide damage to highways before the year 2001. By contrast,

cost categorization is only presented in the discussion as an alternative modeling approach with reduced data requirements. The necessary landslide database information for cost modeling based on LDMMs include a landslide process description, a damage profile, and a fact sheet of repair or mitigation. The two basic assumptions of cost modeling are as follows: (a) highways in the Lower Saxon Uplands are often affected by similar types of landslides and landslide damage, and (b) landslide disaster management for highways in this region usually follows a standardized response, recovery, and/or mitigation management process. Both assumptions are empirically verified and constitute a necessary precondition for cost modeling by allowing the monetization of landslide damage with a high degree of standardization.

Three different LDMMs are designed to model landslide losses for highways: (a) recovery process model, (b) mitigation process model, and (c) maintenance process model. Each LDMM covers one key segment of the disaster cycle and simulates the cost-relevant steps involved in the process of coping with or preventing landslide damage. The LDMMs constitute cost chains that display the major cost factors of disaster management (first response, road closure, etc.) and fulfill the function to provide the basic framework for cost modeling based on landslide databases. Flowcharts are used as a modeling technique to visualize the disaster management processes for exemplary types of landslide damage to highways in the Lower Saxon Uplands. The development of the LDMMs is based on qualitative data material collected by conducting expert interviews with personnel of emergency management agencies (police and fire departments; Federal Agency of Technical Relief, THW) and the NLStBV Regional Office Gandersheim. Further information sources of high importance are federal and/or state emergency laws (Nds. SOG, NRettdG), disaster response laws (NKatSG, THW-Gesetz), and road construction law (NStrG).

The workflow of cost modeling starts with the classification of a landslide damage event (i.e., database entry) to a LDMM (Fig. 3). By means of the LDMM, the cost factors of this landslide damage event are determined, which is the first step of cost modeling. Subsequently, cost modules are used to monetize the identified cost factors. Cost modules refer to specific emergency, repair, mitigation, or maintenance measures and provide an estimate of their total costs. A distinction is made between basic and complex cost modules. Basic cost modules (e.g., geotechnical report) are based on a fixed cost rate and thus are easy to calculate. The costing of complex cost modules, however, is more sophisticated. Thus, one part of the complex cost modules is based on estimates of average costs per meter or square meter (e.g., catch fence, rock fall drapery), while the other part (e.g., road closure, rock buttress) relies on cost formulas that require entering basic or process-related data (e.g., road closure time; depth, length, width of slip surface). Complex cost modules for repair or mitigation structures calculated using average costs are mostly differentiated in categories of usual sizes, e.g., catch fence with low, medium, or high energy absorption capacity. The costing by means of LDMMs is done incrementally, with each cost module being individually calculated. In the last step, the monetized cost factors are totaled, so as to obtain the overall costs of the landslide damage event. This process of cost modeling is repeated for all database entries.

The price data integrated in cost modules are extracted from representative construction cost databases (Baupreislexikon®,

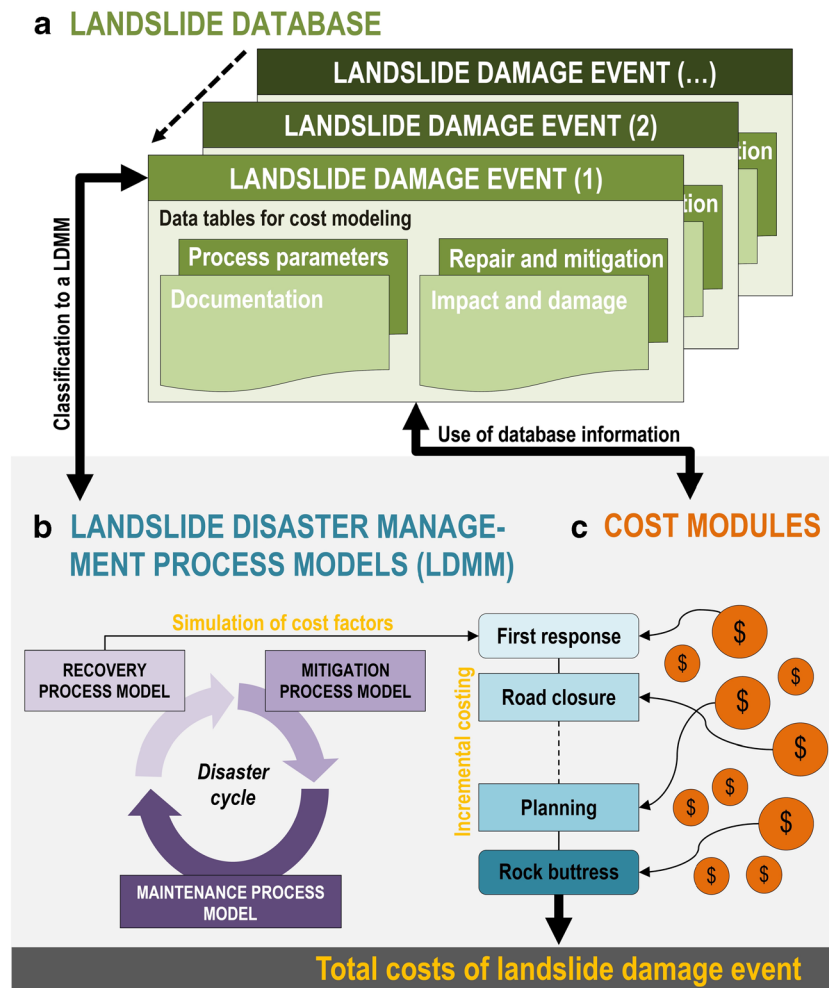


Fig. 3 Tools and workflow of cost modeling based on landslide databases

sirAdos[®]) or refer to cost proxies gathered by questionnaire surveys (mail surveys, $n=25$) and expert interviews (face-to-face and telephone surveys, $n=50$) at geotechnical engineering companies, emergency agencies, and the NLStBV. All prices of these data sources reflect current market prices, and most of them are net prices, which is why they are subject to 19 % value added tax (standard VAT rate). The two exemptions are internal labor costs and fees for emergency services. The design of complex cost modules is based on geotechnical concepts and dimensioning rules found in literature or obtained from engineering practice. Alternatively, directives and guidelines for road design (RAS-Q, RAS-Ew, RAS-LG, M Geok E, etc.) and traffic control (RSA-95, RUB-92) are a valuable basis for the development of complex cost modules.

The tabulation and costing of landslide losses compiled by cost survey and cost modeling are performed using a MS Excel[®] application. This application is a toolset, including (a) a data table giving the total costs on local and regional level, (b) a tool for cost modeling integrated in the data form for each landslide damage event, and (c) data tables storing the price data and the data for cost extrapolation. The different data tables are linked by relationships, and data processing uses custom functions, i.e., cost

formulas for certain cost modules (e.g., embankment infill buttress), both of which enable semiautomatic costing. For example, by entering the input data of a cost module (e.g., length and height of embankment) in the data form of the landslide damage event, this application writes the costs of this cost module in the data table of cost tabulation.

The result of cost compilation is a cost figure for highways in the Upper Weser area. This cost figure is based on the annual average of the total losses over the time period 1980 to 2010. The main idea underlying the cost figure is to break down the annual average costs on the total length of the highway network on a local level. Consequently, the cost figure specifies annual average costs per kilometer of highway in the Upper Weser area.

Example of cost modeling

The concept of cost modeling is illustrated using the example of a shallow landslide blocking a highway in the Upper Weser area in the year 1994 (Fig. 4). First, the landslide damage event is classified to the right LDMM, which is the recovery process model. According to this LDMM, disaster management starts with first response by a police patrol and a basic firefighting unit. The emergency responders report the landslide damage to the local

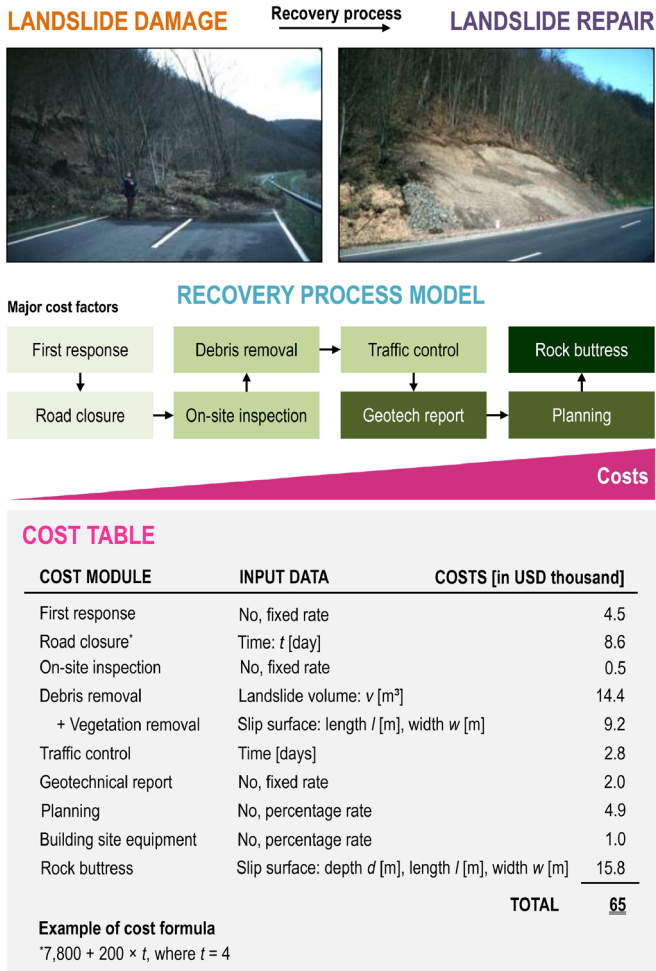


Fig. 4 Example of cost modeling for a landslide damage event affecting a highway near the city of Hann. Münden (Upper Weser area) in the year 1994 (Photos: Database B. Damm)

highway maintenance depot that closes the road and installs a detour. Afterwards, engineers of the NLStBV Regional Office Gandersheim conduct an on-site inspection to define further actions. The first step usually is debris removal undertaken by contracted construction firms. The primary goal is to reopen the highway to a single-lane traffic as soon as possible. Once the traffic is moving again, the planning of landslide repair is made. The planners generally consult expert opinion and rely on a geotechnical report. Landslide repair starts after public awarding of the construction project. The realization of the rock buttress completes the recovery process.

The cost table of this landslide damage event (Fig. 4) lists the applied cost modules with their input data and costs. The fixed rates of the cost module first response and on-site inspection are based on official cost rates and benchmarks of operation time, number of personnel, and equipment. An orthogonal highway network is assumed to estimate the costs of the road closure. This cost module is designed on the basis of a traffic control plan for road closure with off-site detour and cost rates from traffic control companies. While the price of the cost module geotechnical report constitutes a standard market value, the cost module planning and building site equipment are calculated as a

percentage of the net construction costs. Landslide process parameters and various assumptions concerning labor, machinery, and performance enable to apply the cost module debris and vegetation removal. Besides cost rates for necessary traffic signs, the cost module traffic control is based on an exemplary traffic control plan (lane closure on two-lane road using traffic signals). As is the case with the cost module road closure, the time of traffic control is derived from the general landslide documentation in the database. The costing of the rock buttress uses a standard repair concept and database information on the depth, width, and length of the slip surface. The total costs of this landslide damage event are estimated at about US\$65,000.

Regional cost extrapolation: landslide susceptibility model, exposure indexes, and cost index

The developed landslide susceptibility model used as a tool for the regionalization of local landslide losses is based on a bivariate statistical information value approach designed for applications on regional scales (cf. Yin and Yan 1988; Klose et al. 2013). The input data of this landslide susceptibility model for the Lower Saxon Uplands, and the geofactors derived from these input data, are as follows: (a) Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM) (slope gradient, plan curvature, slope aspect), (b) geologic overview map of Lower Saxony at >1:500,000 scale (nine lithological classes), and (c) DLM 50 of Lower Saxony (forest, grassland, arable land, urban area, other land use type). The applied modeling technique calculates an information value I as numerical weight for each geofactor attribute $A(i)$. The value of $I_{A(i)}$ is obtained by opposing the landslide density of $A(i)$ to that of the entire study area, which can be expressed as follows (modified after Yin and Yan 1988):

$$I_{A(i)} = \ln \frac{N_{A(i)} / S_{A(i)}}{N / S} \quad (i = 1, 2, 3, \dots, n) \quad (1)$$

where $N_{A(i)}$ is the number of landslides in attribute class $A(i)$, N is the number of landslides in the entire territory, $S_{A(i)}$ is the total area of attribute class $A(i)$, and S is the total area of the entire territory.

The geofactor weights are used to calculate a susceptibility index $SI(x)$ that describes the level of landslide susceptibility for the basic mapping unit x , which is the grid cell of the ASTER GDEM. $SI(x)$ is defined as the sum of all values of $I_{A(i)}$ in a grid cell x and can be computed as follows (modified after Wang and Sassa 2005):

$$SI(x) = \sum_{i=1}^n I_{A(i)} \frac{N_{A(i)} / S_{A(i)}}{N / S} \quad (2)$$

The susceptibility index ranges from -7.09 to 12.10 and is categorized in two hazard classes, i.e., no hazard area= $SI(x) < 3.00$ and hazard area= $SI(x) \geq 3.00$. This classification is due to the fact that geofactor combinations below $SI(x)=3.00$ are unlikely to promote slope instability, which is the result of expert-based scaling of the hazard classes.

The information on landslide susceptibility is used to calculate a local and regional exposure index. This index measures how

many kilometers of highway are located in potential landslide hazard area on a local or regional level. The calculation of the exposure index is based on spatial intersection of the hazard area identified by landslide susceptibility modeling with a local or regional data set of the location of highways. Furthermore, the information on landslide susceptibility is used to update the cost figure to a cost index. This is done by replacing the reference base of the cost figure with the local exposure index. Consequently, the cost index for the Upper Weser area specifies the costs per kilometer of highway at risk of landslides. The total annual average costs for highways in the Lower Saxon Uplands are obtained by multiplying the local cost index and the regional exposure index.

Results

Landslide losses for highways in the Upper Weser area

Cost structure and temporal patterns of landslide losses

The total landslide loss for highways in the Upper Weser area amounts to US\$23.5 million between 1980 and 2010. Figure 5a illustrates that 19 (61 %) years of this 31-year period show landslide damage. The distribution of the annual number of landslide damage events is relatively homogenous, ranging between zero and three events per year. By contrast, the costs of landslide damage are strongly concentrated on five years in the early 1980s and the mid-2000s which together account for 94 % (US\$22.2 million) of the total loss. As a result, there is huge discrepancy between the annual average costs (US\$0.76 million) and the annual median costs (US\$17,000), a fact of high importance for cost extrapolation (Table 1). Years with minimum costs of at least US\$0.1 million have a return period of $T=3.1$ years. The highest annual costs (US\$7.4 million) are estimated for the year 2006 when two major projects of landslide repair and mitigation had been realized, including stabilization of a failed cut slope (US\$4.6 million) and slope reinforcement by soil nailing (US\$2.8 million). The analysis proves that landslide repair (US\$9.8 million) and mitigation (US\$13.0 million) make up 97 % of the overall costs. Most of the remaining costs are due to maintenance (US\$0.6 million), while the costs of first response (US\$0.1 million) are widely negligible (Table 1). The total annual costs and the number of landslide damage events per year are only weakly correlated (Fig. 5c). Although costs in years with only one landslide damage event are always below US\$0.5 million, there is no clear relationship that the more landslide damage events, the higher the annual costs. As Fig. 5b indicates, the major cost drivers are few exceptional landslide damage events causing expensive repair or mitigation. Thus, about 75 % of the total costs refer to the five most costly landslide damage events. This implicates that 85 % of the landslide damage events only represent 19 % of the overall costs. The importance of repair and mitigation costs is associated with strong cost variability among the different types of landslide repair and mitigation (Fig. 5d). A significant part of this cost variability originates from landslide dimension and cost differences between comparable mitigation measures. This especially applies to rock fall protection by means of catch barriers and rock fall drapery that are less expensive than their counterparts (e.g., catch fence, anchored mesh systems). Such low-cost mitigation structures are identified of only temporary effectiveness, implicating short repair cycles, and thus being the major driver of maintenance costs. Among landslide damage

events >US\$1.0 million, a majority (67 %) is classified to cause mitigation costs. These investments in traffic safety are often a direct reaction to periods of increased landslide activity, which illustrates the high relevance of risk awareness as cost factor.

Validation of the cost compilation

The validation of the cost compilation for the Upper Weser area only concerns those losses gathered by cost modeling. This is because cost survey provides in principle the actual costs of landslide damage. The main idea of the validation is to cross-check the results of cost modeling with available reference data from cost survey. As the developed LDMMs describe prevailing disaster management practices, and thus show a high degree of reliability, the validation is exclusively focused on assessing the quality of applied cost modules. To test their plausibility and accuracy, some cost modules are used to recalculate the losses of repair or mitigation measures evaluated by cost survey. The error between estimated and actual costs is seen as a first indicator for the precision of these cost modules. Such a validation was conducted for six (18 %) landslide damage events included in the cost compilation. According to Table 2, the error is between -11.6 and 18.7 % ($\sigma=9.1$ %), which is within the range of tolerance of $\pm 10-20$ % commonly accepted in project cost estimation. There are two main reasons for the cost difference between estimated and actual costs: (a) uncertainty about major cost drivers (e.g., standardized length of soil nails; case 1 of Table 2) and (b) decreasing unit and average costs (e.g., variable length of repaired road; cases 3, 4, and 5 of Table 2). For example, the decrease in average costs from cases 3 to 5 of Table 2 is about US\$2,000, a difference in costs explaining the error of 18.7 % for case 5. The validation verifies sufficient reliability and accuracy of the tested cost modules but requires more empirical reference data for assessing the overall quality of cost modeling.

Landslide losses for highways in the Lower Saxon Uplands

Highway exposure to landslides and regional cost estimate

The specific setup of the regional landslide susceptibility model leads to the result that slope gradient is the major controlling factor of slope instability in the Lower Saxon Uplands (Table 3). Critical slope gradients are identified to lie between 21° and 49° . The landslide susceptibility model predicts that slopes with a high degree of plane curvature show substantial tendency to landslides. Alternatively, slope aspect is proven to be a controlling factor of only subordinate relevance. Most landslides are related to Mesozoic sedimentary rock, especially sand and limestone or clay and limestone, which exert strong positive effect on landslide occurrence. By contrast, land use shows low importance for regional landslide susceptibility; however, this ignorance of human impact is mainly due to the required model simplicity in applications on large spatial scales (cf. Klose et al. 2013).

The expert-based scaling of the susceptibility index results in 7.5 or 10.1 % of the territory of the Lower Saxon Uplands or the Upper Weser area as being classified as landslide-prone. The local or regional exposure index estimates that 14.5 or 77.0 km of highways are at risk of landslides (Fig. 6). This means that on a local or regional level, 23.9 or 6.2 % of the highway network is located in potential landslide hazard area. The cost index calculated for the Upper Weser area amounts to US\$52,000. By comparison, the cost figure, which only refers to total length of the

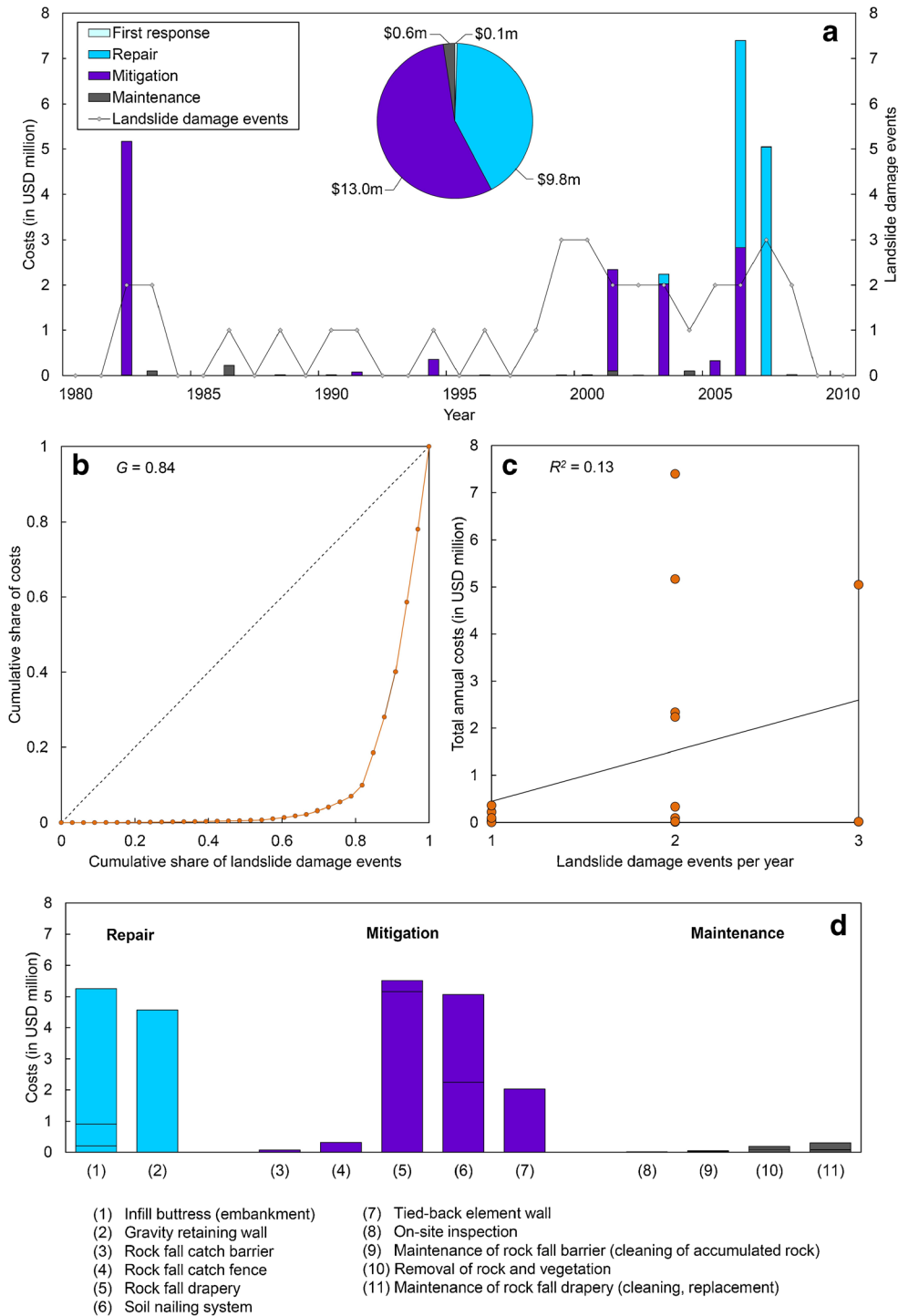


Fig. 5 Landslide losses for highways in the Upper Weser area between 1980 and 2010. **a** Trends of landslide activity and costs and cost structure of landslide disaster management. **b** Lorenz curve and Gini index of the landslide cost distribution. **c** Scatterplot and regression curve of total annual costs in relation to number of landslide damage events per year. **d** Types and cost structure of repair, mitigation, and maintenance measures

local highway network, is about US\$12,000. The average landslide costs for highways in the Lower Saxon Uplands are estimated at US\$4.02 million per year. This corresponds to annual average costs per kilometer of highway of about US\$3,200. A projection of the regional losses per year over the entire 31-year time period reaches the total of US\$125 million.

Validation of the cost extrapolation

The plausibility of the cost extrapolation is tested by a validation of the landslide susceptibility model used to extrapolate landslide losses. This model validation is based on the concept of the success and prediction rate (Fig. 7; cf. Chung and Fabbri 2003). According to the success rate, 88 % of the landslides included in the model

Table 1 Landslide losses and cost statistics for different types of landslide disaster management

Types of landslide disaster management	Landslide damage events		Costs per damage event [in USD thousand]				Total costs [in USD thousand]	
	Total	%	Min	Max	Average	Median	Total	%
All categories	33	100	0.5	5,161	712	18	23,498	100
First response	8	24.2	6	19	–	–	101	0.4
Repair	4	12.1	208	4,571	–	–	9,822	41.8
Mitigation	7	21.2	76	5,161	–	–	13,012	55.4
Maintenance	14	42.4	0.5	222	–	–	564	2.4

(modeling set=85 % of the landslide inventory, 756 landslides) refer to the most susceptible 10 % of the total area. Alternatively, the prediction rate specifies that the most unstable 10 % of this region contains 92 % of the independent landslides (validation set=15 % of the landslide inventory, 133 landslides). Although both rates prove good predictive power and high spatial accuracy, the results of the validation are no indicator of the overall plausibility of this model. This shows a conditional independence test between slope gradient and land use ($C_{corr}=0.59$; $\chi^2=264.69 > \chi^2_{0.01}$) and the fact that some lithological classes are not mutually exclusive (sand- and limestone, clay- and limestone). Despite such data-related problems, which are difficult to avoid in studies with regional focus, the model is from a technical perspective suitable for proper spatial evaluation and zonation of landslide susceptibility for purposes of cost extrapolation.

Discussion

Methodological problems and solutions

The different tools of this methodological approach are designed and coordinated to meet crucial scale-related problems in ex post assessment of landslide losses for transportation infrastructures. Despite the fact that the test application of this methodology verifies its basic capacity for reliable cost estimation on local and regional levels, there are various methodological problems which need to be discussed in detail. Most of these problems relate to challenges of reduced data availability and quality when assessing landslide costs over broad areas and long time periods. The main problems of this methodology and ideas for its solution are presented in the following:

(a) Temporal cost volatility shows the importance of taking time periods of at least more than 10 to 20 years as a basis for reliable cost estimation in areas with low to moderate landslide activity. A major problem of cost modeling is that even comprehensive landslide database systems are characterized by a significant decrease in data completeness and quality over such long time periods (cf. Devoli et al. 2007; Hilker et al. 2009). This primarily affects the applicability of complex cost modules because of their comparatively high data requirements. Tools such as Google Earth® and Google Street View® are helpful to bridge

some few data gaps (e.g., size of repair or mitigation structures), but yet, the landslide database for cost modeling needs to provide most of the necessary data without subsequent optimization. A solution to reduce data requirements in cost modeling is the concept of cost categories (Fig. 8). The idea is to replace LDMMs and cost modules by categories of the total costs for certain types of landslide damage. According to this concept, the costs of a landslide damage event are estimated by its classification to a specific cost category. Although this study provides losses for a number of typical landslide damage events at highways, the available data basis is yet too small to test or apply such preliminary cost categories in practice. A key advantage of cost modeling is to gain knowledge of major cost factors and drivers of landslide losses, which is vital for the development of reliable cost categories. As a result, the cost categories presented in Fig. 8 are likely to describe a reasonable range of costs, and this is most important for landslide cost assessment. Such a standardization of disaster management processes and landslide costs, however, is still associated with methodological problems. Thus, the application of both cost modeling and cost categorization is widely limited to less complex landslide damage events. By contrast, landslides causing exceptional damage to traffic routes (e.g., 2010 Taiwan Highway 3 Landslide; The Landslide Blog 2010) principally require individual assessment (i.e., cost survey), which conflicts with the idea of standardization that underlies both methodological approaches. Consequently, the use of this methodology is largely restricted to areas where transportation infrastructures are often affected by comparable types of landslide damage.

(b) A key component of this methodology is a regional landslide susceptibility model that enables to derive the main tools used for cost extrapolation. The development of regional landslide susceptibility models is generally faced with several methodological and data-related shortcomings (cf. Klose et al. 2013). One problem of high relevance in this study is the limited availability of suitable input data for geofactors other than geomorphometry. As is the case with lithology and land use, the use of low-quality input data often implies further methodological problems, especially regarding the violation of conditional independence. A χ^2 test proves a significant spatial association between slope gradient and land use. This dependency, however, is tested to be of minor

Table 2 Information values for attribute classes of geofactors considered in the landslide susceptibility model for cost extrapolation. A detailed description of the categorization of geofactors and attribute classes is given in Klose et al. (2013)

Geofactors and attribute classes $A(i)$	Information value $I_{A(i)}$
Geomorphometry	
Slope gradient	
0°–7°	–1.71
7°–14°	0.01
14°–21°	2.43
21°–28°	4.07
28°–35°	4.69
35°–42°	4.85
42°–49°	4.72
49°–90°	0.00
Slope curvature	
Strong convex	3.22
Convex	0.05
No curvature	–1.00
Concave	0.13
Strong concave	2.65
Slope aspect	
N	0.17
NO	0.27
O	0.29
SO	–0.10
S	–0.10
SW	–0.04
W	–0.02
NW	–0.11
No aspect	0.00
Lithology	
Quaternary lowland deposits	–2.56
Marlstone	0.52
Clay-/limestone	2.69
Sand-/limestone	1.31
Greywacke/clay shale	–1.01
Granite	0.00
Land use	
Forest	1.05
Grassland	–0.95
Arable land	–1.82
Urban area	0.40
Other land use type	0.00

importance, as only leading to a constant overestimation of $SI(x)$, but not changing the statistical relations in the susceptibility scale.

Consequently, none of these geofactors are excluded in landslide susceptibility modeling (cf. Neuhäuser et al. 2012). The generalized geologic overview map (>1:500,000) is applied because medium- to large-scale geologic maps are too precise in their class representation to support the calculation of useful statistical correlations. Nevertheless, this map shows the deficit of providing lithological classes that are not mutually exclusive, which conflicts with the assumption of conditional independence. A further problem relates to the resolution of the ASTER GDEM of ± 25 m and its capacity to represent artificial slopes along traffic routes with sufficient spatial and topographic precision. Slope parameters derived from DEMs are negatively correlated to the size of their grid cells. This implicates a lack of exactness in relief representation, if applying a DEM with low to medium resolution (cf. Zhang et al. 1999). Several methodologies have been proposed to address this problem by data transformation and rescaling (cf. Qinke et al. 2008), but the slight systematic bias towards underestimating slope gradient ($\sim 5^\circ$ – 10°) identified in this study is widely negligible for cost extrapolation. Future research work has to address major weak points considering the concept of the exposure index. In its current usage, it simply defines an undifferentiated risk for transportation infrastructures located on a probable landslide mass but ignores hazard exposure in potential pathways of landslide movement. The integration of runout distances in regional landslide susceptibility models, however, exceeds the capabilities of today's modeling tools (cf. Klose et al. 2013). Thus, the proposed exposure index will probably remain an incomplete concept that causes significant uncertainty in cost extrapolation.

(c) The result of the regional cost extrapolation is strongly influenced by the decision to operate with a cost index based on annual average costs. Due to outlier resistance, the annual median costs account for only US\$17,000, which is about 45 times less the annual average cost of US\$0.76 million. The use of annual median costs in cost extrapolation leads to a cost estimate for the Lower Saxon Uplands of less than US\$0.1 million per year. This causes a difference in costs of almost US\$4 million (98 %) compared to the cost extrapolation based on annual average costs. The large discrepancy between annual average costs and annual median costs is a consequence of comparatively high cost volatility and concentration, although on much shorter time scales than most other natural hazards. Thus, the annual return period of costs \geq US\$0.1 million is only $T=3.1$ years on a local level, which affects short- to medium-term financial planning. This return period puts temporal cost volatility and concentration into perspective, but still maintains the need for analyzing annual cost trends over tens of years. A further source of error in cost estimation is related to the classification of insidious landslide damage or maintenance costs to one certain accounting year of the time series. As not distributing such costs over time, this study shows the tendency to slightly overestimate the volatility and concentration of annual landslide costs. Against this background, operating with annual average costs is proven to be a reasonable approach but requires keeping in mind high cost uncertainty.

Comparison of the cost estimate for the Lower Saxon Uplands

A comparison of the results of this cost assessment for highways in the Lower Saxon Uplands with landslide losses from study areas worldwide is strongly limited because of data scarcity. However, there are for some regions cost estimates available that support a

Table 3 Validation of cost modeling by comparing estimated costs of applied cost modules with actual costs of cost survey for different types of landslide repair and mitigation

Repair or mitigation measure and relevant cost module	Area/length	Actual costs/ estimated costs [in USD million]	Error [in %]
(1) Slope reinforcement after rock/soil slide, above road (year 2001); cost module: soil nailing, deep slip surface (12 m)	4,300 m ²	2.16 / 1.91	-11.6
(2) Slope reinforcement after rock/soil slide, above road (year 2006); cost module: soil nailing, medium-deep slip surface (6 m)	8,300 m ²	2.48 / 2.65	6.5
(3) Failure of fill slope, highway embankment (year 2003); cost module: infill buttress, medium embankment height (6 m)	20 m	0.18 / 0.17	-1.4
(4) Landslide in fill slope, highway embankment (year 2007); cost module: infill buttress, medium embankment height (6 m)	75 m	0.64 / 0.65	1.5
(5) Settlement of fill slope, highway embankment (year 2007); cost module: infill buttress, medium embankment height (6 m)	550 m	4.06 / 4.82	18.7
(6) Rock fall protection after small rock fall, above road (year 2005); cost module: catch fence, low energy absorption capacity (<100 kJ)	470 m	0.26 / 0.27	3.6

comparison of costs, although such a comparison needs to be interpreted with caution. Some of the most recent data on annual landslide losses for highways are from the USA and include the states of Kentucky (>US\$2 million; USGS 2013), Oregon (US\$5.8 million; Wang et al. 2002), and Wyoming (US\$1.0 million; Wyoming

Homeland Security 2011). At the European level, Vranken et al. (2013) estimate for a regional case study area in the Ardennes, Belgium, annual average costs of landslide repair and/or mitigation for roads (US\$0.8 million) and railways (US\$0.6 million) of about US\$1.4 million. The most comprehensive compilation of landslide

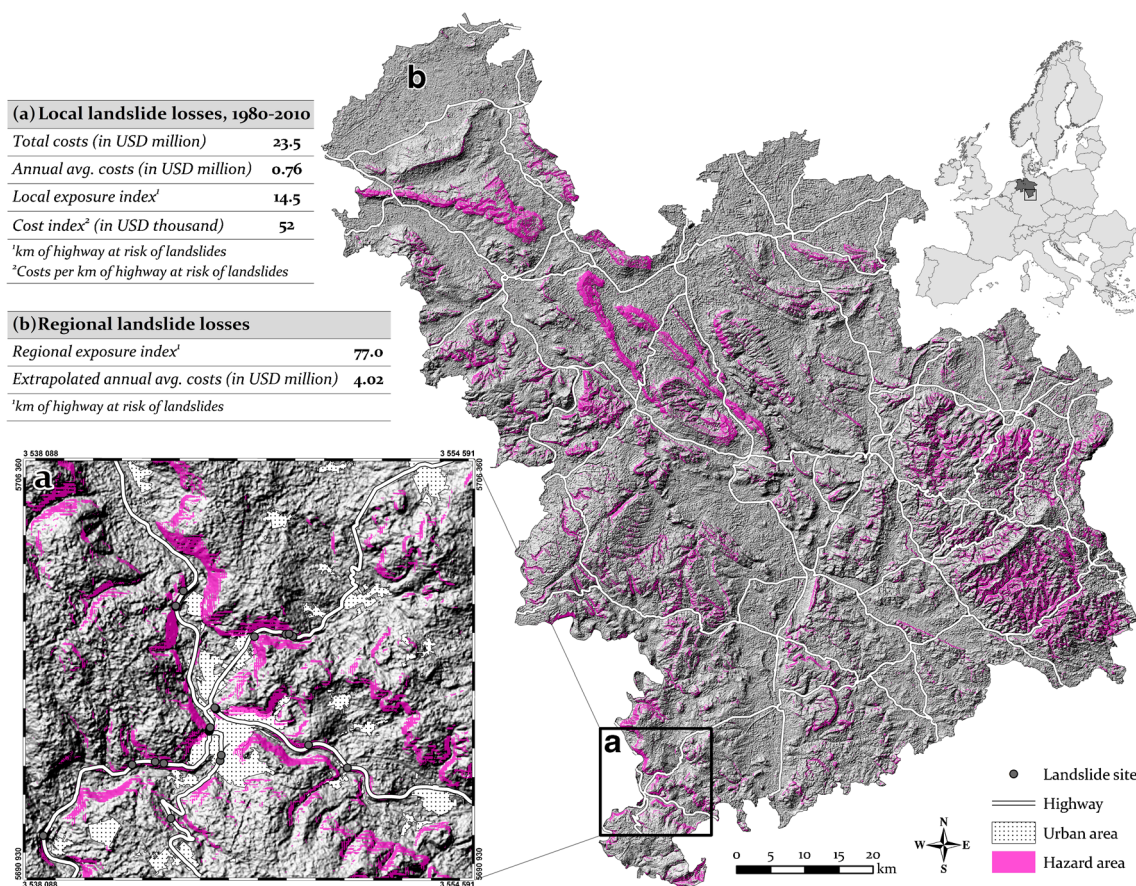


Fig. 6 Landslide losses for highways in the Upper Weser area and cost extrapolation for the entire highway network of the Lower Saxon Uplands (modified after Klose et al. 2013; base map derived from: ASTER GDEM, a product of METI and NASA)

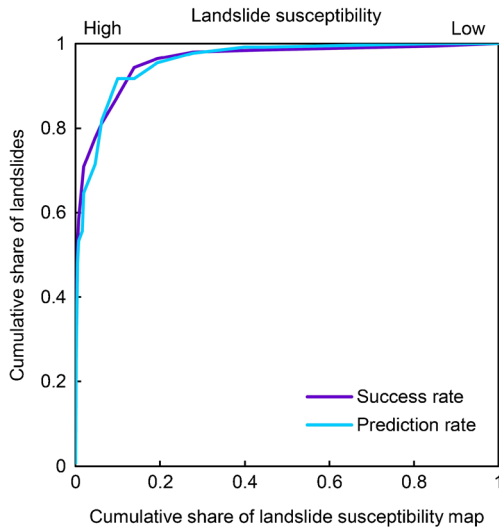


Fig. 7 Success and prediction rate of the landslide susceptibility model for cost extrapolation

losses for highways is still that of Walkinshaw (1992). On the basis of a cost survey for the US state highway systems (~20 % of the 1990 US highway network), this study provided an estimate of national landslide repair and maintenance costs of about US\$190 million per year. Using the data sets published in this study, the costs per kilometer of highway are estimated at US\$150, which strongly contrasts with the reference costs of US\$3,200 for the Lower Saxon Uplands. The costs per kilometer of highway in the Lower Saxon Uplands are thus about

20 times as much as the US cost estimate. An additional study reports landslide repair costs for highways in the Lao PDR of, on average, US\$7.2 million per year (cf. Hearn et al. 2008). According to the data presented in this study, the annual costs per kilometer of highway are about US\$1,000. Although the difference in costs is less pronounced, the reference costs for the Lower Saxon Uplands are more than three times that of the Lao PDR. The comparison shows wide variations between the landslide losses of the different areas and proves that the cost estimates provided by this study are relatively high in value. However, the many influencing factors on these cost estimates (e.g., size of study area, level of landslide hazard, sociotechnical conditions) make their comparison difficult, which is why this comparison only supports a preliminary cross-checking of the obtained results.

Conclusions

The assessment of landslide costs is a challenging task that requires methodologies capable to cope with problems arising from complex spatiotemporal landslide distribution patterns and the lack of functional relationships between landslide intensity, damage impact, and costs. Of the two existing approaches of landslide cost estimation, ex post assessments are identified to better address these problems, but yet, their strict focus on cost survey limits their applicability to mainly local levels and relatively short time periods. The absence of methodological approaches that combine cost survey with tools to quantify and project long-term landslide losses over broad areas is a major obstacle for the development of reliable cost estimates. Thus, the most comprehensive loss data for transportation infrastructures are still those for US state highway systems from before the early 1990s.

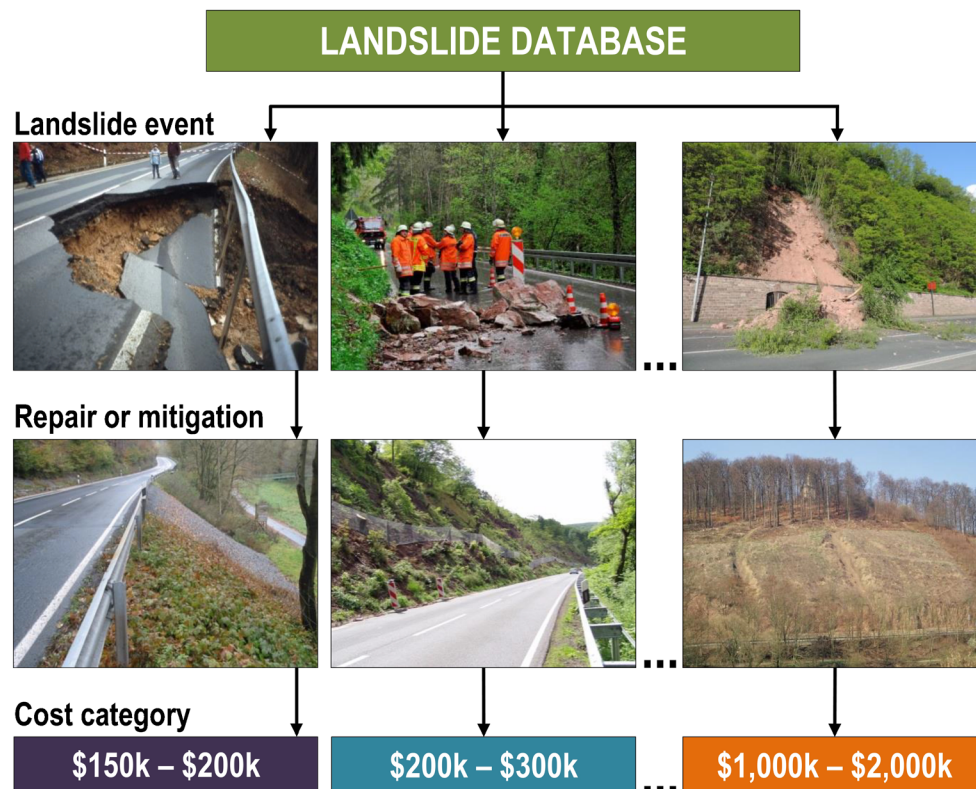


Fig. 8 Example of cost modeling based on categories of total costs for certain types of landslide damage (Photos: Database B. Damm, A. Gidde, Königl GmbH & Co. KG)

Landslide cost estimation by means of the presented methodological approach is still confronted with some major problems. Most of these problems concern high data requirements and the need for standardization in cost modeling. As a result, the application of this methodology is widely restricted to areas that are covered by comprehensive landslide database systems. Alternatively, regional landslide susceptibility modeling is affected by limited availability of adequate input data, which in turn reduces the performance of cost extrapolation. A challenging future research task will be to optimize the exposure index to take account of cost risks in potential pathways of landslide movement. The most significant uncertainty in this methodological approach originates from cost extrapolation based on annual average costs. Finding solutions for these sources of error in landslide cost estimation is at the top of the agenda of upcoming methodological research.

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