ANTHROPOGENIC LANDSLIDES AT TRANSPORTATION INFRASTRUCTURE

Comprehensive analysis of susceptibility, vulnerability, triggers and risk perception for a better understanding of the anthropogenic role in natural hazards in Lower Saxony, Central Germany

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ABSTRACT

The advancing industrialization in Central Europe in the 19th resulted in growing populations and growing demands for transportation infrastructure. Since 1890, the road network of interregional roads almost doubled until today. To minimize construction efforts in regions of high relief, roads were constructed and broadened tracing river valleys. Road cuts have been created by rock blasting or material removal by hand. Then, the removed material was used to broaden the exterior slope in order to create a leveled road surface. Simultaneously with the establishment of modern road construction in the middle of the 18th century, the first landslides were reported at road infrastructure which are closely linked to the road construction practices. In addition, the flourishing industrialization in Central Europe resulted in the realization of artificial waterways like the Mittelland canal connecting the Rhine trading area with the Elbe trading area. While the construction of the western canal branch remained unproblematic, the continuation of the canal between Hanover in the west and the Elbe River in the east resulted in construction-related landslides, especially in the first half of the 20th century. Until today, at least 30% of the registered landslides in southern Lower Saxony are linked to anthropogenic influences. With an ongoing growth of local urban centers and increasing percentages of impervious surfaces, the number of anthropogenic landslides tends to increase, regardless of future climate trends.

Based on historical landslide data, several aspects of anthropogenic interactions considering landslides at transportation infrastructure were analyzed implying different approaches (i.e., descriptive and bivariate statistics as well as empirical analysis). The results have been published as three separate contributions in peer-reviewed scientific journals. The articles are entitled 'Case histories for the investigation of landslide repair and mitigation measures in NW Germany', 'Analysis of historical data for a better understanding of post-construction landslides at an artificial waterway' and 'Rockfall vulnerability of a rural road network — a methodological approach in the Harz Mountains, Germany'.

In the second publication the predisposing and triggering factors of landslides at the Mittelland canal are examined, implementing quantitative statistical methods. In addition, case histories have been developed to examine repair and mitigation measures of landslide at transportation infrastructure. The majority of landslides occurred at three distinct sites: at the tributary canal to Hildesheim, at the main canal at km 195 (Schwicheldt, near Peine) and at the main canal at km 200 (Wenden, near Brunswick). The landslides at these sites are strongly controlled by material characteristics and are linked to over-steepened slopes which have been created by incision into vulnerable fine-grained clay− and marlstone and quickly disintegrate in wet−dry cycles. Strong correlations between landslide occurrence and construction phases can be identified between 1920 and 1938. Further phases of increased landslide activity have been registered during World War II and in the post-war phase between 1946 and 1957. Human influences contribute both to predisposing and triggering landslides. While precipitation can be neglected as landslide trigger, vibrations related to transportation of excavated materials on railroads during construction and faulty (re-)construction and mitigation planning have been reported to contribute to landslide triggering. In addition, during World War II the effects of air blasts due to aerial bombing are plausible as potential landslide trigger, though a final evaluation remains difficult due to the missing accuracy of landslide occurrence.

In order to estimate potential risks of anthropologic landslides considering transportation infrastructure, the rockfall susceptibility has been modeled for the rural road network in the Harz

mountains. In combination, the vulnerability of the road network has been assessed. The approach has been implemented in the publication 'Rockfall vulnerability of a rural road network — a methodological approach in the Harz Mountains, Germany'. For the susceptibility modelling, a bivariate statistical method (information value) was utilized. In addition, the vulnerability of road sections in the Harz mountains was assessed with vulnerability indicators. The indicators are calculated by summarizing the vulnerability factors for each road section, which have been weighted by analytic hierarchy processes. The vulnerability factors include daily traffic volumes, road type, speed reductions, length of alternate routing and mitigation measures.

The susceptibility model assigns for 13 % of the road network area an positive information value which translates to a high or very high susceptibility for rockfall. The relevant road sections are linked to high slope values, NE orientations of road sections and low to moderate vulnerability values. The highest vulnerability values can be found on road sections with high average daily traffic volumes. While sections of high susceptibility are situated at roads connecting marginal with internal roads, sections of high vulnerability are located on marginal roads of the Harz mountains. Since the vulnerability is based on mitigation measures, among other factors, the road sections, where rockfall events have been registered, are characterized by the presence of structural and non-structural rockfall mitigation. Therefore, road section with a high number of registered rockfall events, show rather low vulnerabilities. The combination of the presented methods proposes an easily applicable estimate of vulnerability where conventional methods (i.e., vulnerability curves, matrices) cannot be implemented. For the presented area of the Harz mountains, the role of mitigation measures is emphasized and intact mitigation measures are of great importance for the road network vulnerability.

The role of repair and mitigation measures at transportation infrastructure have been investigated with case histories in the Upper Weser area. This is included in the publication 'Case histories for the investigation of landslide repair and mitigation measures in NW Germany'. In the city of Hann. Münden, three case histories have been developed to illustrate and analyze the landslide activity in interaction with land use practices including the application of structural mitigation measures. The three sites are characterized by anthropologic alterations due to road constructions at the end of the 19^{th} and 18^{th} century, respectively. Phases of increased landslide activity can be identified in the 1770s, 1880s, 1900s, 1930s, 1950s and 1970s, whereas phases of increased mitigation efforts can be observed in the 1900s, 1930s, 1960s, 1980s, 1990s and 2000s. Decades of increased landslide activity coincide and are followed with/by phases increased mitigation activity, respectively. The evolution of mitigation measures in the Upper Weser area can be categorized in distinct phases: During the phases of road construction in the 1770s and 1880s mitigation focused on stabilization of the lower interior slopes by implementing dry walls. The construction of dry walls was intensified to protect higher parts of the interior slopes in the 1900s and 1930s. In addition, engineered mitigation measures were planned for the first time in the 1930s. These measures were not executed until the 1960s by implementing concrete retaining walls and a combination of wire meshes and barriers for rockfall protection. Beginning in the 1980s, the phase of modern mitigation is characterized by comprehensive slope reconstructions with increasing efforts since the 1990s. The comparing case history from the Mittelland canal illustrates the contemporarily development and application of mitigation measures at an artificial waterway in the first half of the 20^{th} century. The required canal depth of 16−17 m was reached by implementing trapezoidal incised slopes with inclinations of 50−70%. Shortly after construction or even during construction between 1920 and 1927, these created ditches failed. The first applied mitigation measures during that time included the installation of drainage trenches, which resulted in accelerated decomposition of the involved fine-grained clay− and marlstones. As a result, the canal profiles were gradually flattened and new profile types were developed in the subsequent construction phase between 1928 and 1938. During World War II the landslides slopes were still regraded to inclination of 1:3. These efforts were constrained by shortages of money, manpower and fuel during the war. Instead, landslide material was removed from the canal to enable a continuing shipping traffic. After the war had ended, reconstructions became necessary for a high percentage of vulnerable slopes along the canal due to shortages during the war. Materials and older drainage systems were removed, canal profiles were regraded and new drainage systems were implemented. In addition, the slopes were stabilized with tree plantations. The presented case histories can be utilized to reflect the public risk perception towards landslides. For the case histories in the Upper Weser area the phases of response, recovery and mitigation within the risk cycle can be clearly identified. Though, a final phase of preparedness has been lacking in the past and as a result, deficient mitigation measures contributed to the landslide hazard.

The presented results suggest strong human influences considering landslides at transportation infrastructure. These include both predisposing and triggering factors. Furthermore, aged mitigation measures contribute to landslide hazards in the area of southern Lower Saxony. In highly developed countries in Central Europe, it is necessary to landslides consider anthropogenic influences in addition to ‘natural’ factors when risk is assessed or mitigation measures are planned and executed.

ZUSAMMENFASSUNG

Die voranschreitende Industrialisierung im 19. Jahrhundert führte in Mitteleuropa sowohl zu steigenden Bevölkerungszahlen als auch zu einer steigenden Nachfrage nach Verkehrsinfrastrukturen. Seit 1890 hat sich das Verkehrsnetz von überregionalen Fernstraßen bis heute fast verdoppelt. Um den Bau von Straßeninfrastrukturen in Regionen mit starkem Relief zu vereinfachen, wurden Straßen besonders in Flusstäler gebaut. Die Straßenanschnitte wurden dabei anfangs durch Sprengungen hergestellt bzw. durch Räumung von Hand. Das anfallende Material fand anschließend für das talseitige Anlegen der Fahrbahn sowie deren Erweiterung Verwendung. Mit der Einführung des modernen Straßenbaus in der beschriebenen Weise, wurde auch über erste Massenbewegungen an Straßeninfrastrukturen berichtet. Im Zuge der voranschreitenden Industrialisierung wurden außerdem auch Wasserstraßen, wie der Mittellandkanal, verwirklicht, um die Gebiete der Schwerindustrie im Elbeeinzugsgebiet mit den Kohlerevieren des Rhein-Ruhr-Gebiets zu verbinden. Nachdem die Konstruktion des westlichen Teils des Mittellandkanals unproblematisch verlief, wurde seine Weiterführung zwischen Hannover und der Elbe besonders in der ersten Hälfte des 20. Jahrhunderts immer wieder von baubedingten Rutschungen beeinträchtigt. Bis heute können mindestens 30 % der in der Datenbank registrierten gravitativen Massenbewegungen aus Südniedersachsen mit anthropogenen Einflüssen verbunden werden. Aufgrund eines anhaltenden Wachstums der lokalen urbanen Zentren und einer kontinuierlich zunehmenden Flächenversiegelung wird der Anteil anthropogener Massenbewegungen vermutlich auch in Zukunft steigen, ungeachtet möglicher zukünftiger Klimaentwicklungen.

In der präsentierten Arbeit werden, basierend auf historischen Rutschungsdaten und unter der Verwendung unterschiedlicher Methoden (deskriptive und bivariate Statistik sowie empirische Studien), verschiedene Aspekte anthropogenen Einflusses an Verkehrsinfrastrukturen vorgestellt. Die Ergebnisse wurden in drei Fachartikeln in wissenschaftlichen Zeitschriften begutachtet und veröffentlich und werden hier kumulativ zusammengefasst. Die Fachartikel wurden unter folgenden Titeln veröffentlicht: „Case histories for the investigation of landslide repair and mitigation measures in NW Germany", „Analysis of historical data for a better understanding of post-construction landslides at an artificial waterway" und „Rockfall vulnerability of a rural road network — a methodological approach in the Harz Mountains, Germany".

Im Rahmen der zweitgenannten Publikation wurden mit Hilfe von statistischen Methoden die Dispositionsfaktoren und Auslöser von Rutschungen am Mittellandkanal untersucht. Zusätzlich wurde eine Fallstudie entwickelt, um Art und Umsetzung von Sanierungs- und Sicherungsmaßnahmen am Kanal zu untersuchen. Der Großteil der Rutschungen am Mittellandkanal wurde an drei räumlichen Abschnitten registriert: am Seitenkanal nach Hildesheim, am Hauptkanal bei km 195 (bei Schwicheldt, nahe Peine) und am Hauptkanal bei km 200 (bei Wenden, nahe Braunschweig). Die aufgetretenen Rutschungen werden vor allem durch die Materialeigenschaften kontrolliert. Einerseits können rutschanfällige feinkörnige Ton- und Mergelsteine unter dem Einfluss von Feucht-Trocken-Zyklen beschleunigt verwittern. Andererseits wurden während des ursprünglichen Kanalbaus an den betreffenden Stellen mit problematischen Materialeigenschaften übersteilte Einschnitte hergestellt. Besonders im Zeitraum zwischen 1920 und 1938 lassen sich Rutschungen und Bauphasen miteinander korrelieren. Weitere Phasen mit erhöhter Rutschungsaktivität konnten während des Zweiten Weltkriegs und in der Nachkriegszeit zwischen 1946 und 1957 beobachtet werden. In diesem Zusammenhang tragen die anthropogenen Einflüsse sowohl zur Disposition von Rutschungen als auch als deren Auslöser bei. Während

Niederschläge als Auslöser für einen großen Teil der Rutschungen am Mittellandkanal ausgeschlossen werden können, wird in zeitgenössischen Fachartikeln über Erschütterungen als mögliche Auslöser berichtet, welche durch den Transport von Abraum auf Loren entstehen. Zusätzlich besteht die Wahrscheinlichkeit, dass Rutschungen durch fehlerhaft geplante und ausgeführte Bau- und Sanierungsvorhaben von Kanalböschungen ausgelöst wurden. Während des Zweiten Weltkriegs könnten Rutschungen außerdem durch Erschütterungen ausgelöst werden, die im Zusammenhang mit der Explosion von Fliegerbomben stehen. Eine abschließende Beurteilung dieses Effekts ist jedoch schwierig, da die zeitliche Auflösung der Rutschungsdaten nicht ausreichend ist.

Um potentielle Risiken von Massenbewegungen in Bezug auf anthropogene Dispositionsfaktoren besser einschätzen zu können, wurde für das Straßennetzwerk im niedersächsischen Teil des Harzes die Suszeptibilität in Bezug auf Steinschlagereignisse sowie die Vulnerabilität des Straßennetzwerks modelliert. Der beschriebene Ansatz ist Teil der Publikation „Rockfall vulnerability of a rural road network — a methodological approach in the Harz Mountains, Germany„. Die Suszeptibilität für Sturzprozesse wurde dabei mit einer bivariaten statistischen Methode (Informationswert) modelliert. Für die Modellierung wurden zunächst für das Untersuchungsgebiet und für Sturzprozesse relevante Umweltfaktoren auf der Basis des zu untersuchenden Gebiets sowie der möglichen Prozesse ermittelt und kategorisiert. Aus der Summe der Rutschungspixel in einer Kategorie und der Gesamtzahl der Pixel in der gleichen Kategorie wurde dann der Quotient gebildet. Bei einem hohen Anteil von Rutschungspixeln in einer Kategorie ergibt sich ein größerer Quotient. Aus der Summe der Quotienten der einzelnen Faktoren konnte für jedes Pixel im Untersuchungsgebiet der Informationswert bestimmt werden. Abschließend wurde das Modell mit einer Grenzwertoptimierungskurve (engl. Receiver Operating Characteristic, ROC) validiert. Zusätzlich wurde die Vulnerabilität des Straßennetzwerks mit Hilfe von Indikatoren modelliert. Die Berechnung erfolgte durch das Summieren von vorher bestimmten Vulnerabilitätsfaktoren für die einzelnen Straßenabschnitte. Die Faktoren vorab mit Hilfe eines analytischen Hierachieprozesses (AHP) gewichtet. Als Faktoren für die Vulnerabilitätsmodellierung wurden die täglichen Verkehrsmengen, der Straßentyp, eventuelle Geschwindigkeitsbegrenzungen, die Länge möglicher Umleitungen sowie vorhandene Sicherungsmaßnahmen verwendet. Das Suszeptibilitätsmodell ergibt, dass 13% des Straßennetzwerks im Harz einen positiven Informationswert aufweisen. Dies entspricht einer hohen oder sehr hohen Suszeptibilität in Bezug auf Steinschlagereignisse. Entsprechende Straßenabschnitte sind charakterisiert durch hohe Neigungswerte und durch eine nordöstliche Ausrichtung der Straßen, die im Zusammenhang mit der tektonischen Entwicklung des Harzes und einer entsprechenden Ausrichtung von Faltenachsen, Störungen und Klüften steht. Häufig sind Abschnitte mit hoher und sehr hoher Suszeptibilität durch eine geringe bzw. moderate Vulnerabilität gekennzeichnet. Straßenabschnitte mit hoher Vulnerabilität treten hingegen vor allem bei hohen täglichen Verkehrsmengen auf. Dabei handelt es sich in der Regel um die Straßen am Gebirgsrand. Straßenabschnitte, die den Harzrand mit der Hochharzstraße verbinden, sind oft durch eine hohe Suszeptibilität gekennzeichnet. Durch den Einfluss von Sicherungsmaßnahmen bei der Berechnung des Vulnerabilitätsindikators, wird Straßen mit vorhandenen Sicherungsmaßnamen eine eher geringe Vulnerabilität zugeordnet. In der Regel handelt es sich dabei um Straßenabschnitte, an denen bereits Steinschlagereignisse aufgetreten sind. Dennoch eignet sich die präsentierte Methode der kombinierten Erfassung von Suszeptibilität und Vulnerabilität gut für eine erste Risikoeinschätzung, besonders wenn eine ausführliche Auflösung der Steinschlagdaten bzw. Kosteneinschätzungen fehlen. Der Einfluss des

Vorhandenseins von Sicherungsmaßnahmen in der vorliegenden Vulnerabilitäts-Modellierung stellt deren Funktionalität in den Vordergrund. Daraus ergibt sich eine große Notwendigkeit von intakten und somit funktionellen Sicherungsmaßnahmen. Andernfalls kann ein Straßenabschnitt, der als wenig vulnerabel kategorisiert wird, besonders schadensanfällig sein. Beispielsweise könnten neben auftretenden Sturzereignissen auch Teile einer vorhandenen baulichen Sicherung einen Straßenabschnitt beschädigen oder Verkehrsteilnehmer bedrohen.

Die Bedeutung von Sicherungs- und Sanierungsmaßnahmen in Bezug auf Massenbewegungen, wurde im Detail anhand von drei Fallstudien an der Oberweser untersucht. Die Ergebnisse werden in der Publikation „Case histories for the investigation of landslide repair and mitigation measures in NW Germany" beschrieben. Mit Hilfe dieser Fallstudien in der Umgebung von Hann. Münden lässt sich die Rutschungsaktivität mit Landnutzungspraktiken und dazugehörigen Sicherungsmaßnahmen gegenüberstellen. Die drei Untersuchungsstandorte stehen dabei im Kontext des Straßenbaus im 18. und 19. Jahrhundert und sind eng verbunden den jeweils verbreiteten Sicherungspraktiken. Eine erhöhte Rutschungsaktivität kann jeweils in den 1770er, 1880er, 1900er, 1930er, 1950er und 1970er Jahren festgestellt werden, Phasen mit erhöhter Sicherungsaktivität liegen in den 1900er, 1930er, 1960er, 1980er, 1990er und 2000er Jahren vor. Es wird deutlich, dass Jahrzehnte mit erhöhter Rutschungsaktivität oft mit Phasen erhöhter Sicherungsaktivität zusammenfallen oder von ihnen gefolgt werden. Die Entwicklung von Sicherungsmaßnamen an der Oberweser kann dabei folgendermaßen beschrieben werden: Während des Straßenbaus in den 1770er bzw. 1880er Jahren beschränkte sich die Sicherung auf den unteren Bereich des bergseitigen Hangs unter der Verwendung von Trockenmauern. Zwischen 1900 und 1930 wurden weiterhin Trockernmauern genutzt, um nun auch höhere Bereiche der bergseitigen Hänge zu sichern. In den 1930er Jahren kam erstmals die Hangsicherung durch ingenieurtechnische Maßnahmen hinzu, diese Verfahren wurden jedoch erst in den 1960er umgesetzt. Dazu zählt die Verwendung von Betonstützmauern sowie Netzen und Palisadenzäune, um gegen Sturzereignisse zu sichern. Mit den 1980er Jahren begann die Phase der modernen Sicherungsmaßnahmen mit umfassenden Maßnahmen, die ab den 1990er Jahren noch einmal intensiviert wurden. Dabei fanden neben modernen Vernetzungen und Fangzäunen auch Verankerungen Anwendung.

Die vergleichende Fallstudie am Mittellandkanal zeigt mit dem Auftreten von Rutschungen eine zeitgleiche Entwicklung von Sanierungs- und Sicherungsmaßnahmen an einer künstlichen Wasserstraße in der ersten Hälfte des 20. Jahrhunderts. Der notwendige Einschnitt von bis zu 17 m unter Geländehöhe wurde durch das Anlegen trapezförmiger Böschungen mit Steigungen zwischen 50 % und 70 % erreicht. Jedoch traten zwischen 1920 und 1927 immer wieder Rutschungen während bzw. kurz nach Fertigstellung der Böschungen auf. Die ersten Sicherungsmaßnahmen bestanden aus dem Anlegen von Sickerschlitzen, was zu einer beschleunigten Verwitterung der betroffenen feinkörnigen Ton- und Mergelsteine führte. Zwischen 1928 und 1938 wurden die Kanalprofile daher flacher gestaltet und es folgte die Entwicklung neuer Profiltypen. Während des Zweiten Weltkriegs wurden die Böschungen noch einmal auf 1:3 abgeflacht. Häufig kam es jedoch zur Unterbrechung der Arbeiten aufgrund des Mangels an Betriebsmitteln. Um die Schifffahrt auf dem Kanal während des Krieges dennoch aufrecht zu erhalten, wurde abgerutschtes Material regelmäßig aus der Fahrrinne geräumt. Nach Kriegsende waren dadurch Sanierungsarbeiten an einem Großteil der rutschgefährdeten Böschungen notwendig. Deren Ausführung ab 1950 beinhaltete das Ersetzen von alten durch neue Drainagesysteme und die Beseitigung von abgerutschten Massen. Zusätzlich wurden die Hänge durch Baumanpflanzungen stabilisiert.

Die vorgestellten Fallstudien spiegeln die unterschiedliche Risikowahrnehmung gegenüber Massenbewegungen an Verkehrsinfrastrukturen wider. Die klassischen Phasen im Krisenmanagement, dazu zählen die Bewältigung, Nachbereitung und Prävention werden nach einer erhöhten Aktivität in Bezug auf Massenbewegungen durchlaufen. Jedoch fehlt die finale Phase der Vorbereitung auf das nächste Ereignis. Nachdem Sicherungsmaßnahmen aufgestellt wurden, sinkt das Bewusstsein für ein erneutes Auftreten von Massenbewegungen. Über die Jahrzehnte hinweg können Sicherungsmaßnahmen jedoch ihre Schutzwirkung verlieren und bei einer erneuten Massenbewegung beginnt der Zyklus von Neuem.

Die präsentierten Ergebnisse zeigen einen engen Zusammenhang zwischen Massenbewegungen an Verkehrsinfrastrukturen und anthropogenen Einflüsse in Bezug auf Dispositionsfaktoren von Massenbewegungen und deren Auslöser. Hinzu können nicht in Stand gehaltene und veraltete Sicherungsmaßnahmen, die zur Gefährdung durch Massenbewegungen beitragen. Zum einen ergibt sich daraus neben der notwendigen Prozessunterscheidung in Bezug auf die gravitativen Massenbewegungen, eine Berücksichtigung der Dispositionsfaktoren sowie der Auslöser und inwiefern diese anthropogen geprägt sein könnten. Besonders in hoch entwickelten Industrieländen in Mitteleuropa vermischen sich „natürliche“ mit anthropogenen Einflüssen.

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1 INTRODUCTION

Gravitational mass movements summarize different types of processes with variable sizes and materials. The definition includes movements which are referred to as rockfalls as well as landslides. While rockfalls imply both falling and toppling of rock fragments, the term "landslide" integrates movements of a sliding, spreading and creeping nature (Varnes 1978; Cruden and Varnes, 1996; Highland and Bobrowsky, 2008; Hungr et al., 2014). In a simplification, the term "landslide" is used for all types of mass movements.

The terms "anthropogenic", "human-induced" or "post-construction" landslides have been introduced to describe any human influence in the occurrence of landslides (Terzaghi, 1950; De Puy, 2016; Jaboyedoff et al., 2016). This implies both preparatory and triggering factors. Preparatory factors can be influenced by altering slope characteristics (i.e., excavating and cutting existing slopes, construction of embankments, mining), changing the groundwater or surface water flow, or installing loads on existing slopes (cf. Terzaghi, 1950; Glade and Crozier, 2005; Jaboyedoff et al., 2016; Schuster and Highland, 2007). For the described scenarios, the slope stability is decreased near a critical value and affected slopes may collapse with minor triggering. In addition, miss-planed or aged infrastructure and mitigation measure can be categorized as anthropogenic preparatory factors for landslides (cf. Jaboyedoff et al., 2016; Luino and De Graff, 2012; Marquis, 2002). As anthropogenic landslide trigger, construction work itself can be considered, for instance due to undercutting or the construction of embankments, as well as related vibrations (cf. Popescu, 1994; Jaboyedoff et al., 2016; Bednarczyk, 2017). Anthropogenic landslides are registered especially at transportation infrastructure (cf. Laimer, 2017; Skilodimou et al., 2018; Pellicalli et al., 2017) and therefore impose high socioeconomic risks due to cost-intense damages and disruptions of essential routes (Klose et al., 2015; Schlögl et al., 2019). With the growth in global population and consequent urbanization, an increase in anthropogenically influenced or induced landslides can be observed (Schuster and Highland, 2007; Jaboyedoff et al., 2016).

In order to estimate the landslide risk of transportation infrastructure, information on the hazard (the product of spatial probability or susceptibility and temporal landslide probability), the physical vulnerability and costs of the element at risk is needed (Dai et al., 2002; van Westen et al., 2006; Corominas et al., 2014). Then, the risk is given by:

$$R_L = \mathrm{H}_L \cdot \mathrm{V}_L \cdot \mathrm{E}$$
$$H_L = P(X) \cdot P(T), \tag{1}$$

where R_L is the landslide risk, H_L is the landslide hazard, V_L is the physical vulnerability of the transportation infrastructure, and E is the Element at risk (i.e., transportation infrastructure).

In order to analyze the susceptibility, geo-environmental factors are taken at mapped landslide locations to identify potential areas of failure (Van Westen et al., 2006; Ayalew and Yamagishi, 2005). Depending on the availability and the quality of the data, as well as the scale of the study area, different methods can be applied (Van Westen et al. 2008; Corominas et al. 2014). In general, qualitative and quantitative methods can be distinguished (Van Westen et al., 2006). Whereas qualitative (heuristic) methods are based on expert opinion, quantitative methods use statistical or deterministic approaches to estimate landslide susceptibility. Statistical methods can be subdivided into bivariate and multivariate. While, in bivariate statistics, landslide densities are combined with weighted factors, in multivariate statistics, correlations and interactions of these factors are considered (Soeters and van Westen, 1996; Süzen and Doyuran, 2004). For regional scales, bivariate statistical methods are well established (Soeters and van Westen, 1996; Süzen and

Doyuran, 2004; Pellicalli et al., 2017), among which are the information value method (Kobashi and Suzuki, 1988; Yin and Yan; 1988) and the weights-of-evidence (Bonham-Carter et al., 1989).

In comparison to susceptibility, vulnerability is not as clearly defined. In general, vulnerability includes a degree of loss of a given element or a set of elements at risk (Corominas et al., 2014; Papthoma-Köhle, 2016). When considering the vulnerability of a road network, the degree of loss is reinterpreted as a reduction in road network serviceability (Berdica, 2002). Methods to quantify vulnerability vary depending on the elements at risk. Whereas the vulnerability of people concerns the fatalities and injuries of people, physical vulnerability refers to the damage of buildings, utilities, and infrastructure (Corominas et al., 2014; Papathoma-Köhle 2016). Different approaches can be distinguished to quantify physical vulnerability. The most common include vulnerability matrices, curves, and indicators (Papathoma-Köhle et al., 2017; Kappes et al., 2012). While vulnerability matrices estimate the degree of loss based on damages, vulnerability curves are used to quantify potential damages by a monetary value. Vulnerability indicators were originally applied in social vulnerability assessment and can be described as "variables which are operational representations of a characteristic or quality of the system able to provide information regarding the susceptibility, coping capacity and resilience of a system to an impact of an albeit ill-defined event" (Birkmann, 2006).

A key concept in the assessment of susceptibility and vulnerability is the investigation of historical datasets (Varnes and IAEG, 1984; van Westen et al., 2006; Raška et al., 2014). In addition to hazard assessment, historical landslide inventories can be used to analyze triggers and impacts, as well as concepts and the development of mitigation (Malamud et al., 2004; Klose et al., 2016). Therefore, the analysis of risk management can be achieved from historical landslides in interaction with mitigation measures, including applied as well as planned measures. Risk management describes four phases after a landslide event: response, recovery, mitigation and preparedness (Alexander 2002; Godschalk 1991). Mitigation is defined as application of measures in order to prevent an event or reduce its damage potential. Mitigation is related to structural (i.e., construction) and non-structural (i.e., planning, hazard mapping) measures.

In the South of Lower Saxony, landslides have been studied for more than 30 years. Previous studies focused on the Upper Weser area and the city of Hann. Münden (e.g., Damm 2000; Damm et al., 2010; Klose et al. 2013a; Klose et al., 2015; Wohlers et al., 2017). A regional analysis of susceptibility using an information value approach indicated that 6% of interstate roads ("Bundesstraße") show a high exposure to landslides in the area (Klose et al., 2013b). At road infrastructure, rockfalls are particularly linked to the over-steepened interior slopes of the road side, whereas landslides occur at the exterior slope, especially when materials for road construction are not sufficiently consolidated (Wohlers & Damm, 2022; Damm 2000). Mitigation of landslides in the region is documented since modern road construction and ranges from low-cost, (i.e., removal of material from susceptible outcrop areas, rock blasting and road closure) to expensive measures (i.e., catch fences, mesh wiring and concrete injections).

Different aspects of anthropologic influences are studied in detail at three different sites in Southern Lower Saxony. At the Mittelland canal (Figure 1, A) anthropogenic triggers (construction, aerial bombing during World War II) are analyzed utilizing a quantitative approach. The large number of landslides at a waterway is unique and described in relevant German literature (i.e., Bendel, 1948; Prinz and Strauß, 2018). Worldwide, only the Panama Canal is known for higher and more momentous landslide activity (cf. De Puy, 2016).

In the Harz mountains (Figure 1, B) the rockfall susceptibility of the road network corridor is modeled in a GIS-based environment, applying an information values method. Afterward, the model is tested with a receiver operating characteristic (ROC) analysis. In addition, the vulnerability of the road network is assessed using an indicator-based-method. The presented combined methods are suggested for a preliminary risk assessment, when loss data are not available.

In the Upper Weser area, three case histories have been developed in the city of Hann. Münden (Figure 1, C) the risk perception regarding landslides is studied implementing case histories. In combination, the applied methods provide a comprehensive overview of the anthropologic influence on landslides affecting transportation infrastructure.

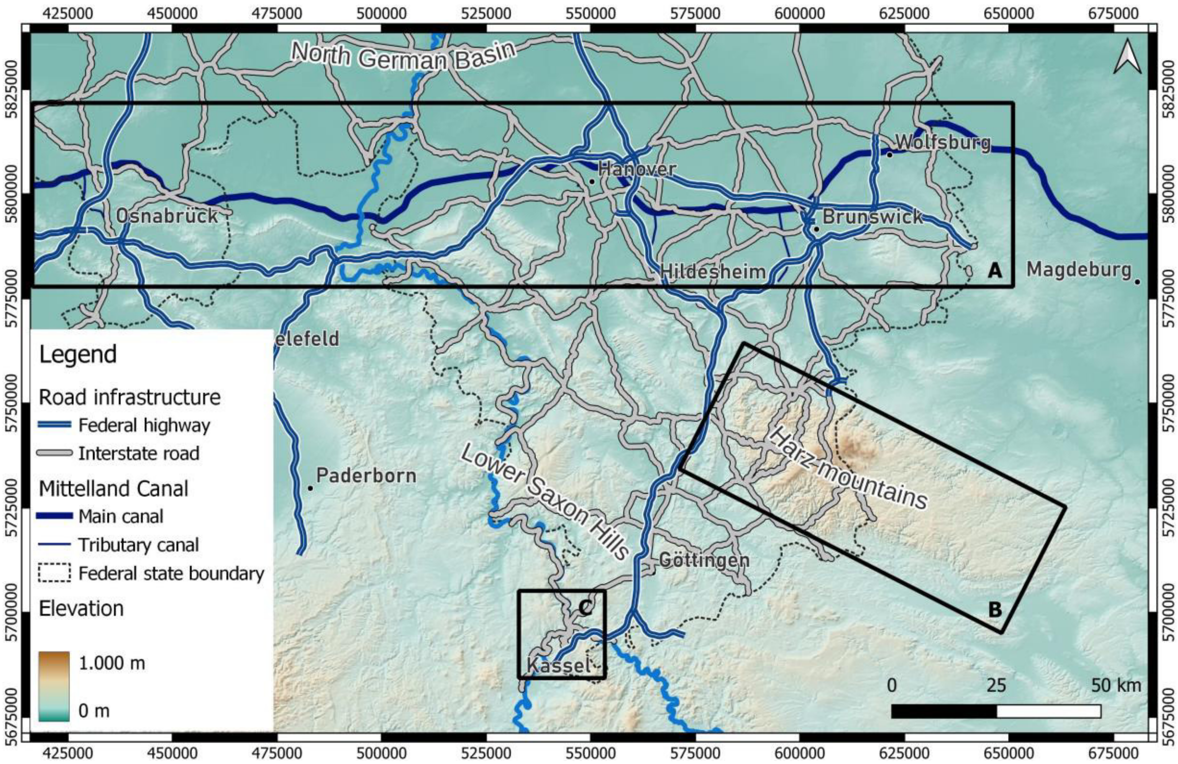


Figure 1. The area of Southern Lower saxony and transportation infrastructure: (A) the Mittelland canal in Lower Saxony, (B) the Harz mountains, (C) the city of Hann. Münden representing the Upper Weser valley. Elevation data from Aster GDEM, NASA/Meti.

2 STUDY AREA

The study area (Figure 1) is situated in Southern Lower Saxony, Central Germany. To the north, it is bound by the Northern German Basin as part of the Central European basin system. The vast area of Southern Lower Saxony is part of the Central German Uplands. The uplands are characterized by a Paleozoic basement, which crops out in the Harz mountains. In addition, cuesta landscapes have been created from Mesozoic rocks by a combination of fault block movements and river incision. As a result, a moderate relief was created with elevations ranging between 25 m a.s.l. at the western end of the Mittelland canal and 1141 m a.s.l. at the Brocken summit in the Harz mountains.

The region is characterized by a moderate population density of ∼ 170 persons per km² (Destatis, 2020). The transportation infrastructure is represented by a well-established federal highway system ("Bundesstraße"), which connects local centers with the regional urban centers (Brunswick, Hanover, Kassel) and the national highways ("Autobahn", cf. Figure 1). In addition, the Mittelland canal links the waterways of the Rhine trading area in the west (i.e. the Netherlands, Belgium and France) with the waterways of the Elbe trading area in the east (i.e. Poland and Czech Republic) via two connecting canals. Within Germany, the canal connects the important commercial and industrial locations of the cities of Hanover, Brunswick, Wolfsburg and Magdeburg. With a total length of approximately 325 km, it is the longest artificial waterway in Europe. The Mittelland canal can be considered as one of the most important artificial waterways in Europe, with 17.5 MT of goods being transported in 2020. In Germany, about 10% of inland water transportation is transported on the Mittelland canal (BDB, 2021).

2.1 Geological Setting and Material Characteristic

The study area includes parts of the North German Basin as well as the Lower Saxon Uplands and the Harz mountains. As a results, the geological setting and the material characteristics vary strongly within in the area. The oldest rocks in the area can be found in the Harz mountains, where Paleozoic sedimentary rocks from the Devonian crop out.

The Northern Part of the study area, where the Mittelland canal has been constructed (A in Figure 2), is characterized by a sedimentation since the Paleozoic era. Starting in the early Cretaceous the sediments have been faulted, bent and transported upwards by halokinesis of Permian salts (Voigt et al., 2008). As a result, the Mesozoic sediments have been locally uplifted, eroded and are covered by a thin layer (0–3 m) of Tertiary and Quaternary deposits (Vinken, 1977; Lepper, 1984). The Eastern part of the canal incises into fine-grained carbonatic sediments from the Jurassic to the Cretaceous periods. On this branch of the canal the majority of registered landslides can be found (71%). Even though of different age, the sediments near those sites possess similar materials and geotechnical characteristics. The rocks consist of fine-grained sediments with low carbonate contents (cf. Goetzcke, 1927; Kirchhoff, 1930; v. Vittinghoff, 2003). The described rocks tend to decompose quickly due to weathering and bulging; they are exposed to shrinking in wet–dry cycles, therefore they can be characterized as over-consolidated slaking rocks (Schulze and Köhler, 1999; v. Vittinghoff, 2003).

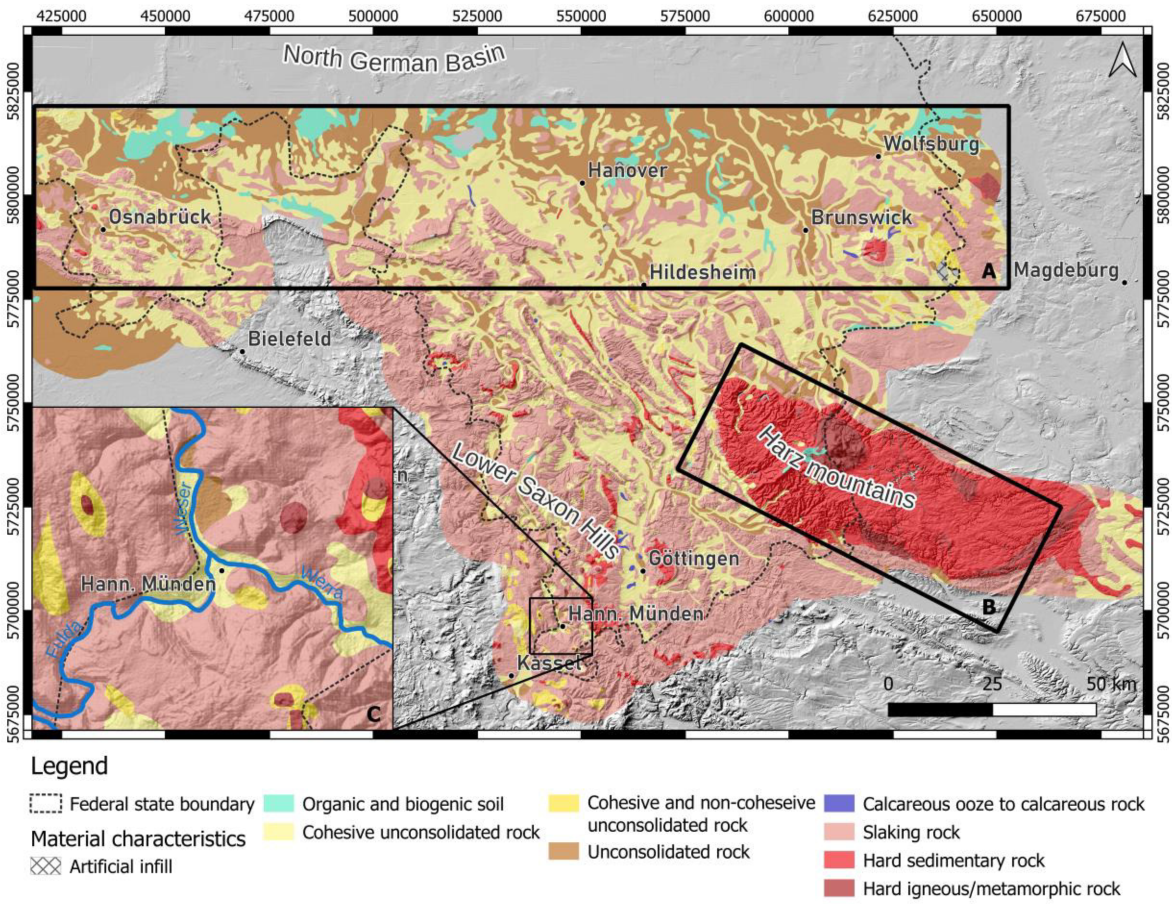


Figure 2. Material characteristics in the area of Southern Lower Saxony. While the area of the Mittelland canal (A) is characterized by sediments of the North German Basin, which consist of unconsolidated rocks. The area of the Harz mountains is characterized by hard rocks. In the area of Hann. Münden (C) slaking rock material can be found. In the river valleys, slaking rocks are covered by unconsolidated rocks. Elevation data from Aster GDEM, NASA/Meti.

The area in the East of Southern Lower Saxony is shaped by the mountain range of the Harz mountains. With the Rhenish Massif in the West, the Harz mountains represent the remains of the Variscan orogeny in Germany (Mohr, 1978). The mountain range shows an NNE-SSW-striking direction. Due weathering and erosion processes, Paleozoic sediments can be found at the surface today. Occasionally, the sedimentary rocks, especially of Devonian and Carboniferous periods, show metamorphic recrystallizations due to low-temperature and low-pressure conditions. Near the Brocken summit and the valley of the river Oker, plutonic rocks can be found. In the valleys, the rocks are covered with alluvial and glacial deposits (Mohr, 1978). In general, the outcropping rocks can be characterized as hard (sedimentary and metamorphic/igneous) rock.

The area of Hann. Münden is characterized by the Mesozoic block of the Solling anticline which consists of sediments of the Middle Lower Triassic. The formation is built up by interbedded fine to medium-grained sandstone and fragile silt- and claystone. The rivers of Fulda, Werra and the resultant junction of the river Weser incise 200-300 m deep into the bedrock formations (Damm et al., 2010). Especially in the river valleys, the bedrock is covered by a Quaternary layer of slope debris, which is susceptible to landslides in the case of high soil moisture content (Damm, 2005).

2.2 Climate Setting

The climate in Sothern Lower Saxony can be described as temperate oceanic, except for the Harz mountains, where a temperate continental climate can be observed. Precipitation is registered all year round, with slightly higher precipitation in summer than in winter months. Due to the westward movement of low-pressure zones, precipitation sums decrease from West to East and from high to low elevations. For instance, at the Mittelland canal the long-term annual mean between 1990 and 2020 decreases from West to East with values of 821 mm/a at the Western part of the canal and 630 mm/a at the state border between Lower Saxony and Saxony-Anhalt in the East. The highest values can be found in the Harz mountains. At the Brocken summit, the long-term mean annual precipitation is 1799 mm/a at an elevation of 1135 m a.s.l, in the eastern part of the Harz mountains the long-term annual mean sums up to only 639 mm/a. In the Lower Saxon Hills the mean of annual precipitation sums vary between 792 mm/a and 1109 mm/a (values of annual means between 1990 and 2020 in combination with elevation values are displayed in Figure 3).

Table 1. Description of selected climate stations in Southern Lower Saxony. Stations are displayed in Figure 3.

Region	Station name	Station ID	Latitude	Longitude	Elevation [masl]	Data Coverage from	to
Mittelland Canal	Bramsche	101	52.408	7.968	75	01/1931	today
	Espelkamp-Isenstedt	102	52.345	8.648	65	09/1890	today
	Bad Rehburg	103	52.437	9.214	85	01/1941	11/2006
	Hannover-Kirchrode	104	52.367	9.819	57	01/1961	today
	Abbensen	105	52.381	10.186	61	01/1941	12/2006
	Danndorf	106	52.427	10.917	69	01/1941	today
Lower Saxon Uplands	Bad Iburg-Glane	201	52.145	8.046	105	01/1931	12/2019
	Rinteln-Steinbergen	202	52.200	9.117	84	01/1931	07/2006
	Nienstedt/Deister	203	52.259	9.444	170	01/1931	03/2004
	Aerzen-Reher	204	52.031	9.235	115	01/1931	04/2003
	Kaierde	205	51.933	9.783	165	01/1951	07/2003
	Heinade-Hellental	206	51.812	9.618	270	01/1941	today
	Bodenfelde-Amelith	207	51.696	9.514	258	01/1931	today
	Krebeck-Renshausen	208	51.600	10.111	192	01/1931	07/2003
	Münden-Gimpte	209	51.439	9.645	122	01/1931	today
Harz	Langelsheim (Innerstetalsperre)	301	51.917	10.299	233	09/1968	today
	Herzberg-Lonau	302	51.689	10.357	340	01/1971	today
	Brocken	303	51.799	10.618	1135	01/1896	today
	Hasselfelde	304	51.687	10.863	461	01/1969	12/2006
	Königerode	305	51.601	11.206	375	01/1969	12/2001

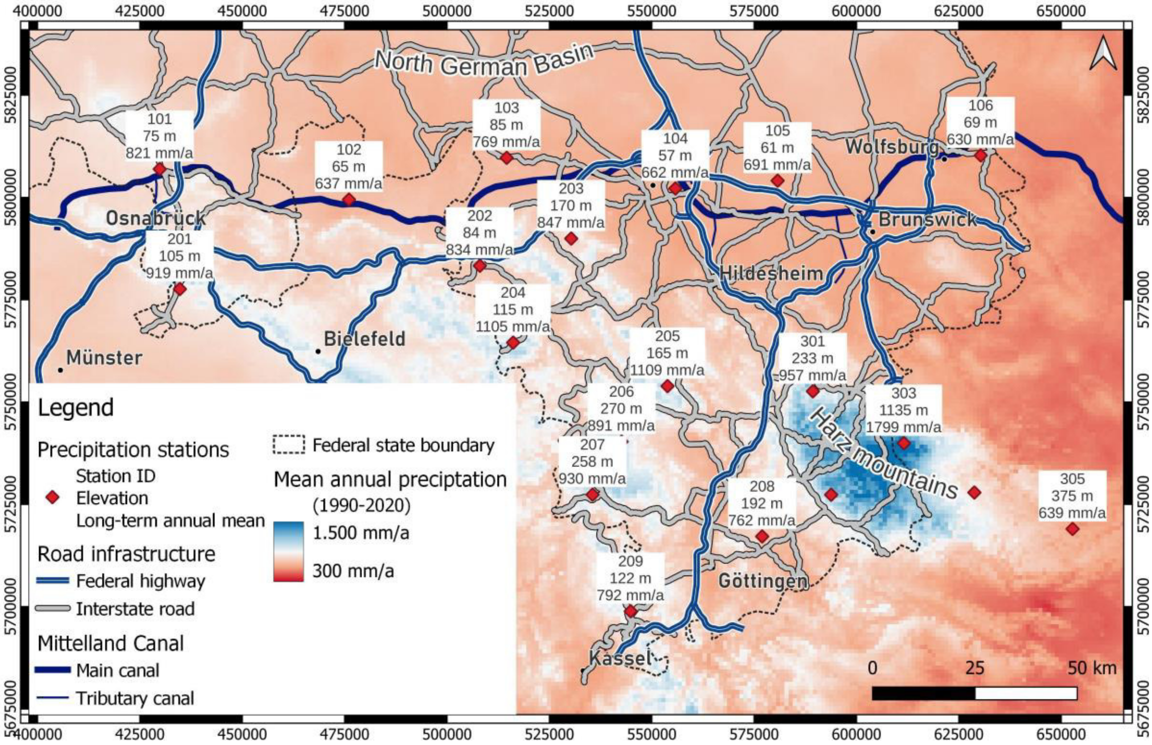


Figure 3. Annual sums of precipitation in Southern Lower Saxony. The elevation of the meteorological stations is displayed as well. The values decrease from West to East und from high to low elevation. Precipitations stations are listed in Table 1. Precipitation data from DWD.

2.3 Construction of transportation infrastructure in Southern Lower Saxony

Modern road construction in Southern Lower Saxony can be dated back to the 18th century (Kappel, 2016). Formerly interregional dirt roads ("Poststraße") have been paved and upgraded to a so-called "Chaussee" accordingly to the French standard (Lay, 1992). The majority of road network in the region of Southern Lower Saxony has been established until 1893 (Federal directorate of Lower Saxony, 1893). Exceptions are roads tracing historical trains lines or local bypasses that have been created to reduce traffic volumes in town centers. Phases of increased road construction are reported in the 19th century, the 1920s and the 1950s (Baldermann, 1968).

In regions of high relief (i.e. Harz mountains and Lower Saxon Uplands), the road network is closely linked to the valleys as efforts in road construction have been minimized in that manner. Road-cuts have been created by rock blasting or material removal by hand on the interior slope of the road. Then, the removed material was used to create the exterior slope with a leveled road surface (Baldermann, 1968; Klose, et al., 2016; Damm, 2000; cf. Figure 4). Figure 5 illustrates a typical road profile in an area of high relief. With an increasing traffic volume, the existing roads were expanded in the same manner.

Figure 4. Road Construction in the Harz mountains: road ditches were constructed by rock blasting (a) and removal by hand (b). A leveled road surface was created by using removed material from the inner slope (c). Photos by Sternal, 2021.

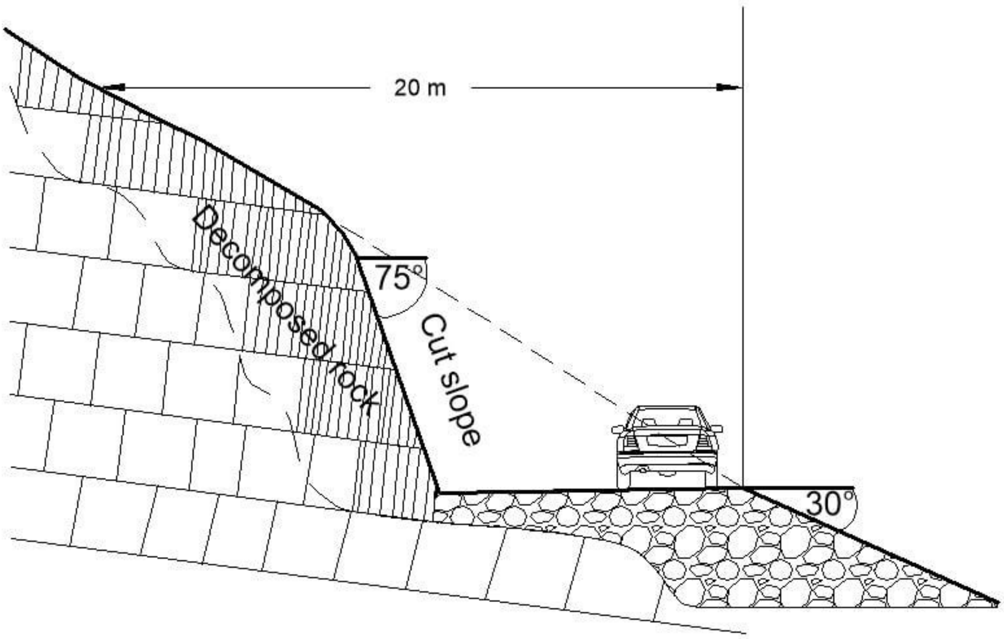


Figure 5. Typical road profile in regions of high relief (Harz mountains, upper Weser valley). Roads have been constructed by cutting the interior slope and using the removed material on the exterior slope for the road surface. As a result, over-steepened interior slopes have been created which are susceptible to rockfalls and at the exterior slopes, landslides are linked from deficient consolidation.

First drafts for a canal construction in the center of Germany emerged in the 19th century, in order to satisfy increasing demands for transporting goods in the era of pending industrialization. Due to controversial discussion about canal routing, the canal construction could not start until almost 50 years later. In 1906, the first construction phase began in the west, where the canal branches out from the connecting Dortmund-Ems-canal to Hanover. In 1916, more than 170 km of canal was finished. To employ returning soldiers after World War I, the continuation of the canal was decided and executed. In the second construction phase between 1920 and 1928, approximately 30 km at the Mittelland canal and the tributary canal to Hildesheim were constructed. In 1933, another 20 km were finished. The final 102 km were finished in 1938, north of Magdeburg (phase 3). An overview of the canal path, as well as the construction phases, is given in Figure 6.

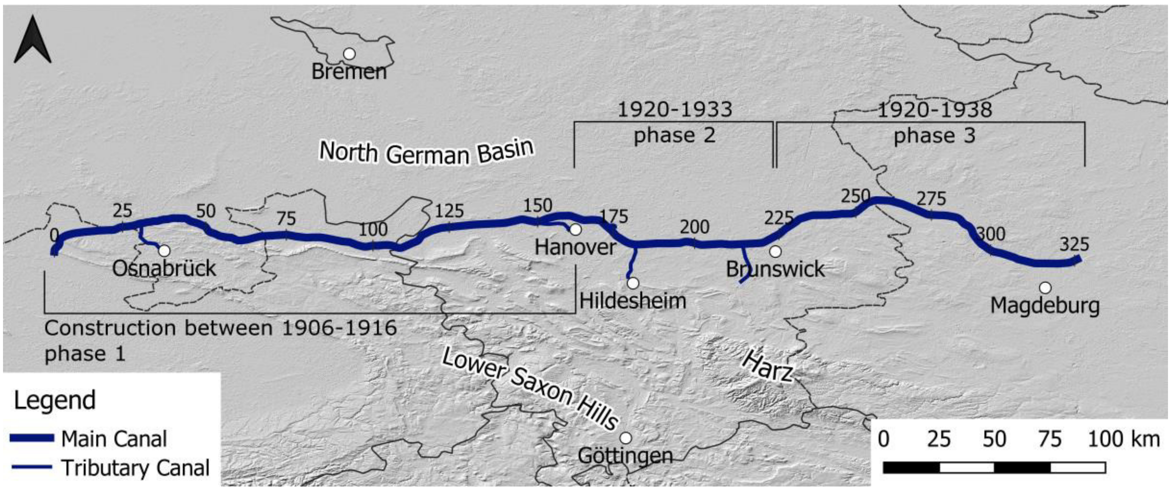


Figure 6. The construction of the Mittelland canal was executed sequentially from West to East. The first construction phase was registered between 1906 to 1916, the second phase of construction between 1920 to 1928 and the third construction phase between 1920 to 1938. Topographic data are derived from Aster GDEM, NASA/METI.

In 1961, large parts of the canal were reconstructed in depth and width, according to European waterway standards (Schmidt-Vöcks, 2000). Due to the separation of Germany, the widening of the canal in the German Democratic Republic was not finished until 2008, 19 years after the unification of Germany.

3 MATERIAL AND METHODS

3.1 Landslide data

In the area of Southern Lower Saxony and adjacent regions in the Harz mountains a number n = 1038 of landslides (i.e., gravitational mass movements) have been registered between 1900 and 2021. Of the total number of landslides, 31 % can be linked to anthropogenic influences. In addition, n = 159 reparation or mitigation measures have been reported in the area.

The main source of landslides is the landslide database for Germany (Damm and Klose, 2015). Information within the database is gathered by means of archive studies from inventories of emergency agencies, state, press and web archives, company and department records, as well as scientific and geotechnical literature. Furthermore, the database contains data from various sources, including field surveys, climatic records, and satellite imagery. In addition, information on landslide characteristics, dimensions and dynamics and soil and lithologic, as well as geomorphometric properties are stored within the database. Beyond that, it includes information about land use effects, damage impacts and economic losses (Damm and Klose, 2015). In order to condense the dataset, archive studies have been executed to enrich the dataset especially with information about reparation and mitigation measures.

Information on landslide type, dimensions and involved material is collected in Table 2. In addition, anthropologic influences are displayed. The block size for rockfall events is noted as the maximum length of block edges and varies between very small (<10 cm) and intermediate size (50–100 cm). Some examples of landslide events in the area are given in Figure 7.

Table 2. Characteristics of landslides in Southern Lower Saxony. Information is extracted from Landslide database of Germany (Damm and Klose, 2015)

Type of landslide				
Slides (Rotation & Translational)	Rockfall (Falls, Topples)	No information	Mitigation	Total number
31,6%	28,6%	26,5%	13,3%	1197

Anthropogenic influence					
Slope reprofiling	Groundwater flow perturbation	Surface water flow perturbation	Landuse changes	Inappropriate and degrading artificial structures	Total number
70,4%	21,3%	0,9%	1,5%	4,6%	652

Landslide Volume							
<50 m^3	50–100 m^3	100–1,000 m^3	1,000–10,000 m^3	10,000–100,000 m^3	>100,000 m^3	No info	Total number
60%	4%	3%	3%	1,5%	0,5%	28%	1018

Block size					
<10 cm	10–50 cm	50–100 cm	>100 cm	No information	Total number
14%	70,6%	2,5%	0,2%	12,7%	521

Figure 7. *Cont.*

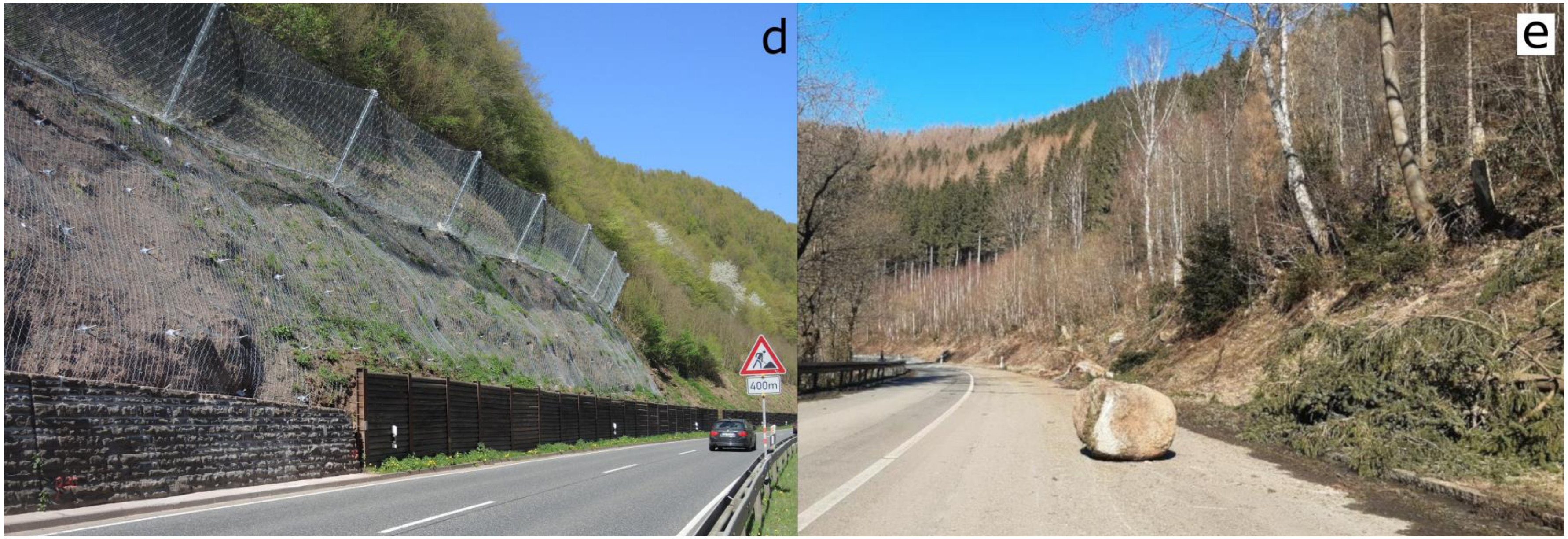


Figure 7. Landslides in Southern Lower Saxony: **(a)** Translational landslide in 1914 at the Mittelland canal (photo: Federal Waterways Engineering and Research Institute, BAW). **(b)** Rotational landslide in 1929 at the Mittelland canal (photo: Lower Saxon State Archive, NLA BigS Nr. 5,548/2 Br. 129). **(c)** Rockslide event in 1937 in Hann. Münden in the Upper Weser area (photo retrieved from German Landslide Database). **(d)** Rockfall mitigation in Hann. Münden in the Upper Weser area (photo: A. Wohlers). **(e)** Rockfall in 2021 in the Harz mountains (photo: State Forest of Lower Saxony)

3.2 Analysis of potential landslide trigger

In order to establish potential triggers, the occurrence of landslides has been linked to different parameters (i.e. precipitation, construction of transportation infrastructure, aerial bombings during WWII). The days of bombings, high precipitation sums and phases of increased construction, respectively, have been linked to landslide data.

Information on construction periods of transportation infrastructure has been retrieved the from Landslide database of Germany (Damm & Klose, 2015). Especially for the Mittelland canal, the information has been enriched by archive studies (cf. Wohlers & Damm, 2020). Historical data on bombing missions at the Mittelland canal have been researched from war reports and secondary literature (USSBS, 1947; Grabe et al., 1983; Meyer-Hartmann, 1985; Mlynek and Brosius, 1994). During the war, at least 11,000 explosive aerial bombs were dropped in the area between Hanover and Brunswick. For aerial bombings, accurate dates are available (i.e. day/night of bombing). From the descriptions, the localities of the bombing impacts and potential triggering radii have been calculated. The detonation of bombs results in characteristic seismic and acoustic waves (Koper et al. 2002). While seismic magnitudes might not be sufficient to trigger landslides (cf. Khalturin et al. 1998, Keefer 2002, Hinzen 2014), the air blast can cause structural damage to buildings and therefore might be considered to destabilize slopes (cf. BAuA, 2022). In addition, reports from bombing nights indicate the shattering of windows at distances of 4.3−6.6 km from the detonation sites (Meyer-Hartmann, 1985). In general, the resultant air blast depends on the explosive yield and the distance from the detonation site (BAuA, 2022). An impact radius with an air blast sufficient to destroy and demolish windows as well as roods can be calculated with the formula:

$$D = 22 \cdot \sqrt[3]{M}, \qquad (2)$$

where D is the distance from the detonation site in meters and M is the explosive weight in kg (BAuA, 2022). The explosive weight is estimated from size of bombs stated in war reports (USSBS 1947). While during 1940 and 1942 the most common bombs had a weight of 250 lb (~113 kg), in later years mainly bombs of 500 lb (~226 kg) have been produced.

3.3 Thematic maps for susceptibility assessment

For the rural road network in the Harz mountains, the susceptibility towards rockfalls has been modelled. For that purpose, various geo-environmental factors are used in a GIS-based analysis. The spatial propensity for future rockfalls is based on the properties of existing rockfalls. The selection of the susceptibility affecting factors depends on the study area, landslide types, and failure mechanisms (Corominas et al. 2014). For the analysis in the Harz mountains, the following factors were used: elevation, slope angle, material characteristics (geotechnical classification), orientation of road section and distance from faults, annual precipitation, and number of ice days (cf. Wohlers & Damm, 2022). The classification of factors is summarized in Table 3.

.

Table 3. Classification of geo-environmental factors. Material characteristics are not included.

	Elevation	Slope	Road section orientation	Distance to faults	Precipitation	Ice days
Classes	<300 m	<15°	N (0–11.25°)	<500 m	<1000 mm	<20
	300–400 m	15–20°	NNE (11.25–33.75°)	500–1000 m	1000–1100 mm	20–25
	400–500 m	20–25°	NE (33.75–56.25°)	1000–1500 m	1100–1200 mm	25–30
	500–600 m	25–30°	ENE (56.25–78.75°)	1500–2000 m	1200–1300 mm	30–35
	600–700 m	>30°	E (78.75–101.25°)	>2000 m	>1300 mm	35–40
	700–800 m		ESE (101.25–123.75°)			>40
	>800 m		SE (123.75–146.25°)			

Elevation data are retrieved from Opendataportal.at and have a ground resolution of 20 m. Elevation at rockfall sites is most probably underestimated as rockfalls are closely linked to cut slopes at roads near the valley bottoms. From elevation data, slope values are calculated in QGIS. As a result, slope values in the road corridor must be considered underestimated, due to the ground resolution of the elevation data of 20 m. Values of cut slopes, which have been created during road construction, are not displayed in the elevation model.

Information on material characteristics was extracted from the engineering geological map of Lower Saxony with a scale of 1:50,000. Material characteristics are closely linked the mapped geologic units and display the ground material type at a depth of 2 m beneath the surface. This implies that covering deposits with an estimated depth of less than 2 m are not considered. Of 23 different ground material, 18 can be found in the Harz mountains area. Table 4 lists the categories and gives a description of the involved materials.

Table 4. Geo-engineering classification of materials in the Harz mountains

Ground type	Category	Material description
2	Artificial infill	Different types of material: natural soil mixed with artificial and waste material
3	Organic and biogenic soils	Peat, sludge, organic silt
4	Cohesive unconsolidated rock	Silt to clay, partly peat
5		Alluvial clay
6		Loess, loess loam
8		Till, solifluction deposits
11	Non-cohesive unconsolidated rock	Dune sand, sand drift
12		Fluvial and glacial-fluvial deposits
14	Sub-recent deposits of mass movements	Separated blocks, weathered
15	Highly soluble rocks	Gypsum
16	Slaking rocks	Claystone, siltstone, marlstone with gypsum, limestone
17		Claystone, siltstone, marlstone
18		Dolostone, marlstone, limestone
19		Marlstone, claystone, siltstone, sandstone
20		Limestone, sandstone, greywacke
21	Sedimentary rock	Limestone, sandstone, slate
22		Limestone, sandstone, greywacke
23	Igneous/metamorphic rock	Basalt, granite, greenstone, gneiss

The structural features often coincide with the valleys of the Harz mountains and therefore affect the orientation of the road network. Hence, orientation of the road sections was used as a measure of tectonic influence. The orientation was noted as a direction between 0 and 180°. The values were noted as the true direction, not the strike direction. In addition to the road segment orientation, the distance to tectonic faults was determined. The tectonic faults were taken from the Geologic Map of Lower Saxony 1:200,000.

Meteorological data were extracted as raster data from German Meteorological Service (DWD) with a resolution of 1×1 km. For precipitation, the 30-year mean of annual sums between 1991 and 2020 was calculated from monthly precipitation sums. Precipitation in the region can be considered as predisposing as well as triggering factor (cf. Rupp et al., 2018). In addition, the mean annual number of ice days has been retrieved from DWD. An ice day is defined, when the maximum air temperature is below 0 °C. The mean value of annual ice days was calculated from raster data between 1991 and 2020.

3.4 Susceptibility Modeling and Model Validation

For the rockfall susceptibility model, a bivariate statistical approach, i.e., information value method, was used (Wohlers & Damm, 2022). In this method, a weighted value (IV) was calculated from the categorized factors. The information value for each class X_i is calculated in the following form (Yin & Yan, 1988):

$$I_i = ln \frac{N_i/S_i}{N/S}, \quad (3)$$

where N_i is the number of pixels in class X_i, N is the total number of pixels affected by rockfalls in the area, S is the number of pixels in class X_i, and N is the total number of pixels in the area. The natural logarithm of the quotient results in an easier interpretation of the values. Negative values for the information value imply a rockfall density lower than average, positive values indicate a density higher than average of registered rockfall events. This implies that areas with positive information values are more susceptible for rockfalls, and the higher the value, the more likely slope instabilities become (Klose et al., 2013b; Zêzere, 2002).

In classes where an information value could not be calculated (no rockfall pixels in the relevant class), the information value was set to −10. A rockfall susceptibility index for each pixel is then calculated by:

$$SI = \sum_{i=1}^{n} I_i, \quad (4)$$

The described method was performed for a road corridor of 100 m width in a GIS environment using QGIS software (2022). Then, the susceptibility was categorized using natural breaks. In order to validate the susceptibility model, not the complete dataset was taken for modelling. The remaining data were taken for model testing to evaluate the reliability. For that purpose, a receiver-operating characteristic (ROC) plot was prepared (Beguería, 2006). The plot displays the false positive rate versus the true positive rate. From the calculated area under the curve (AUC), the success rate of the model can be evaluated. The AUC varies between 0.5 and 1. From values close to 1 of the AUC, a good fit of the model could be inferred (Beguería, 2006). The rockfall data for model testing were not chosen randomly (cf. Pellicalli et al., 2017; Klose et al., 2013b); instead, mitigation sites were selected (n = 65), which sum up to an area of 0.48 m². The training data covers an area of 0.17 km².

3.5 Assessment of road network vulnerability to rockfalls

In addition to the susceptibility towards rockfall, the vulnerability of the road network in the Harz mountains was assessed (Wohlers & Damm, 2022). For that, the road network was subdivided into 139 road sections according to the road information data pool of Lower Saxony (NWSIB, 2022). In general, a road section marks a segment between two road intersections, for instance between an interstate and a district road. The road network vulnerability was estimated with the indicator-based method (IBM; Berdica, 2002; Birkmann, 2006). Vulnerability factors were chosen, weighted, and summarized. For each road section, the vulnerability index (VI_s) was calculated as follows:

$$VI_s = \sum_{i=1}^{n} w_i \cdot J_i, \quad (5)$$

where w_i is the weighted factor of the indicator and J_i is the indicator value of the vulnerability factor. As vulnerability factors mitigation measures, average daily traffic volume, the average daily heavy traffic volume, the type of road, speed reductions, and length of alternative routes were selected. Table 5 summarizes the vulnerability factors, categories, indicator value, and weighting factors.

Table 5. Vulnerability indicators that were used for the vulnerability assessment and corresponding categories. The weighting factors were calculated with the analytical hierarchy process.

Vulnerability Indicator	Category	Indicator Value	Weighting Factor
Mitigation	Scaling and trimming	−0.10	0.359041
	<25% with structural measures[1]	−0.20	
	25–50% with structural measures[1]	−0.30	
	>50% with structural measures[1]	−0.40	
Average daily traffic volume	<4000	0.10	0.237229
	4000–8000	0.15	
	8000–12,000	0.20	
	12,000–16,000	0.25	
	>16,000	0.30	
Average daily heavy traffic volume	<400	0.10	0.176031
	400–800	0.15	
	800–1200	0.20	
	1200–1600	0.25	
	>1600	0.30	
Type of road (width)	State road, narrow (5–7 m)	0.35	0.119928
	State road, two lanes (6–8 m)	0.25	
	Interstate road, two lanes (6–9 m)	0.25	
	Interstate road, three lanes (11–12 m)	0.15	
	Interstate road, four lanes (14–16 m)	0.10	
Speed reduction[2]	<20%	0	0.042860
	20–40%	−0.10	
	40–60%	−0.25	

	60–80%	−0.30	
	>80%	−0.35	
Length of alternative routes[3]	<200%	0.05	0.064850
	200–500%	0.10	
	500–1000%	0.20	
	1000–2000%	0.30	
	>2000%	0.35	

[1]Structural measures: nets, fences, and shotcrete; [2]in percent in terms of length and the reduction in the speed limit of 100 km/h (applies to roads without structural separated lanes); [3]Percentage of original length of road section.

Mitigation measures were categorized according to the type of applied mitigation (i.e., scaling and trimming or structural measures) and the percentage of retained road length. Average daily traffic volumes were extracted from the map of traffic volumes of Lower Saxony of 2015 (NLStBV, 2022). The road type was determined according to the state authority for road construction and traffic (NLStBV, 2022) and the number of lanes and road width were extracted from aerial photographs (Google Earth, 2022). The speed reductions were estimated in terms of length and type of speed limit. Afterward, the percentage of speed reductions was calculated by comparing it to the speed limit of 100 km/h, which applies to roads without structural separated lanes. The speed limit values were extracted from OSM data. Alternative routes were determined with OSM routing and expressed as percentage of alternative route length versus original road section length.

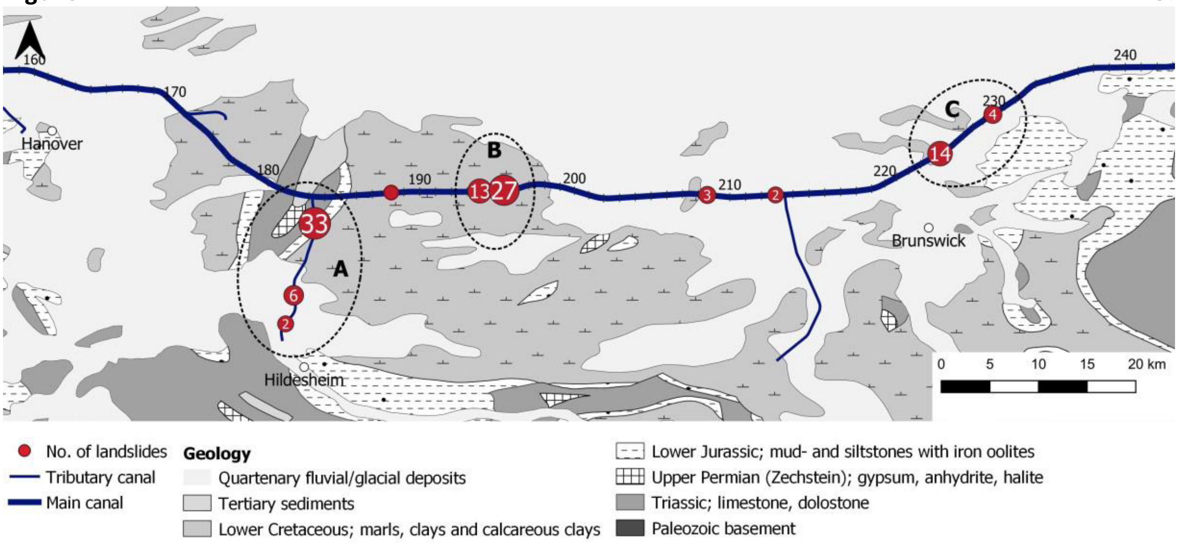
The weighting factors were determined with an analytical hierarchy process (AHP; Saaty, 1980). In the first step in the process, the factors were compared to each other and were ranked with a value between 1 and 9 or the reciprocal, according to their importance. The value 1 implies that the factors are equally important, a value of 3 marks a moderate importance, a value of 5 marks a strong importance, a value of 7 marks a very strong importance, and a value of 9 marks a very high importance. The values were listed in a matrix and the eigenvector values were calculated in a simplified calculation. Figure 8 displays the vulnerability factors and the analytical hierarchy process for the weighting factors.

Vulnerability indicators	
1	Mitigation measures
2	Average daily traffic volume
3	Average daily heavy traffic volume
4	Type of road
5	Speed reductions
6	Length of alternative route

Importance value	
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Highest importance
2, 4, 6, 8	Values in between

	1	**2**	**3**	**4**	**5**	**6**	Weighting factors
1	1	3	4	4	5	6	0.359041
2	1/3	1	2	3	5	4	0.237290
3	1/4	1/2	1	2	4	5	0.176031
4	1/4	1/3	1/2	1	4	3	0.119928
5	1/5	1/5	1/4	1/4	1	1/3	0.042860
6	1/6	1/4	1/5	1/3	3	1	0.064850

Figure 8.



3.6 Case histories to analyze mitigation measures

From the analysis of landslide data and mitigation measures, case histories have been developed for the Mittelland canal and three road sections in Hann. Münden. In hazard assessment, the study of historical data sets is a key concept to analyze impacts as well as costs of landslides (Varnes and IAEG 1984; Glade 2001). In this regard, case histories can be used to understand the interaction of landslide activity and land use practices including mitigation measures (Calcaterra et al. 2003; Klose et al. 2016). Although case histories are limited to a local area by design, they are used for the area of the Southern Lower Saxony to differentiate landslide mitigation over time in order to identify local construction patterns. The main purpose is to understand the correlation of landslide activity, resulting vulnerability, concepts of mitigation as measures of public risk perception, and the resilience of different transportation infrastructures.

4 RESULTS

4.1 Analysis of potential landslide trigger

The temporal and spatial distribution of landslides in Southern Lower Saxony gives first insights of anthropogenic influences in triggering landslides. Of the total number of landslides in the area (n = 1038), a number of n = 809 occurred at a distance of less than 100 m from transportation infrastructure (i.e. Federal highway, interstate and state road, Mittelland canal). At the Mittelland canal exclusively, n = 112 landslide events have been registered. The majority of landslides occurred at the three sites: at the tributary canal to Hildesheim (A), the main canal at km 195 (B) and the main canal between km 225-230 (C). These sites are shown in Figure 9.

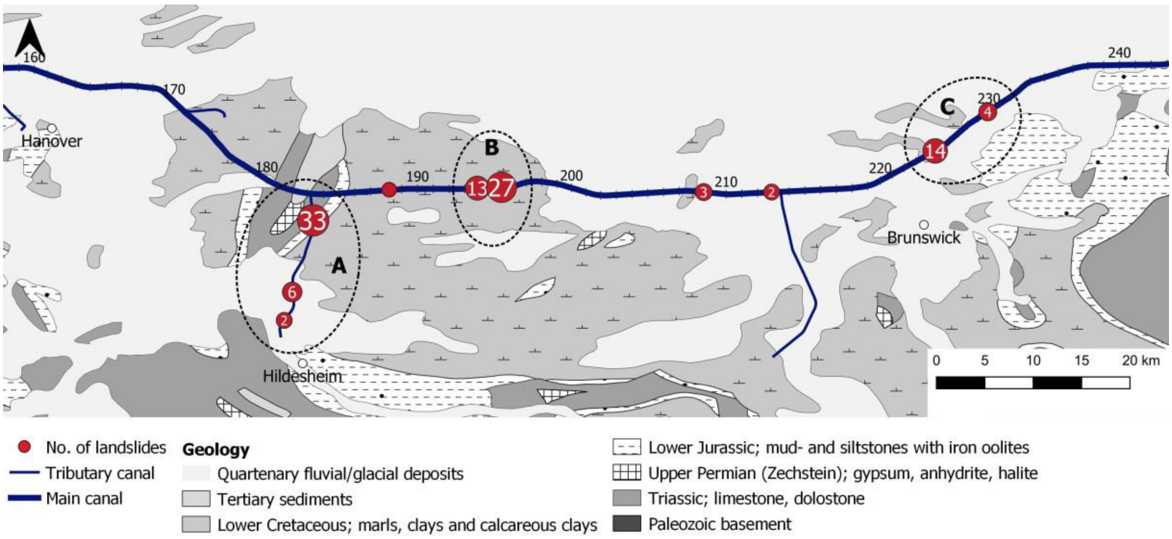


Figure 9. Spatial overview of landslides at the Mittelland canal in combination with stratigraphy/geology. The majority of landslides occurred in three confined areas: (A) at the tributary canal to Hildesheim, (B) at the main canal at km 195 and (C) at the main canal at km 225/230.

Considering the temporal distribution, it can be observed that 42% (n = 47) of the occurring landslides are linked to the construction phases between 1906 and 1938 (cf. Figures 10−12). Another phase of increased landslide activity can be identified during World War II between 1939 and 1945, with 22 landslides occurring during that time. A third phase of increased activity can be extracted from the landslide data in the post-war years between 1946 and 1957 (n = 35 landslides).

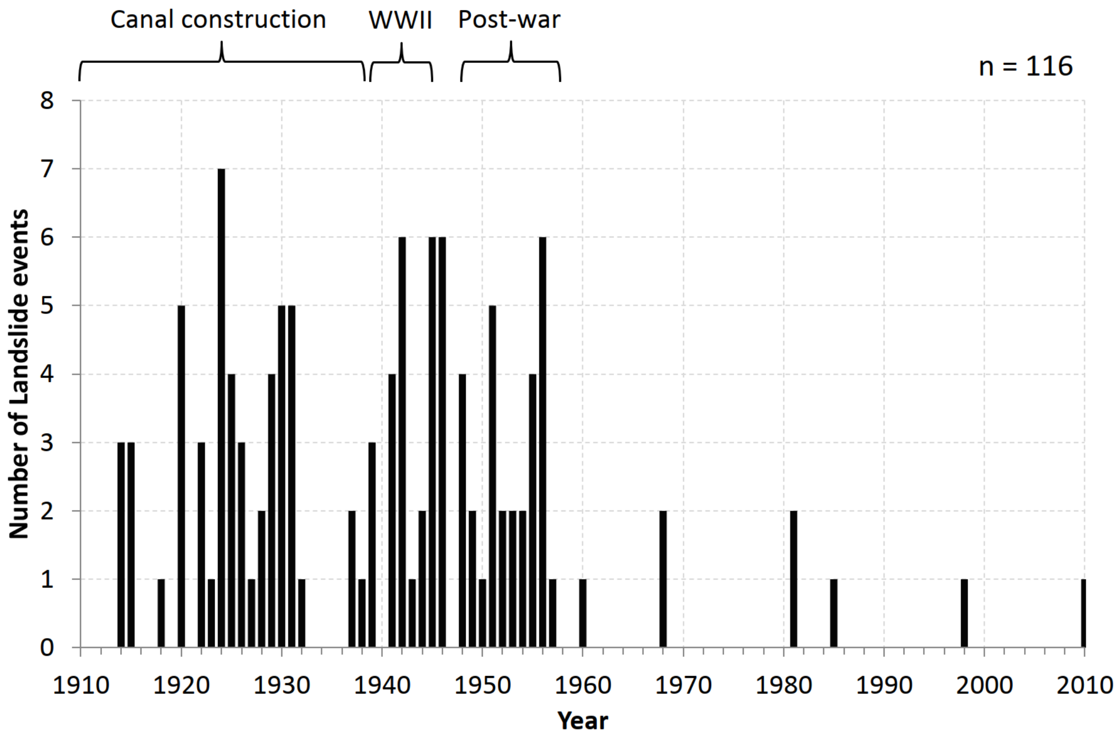


Figure 10. Temporal distribution of landslides at the Mittelland canal showing phases of increased activity during canal construction, WWII and in a post-war phase.

At the main canal, at the problematic sites B and C (cf. Figure 9), the majority of landslides was reported during construction phases. After construction was finished, landslides were registered near km 195. During reconstruction, few landslides were registered (*n* = 4, Figure 11).

At the tributary canal to Hildesheim, most landslides were observed during wartime and post-war periods (*n* = 31, *n* = 28) between km 2 and 4 (Figure 12). Unlike the two other problematic sites at the main canal, very few landslides occurred during canal construction at the tributary canal (*n* = 8).

Both the spatial and the temporal landslides distributions are strongly linked to anthropogenic construction phases (1906-1938). Precipitation records suggest, that there is no strong relationship between landslide data and precipitation records (Wohlers & Damm, 2020). While the post-war period is marked by major reconstruction and reparation efforts, the constructions works were limited to a minimum during WWII. Instead, aerial bombings can be considered as potential landslide trigger.

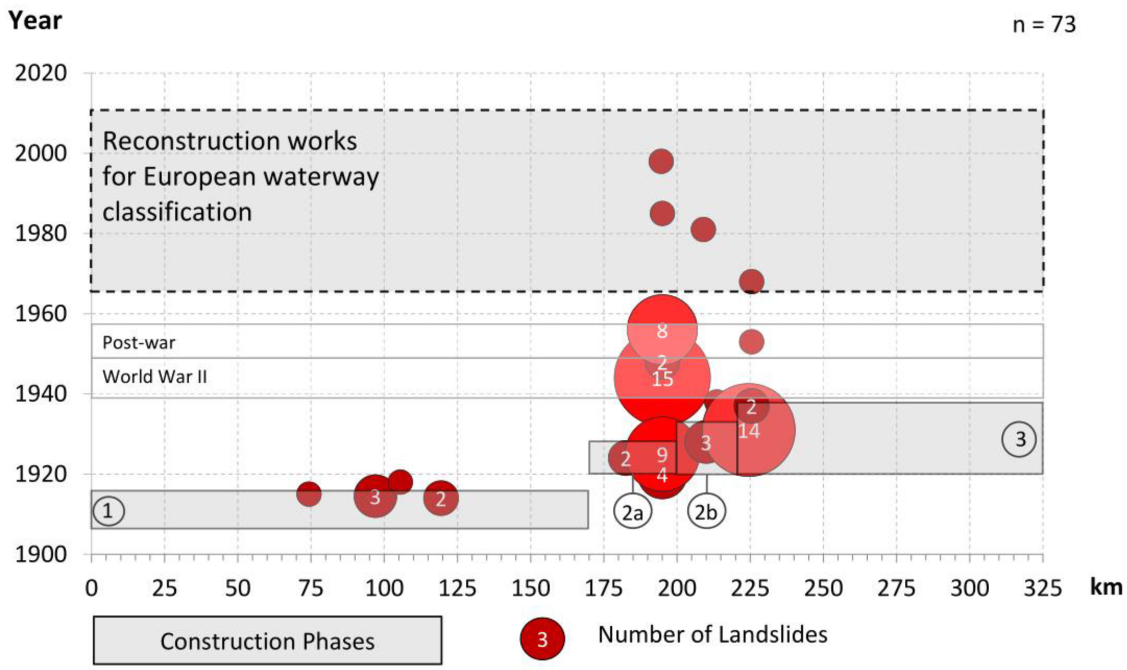


Figure 11. Spatio-temporal distribution of landslides at the main canal of the Mittelland canal. Construction phases between 1920 and 1938 are accompanied by increased landslide activity. At km 195, a large number of landslides occurred during war and post-war periods (1939–1957).

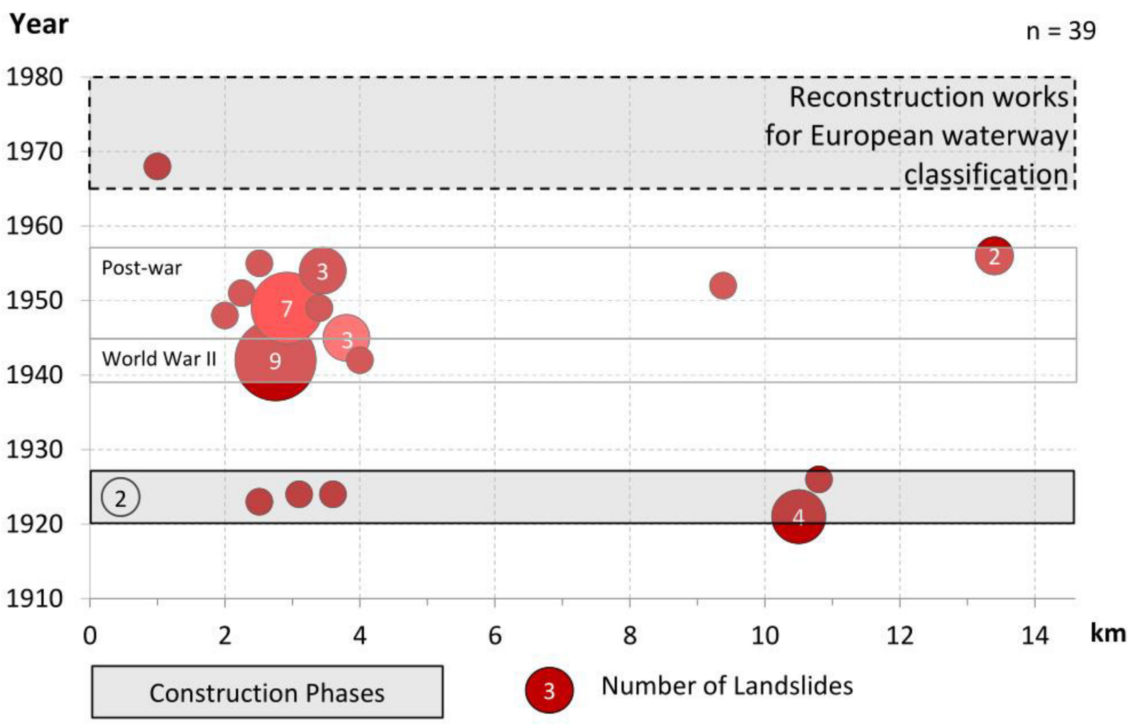


Figure 12. Spatio-temporal distribution of landslides at the tributary canal to Hildesheim. The construction of the tributary canal (construction phase 2) is accompanied by low landslide activity. Instead, a large number of landslides during war and post-war period (1939-1957) between km 2 and 4.

From the original landslide dataset at the Mittelland canal occurring in WWII, 30 landslides had to be excluded. They are either not in the set time interval or include inaccurate dates, spanning more than one year. For the remaining landslide data, only the years of occurrence are available. They were observed solely at the tributary canal and at the main canal at km 195. At km 195 of the main canal, aerial bombings are reported only in September and October 1940. Only one landslide occurred in these months, at a distance of 3–5 km from the bombings.

At the tributary canal to Hildesheim, several bombings were reported between 1940 and 1944. Table 6 gives an overview of landslides, aerial bombings and distances. For 6 of 10 landslides that occurred during the war, no bombings were reported in the same year. For three landslides, bombs were dropped at distances of <1 000 m (i.e. MLK52, MLK53 and MLK64; cf. Figure 13). A landslide triggered by bomb blast is feasible, though the local wind field can strongly influence the aerial blast and resultant effects (cf. Hinzen, 2014). For the remaining landslide, a bombing was registered at a distance of 3 100 m away (MLK62).

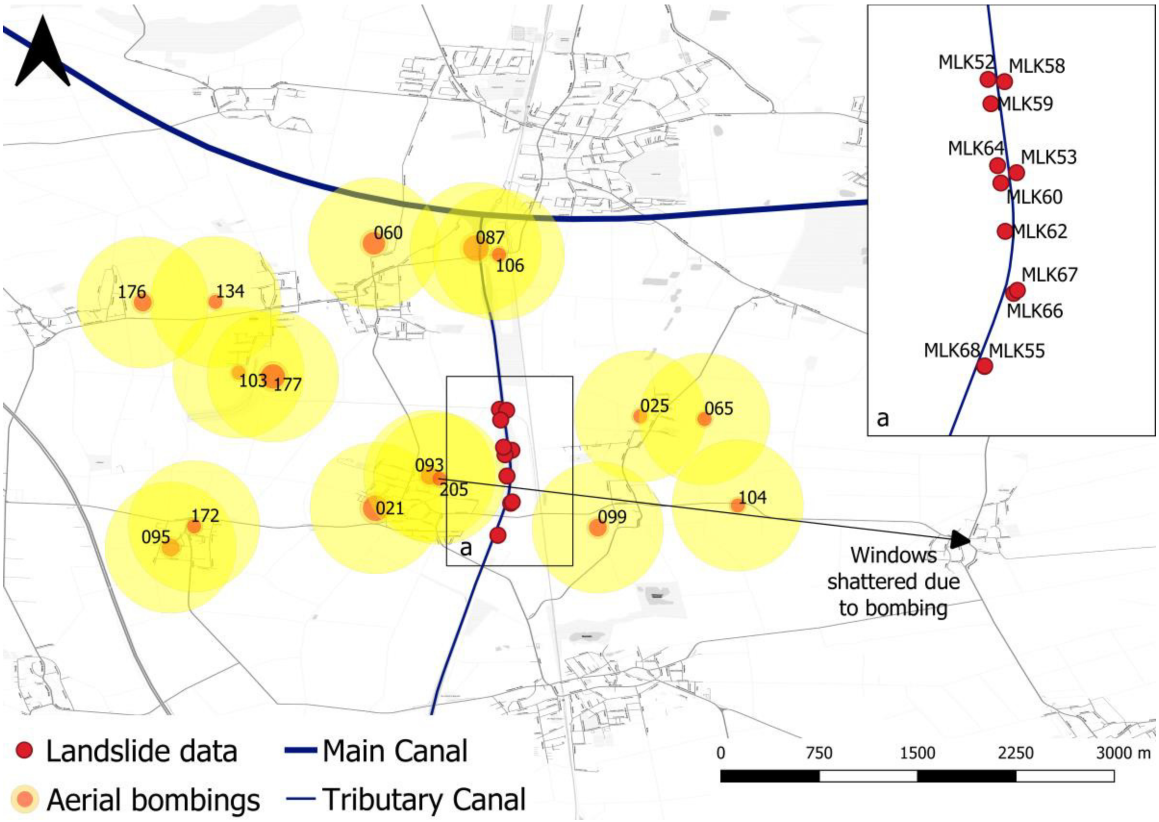


Figure 13. Overview of landslides during WWII at the tributary canal to Hildesheim and the reported aerial bombings in a 4-km radius from the canal. For blast impact, radii are calculated with formula from BAuA (2022) for 250 and 500 lb bombs. UNMAS (2013) gives a security radius of 1,000 m for discharging bombs, but a 500-m radius is displayed for the sake of clarity. Maps by Stamen Design from OSM data.

Table 6. Overview of landslides at the Tributary canal to Hildesheim, and aerial bombings in a 4-km radius of the canal

Year	Landslide ID	Date of bombing	Bombing ID	Distance from canal
1941	MLK52 MLK53	15.-16.05.; 15.-16.06.; 12.-13.08.; 14.-15.08.	060; 065; 087; 093; 095; 099; 103; 104; 106	980–3000 m 700–2900 m
1942	MLK55 MLK58 MLK59 MLK60	No bombings		
1943	MLK62	22.-23.09.	134	3100 m
1944	MLK64	20.02.; 21.02.; 06.09.	172; 176; 177; 205;	600–3300 m
1945	MLK66 MLK68	No bombings		

4.2 Susceptibility to rockfalls in the Harz mountains

The calculated values of rockfall susceptibility in the Harz mountains vary between -5.13 and 2.00 (if values of -10.0 are not considered). The calculated information values are listed in Table 7. To 55% of the road network area of the Western Harz mountains, a very low or low susceptibility considering rockfalls is assigned (46% very low, 9% low) in the classification. A moderate susceptibility is calculated for 22% of the area; in the categories of high and very high susceptibility, 19% resp. 4% of the area can be found. Road sections, highly susceptible to rockfalls, are linked to high slope values with hard sedimentary rock cropping out and a NE orientation of the road.

Figure 14 shows an example for a road section (see Figure 15 for the location of the road segment) with high and very high susceptibility. The slopes in the photographs are located at elevations of 420 m, with slope angles of >25° and hard sedimentary rock. In Figure 14, further mass movements that cannot be categorized as rockfalls are displayed along the road. Most of them are linked to subsidence of the exterior slope of the rock.

Table 7. Information values for susceptibility modeling; where a calculation of values was not possible (landslide area 0%), the values were set to −10.

Factor	Classes	Information Value	Total Area (%)	Landslide Area (%)
Elevation[1]	<300 m	−0.641473	34.59	18.21
	300–400 m	1.362817	20.28	79.24
	400–500 m	−5.127046	13.72	0.08
	500–600 m	−1.932988	17.05	2.47
	600–700 m	−10.000000	7.81	0.00
	700–800 m	−10.000000	4.85	0.00
	>800	−10.000000	1.71	0.00
Slope[1]	<15°	−1.269577	82.08	23.06
	15–20°	0.834263	8.69	20.02
	20–25°	1.743032	5.55	31.72
	25–30°	2.003805	2.67	19.83
	>30°	1.678186	1.00	5.36

	2	−2.980840	1.54	0.08
	3	−10.000000	0.80	0.00
	4	−10.000000	0.02	0.00
	5	−10.000000	1.11	0.00
	6	−10.000000	4.85	0.00
	8	−10.000000	7.58	0.00
	11	0.424239	6.13	9.37
	12	0.535791	21.45	36.66
Material Character-ristics	14	−10.000000	0.17	0.00
	15	−10.000000	0.31	0.00
	16	−10.000000	2.00	0.00
	17	−10.000000	0.53	0.00
	18	−10.000000	0.94	0.00
	19	−10.000000	0.52	0.00
	20	−10.000000	0.85	0.00
	21	−2.446112	16.09	1.39
	22	0.616785	28.28	52.40
	23	−4.303761	6.82	0.09
Road section orientation	N (0–11.25°)	−0.176030	13.04	10.93
	NNE (11.25–33.75°)	−0.391955	11.25	7.60
	NE (33.75–56.25°)	1.526976	12.03	55.39
	ENE (56.25–78.75°)	0.230975	13.54	17.05
	E (78.75–101.25°)	−1.513952	14.19	3.12
	ESE (101.25–123.75°)	−1.687862	11.82	2.19
	SE (123.75–146.25°)	−1.875752	11.83	1.81
Distance to faults	<500 m	−0.712056	32.86	16.12
	500–1000 m	0.366012	24.26	34.98
	1000–1500 m	0.3360609	14.79	20.69
	1500–2000 m	−0.1558190	12.66	10.84
	>2000 m	0.1182856	15.43	17.37
Precipitation	<1000 mm	−2.492298	36.48	3.02
	1000–1100 mm	1.723268	11.34	63.54
	1100–1200 mm	0.437078	11.59	17.94
	1200–1300 mm	−0.514383	15.73	9.40
	>1300 mm	−1.406148	24.86	6.09
Ice Days	<20	−10.000000	21.80	0.00
	20–25	0.827132	19.38	44.31
	25–30	−0.446209	11.72	7.50
	30–35	0.023274	15.93	16.30
	35–40	0.668763	16.34	31.88
	>40	−10.000000	14.84	0.00

[1] Values of elevation and slope are underestimated due to resolution digital elevation model of 20 m (opendataportal.at).

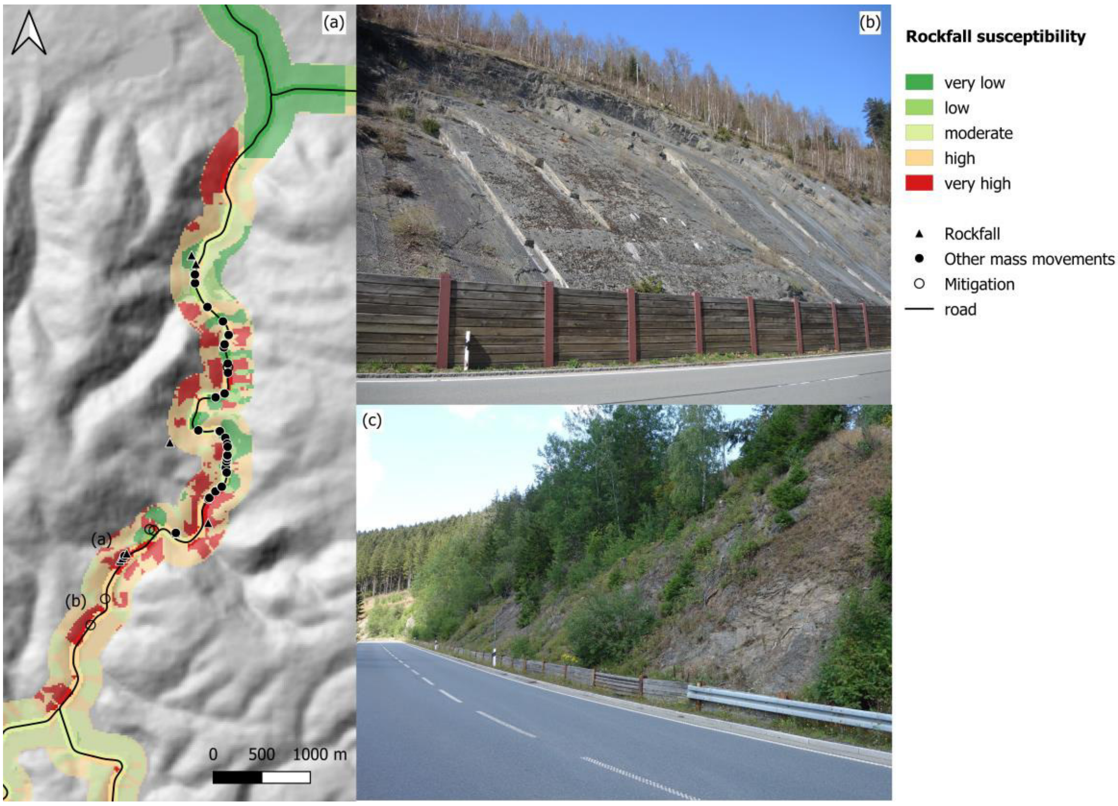


Figure 14. (a) Rockfall susceptibility for the road section in Oker valley, Harz mountains (see Figure 15 for position). To improve the presentation, the susceptibility is displayed in a 500-m-corridor, though the susceptibility has been modelled in a 100-m-corridor. **(b)** and **(c)** illustrate mitigation measures in the Oker valley.

The model validation by receiver operating characteristic (ROC) analysis reveals an area of 82% under the ROC curve (cf. Figure 15).

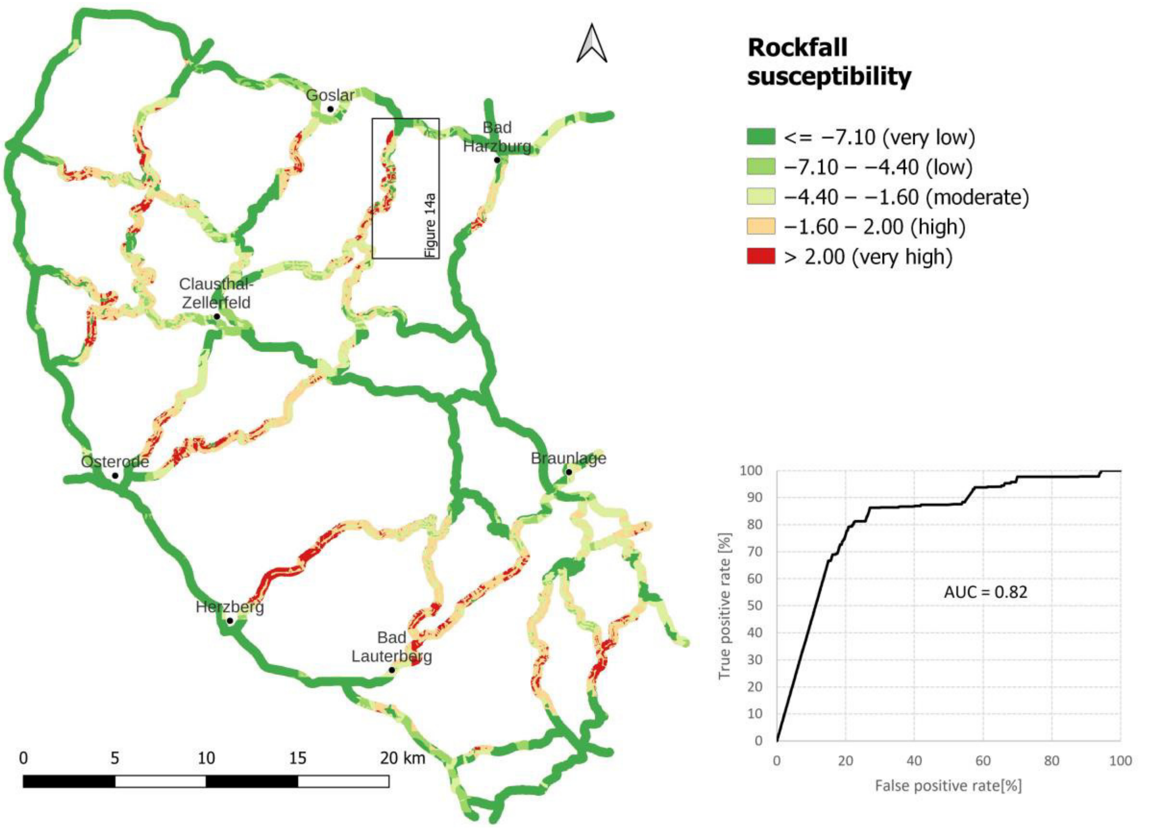


Figure 15. Rockfall susceptibility model by information value and model validation for road corridors in the Harz mountains. To improve the presentation, the susceptibility is displayed in a 500-m-corridor, though the susceptibility has been modelled in a 100-m-corridor. Model validation results in an AUC of 0.82.

4.3 Road network vulnerability in the Harz mountains

According to equation (5, the vulnerability index theoretically may vary between -0.400 and 1.300. The lowest value can be calculated for the road section with complete structural mitigation at rockfall sites, low traffic volumes, with a preferably wide road, high speed reductions due to speed limits, and with a short length of alternative routes in the case of road closure. The highest values accordingly are reached for no mitigation, high traffic volumes, and narrow roads without any speed limits and with long alternative roads in the case of closure.

The calculated values are not reflected in the theoretical ones with minimum and maximum indices at the road sections of –0.066 and 0.147, respectively. The determined values are categorized in three evenly distributed classes (Figure 16).

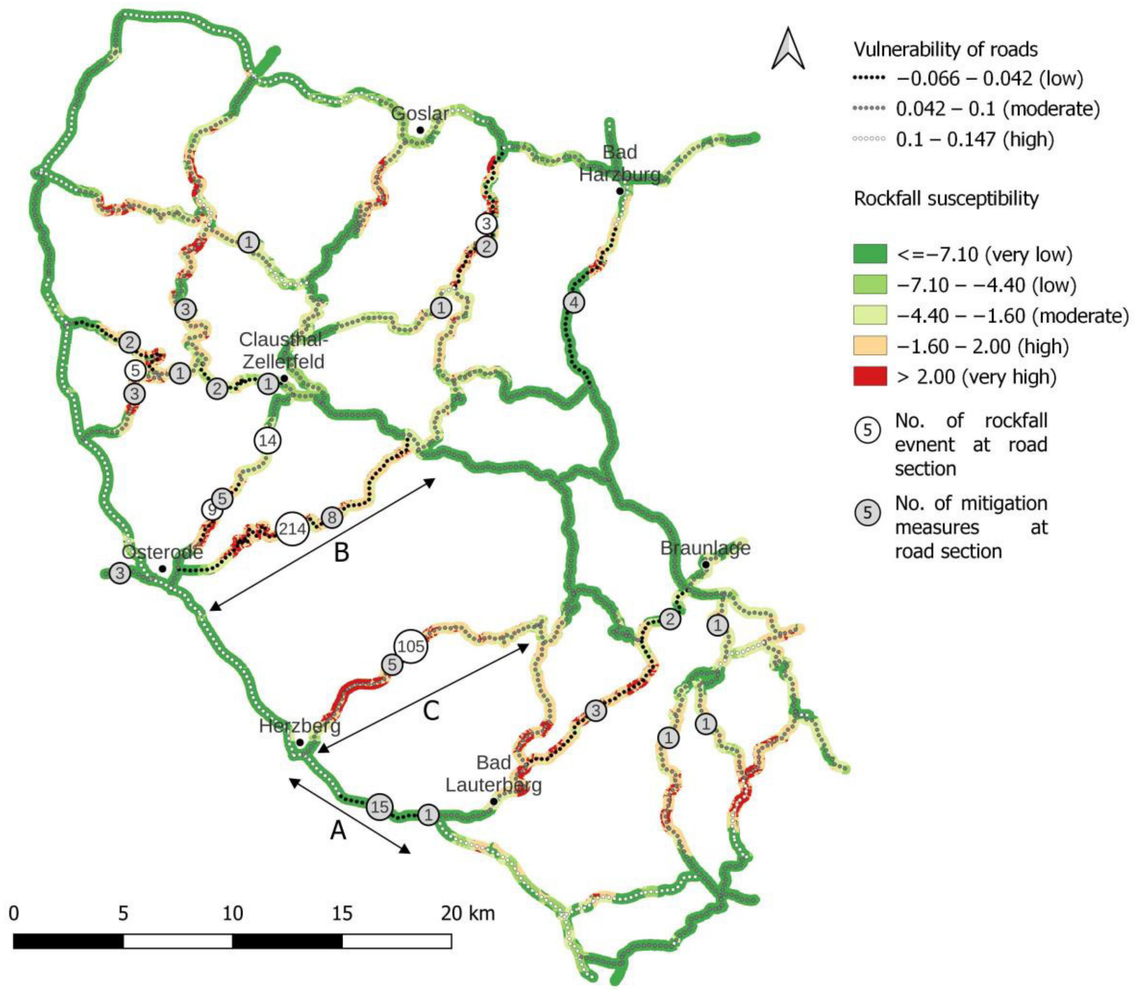


Figure 16. Vulnerability of road sections in the Harz mountains combined with rockfall susceptibility, number of rockfalls and mitigation measures at the road section. In general, marginal road sections show low susceptibility and high vulnerability, except for road A, which shows a low vulnerability caused by a high number of mitigation measures. Roads B and C represent sections with high susceptibility, but low resp. moderate vulnerability.

The highest values of vulnerability indicators of >0.1 are linked to road sections on the marginal roads of the Harz mountains with mean daily traffic volumes of >12,000 vehicles per day. The susceptibility at these sections can be categorized very low. An exception is the road section marked with an A in Figure 16. Due to the high number of structural mitigation measures on this section (n = 15), the vulnerability is one of the lowest. Low vulnerability values can be found on roads connecting the internal with the external roads. The road sections are often characterized by low average daily traffic volumes of <4,000 with adequate road widths, partly complemented by speed limits and structural mitigation. On one of these sections, the highest number of rockfalls is registered with 214 events (B in Figure 16), resulting in a high modeled susceptibility. In general, road sections with a high or very high susceptibility are linked to comparably low vulnerability indicators, except for the road section with 105 rockfalls. The section is mapped with a moderate indicator value (C in Figure 16).

4.4 Case histories for mitigation measures

4.4.1 LANDSLIDE MITIGATION IN THE UPPER WESER VALLEY

For the upper Weser valley and the city of Hann. Münden three case histories have been developed at different localities. The first site is a section at an interstate road with a strongly anthropogenically altered slope. The second site represents a rural interstate road and the third site is located at an interstate junction combined with railroad and river traffic in the city of Hann. Münden (Wohlers et al. 2017). Figure 17 shows the location of the sites.

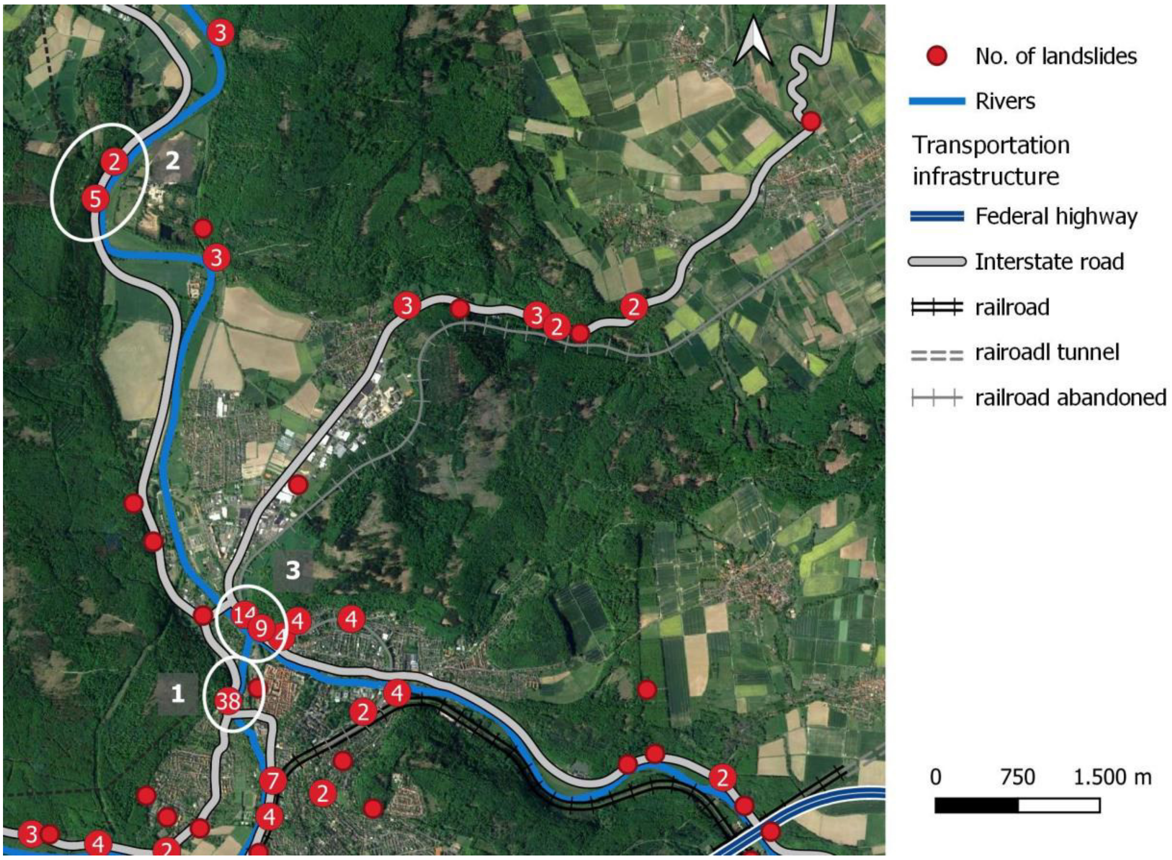


Figure 17. Case histories in the Upper Weser area (Hann. Münden). Site 1 is located at a strongly altered slope. Site 2 is a rural interstate road section in Hesse. Site 3 represents an important regional transportation infrastructure junction. (Aerial photograph by Google).

The first site involves a slope of 300 m length and 50–70 m height, formed as a river cut bank. The natural slope gradient varies between 30° and 50°. The road construction in 1880–1882 is accompanied by the first landslides. At the same time, first mitigation measures were realized (masonry gravity walls). The contemporary high financial relevance is linked to the increased construction costs and mitigation during that time according to expert opinion (Klose et al. 2016). Subsequent landslides (n = 30) can be clustered in events in the 1920s (n = 2), 1936/1937 (n = 5), 1960s (n = 3), 1970-1975 (n = 6), 1999-2001 (n = 7). For long time, mitigation measures were very simple and focused on the removal of loose rock and vegetation from the susceptible outcrop areas within the slope (1924, 1936, 1961/1962 and 1994). In 1937, 1994 and 2000 a wooden barrier was constructed to protect road traffic against rockfall. In addition, in 1994 wire meshes were installed. In 2001 a comprehensive reconstruction of the slope was undertaken including rock blasting, concrete injections and a rear anchored concrete wall (Damm 2005).

The second site is located at a federal highway between two small cities. It is situated in the federal state of Hesse and therefore in the responsibility of a different state office for transportation. Consequently, it is possible to compare mitigation measures in the federal states of Hesse and Lower Saxony. The 2.2 km long and 80–120 m high slope with an average natural gradient of 40° is formed as a river cut bank. The total number of reported landslides is considerably less than at the first site (n = 9), probably linked to an incomplete landslide record. Under the consideration that most data are extracted from newspaper articles, it can be assumed that newspaper coverage focused on events in urban areas. Clusters can be found in the 1890s/1900s (n = 3), 1960s (n = 1), 1980s (n = 3) and 2010s (n = 2). The mitigation measures are similar to those of site 1. Apart from drywall construction in 1907 to stabilize the slope, mitigation focused on removal of loose material. In the 1960s a gravity wall was constructed for slope stabilization. In 1983/1984 the slope was comprehensively reconstructed implementing the use of rock nailing, new gravity walls, wooden barriers, catch fences and wire meshes. A cascade system was installed to prevent gully erosion. In 2015/2016 the mitigation was modernized. While the gravity walls and wooden barriers are still intact, catch fences with a system of dynamic brakes and anchored wire meshes are installed. Gullies are reshaped to control erosion.

The third site represents a 550 m long and 70 m high slope formed as a river cut bank, which is situated at an important infrastructural junction. The importance of the site for the city is emphasized by occurrence of a federal highway in the vicinity of a river port and a railway line. Even though the port is no longer in use, and the railway only seldom for heavy load transportation, the site is still of some infrastructural importance for the upper Weser area since it represents the alternative route to the national highway in case of full closure. The importance is reflected by the early road construction in the 1770s with first documented landslides during that time (n = 4). The number of subsequent landslides (in total n = 30) can be clustered in events in the 1880s (n = 2), 1900s (n = 2), 1925-1930s (n = 3), 1950-1960s (n = 8), 1970-1980s (n = 2), 2000s (n = 4) and 2010s (n = 3). Early mitigation measures focused on slope stabilization on both sides of the road (slope cut and roadbed) by constructing gravity walls (1770s, 1930s). Aside from drywall construction, sliding and falling material in general was removed from the road for a long time (until the 1950s). Some of the small to medium scale (50-150 m³) events are related to construction works. With the broadening of the highway from 1962-1975 the slope was reshaped and mitigation measures were installed. To decrease the slope gradient 7,000-8,000 m³ material was removed. A concrete barrier with retention space, wire meshes and a drainage system was realized. The concrete barrier was shortly replaced by a wooden barrier. In 1986 the wire meshes were renewed. In 2015/2016 new mitigation measures were installed including concrete injections, anchored wire meshes covered with geofabrics and shotcrete.

The reported case histories show the occurrence and clustering of landslides in the Upper Weser Valley since the modern road construction in the 19th century. Clusters of landslides are registered in the 1770s, 1880s, 1900s, 1930s, 1950s and 1970s. For the last four decades (since the 1980s) the number of landslides is constant. The peaks of landslides events can be explained by construction phases on one side (i.e., 1770s, 1880s and 1930s), and high precipitation phases on the other in the 1960s and 1970s (Wohlers et al., 2017; Damm & Klose, 2015). Corresponding to the event clusters, construction and mitigation phases can be identified in the 1770s, 1880s (both construction), 1930s, 1960s, 1980s and 2010s (mitigation combined with road extension). Clusters of landslide events are followed by an intensified period of mitigation (cf. Figure 18).

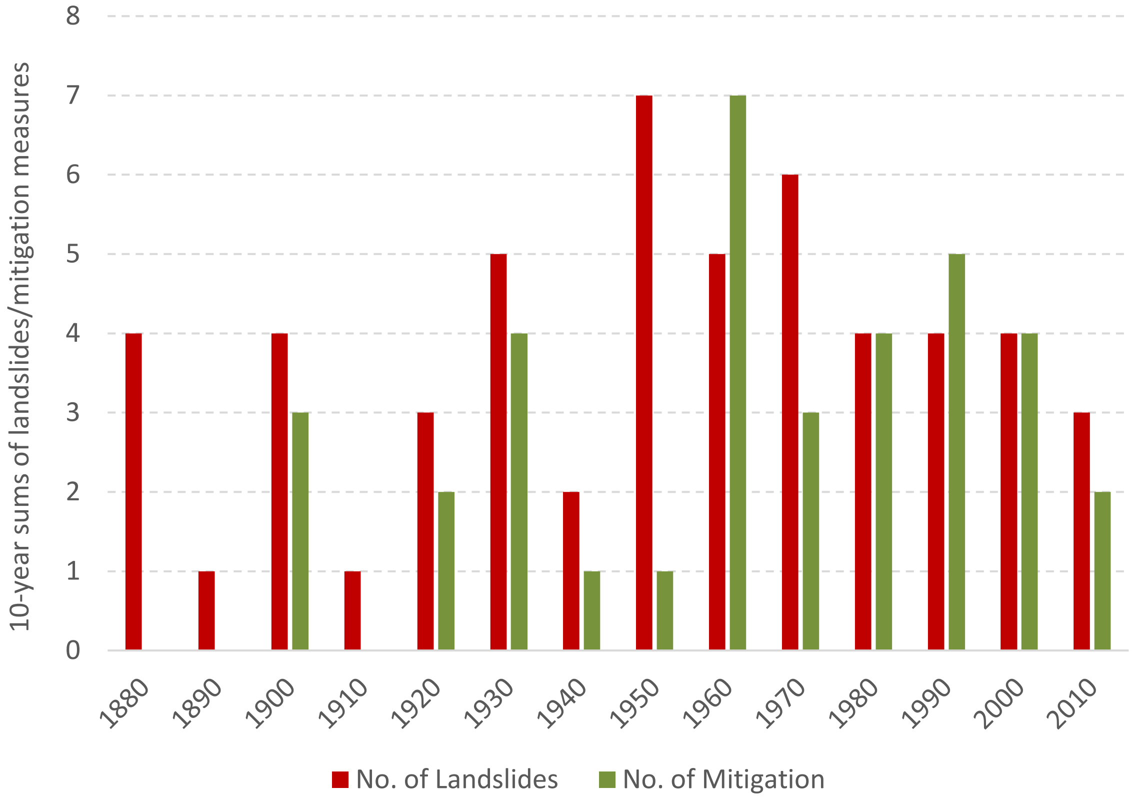


Figure 18. 10-year sums of landslides/mitigation measures at the presented sites in the Upper Weser area. Phases of increased landslide activity (1880s, 1900s, 1930s, 1950s and 1970s) coincide (1900s, 1930s, 1980-2000s) and are followed (1960s, 1990-2000s) with/by phases of increased mitigation activity respectively.

Mitigation phases in the Upper Weser area can be differentiated by the distinct reported measures. In the road construction phase in the 1770s and 1880s mitigation focused on slope stabilization by constructing dry walls (Figure 19a). Protection against rockfall was not achieved, falling material had to be removed during road closure. The construction of higher dry walls was intensified at the beginning of the 20th century and especially in the 1930s.

Figure 19. Development of mitigation measures in southern Lower Saxony, NW Germany. **(a)** The drywall construction from the 1930s in the front did not contribute to protection against rockfalls/slides. **(b)** Removal of loose rock and vegetation in the Upper Weser area in 1936. **(c)** Combination of steel buttress/wooden planks as a barrier against rockfall on an interstate road in the Harz Mountains, NW Germany. **(d)** Rockfall mitigation in the Upper Weser area. The barrier wall in the left and wooden barrier in the right foreground are constructed in 1983, rock drapery and catch fence constructed in 2015.

After a period of high landslide activity, engineered mitigation was planned at some sites but not realized. Instead, loose material from cover beds and vegetation was removed by clearing and rock blasting (Figure 19b).

Engineered mitigation was executed in the 1960s. Slope stabilization was realized by constructing concrete walls and piles. Protection against rockfall was achieved by building wires meshes and barriers in a combination of steel buttress and wooden planks (Figure 19c).

In the 1980s the use of wire meshes and rock drapery increased. In addition to the 1960s, they were nailed to the ground. Rockfalls were mitigated by installing catch fences. Furthermore, drainage systems were realized to improve slope stability. Comprehensive mitigation measures have been installed since the turn of the millennium to stabilize sediment layers with concrete injections and anchor them deep in the ground. Dynamic catch fences are not only designed to protect against rockfalls but against falling trees likewise (Figure 19d). In modern mitigation measures esthetic and ecologic aspects are considered as well (cf. Popescu and Sasahara 2009). Geofabrics and colored shotcrete are used to maintain the impression of a natural slope.

4.4.2 DEVELOPMENT OF LANDSLIDE MITIGATION AT THE MITTELLAND CANAL

Due to the high number of landslides during the construction of the eastern segments and the tributary canal to Hildesheim, mitigation was developed contemporarily. The construction of the canal was executed with profiles similar to those at the western canal, though material characteristics are very different. During construction, incisions of up to 17 m at the tributary canal and 16 m at the main canal were created. Canal construction implied trapezoidal ditches, including slopes with a 70% inclination above the towpath and 70% to 50% beneath it (cf. Figure 20).

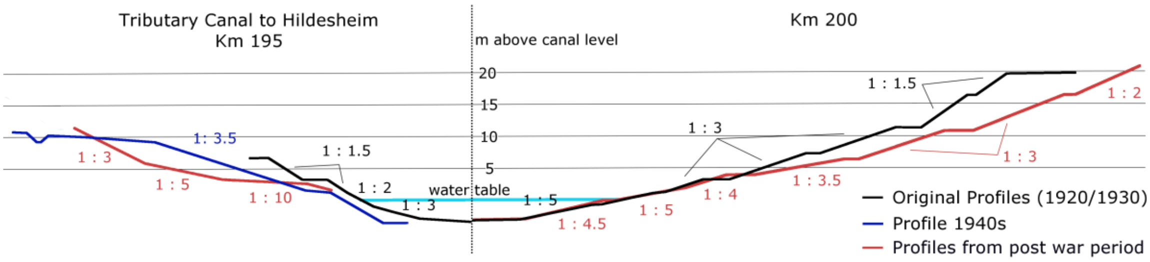


Figure 20. Developed canal profiles at the Mittelland canal, Km 195 and the tributary canal to Hildesheim (left-side). The right side presents applied canal profiles at the Mittelland canal at Km 200.

In the first phase between 1920 and 1927, mitigation measures included material removal and the application of drainage trenches. The main problem was considered to be aquiferous Quaternary covering deposits underlain by aquiclude fine-grained sedimentary rocks. Hence, the drainage of the quaternary beds was supposed to stop the slopes from destabilizing. Occasionally, slopes were regraded to 1:3, although in general, flattening was considered too cost intensive. In 1927, constructors became aware that landslides were caused by the underlying fine-grained and calcareous sedimentary rocks (Goetzcke, 1927). As a result, affected slopes were flattened and benched (if possible), and in addition to swales for drainage, a stabilizing wedge created from gravel was implemented. Where all these measures failed, rectangular-trapezoidal profiles were implemented. At least n = 10 landslides are linked to failed drainage trenches. At another landslide event, the stabilizing wedge steel pilings failed and had to be removed in subsequent phases.

Between 1928 and 1938, the majority of landslides (n = 20) were reported at the main canal at km 225 (area C in Figure 9). In this section, the canal is incised up to 25 m into Quaternary sediments and fine-grained and calcareous sedimentary rocks. Due to former experiences during canal construction, the slopes were constructed with lower inclinations of 1:3 to 1:5, with trapezoidal profiles (Figure 20). Where landslides began to emerge, concrete injections were applied to the sliding surfaces to stabilize the slope and to prevent further seepage. Until 1936, approximately 900,000 m^3 of vulnerable soil material was stabilized in that manner (Sartorius and Kirchhoff, 1936). Concrete injections were sporadically implemented at landslide sites in the areas A and B, but failed to stabilize the slopes long term in these areas, whereas the injections helped to mitigate additional landslides at the main canal at km 225.

In the years 1939 to 1945, a number of n = 22 landslides were reported exclusively at the main canal at km 195 and the tributary canal to Hildesheim in the years 1939-1945. The most applied mitigation was the regrading of slopes to an inclination of 1:3. Often, the planned reconstructions could not be applied due to budget shortages, or lack of manpower and fuel. As a result, regrading required a lot of time, between several months and three years. In the meantime, the destabilization of slopes continued and additional masses were involved. Where lack of money prohibited regrading, landslide masses were removed to enable shipping traffic to continue.

After WWII ended, many slopes had to be reconstructed. In the post-war years (1946-1957) 35 landslides occurred at the main canal at km 195 and the tributary canal to Hildesheim (one landslide at the main canal near Brunswick). In mitigation, the period indicated major reconstructions of the involved slopes: materials and older drainage systems were removed, profiles were regraded, new drainage systems were implemented and the slopes were forested according to plantation plans. New canal profiles (though still trapezoidal) were developed and applied.

5 DISCUSSION

The landslides in the area of Southern Lower Saxony are analyzed to evaluate different aspects of anthropologic influences concerning transportation infrastructure, such as potential triggers, susceptibility, vulnerability and applied mitigation measures. The presented results give insights into the anthropogenic influences of landslides at road infrastructure in Southern Lower Saxony. It is completed by the analysis of landslides at the Mittelland canal.

The presented results are based on historical landslide records, which enable the analysis of conditional and preparatory factors, susceptibility, potential triggers, and the analysis of applied mitigation measures, though, some challenges are inherited from the dataset. Available data from the Landslide Database of Germany (Damm and Klose, 2015) are supplemented by studies of federal archives and archives of transportation offices. As a result, the data coverage varies strongly both temporarily and locally. For instance, the dataset is very dense at the Mittelland Canal between the 1920s and mid-1950s (except for the period of WWII) and in the Harz mountains between 1995-2008. In addition to archive studies, the landslide data are collected from press and web archives of emergency agencies, company and newspaper records as well as scientific and geotechnical literature. The resultant dataset emphasizes landslides of small volumes (60% with less than 50 m³ volume; cf. Fell et al., 1994). Small-volume landslides are often underrepresented in datasets based on newspaper records, since these events do not arise public interests due to low direct damages (cf. Voumard et al., 2018; Taylor et al., 2015; Ibsen and Brunsden, 1996).

The Mittelland Canal illustrates the anthropogenic actions modifying both the disposition towards landslides and triggering them as well. A controlling factor is the incision of over-steepened slopes into Mesozoic sediments (Triassic to Cretaceous) with particular material characteristics. The abundant fine-grained clay- and marlstones with low carbonate contents (Kirchhoff, 1930) are geotechnically considered to be solid rocks, however they quickly deteriorate after immersion in water (DIN EN ISO 14689-1, 2011). As a result, soft rocks disintegrate in wet–dry cycles under dynamic stress (v. Vittinghoff, 2003). The described issue of incision into materials with problematic characteristics are known worldwide (cf. Skempton, 1964, Mikos et al., 2009, Fletcher et al., 2002). Incised over-steepened slopes have been created along the road infrastructure in Southern Lower Saxony as well. Due to differing material characteristics, particular combinations of mass movements are the result. In the Harz mountains, which are characterized by hard rock, rockfalls (i.e., falls and topples) can be observed at the steep interior slopes, while roads damages at the exterior slope are linked to sliding or creeping caused by non-sufficient consolidation of the leveled road surface (Klose, et al., 2016; Damm, 2000). In the Upper Weser area, landslides (i.e., translational and rotational slides, spreads as well as creeping) are linked to Quaternary covering deposits, which quickly decompose in case of high soil moisture content (Damm, 2005; Wohlers et al., 2017). Where vulnerable layers of interbedded sedimentary rocks have been weathered and eroded, the more resistant layers destabilize and result in rockfall events. In general, material characteristics are the main conditioning factor for landslides, the creation and over-steepening as well as altered conditions for groundwater and surface water flow as anthropogenic influences can be considered as preparatory and, in some cases, triggering factors.

Landslides in the region of Southern Lower Saxony are linked to precipitation as proxy for soil moisture content (cf. Wohlers et al., 2017; Damm et al., 2010). At the Mittelland canal, where strong modifications in slope geometry can be observed, landslides and precipitation values do not correlate (cf. Wohlers and Damm, 2020). Instead, the canal construction can be considered a main trigger for landslides, especially in the later phases of construction (i.e., 1920–1938). For landslides during WWII, aerial bombings are suggested to be a potential trigger. Due to the limited accuracy of the landslide data at the canal, a final evaluation appears difficult, but it remains possible that aerial bombs which impacted at a distance of 600–3,000 m from the canal could affect the slope stability. In a different setting, analogous influences of explosives can be observed at opencast mines (Ma et al., 2016; Bednarczyk, 2017). Other potential triggers in the region include surface water runoff and, for the Mittelland canal, erosion by wave action. In the Harz mountains weathering caused by freeze-thaw-cycle might be a possible natural trigger for rockfalls (cf. Nissen et al., 2022).

For a preliminary risk assessment of the road network in the Harz mountains, the rockfall susceptibility in addition to the road network vulnerability has been modeled. For that purpose, a bivariate statistical approach (i.e., information value method) was used for the susceptibility modelling and the vulnerability was assessed with an indicator-based method. The information value method offered an easily applicable approach to estimate landslide as well as rockfall susceptibility. In the method, the interconnected dependencies of the factors were not considered (Corominas et al., 2014), compared to multivariate statistical approaches. Therefore, the factors should be independent from each other. Klose et al. (2013b) implemented information values in the area of southern Lower Saxony before, revealing good results. The study mentioned that susceptibility estimation in the Harz mountains might be underrepresented due to a lack of data (Klose et al., 2013b). The susceptibility model presented here was tested with a receiver operation characteristic analysis, producing an AUC of 0.82, implying a good quality of the model. The factors for susceptibility mapping were chosen based on regional and methodological backgrounds. Usually in susceptibility mapping, land cover is applied as the modeling factor. The land cover along the Harz mountains road network is dominated by (coniferous) woodland. Therefore, land use was eliminated, as only road sections were considered for modeling. In addition to elevation, slope, material characteristics, and distance from faults, the orientation of the road segments was selected. Due to the resolution of the elevation data, slope values must be considered underestimated; therefore, sites of rockfalls can be found at sites of <30° (cf. Figure 5). A large number of rockfalls can be observed at distances to faults of 500–1,500 m. These values question the influence of the mapped tectonic faults. The geologic maps, from which the faults were extracted, have been created by several authors across time (1920s to 1990s). As a result, tectonic faults might be incomplete and incoherent. In addition, field observation suggests highly fractured rocks independent of the distance to faults. Overall, no alternative data are available to estimate rock strength, which is considered a crucial variable in rockfall susceptibility (Corominas et al., 2014). The orientation is chosen to represent the tectonic influence in valley formation. The general strike of bedding and foliation is directed to the NE, which coincides with the class of NE-oriented road showing the highest rockfall susceptibility. The foliated surfaces usually dip to the SE (Mohr, 1978), making rockfall events more likely at SE-facing slopes. The road section with the highest number of registered rockfalls (n = 214), as well as the road in the Oker valley in the northern part of the Harz (n = 3 rockfalls), exhibit SE-facing slopes. The listed factors are completed with the 30-year mean of annual precipitation sums and the average number of ice days. While short-term peaks of precipitation sums can be considered as a trigger for landslides in the area (Rupp et al., 2018), long-term values contribute to the predisposing of landslide and rockfall events. The rockfall densities in the relevant classes suggest that values of <1,200 mm/a influence the soil moisture and therefore influence the predisposition to landslides; for higher values, a saturation of soil moisture is reached. The number of ice days is used to represent frost–thaw cycles, which might contribute to the weathering of rocks as a predisposing factor (Corominas et al., 2014), as well as a triggering factor (Nissen et al., 2022).

For the vulnerability assessment, an indicator-based model is used. In general, in estimating the physical vulnerability of road infrastructure, the application of vulnerability curves is more established (Winter et al., 2014). Indicator-based methods for landslide vulnerability have been used in assessing the vulnerability of buildings (Papathoma-Köhle et al., 2007). In the presented approach, vulnerability is not expressed as a degree of loss; instead, the propensity of the road network to undergo any type of damage. A disadvantage may be that the size of a damaging event is not considered. This implies that the vulnerability is indicated with the same value whether many small rockfalls or one big event occurs. The presented method can be useful, especially when information on the impact of landslides is lacking. In addition, it can be used to visualize the vulnerability of elements at risk, in the present study for a rural road network. However, vulnerability indicators strongly depend on the set of selected factors. The average daily traffic volumes and type of road (width) are considered as key variables to assess road infrastructure vulnerability (Corominas et al., 2014). In a client-based approach for the quantification of a road network susceptibility in Austria, the length of alternative routes was implemented (Schlögl et al., 2019). Therefore, the applied indicators for the vulnerability assessment were average daily traffic volumes, road type, and alternative routing. In addition, negative scores have been used for speed reductions on the road segments. Speed limits are considered as additional mitigation measures. As the direct impact of a rockfall against a travelling car can be considered unlikely due to low traffic volumes, it is more probable that a travelling car hits a block in the aftermath of a rockfall event. The incident of the car hitting the block depends on the travelling speed of the car then. A speed reduction of 50% reduces the distance to 25% of the original breaking distance. Additional applied mitigation measures have not been considered for the vulnerability assessment, as the record of measures appears to be incomplete.

The observed mitigation measures in the Upper Weser area, which reflect an increase of efforts and resultant costs since the beginning of modern road construction in the 19th century, can be linked to the public risk awareness. The risk management then follows a cycle of event with a short-term response in terms of material removal from the affected site, recovery, which means the reinstatement of the infrastructure, and mitigation measures. Finally, a period of awareness/preparation should follow (Crozier and Glade 2005; Alexander 2002) to maintain high sensibility to the risk. That includes investments into existing mitigation measures. Instead, public awareness to landslide vulnerability decreases and subsequently mitigation measures are neglected which may result in a decrease of structural integrity (cf. Figure 21). As a consequence, landslide events cannot be prevented and instead dysfunctional mitigation measures may contribute to predisposing and triggering new landslides, which might be more damaging than before (i.e., loose wire meshes and wooden planks from barriers). From the new phase of landslide activity, the risk management cycle starts from the beginning. Public risk awareness raises and new mitigation measures are installed. An increase in mitigation effort and costs is intensified by technical standards. Introduced in the 1960s technical standards are created to define slope stability and calculate modes of failure (cf. Eurocode 7, 2014). With the technical development the standards for slope stability increased and consequently mitigation measures become outdated and must be reconstructed. The trend of installing cost intensive and maybe oversized mitigation measures is enhanced by producers of relevant systems. Technical warranties of 50 years and more are common, even though construction engineers argue that these numbers are hardly realistic. Decision makers in transportation offices and involved communities might be under the impression that measures with extended warranties are highly efficient long-term solutions to landslide hazards. Mitigation concepts from the 1980s show, that this argument is only valid, if regular maintenance is applied.

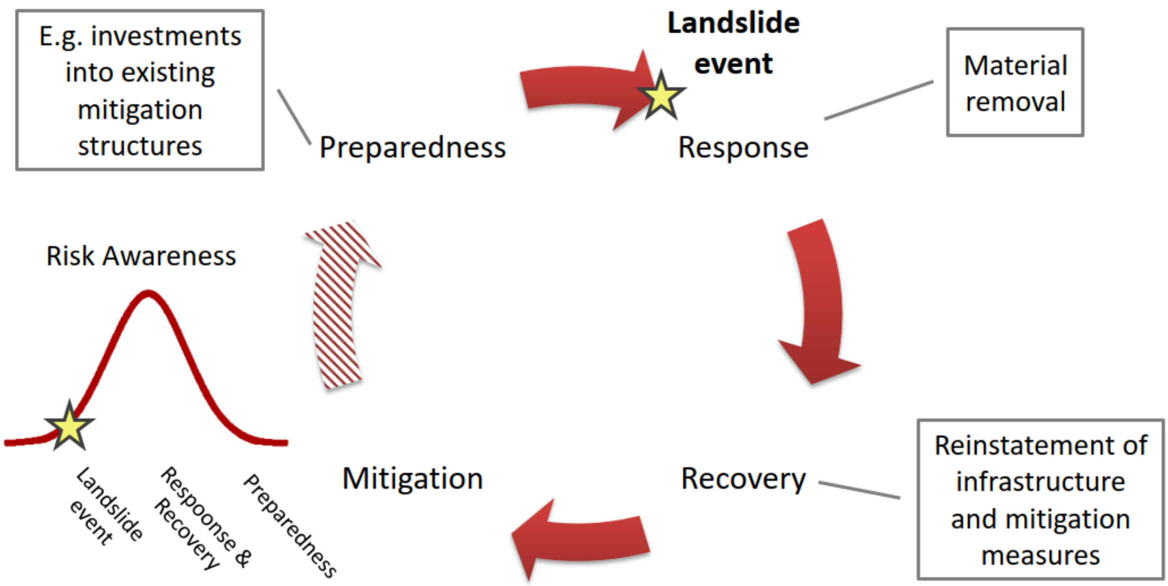


Figure 21. Schematic procedure after a landslide event in the Upper Weser area: After the event, the risk awareness increases and in a first response, the involved material is removed. In the phase of recovery, infrastructure is repaired and mitigation measures are planned and executed. After no new landslides occur, risk awareness decreases and existing mitigation measures are neglected. A new phase of landslide activity starts (risk cycle after Godschalk, 1991).

The application and development of mitigation measures at the Mittelland canal differs from the area of the Upper Weser river. While at the Weser river, mitigation depends on contemporary available methods and public funding, the Mittelland canal benefits from a high prioritization. With first landslides occurring during the construction of the canal combined with an urge of a fast completion, mitigation measures were developed for the canal. As a result, the first period of mitigation (construction phase 2) is marked by major construction mistakes, which were followed by mitigation mistakes. The second period of mitigation in the 1930s involved more new concepts and methods. Introduced concrete injections are, in modified form, still used today (cf. Wohlers et al., 2017). Overall, the mitigation applied in this period can be considered successful, even though the injections applied at the main canal at km 195 and the tributary canal failed in later phases. War and post-war periods are marked by shortages of money, material and manpower, therefore mitigation involved simple, low-cost measures. At the end of the post-war period, budgets for mitigation increased, and more complete measures were planned and executed, involving the development of new profiles, drainage and forestation concepts. Since no reports on landslides can be found in the archive afterwards, the new concepts can be considered to have been successful.

In contrast to periodically applied mitigation in the Upper Weser area (cf. Klose et al., 2016; Wohlers et al., 2017), the continuous development of mitigation measures at the Mittelland Canal reflects the high-risk perception of local authorities towards landslides. Even though the presented landslide record cannot be considered complete, a reduction of landslides can be inferred. The high-risk perception is supported by the severe consequences of landslides at the canal after dam failures, which have only been reported five times at non-clustering sites at the western part of the canal, and blockages due to landslide masses in the canal, which occurred at least four times (i.e. partial blockages) at problematic sites.

6 CONCLUSION

The registered landslides in Southern Lower Saxony are closely linked to human influences, especially at transportation infrastructure in the region. The effects of anthropologic activities include both preparatory or dispositioning factors and triggering factors. At the Mittelland canal, the excavation of over-steepened canal profiles into highly vulnerable Mesozoic claystones resulted in increased landslide activity (i.e., slides, spreads and creeps) during the construction and post-construction phases of the canal. In addition, landslides were triggered by the construction works and connected ground motions in the 1920s and 1930s, as well. During World War II, aerial bombings and the resultant aerial blasts can be considered as potential triggers.

In the Harz mountains the rockfall susceptibility for a rural road network was estimated using a bivariate statistical approach information value method). The susceptibility model afterward was validated with a receiver operating characteristic (ROC) analysis. Susceptibility mapping revealed a high susceptibility for 23% of the road network corridor. The vulnerability of the road network was determined using the indicator-based method. The indicator values were weighted with an analytical hierarchy process. The combined map showed a discrepancy between susceptibility and vulnerability. High vulnerabilities were located on the SW and N margin of the road network and can be linked to high traffic volumes. Internal roads showed a low vulnerability, while roads connecting these internal roads with the margin of the Harz mountains exploited high and very high susceptibility values. The latter roads were strongly linked to high slope values due to road construction and a NE orientation. The presented results illustrate the discrepancy between rockfall susceptibility and the vulnerability of the relevant road sections.

The combination of the applied methods for susceptibility and vulnerability assessment gives an easily applicable method in a preliminary risk assessment. In particular, when damage values are missing, the application of vulnerability indicators can be useful. Vulnerability indicators are easily adaptable and in combination with weighting factors may help public decision makers to plan and manage mitigation measures.

Case histories of landslide activity and mitigation measures in the Upper Weser area and at the Mittelland canal were analyzed to illustrate and compare repair and mitigation strategies of different transportation infrastructure. In the Upper Weser area, phases of increased landslide activity are followed with a small delay by a period of intense mitigation construction. Linked to risk awareness, after a series of landslide events, awareness raises together with public need for mitigation. In a phase of functional mitigation, only a few and small volume landslides occur. As a result, risk awareness decreases and aged mitigation measures lose their integrity. In a next phase of high landslide activity mitigation is inefficient and infrastructure is vulnerable again.

After major reconstruction in the post-war phases, landslides are reported only sporadically. This fact can be linked to successful mitigation concepts, particularly the severe flattening of slopes which helped to stabilize the slopes. The dataset is compromised by anthropogenically influenced landslides and therefore includes different triggers and preparatory factors from 'natural' landslides. Particularly in densely populated countries such as Germany, the anthropogenic influence on landslides should be considered, especially when these data are used for risk assessments.

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APPENDIX

List of publications:

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