Potential future exposure of European land transport infrastructure to rainfall-induced landslides throughout the 21st century

Matthias Schlögl and Christoph Matulla

January 22, 2018

1 General Response

We would like to thank the two anonymous referees as well as the editor for the evaluation of our manuscript and the helpful feedback they provided. Both reviewers indicated similar items to improve, in particular as far as clarity of methods and structure is concerned. We have implemented the changes and improvements as proposed by the reviewers, putting special emphasis on the consistency of the manuscript. We are confident that the reworked data and methods sections should lead to a better golden thread throughout the manuscript.

Please find our detailed responses below, with referee comments in italics, and authors responses in standard format.

In addition, we have added a latexdiff version as this supplement to highlight the changes between the two manuscripts.

2 Response to Reviewer 1

2.1 General Comments

This paper displays some useful and interesting results and will be a useful paper to publish. It contributes to the understanding of landside hazards and provides new ideas. There are a number of issues with the methods section, as the results presented are not described by the methods. In order for this paper to be duplicable, the methods section needs to be completely re-written.

2.1.1 Scientific Significance

Scientific Significance: The paper will potentially offer a contribution to the understand- ing of landslide hazards and provides some new ideas.

2.1.2 Scientific Quality

The approaches used are confused, and methods are not apparent. The results and discussion section is unclear, and contains datasets and ideas which are not previously presented in either the introduction or methods sections (e.g. the CORINE dataset is first mentioned on p. 9 in the results and discussion section). References are generally appropriate, although there is an overreliance on IPCC pub- lications, and there are a number of recent publications I consider to be missing.

Thank you for pointing out possible difficulties in understanding parts of the results and discussion section without a proper introduction of certain data sets used and a more concise description of the methods applied. This is helpful information, since data and methods sections indeed offer room for improvement. While data sets used are referenced at the end of the manuscript in the data availability section, not all of them are described in the respective sections in the text. We have rewritten and extended the data and methods sections accordingly.

2.1.3 Presentation Quality

The results and discussion are not presented in a clear and concise manner. This is due to the methods section not describing the methods used. Structure is therefore lacking as much of the results and discussion section brings in new ideas and analyses not previously discussed. Language used is not always appropriate and there are grammatical and spelling errors.

We reworked both data and methods sections to clarify and straighten out this issue. In addition, we have reworked the results section to match the reworked methods section.

2.2 Specific comments

- *P. 3, L. 23 – The authors select a threshold of 37.3mm and 25.6mm however, refer- ences for these are not introduced until p. 4.*

  We have add the reference to the CI.

- *P. 4 – The methods section does not describe the results discussed in the results and discussion section. This section needs to be re-written to ensure the duplicability of the study.*

  Thank you for pointing this out. We have reworked the data and methods sections.

- *P. 4, L. 29 KLIWAS17 is not introduced at all.*

  We have replaced "KLIWAS17" with "ensemble of 17 climate model runs (Imbery et al.,2013)" to avoid the introduction of a new term that is not used elsewhere in the manuscript.

- *P. 5, L. 5/6 – "While the first row of each figure refers to the near future, the second row displays projection results for the remote future. The three columns represent the quartiles in increasing order respectively" should be in the figure caption, not the text.*

  We have moved this sentence to the figure caption as proposed by the reviewer.

- *P. 5/6 – Figures 1 and 2 are unclear. The authors need to clarify what the data are and how these were calculated.*

  We have clarified this in the text, in particular by reworking the data and methods sections.

- *P. 6/7 – It is unclear whether the authors are talking about landslide events or precipi- tation events when discussing change between the two reference periods.*

  These two are linked to each other via the CI. Changes between the two reference periods refer to the changes in the CI. The CI is based on precipitation data, but serves as a proxy for landslide events. We have also clarified this in the text.

- *P. 8 – I am not sure how the authors use topography and lithology/geology or soil typology in their analysis.*

  We have clarified this in the text, in particular by reworking the data and methods sections.

- *P. 8/9 – Figures 3 and 4 are good, but again, I am not sure how these were calculated; the authors need to clarify this.*

  We have clarified this in the text, in particular by reworking the data and methods sections.

- *P. 9. I am not sure how the authors use erosivity or land cover in their analysis.*

  We have clarified this in the text, in particular by reworking the data and methods sections.

- *In the abstract, the authors state "Results indicate overall increases of landslide occur- rences. While flat terrain at low altitudes exhibits increases of about two more landslide events per year until the end of this century, higher elevated regions are more affected and show increases of up to eight additional events", but do not show how these results are obtained from descriptions provided in the methods section. Furthermore, this "result" is not mentioned in the results and discussion section and also not mentioned in the conclusion; this needs to be clarified.*

  We have clarified this in the text.

- *P. 10 – I am not sure how the mapping for Figures 5 and 6 was carried out. The authors need to be clear when it is their work that is being referenced, or the work of others. Figures must be referenced correctly if data were obtained from other sources. The use of these data must also be described in the methods section as these are first introduced in the results and discussion.*

  We have clarified this in the text, in particular by reworking the data and methods sections.

- *P. 11 – I think that the authors conclusion sums up the findings of the paper, but does not reflect the results and findings described in the abstract and is confusing to read for this reason.*

  We have clarified this in the text and increased consistency with respect to conclusions throughout the manuscript.

3 Response to Reviever 2

3.1 GENERAL COMMENT

The article presents an evaluation of possible future variations in the overcoming of an already-defined rainfall threshold for landslide occurrence in Central Europe, as a result of the application of an ensemble of downscaled climate projections, with particular regard to roads and railways. The paper is clear, sufficiently well-written and potentially publishable. It follows somehow the IMRaD structure, even if with some drawbacks, that should be improved. The English language is good. In my opinion, the manuscript needs major revisions before being accepted for publication, for several reasons listed below.

- *Mainly, the theoretical background and the proposed method are not well defined. In particular, the definition of the climate index is not well explained in the text (it can be deduced after reading the results), and the procedure for obtaining the maps of changes in threshold exceedance related to infrastructures are not clear.*
  The methods section has indeed some room for improvement. We have reworked this section in order to provide a more concise and clear description of the methods employed. In particular, we have described the definition of the climate index as well as the procedure for obtaining the maps.

- *Moreover, is not explained how the Authors used the information contained in the maps of slope, TRI, geology, soil types, rainfall erosivity, and CLC. These maps were used only for comparison with the obtained results? Or they were used also in the calculations? This should be explained.*
  The maps have been used to support the discussion of the implications of meteorological impacts imposed by the CI in a more practical/realistic

context. They were not used for the calculation of the CI or the results presented in maps 1 and 2. We have added this explicitly (two times) in order to clarify this in the text.

- *In several parts of the manuscript, Authors refer both to "landslides" and "landslide events". I would suggest to define what a "landslide event" is or to use the simple "landslide".*
  We have replace "landslide event" with "landslide" throughout the text in order to avoid confusion.

- *If I have well understood, Authors are referring on threshold overcoming as climate index for landslide occurrence. Thats true? If yes, this should be reported and defined clearly in the text.*
  Yes, this is correct. We have clarified this in the text.

- *Moreover, several toponyms and names of regions are reported in the text. A map with all those names (also as supplementary material) would be useful for non-Europeans readers. At least, I suggest adding the names of the Countries in which the cited regions are located (e.g., Alsace, France).*
  Thank you for pointing this out. We have provided a supplementary map containing all toponyms. We have added this map at the end of this response.

- *For what concern the structure of the paper, the "Introduction" section is not very easy- to-read. At the beginning there is a summary of the work (lines 3-6), which should be better located and the end of the section.*
  As proposed by the reviewer, we have moved the respective part to the end of the section. In addition, we have reworked and slightly extended the introduction in order to be better readable.

- *The "Data" section is good, but another subsection with details about other used data could be appreciated.*
  We have added another subsection (2.4 Additional geodata) covering all other data sources used for figures 5 and 6.

- *The "Method" section is not clear. The definition of the climate index is not effective and the procedure used to pass from whole maps to infrastructure maps should be better described. Moreover, the cited work made by Matulla et al. (2017) present a very similar approach and similar results. Thus, differences and improvements proposed in this new paper should be strongly described.*
  We have reworked the methods section. We have added more precise information on the CI and the procedure of deriving the infrastructure maps from the gridded data sets. We have pointed out the improvements of this work compared to the work by Matulla et al., 2017.

- *The "Results and Discussion" section is well-structured. However, two subsection could be added, referring to "Central Europe" and "Target area".*
  We have added these two subsections as proposed by the reviewer.

- *The "Outlook" section should be reworded, presenting the main findings and innovations of the work, and not only the future developments.*
  We have reworked the outlook section by including the main findings and innovations of the present work as proposed by the reviewer.

- *The reference list is complete, and all the articles are cited in the text.*

3.2 SPECIFIC COMMENTS

- *The abstract should be shortened, particularly in the parts at lines 1-8 and 20-25.*
  We have shortened the abstract to be more concise, particularly the parts mentioned by the reviewer.

- *The Central European region should be geographically defined.*
  We have defined the region in the introduction after the first occurrence of the term "Central Europe".

- *Please, for a good understanding, add letters (a, b, . . .) in the panels of all figures. Consequently, add information in the captions. As an example, the text reported at page 5, lines 5-6 (The first row of each figure refers to the near future, the second row displays projection results for the remote future. The three columns represent the quartiles in increasing order respectively) should be better written in the caption of Figure 1. The same for the other figures.*
  We have reworked the caption by moving the text mentioned by the reviewer from the text body to the caption. We have added letters to the figures as proposed and added them to the caption.

- *Table 1 could be changed in two tables: one referring to values related to roads, and another with values related to railways. In the caption, just mention the CI, without re- peating the threshold values.* While table 1 could indeed be changed into two tables, differences in the resulting summary statistics for road and railway network deviate only to a minor extent. The summary statistics are based on all raster cells that cover road or railway infrastructure segments. Since the underlying climatological raster data sets are the same and both road and railway networks are quite dense in Central Europe, the raster cells selected for calculating the summaries are almost identical. We would therefore suggest to keep one table, since the additional information gained by splitting the table into two tables is negligible.
  We have adjusted the caption accordingly to be clear on what the table describes.

- *I suggest moving to the method section the text reported at page 8 lines 6-9 and lines 15-20.*
  We have moved the paragraphs as proposed by the reviewer.

- *Figure 6b: I suggest considering only the second level of the CLC classification. Please be sure that all the characters in the figures will be readable.*
  We have decided to use all three levels of CLC in order to provide a consistent land cover image. We have used the official legend and color coding for CLC level 3. By using only level 2, we would need to define custom colors for each level, which will lead to inconsistencies with other CLC maps.

- *Please check the text and correct some typos and errors in referencing in the text.*
  We have double-checked the whole text in this respect.

- *Finally, I would suggest some works dealing with: i) climate change and infrastructures (Loveridge et al., 2010); ii) landslide hazard and risk hotspots in Europe (Jaedicke et al., 2014); iii) effects of environmental changes on landslide occurrence (Begueria, 2006; Gariano et al., 2017), on susceptibility evaluations (Van Den Eeckhaut et al., 2012; Pisano et al., 2017), and on risk analysis (Papathoma-Köhle and Glade, 2013; Promper et al., 2014).*
  We have consulted these works and included most of them as references into the manuscript.

3.3 TECHNICAL CORRECTIONS

All technical corrections have been implemented/corrected as proposed by the reviewer.

Figure 1: Supplement: Names and toponyms of Central Europe used in this manuscript

Potential future exposure of European land transport infrastructure to rainfall-induced landslides throughout the 21st century

Matthias Schlögl[1,2] and Christoph Matulla[3]

[1]Transportation Infrastructure Technologies, Austrian Institute of Technology (AIT), Vienna, Austria
[2]Institute of Applied Statistics and Computing, University of Natural Resources and Life Sciences (BOKU), Vienna, Austria
[3]Department for Climate Research, Zentralanstalt für Meteorologie und Geodynamik (ZAMG), Vienna, Austria

Correspondence to: Matthias Schlögl (matthias.schloegl@ait.ac.at), Christoph Matulla (christoph.matulla@zamg.ac.at)

Abstract. In the face of climate change, the assessment of land transport infrastructure exposure towards adverse climate events is of major importance for Europe's economic prosperity and social wellbeing. ~~Robust and reliable information on the extent of climate change and its projected future impacts on roads and railways are of prime importance for proactive planning and the implementation of targeted adaptation strategies. Among various menacing natural hazards, landslides stand out as most destructive hazards to the functional effectivity and structural integrity of land-bound transport systems, since they cause long-lasting downtimes and exceedingly expensive repair works. Periods of heavy precipitation persisting over several days are known to be a major trigger for increased landslide activity. Along with climate change such events can be expected to increase in frequency, duration and intensity over the decades to come.~~

In this study, a ~~Climate Index (CI)~~ climate index picturing rainfall patterns which trigger landslides in Central Europe is analyzed until the end of this century and compared to present day conditions. The analysis of potential future developments is based on an ensemble of dynamically downscaled climate projections which are driven by the SRES A1B socio-economic scenario. Resulting regional scale climate change projections across Central Europe are concatenated with Europe's road and railway network.

Results indicate overall increases of landslide occurrences. While flat terrain at low altitudes exhibits ~~increases of about two more landslide events~~ an increase of about one more potentially landslide-inducing rainfall period per year until the end of this century, higher elevated regions are more affected and show increases of up to ~~eight additional events~~14 additional periods. This general spatial distribution emerges already in the near future (2021-2050) but gets more pronounced in the remote future (2071-2100). ~~Largest~~ Since largest increases are to be found in the Alsace~~. Consequently~~, potential impacts of ~~increasing landslide events~~ an increasing amount of landslides are discussed using the example of a case study covering the Black Forest mountain range in Baden-Württemberg by further enriching the climate information with and additional geodata.

Derived findings are suitable to support political decision-makers and European authorities in transport, freight and logistics by offering detailed information on which parts of Europe's land-bound transport network are at particularly high risk concerning landslide activity. ~~This study supports proactive development of adaption strategies and the realization of cost-efficient and effective protection programmes as well as the generation of guidelines for climate proofing. This refers to the design~~

~~of transport networks, intermodal logistics as well as the setting up of maintenance and reinforcement strategies in order to safeguard one of the most essential backbones of Europe's economic prosperity.~~

1 Introduction

~~This study is devoted to the assessment of climate change driven landslide hazards to European transport infrastructure (rails and roads) in the near (2021-2050) as well as the remote (2071-2100) future. Results are based on the so-called A1B socio-economic scenario (IPCC, 2000) and shall provide European Transport Authorities with auxiliary information for setting up cost effective and spatially targeted protection measures in order to safeguarde Europe's transport system in the future. As for~~ Given the outstanding importance of land transport modes for Europe's social and economic prosperity, the free and uninterrupted movement of persons and freight is of central magnitude. For instance, the accessibility of healthcare facilities, the supply of daily goods as well as a broad range of services to communities rely on the continuous availability of roads and railway connections. ~~Climate change and alterations in extreme weather events, which are affecting ecosystems and man-made infrastructure have been investigated, published and discussed since some decades by now (e.g. IPCC, 1990, 1995, 2001, 2007, 2012, 2014b). Even though observed changes in extreme events in terms of frequency, intensity and duration may not be directly associated with global warming, trends concerning landslide events are visible (Gariano and Guzzetti, 2016; McBean, 2011; Crozier, 2010)~~

Extensive soil sealing across Europe (Nestroy, 2006), climate change (European Environment Agency, 2014; Loveridge et al., 2010) and extreme weather impacts (Schlögl and Laaha, 2017) challenge the resilience of transport systems, which have thus grown into a matter of major concern – not only because of physical damages to assets (Kellermann et al., 2015), but also due to potential overall societal losses caused by network failures and interruptions, which often exceed infrastructure damages by far (Postance et al., 2017; Pfurtscheller and Vetter, 2015; Bíl et al., 2015; Pfurtscheller, 2014; Pfurtscheller and Thieken, 2013; Meyer et al., 2 . Thus, the assessment of land transport infrastructure exposure towards adverse climate events and related natural hazards is of ~~significant~~ great importance for Europe's economy, for its intermodal transport, its freight and logistics networks as well as for settlements in hazard-prone regions (Koetse and Rietveld, 2009; Doll et al., 2014). Therefore, information on current climate and its variability as well as on potential future climate changes is of prime importance for proactive planning and the development of adaptation strategies concerning operation, maintenance, reinforcement and construction works and for civil protection.

~~Extensive soil sealing across Europe(Nestroy, 2006), climate change (European Environment Agency, 2014) and extreme weather impacts (Schlögl and Laaha, 2017) challenge the resilience of transport systems, which have thus grown into a matter of major concern – not only because of physical damages to assets (Kellermann et al., 2015), but also due to potential overall societal losses caused by network failures and interruptions, which often exceed infrastructure damages by far (Postance et al., 2017; Pfurtsc~~
~~.~~

~~The derivation of climate change induced future hazardsis essentially based on two key components: (i) on sets (so-called ensembles) of Global Climate Model (GCMs) runs, which are driven by potential future pathways of mankind and cascaded~~

down to regional-scales via downscaling techniques (e.g. von Storch et al., 1993; Matulla et al., 2003) and (ii) on relationships (so-called Climate Indices Climate change and alterations in extreme weather events – which are affecting ecosystems and man-made infrastructure – CIs) between regional-scale climate phenomena (e.g. long term rain exceeding certain thresholds) and damage events. Ensembles of climate change projections depicting corridors of future climate evolutions and CIs can be arranged in so-called Cause-Effect Tensors, which have already been successfully applied to access potential future damage events to European transport infrastructure (Matulla et al., 2017)have been investigated since some decades by now (e.g. IPCC, 1990, 1995, . Among various menacing hazards, landslides stand out as destructive hazards to the functional effectivity and structural integrity of land-bound transport systems, since they cause long-lasting downtimes and exceedingly expensive repair works. Even though observed changes in extreme events in terms of frequency, intensity and duration may not be directly associated with global warming, trends concerning landslide occurrences are visible (Gariano and Guzzetti, 2016; McBean, 2011; Crozier, 2010) . Therefore, information about expected future changes in landslide occurrence and its impacts on land transport infrastructure may provide a basis for the implementation of adequate adaptation measures.

Studies about the effects of climate change on landslide activity have gained center stage in recent years. Crozier (2010) was one of the first to systematically examine the underlying mechanisms linking climate change impacts and slope stability. It was pointed out in this work that while there is a strong theoretical basis for increased landslide activity as a result of a changing climate, a certain extent of uncertainty remains due to inherent incompleteness and inhomogeneities of historic data on climate and landslide recordings, the nature of scenario-based projections and the lack of downscaled data at an appropriate spatial resolution. However, changes in annual and seasonal precipitation patterns (in terms of both , precipitation totals and intensity) have been detected as key determinants affecting landslides Gariano and Guzzetti (2016); Sidle and Ochiai (2013) (Gariano and Guzzetti, 2016; Sidle and Ochiai, 2013).

Since the difficulties of establishing a universal relationship between climate change and landslides across the entire of Europe has been was pointed out by Dikau and Schrott (1999), citing the complexity of the problem as the main obstacle, several authors have undertaken efforts to establish such relationships for different parts of the continent (Gariano and Guzzetti, 2016; Crozier, 201 . (e.g. Gariano et al., 2017b; Gariano and Guzzetti, 2016; Jaedicke et al., 2014; Promper et al., 2014; Van Den Eeckhaut et al., 2012; Crozi .

The derivation of climate change induced future hazards is essentially based on two key components: (i) on sets (so-called ensembles) of Global Climate Model (GCM) runs, which are driven by potential future pathways of mankind and cascaded down to regional-scales via downscaling techniques (e.g. von Storch et al., 1993; Matulla et al., 2003) and (ii) on relationships (so-called climate indices – CIs) between regional-scale climate phenomena (e.g. long term rain exceeding certain thresholds) and damage events. Ensembles of climate change projections depicting corridors of future climate evolutions and CIs can be arranged in so-called Cause-Effect Tensors, which have already been successfully applied to access potential future damage events to European transport infrastructure (Matulla et al., 2017).

Rainfall periods exceeding certain thresholds have been found to serve as a proper proxy for landslide occurrences landslide occurrences and been applied in Central Europe (Peruccacci et al., 2017; Matulla et al., 2017; **?**; Brunetti et al., 2010; Guzzetti et al., 2008, (Peruccacci et al., 2017; Matulla et al., 2017; Gariano et al., 2017a; Brunetti et al., 2010; Guzzetti et al., 2008, 2007; Dixon and Brook, 20

. Based on these findings, we employ a CI that inherits ~~the intensity and the~~ intensity and totals of severe rainfall events, which have been shown to act as a primary trigger of rapid-moving landslides in Central Europe (Gariano and Guzzetti, 2016).

It has to be noted that there are no unambiguous criteria that could be used for a geographically distinct delimitation of the Central European region. In this study, we adjust the most widely accepted definition of Central Europe – as used e.g. in the World Factbook (CIA, 2017) – according to the given data availability. Thus, the following countries are considered (at least partially) in the present study: Austria, Belgium, Czech Republic, France, Germany, Liechtenstein, Luxembourg, the Netherlands and Switzerland.

In order to illustrate the implications of these meteorological impacts in a more practical context, results of the CI exposure mapping are enriched with additional environmental information at the example of a selected, risk-prone area located around the tripoint of France, Germany and Switzerland in the Upper Rhine valley. Hence, we amplify the scope of the discussion by embedding mesoscale CI data (obtained via downscaling of GCMs) into a specific regional context featuring additional information about environmental properties such as data about geomorphology, soil or land cover.

This study is devoted to the assessment of climate change driven landslide hazards to European transport infrastructure (rails and roads) in the near (2021-2050) as well as the remote (2071-2100) future. Results are based on the so-called A1B socio-economic scenario (IPCC, 2000) and shall provide European Transport Authorities with auxiliary information for setting up cost effective and spatially targeted protection measures in order to safeguard Europe's transport system in the future.

2 Data

2.1 Climate

Since the goal of this study is to investigate potential changes in landslide ~~events~~ occurrence jeopardizing Europe's transport infrastructure, climate data used refer to two future periods relative to past conditions: the near future (2021–2050) and the remote future (2071–2100). Thereby an ensemble consisting of 17 dynamically downscaled and bias-corrected climate change projections (Imbery et al., 2013), which are driven by the so-called A1B SRES socio-economic scenario (IPCC, 2000), is applied to calculate future frequencies of ~~landslide events~~landslides. The A1B scenario describes a future world characterized by a dynamical economic development, decreasing social and income inequalities a rapid dissemination of new and efficient technologies as well as a balanced use of energy sources. Daily precipitation totals, given on a 5 km grid across large parts of Central Europe (see Fig. 1) are analyzed in order to identify changes in the occurrence of rain-periods stretching over three days, exceeding 37.3 mm and exhibiting at least one total larger than 25.6 mm (Guzzetti et al., 2008).

2.2 Infrastructure

The graph of the road infrastructure network is based on a data extract of OpenStreetMap (OSM) obtained in June 2017. The high-level road network used in this study is derived from the OSM data set by applying a filter selecting only the following highway tags: `motorway`, `motorway_link`, `trunk`, `trunk_link`, `primary` and `primary_link`. The

~~thusly selected network~~ network selected in this way contains highways as well as major roads(OSM, 2017). The railway network is represented by the Natural Earth Railroads vector data set, version 3.0.0 (Natural Earth, 2017). In order to obtain results at an adequate resolution, all connections exceeding 500 m have been split into multiple segments every 500 m.

2.3 Topography

The EU-DEM v1.1 Digital Elevation Model (DEM) is used in this study to analyze topographic properties. This DEM, which is a hybrid product based on SRTM (Shuttle Radar Topography Mission) and ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) DEM data, fused by a weighted averaging approach, is provided by the Copernicus programme (Copernicus, 2017). The slope and Terrain Ruggedness Index (TRI) are derived from this DEM with `gdaldem` using Horn's formula (Horn, 1981).

2.4 Additional geodata

In addition, data sets about geological and soil properties as well as data about rainfall erosivity and land cover data have been used to augment the discussion of the implications imposed by the derived CI. CORINE Land Cover data are provided by the Copernicus programme (Copernicus, 2017). The geology data set (IGME 5000) is provided by the Federal Institute for Geosciences and Natural Resources (Asch, 2005), while soil data and rainfall erosivity are accessible through the European Soil Data Centre (Panagos et al., 2012). Please note that all of these data sources are freely accessible. The respective sources for all data sets are referenced in the *data availability* section at the end of the paper.

3 Methods

Ever since the impact of mankind on the climate system has been proven (e.g. IPCC, 2000) it has become increasingly important to derive estimates of future climate states. Global Climate Models ~~(GCMs)~~ are presently the state-of-the-art tools to investigate future climate developments, mimicking global scale consequences for the climate system of the Earth. GCM results are valid on global and continental scales and have to be 'downscaled' (e.g. von Storch et al., 1993) to regional scales for the assessment of future hazard occurrences. This approach has been shown to yield valuable results for the evaluation of rainfall-induced landslides at regional scales ~~(?Matulla et al., 2017)~~(Gariano et al., 2017a; Matulla et al., 2017). The assessment of associated future climate threats jeopardizing Central European transport assets relies on ensembles of daily-based, regional-scale climate change projections. Such ensembles of climate change projections driven by potential pathways of mankind can be generally derived via two techniques: dynamical and statistical-empirical downscaling (Matulla et al., 2002; von Storch et al., 1993). Here we make use of ~~an ensemble consisting of 17 projections~~ a 17-member ensemble of climate model runs forced by the A1B socio-economic scenario ~~(see above) .~~

~~Potentially~~ that has been used to create dynamically downscaled and bias-corrected (and hence physically consistent) future projections of climate states for climate change impact investigations (Imbery et al., 2013). The gridded data sets of daily precipitation totals, which are available on a 5 km raster) were used to calculate the landslide CI for Central Europe at the same spatial resolution. The CI for potentially landslide triggering events ~~are~~ was established by using a proxy indicating precipitation periods extending over at least three days, which are generating overall totals of more than 37.3 mm, and comprising at least one day with a total exceeding 25.6 mm~~(Matulla et al., 2017; Guzzetti et al., 2008)~~. This threshold for landslide activity was proposed by Guzzetti et al. (2008) and was recently used to establish a CI for landslide occurrence based on threshold exceedance in Matulla et al. (2017). Changes in hazard occurrences (predefined via this CI) over time can be analyzed by comparisons of past and potential future probability density functions.

In order to obtain infrastructure exposure of the road and railway assets in Central Europe at the network level, CI values from above described gridded data sets ~~have been extracted at respective grid points – considering the skillful scale (Jóhannesson et al., 1995; von Storch et al., 1993) – and assigned to underlying road segments~~were mapped to the underlying road and rail segments. This was achieved by extracting and interpolating corresponding values from the raster grid towards the road and railway network graphs.

For the sake of putting the obtained landslide exposure maps into a more expressive context concerning the interpretation and discussion of practical implications, maps depicting slope angles, terrain ruggedness, geomorphologic properties as well as rainfall erosivity and land cover were created. The obtained landslide exposure, which is based on the selected CI is then analysed and discussed against the background of these additional environmental features that are widely used in landslide studies (e.g. Jaedicke et al., 2014; M. and T., 2013; Van Den Eeckhaut et al., 2012).

As far as topography is concerned, the slope angle and the TRI are considered. Slope angles are known to be a key parameter in estimating susceptibility to developing earth flows (Donnarumma et al., 2013). The TRI is defined as the mean difference between a central pixel and its surrounding cells (Wilson et al., 2007) and can be used to quantify landscape heterogeneities, which could exert influence on the localization of the triggering area of shallow landslides (Persichillo et al., 2016). Both properties are derived from the DEM using Horn's formula (Horn, 1981).

Information concerning the nature and the properties of the ground, which are known to be important aspects affecting landslide susceptibility, rock and soil type have been mapped for the target region. Lithological types are obtained from the International Geological Map of Europe and Adjacent Areas (Asch, 2005), and the dominant Soil Typology Unit is mapped according to the World Reference Base for Soil Resources as available in the Euopean Soil Database (Panagos et al., 2012; Panagos, 2006) .

The data sets about topographic, geological and soil properties as well as data about rainfall erosivity and land cover data have solely been used to augment the discussion of the implications imposed by the derived CI.

4 Results and Discussion

In terms of the time horizon under consideration, results of this study refer to two different time periods throughout the twenty-first century. The first period (near future) covers the years 2021 to 2050, while the second period (remote future) ranges from 2071 to 2100. In this context it has to be noted that projected ~~values of KLIWAS17~~ precipitation values obtained from the ensemble of 17 climate model runs are relative to current climate conditions. This entails that all results have to be interpreted as variations that are averaged over the whole future period with respect to present day conditions as a baseline reference.

4.1 Central Europe

Results are visualized as exposure maps for both the high-level road network (Fig. 1) as well as the railway network (Fig. 2) . in Central Europe.

In order to provide information about future probability density functions of the selected CI (and not only about the best estimate), their quartiles (i.e. 25th percentile, median and 75th percentile) are reported for each of the two time periods under consideration, resulting in six different facets. While the first row of each figure refers to the near future, the second row displays projection results for the remote future. The three columns represent the quartiles in increasing order respectively.

Generally speaking, results show that the most risk-prone areas are located in regions that are characterized by structured topography, e.g. in uplands or in the Alpine forelands. Concerning near future changes, at least a slight increase of rainfall-induced landslides has to be expected all over the entire region. As expected, only the near future 25th percentile does not show any changes in potential landslide occurrences in certain lowland areas, which are mainly located in north-eastern and middle Germany. This is consistent with the physics of maritime influenced regions since large water bodies tend to damp rapid changes in surrounding areas. In contrast, there are several regions that are expected to face up to seven additional landslide-inducing periods, namely the Vosges, the Black Forest ("Schwarzwald"), the Swabian Jura ("Schäbische Alb"), the Bergisches Land, the Jura Mountains, the foothills of the Northern Limestone Alps, the Alpine foreland in Austria and Bavaria as well as the Bohemian Forest ("Šumava" or "Böhmerwald"). Our findings show that changes in occurrence frequencies of landslide-triggering extreme climate events slightly increase over time, as is clearly visible when comparing the second row of Figs. 1 and 2 to the first row of each Figure respectively. Basically, the same patterns apply, but the magnitude of the changes is increased in the remote future period. This is largely consistent with findings from the IPCC's fifth assessment report (IPCC, 2014a). It has to be noted, though, that the overall occurrence of landslide-inducing rainfall events appears to increase only slightly in pace throughout the twenty-first century. Nevertheless, the aforementioned areas along the north side of the Alps are likely to experience substantially increased landslide activity in the remote future compared to current climate conditions, pointing to an acceleration of landslide occurrences and showing a possible increase of up to 14 additional landslide-triggering rainfall events (c.f. Tab. 1).

As uncertainty about future projections increases, the spread between the first and third quartile of the projections grows as well, showing variations of up to seven events for the far future period. This coincides with our expectations, since coherence amongst projections decreases towards the end of this century. In addition, the underlying patterns of the geographical distributions of the results are similar, indicating overall robust results.

With respect to infrastructure exposure towards potential landslide susceptibility the following regions can be discriminated:

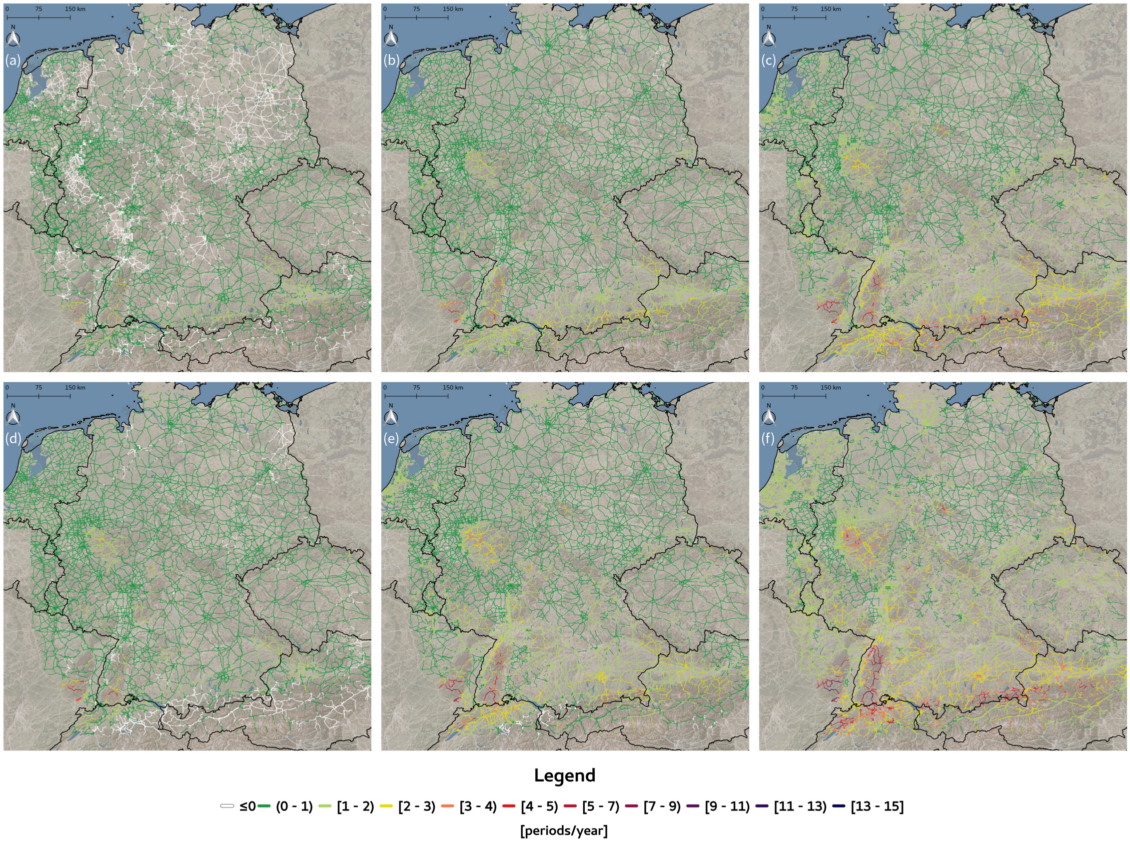

Figure 1. Projected changes in the annual number of periods exceeding rainfall thresholds for the possible occurrence of landslides (RR > 25.6 $\mathrm{mm/d}$ ~~&~~ and RR > 37.3 $\mathrm{mm/3d}$) concerning the high-level road network in Central Europe. The first row of each figure (a –c) refers to the near future, the second (d –f) row displays projection results for the remote future. The three columns represent the quartiles in increasing order respectively, with (a) and (d) displaying the lower quartile, (b) and (e) displaying the median, and (c) and (f) displaying the upper quartile

1. regions with a substantial increase in rainfall-induced ~~lanslide~~ landslide activity are the Jura Mountains, the Vosges, the Black Forest, the Swabian Jura, the Bavarian ~~pre-Alps~~Prealps, the foothills of the Austrian Alps and the Bohemian Forest;
2. regions with less pronounced variations in the CI under consideration, that are nonetheless clearly distinct from their surroundings are the Bergisches Land, the Harz, the Fichtel Mountains, Vogtland and the Ore Mountains;
3. the rest of Central Europe, where changes in occurrence frequencies of rainfall-induced landslides have to be expected only to a minor extent.

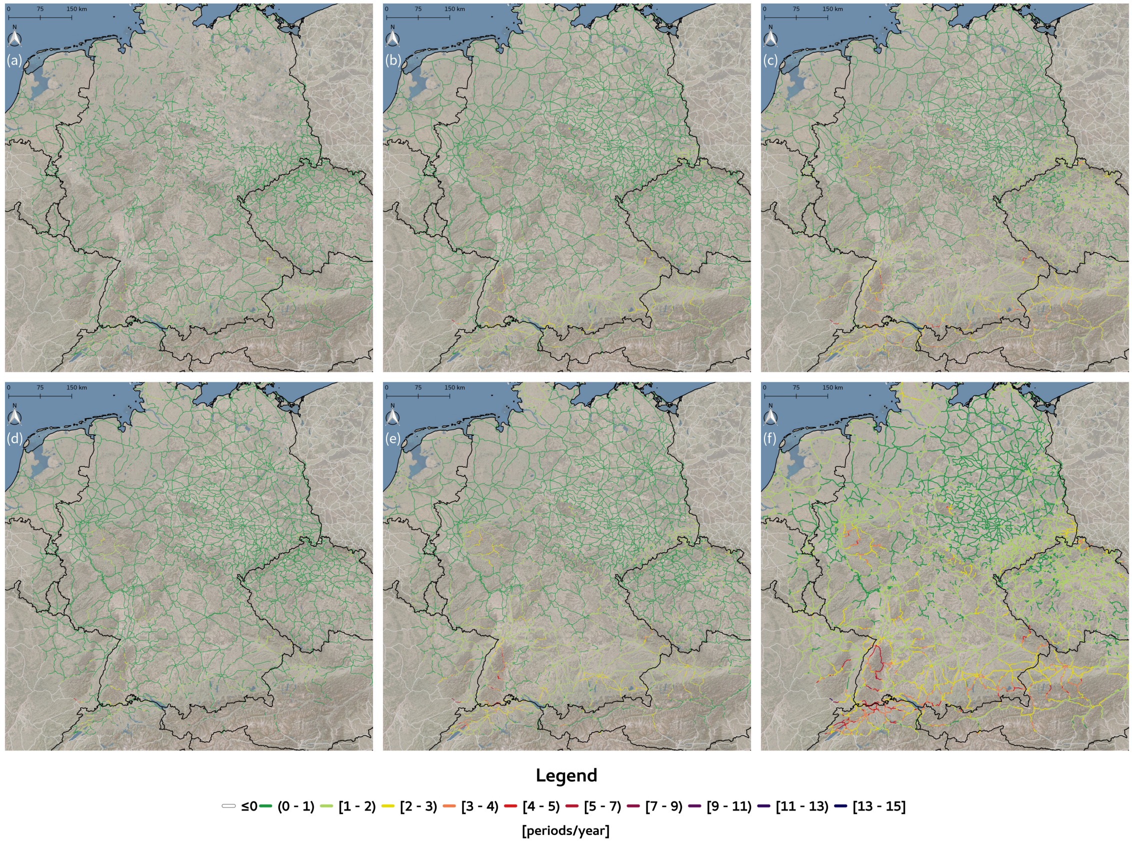

Figure 2. Projected changes in the annual number of periods exceeding rainfall thresholds for the possible occurrence of landslides (RR > 25.6 $\mathrm{mm/d}$ & and RR > 37.3 $\mathrm{mm/3d}$) concerning the railway network in Central Europe. The first row of each figure refers to the near future, the second row displays projection results for the remote future. The three columns represent the quartiles in increasing order respectively, with (a) and (d) displaying the lower quartile, (b) and (e) displaying the median, and (c) and (f) displaying the upper quartile

As far as the backbones of the European road and railway infrastructure – the so-called Trans-European Transport Networks (TEN-T) – are concerned, most TEN-T core-network corridors are likely to be affected by increased landslide activity. In particular, the Rhine-Danube corridor (Strassbourg – Karlsruhe, Munich – Rosenheim – Salzburg – Linz, Regensburg – Passau – Linz), the Scandinavian-Mediterranean (Munich – Rosenheim – Kufstein), the Rhine-Alpine and North Sea-Mediterranean corridors (Karlsruhe – Strasbourg – Basel, onwards to Belfort, Bern, Lucerne and Zurich) as well as the North-Sea Baltic corridor (in the area of Wuppertal) have been identified to face an increased exposure to landslide inducing rainfall events.

4.2 Target area

Meteorological impacts on geomorphological events and driving landscape-change processes over short time scales have been found to have serious consequences, particularly in climatically sensitive regions such as the European Alps Keiler et al. (2010).

Table 1. Summary statistics for the six different facets displayed in Figs. 1 and 2 based on all raster cells covering road or rail infrastructure links. Results refer to the relative changes compared to present-day-conditions, values indicate the magnitude of changes in the number of ~~3-day rainfall-periods~~ periods exceeding ~~37.3 mm and exhibiting at least one total larger than 25.6 mm~~the CI thresholds.

Period	Minimum	First quartile	Median	Third quartile	Maximum
near future (first quartile)	-1.53	0.00	0.13	0.33	4.97
near future (median)	-0.07	0.30	0.50	0.83	5.97
near future (third quartile)	0.13	0.63	0.90	1.40	7.37
remote future (first quartile)	-6.08	0.17	0.33	0.57	6.72
remote future (median)	-1.80	0.53	0.73	1.13	10.54
remote future (third quartile)	-0.53	0.90	1.20	1.83	13.97

Yet it has to be noted that while this analysis refers to potentially hazardous rainfall events that may trigger landslides, other environmental information have not been taken into account so far. Therefore, the consideration of reduced static information commonly used for landslide susceptibility evaluations (Günther et al., 2014, 2013; Hervás et al., 2007) is illustrated and discussed at the example of a selected, risk-prone area, henceforth called “target region”.

The selected region is centered around the lowlands of the Alsace and the Black Forest mountain range, covering parts of France, Germany, Switzerland, Luxembourg and Austria (Fig. 3). This area has been selected for two reasons. First, it is one of the regions showing the largest increase in the selected CI. Second, consequences of interruptions are quite severe in this area, as the recent mass movements in the Rhine Valley between Baden-Baden and Rastatt have shown (Ackeret, 2017).

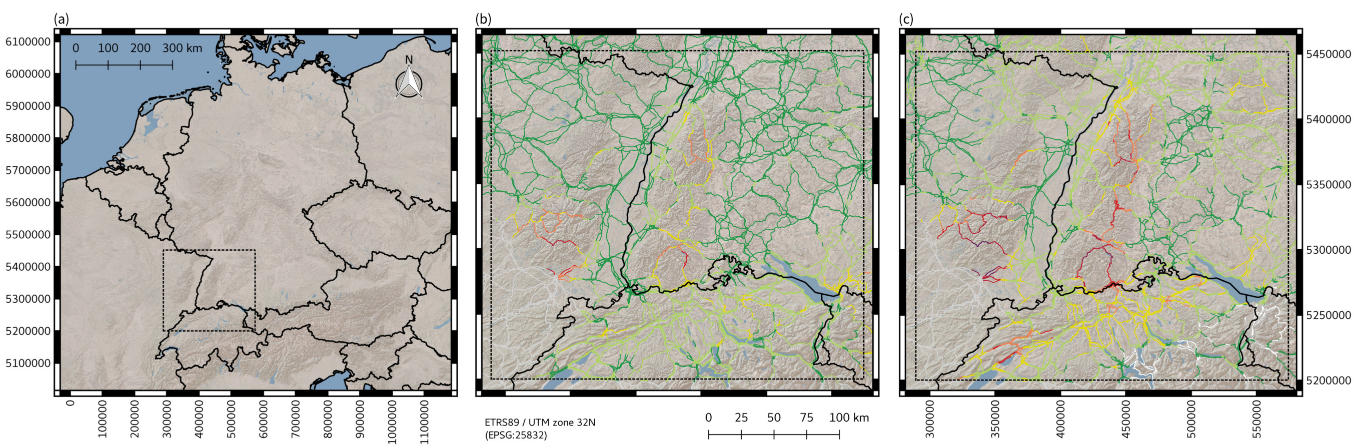

Figure 3. Overview of the target region: (a) Location of the region in Central Europe, median of the increase in landslide triggering climate events for (b) the near future and (c) the remote future.

As far as topography is concerned, ~~the slope angle and the Terrain Ruggedness Index (TRI) are considered. Slope angles are known to be a key parameter in estimating susceptibility to developing earth flows (Donnarumma et al., 2013). The TRI is defined as the mean difference between a central pixel and its surrounding cells (Wilson et al., 2007) and can be used to quantify landscape heterogeneities, which could exert influence on the localization of the triggering area of shallow landslides (Persichillo et al., 2016). Results~~ results show that the target region is not only prone to an increased amount of rainfall that induces landslides, but also susceptible to mass wasting due to its topographic properties (Fig. 4). Both road and rail infrastructure in this area are frequently located in rugged terrain, in valleys, on hillsides or at foothills of mountains. This is particularly the case for the Rhine-Alpine Core-Network Corridor, parts of which are located along the steep western slopes of the Black Forest.

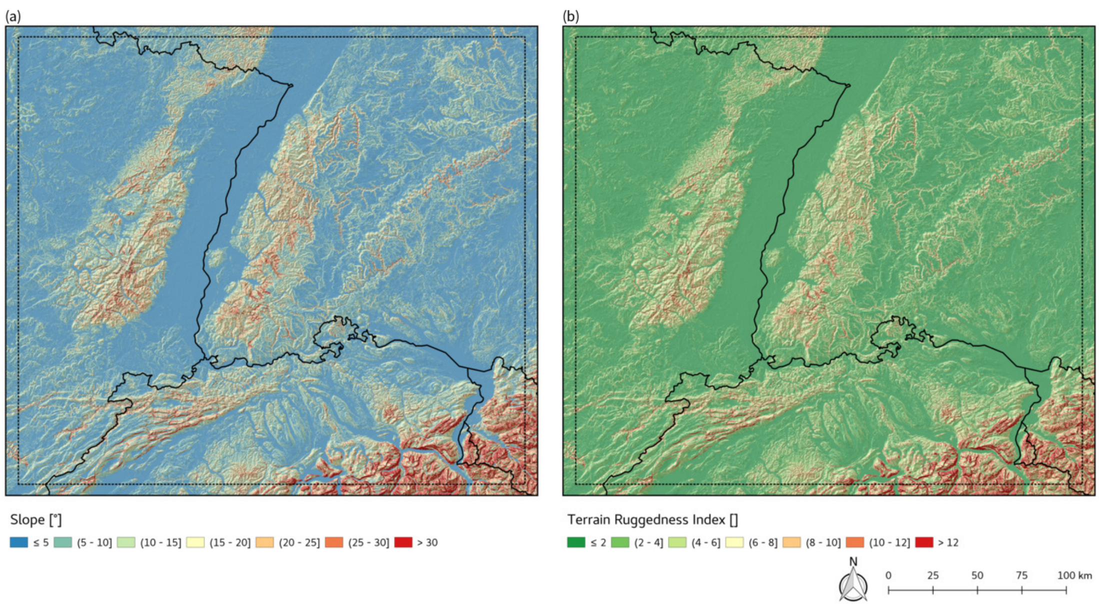

Figure 4. (a) Slope and (b) Terrain Ruggedness Index in the target region.

~~In order to account for the~~ Regarding nature and the properties of the ground ~~, which are important aspects affecting landslide susceptibility too, rock and soil type have been mapped for the target region~~ (Fig. 5) ~~. Lithological types are obtained from the International Geological Map of Europe and Adjacent Areas (Asch, 2005), and the dominant Soil Typology Unit is mapped according to the World Reference Base for Soil Resources as available in the Euopean Soil Database (Panagos et al., 2012; Panagos, 2006) . Sedimentary~~ sedimentary rock types (sandstone, mudstone and limestone) are prevalent in the area. Igneous (granite and basalt) and metamorphic (gneiss and schists) rocks can be found in the Vosges and Schwarzwald mountain ranges as well as the Kaiserstuhl volcano. Generally speaking, the higher the rock strength, the more rainfall is required to trigger landslides. It has been found that the rainfall threshold for sandstone and marl is smaller than the threshold for limestone, with limited marl and chert, which in turn is lower than the threshold for metamorphic rocks (Peruccacci et al., 2017). Cambisols are the prevailing soil type across major parts of the study area. The Upper Rhine Plane shows a predominance of Fluvisols. While the Vosges as well as the Palatinate Forest are characterized by Podzols, the Swabian Alb is mainly covered by Leptosols. The South-Eastern parts, towards the alpine foothills, are highly structured – soil types with a clay-enriched subsoil, soils influenced by water, as well as Leptosols and Podzols are common in these areas. Landslide susceptibility studies in the Swabian Alb have found that slopes with angles from 11° to 26°, consisting of colluvial layers, rendzic Leptosol and clayey soils superimposed on marl debris are indicators for slope instability in this area (Terhorst, 2007; Neuhäuser and Terhorst, 2007).

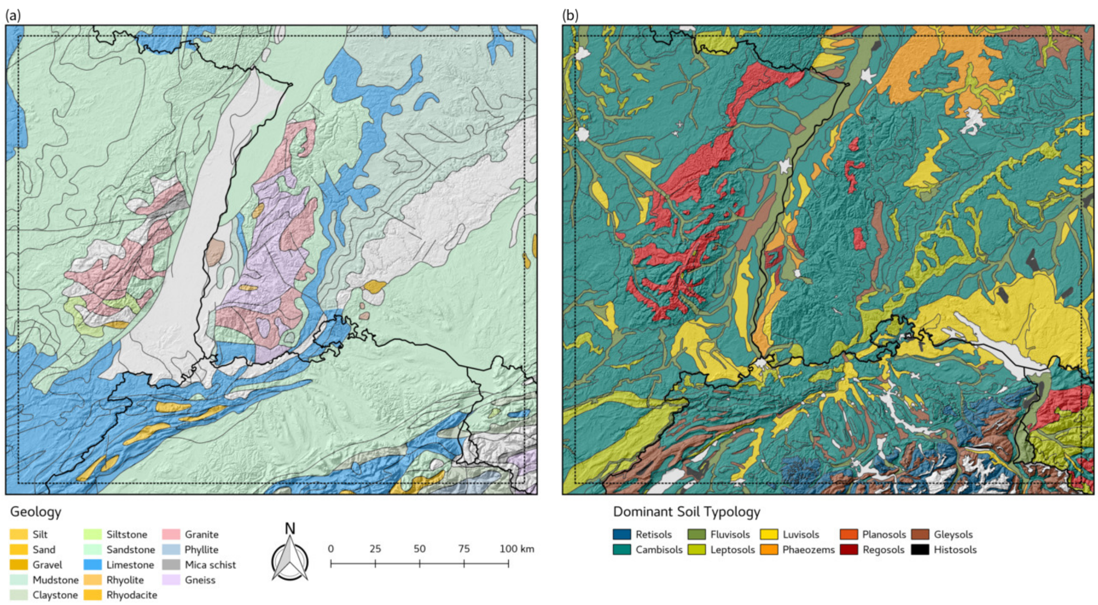

Figure 5. (a) Geology, including geological faults and (b) soil in the target region.

Our analysis is closed by mapping rainfall erosivity in terms of the R-factor (Panagos et al., 2015) and land cover (using the CORINE Land Cover dataset from 2012) for the target region (Fig. 6). R-factors between 700 and 1500 $\mathrm{MJ\,mm\,ha^{-1}\,h^{-1}\,yr^{-1}}$ can be observed across extensive parts of the target region. While rainfall erosivity is comparably low in the lowlands of the Alsace, it rapidly increases in the adjacent uplands, particularly towards the South. As pointed out by Panagos et al. (2015), a combination of large rainfall amounts and high erosivity densities – a condition that applies to major parts of the target region – is a precondition for landslides. Concerning land cover, the target region is characterised by a multitude of small-scale areas featuring different land cover classes, which are typical for heterogeneous areas in complex terrain in Central Europe. Lowland areas are typically characterized by arable land (e.g. vineyards in the Upper Rhine Plain), while forests prevail with increasing altitude. It is broadly recognized in landslide research literature that forested areas favor terrain stability, while agricultural areas and abandoned cultivated lands that gradually recovered through natural vegetation are particularly susceptible to instability ~~(Persichillo et al., 2017; Peruccacci et al., 2017; Petitta et al., 2015; Reichenbach et al., 2014)~~ (Persichillo et al., 2017; Peruccacci et al., 2017; Petitta et al., 2015; Reichenbach et al., 2014; Beguería, 2006).

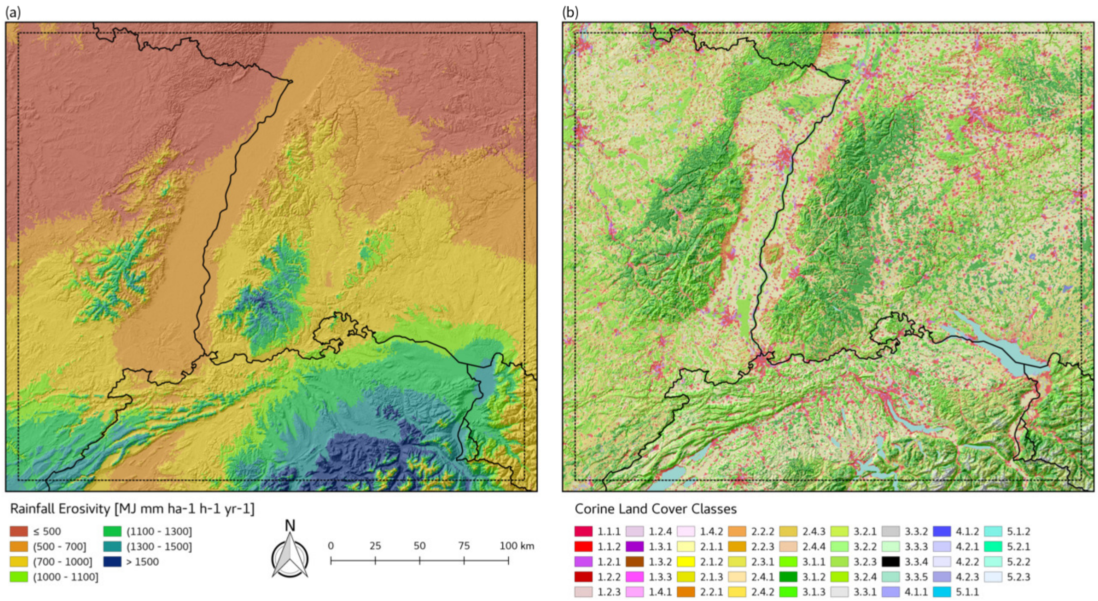

Figure 6. (a) Erosivity and (b) land cover in the target region.

Consequences of traffic interruptions in this area are severe, as, for instance, the closure of the Rhine valley railway from August 13 to October 2, 2017 has shown. This interruption of this important north-south transport corridor, caused by mass movements at the construction site of the Rastatt-Tunnel, has led to considerable delays and increased costs, particularly for freight transport. Usually, up to 350 trains use this traffic artery – which connects Italian ports with the ports of Rotterdam, Hamburg and Bremerhaven as well as Basel to the container port Duisburg – per day. The interruption of the track at Rastatt has resulted in a massive congestion of freight trains all along the route due to the lack of alternative transport lines as well as the lack of engines and railroad engineers at alternative routes (FAZ, 2017; Ackeret, 2017; Gafner and Sommer, 2017). In addition to the direct economic damage, indirect and intangible costs such as noise disturbance as well as air pollution caused by an increased amount of cargo trains and heavy goods vehicles at alternative routes or an increased travel time for commuters, travellers and vacationers have to be considered (Postance et al., 2017).

5 Outlook

In this paper we highlight potential future changes of rainfall-related climate phenomena linked to landslide activities. We derive and present general patterns regarding the future rainfall-induced landslide exposure of road and railway networks in Central Europe and delineate the enrichment of such climate change related exposure information with additional relevant geodata in selected risk-prone areas. Our findings indicate overall increases of landslide activity in the Central European region, which is more pronounced in complex terrain than across flat orography. On the example of a particularly risk prone area covering parts of France, Germany, Switzerland and Austria, the added value attained by including additional maps derived from various geodata sources is demonstrated.

Future work should focus on the implications of exposure analyses for infrastructure users. This includes the extension of the investigated region to the whole of Europe as well as the consideration of additional Climate Indices climate indices describing further climate driven impacts. In order to provide decision support for stakeholders, future efforts should include network analysis and traffic modelling, as this will foster a deeper insight into regional mobility behaviour and criticality assessment of important links in the network. Eventually, investigating socio-economic impacts as well as vulnerability and risk management is of prime importance for the establishment of effective adaption measures in the context of climate change.

Data availability. Strong focus was put on using open access data wherever possible. Road data are accessible via the OSM API under http://api.openstreetmap.org/ and railroads data from Natural Earth are available at https://github.com/nvkelso/natural-earth-vector/tree/master/10m_cultural or via the frontend at http://www.naturalearthdata.com/downloads/10m-cultural-vectors/railroads/. CORINE Land Cover data and the EU-DEM are provided by the Copernicus land monitoring service and can be accessed at http://land.copernicus.eu/. The geology data set (IGME 5000) is provided by the Federal Institute for Geosciences and Natural Resources at https://produktcenter.bgr.de/. Soil data and rainfall erosivity are accessible through the European Soil Data Centre (ESDAC) at http://esdac.jrc.ec.europa.eu/resource-type/datasets.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. The authors would like to thank Melitta Dragaschnig (AIT) for providing assistance with the OSM data extract. We thank the two anonymous reviewers as well as the editor for providing insightful comments and suggestions on an earlier draft of the manuscript.

References

Ackeret, M.: Rheintalbahn-Sperrung: Desaster für den Güterverkehr, Neue Züricher Zeitung, 16.8.2017, https://www.nzz.ch/panorama/sperrung-der-eisenbahnlinie-bei-rastatt-desaster-fuer-den-gueterverkehr-und-fuer-die-neue-deutsche-rheintalstrecke-ld.1311011, 2017.

Asch, K.: IGME 5000: 1 : 5 Million International Geological Map of Europe and Adjacent Areas, BGR (Hannover), https://www.bgr.bund.de/EN/Themen/Sammlungen-Grundlagen/GG_geol_Info/Karten/International/Europa/IGME5000/IGME_Project/IGME_Projectinfo.html, last access: 21 August 2017, 2005.

Beguería, S.: Changes in land cover and shallow landslide activity: A case study in the Spanish Pyrenees, Geomorphology, 74, 196–206, https://doi.org/10.1016/j.geomorph.2005.07.018, 2006.

Bíl, M., Vodák, R., Kubeček, J., Bílová, M., and Sedoník, J.: Evaluating road network damage caused by natural disasters in the Czech Republic between 1997 and 2010, Transportation Research Part A: Policy and Practice, 80, 90–103, https://doi.org/https://DOI.org/10.1016/j.tra.2015.07.006, 2015.

Brunetti, M. T., Peruccacci, S., Rossi, M., Luciani, S., Valigi, D., and Guzzetti, F.: Rainfall thresholds for the possible occurrence of landslides in Italy, Natural Hazards and Earth System Sciences, 10, 447–458, https://doi.org/10.5194/nhess-10-447-2010, 2010.

CIA: The World Factbook, Central Intelligence Agency, https://www.cia.gov/library/publications/the-world-factbook/fields/2144.html, 2017.

Copernicus: EU-DEM v1.1, http://land.copernicus.eu/pan-european/satellite-derived-products/eu-dem/eu-dem-v1.1, last access: 21 August 2017, 2017.

Crozier, M.: Deciphering the effect of climate change on landslide activity: A review, Geomorphology, 124, 260–267, https://doi.org/10.1016/j.geomorph.2010.04.009, recent advances in landslide investigation, 2010.

Dikau, R. and Schrott, L.: The temporal stability and activity of landslides in Europe with respect to climatic change (TESLEC): main objectives and results, Geomorphology, 30, 1–12, https://doi.org/10.1016/S0169-555X(99)00040-9, 1999.

Dixon, N. and Brook, E.: Impact of predicted climate change on landslide reactivation: case study of Mam Tor, UK, Landslides, 4, 137–147, https://doi.org/10.1007/s10346-006-0071-y, 2007.

Doll, C., Trinks, C., Sedlacek, N., Pelikan, V., Comes, T., and Schultmann, F.: Adapting rail and road networks to weather extremes: case studies for southern Germany and Austria, Natural Hazards, 72, 63–85, https://doi.org/10.1007/s11069-013-0969-3, 2014.

Donnarumma, A., Revellino, P., Grelle, G., and Guadagno, F. M.: Slope Angle as Indicator Parameter of Landslide Susceptibility in a Geologically Complex Area, in: Landslide Science and Practice: Volume 1: Landslide Inventory and Susceptibility and Hazard Zoning, edited by Margottini, C., Canuti, P., and Sassa, K., pp. 425–433, Springer, Berlin, Heidelberg, https://doi.org/10.1007/978-3-642-31325-7_56, 2013.

European Environment Agency: Adaptation of transport to climate change in Europe, European Environment Agency, EEA Report No 8/2014, 2014.

FAZ: Gesperrte Rheintalbahn: Wieder Erdbewegungen an Bahnstrecke in Rastatt, Frankfurter Allgemeine Zeitung, 15.8.2017, http://www.faz.net/aktuell/gesellschaft/ungluecke/rheintalstrecke-sperrung-haelt-weiter-an-15152374.html, 2017.

Gafner, B. and Sommer, A.: Transport-Chaos wegen Deutschland, Basler Zeitung, 17.8.2017, https://bazonline.ch/schweiz/transportchaos-wegen-deutschland/story/18399414, 2017.

Gariano, S., Rianna, G., Petrucci, O., and Guzzetti, F.: Assessing future changes in the occurrence of rainfall-induced landslides at a regional scale, Science of The Total Environment, 596, 417–426, https://doi.org/10.1016/j.scitotenv.2017.03.103, 2017a.

Gariano, S. L. and Guzzetti, F.: Landslides in a changing climate, Earth-Science Reviews, 162, 227–252, https://doi.org/10.1016/j.earscirev.2016.08.011, 2016.

Gariano, S. L., Petrucci, O., Rianna, G., Santini, M., and Guzzetti, F.: Impacts of past and future land changes on landslides in southern Italy, Regional Environmental Change, https://doi.org/10.1007/s10113-017-1210-9, 2017b.

Günther, A., Reichenbach, P., Malet, J.-P., Van Den Eeckhaut, M., Hervás, J., Dashwood, C., and Guzzetti, F.: Tier-based approaches for landslide susceptibility assessment in Europe, Landslides, 10, 529–546, https://doi.org/10.1007/s10346-012-0349-1, 2013.

Günther, A., Eeckhaut, M. V. D., Malet, J.-P., Reichenbach, P., and Hervás, J.: Climate-physiographically differentiated Pan-European landslide susceptibility assessment using spatial multi-criteria evaluation and transnational landslide information, Geomorphology, 224, 69–85, https://doi.org/10.1016/j.geomorph.2014.07.011, 2014.

Guzzetti, F., Peruccacci, S., Rossi, M., and Stark, C. P.: Rainfall thresholds for the initiation of landslides in central and southern Europe, Meteorology and Atmospheric Physics, 98, 239–267, https://doi.org/10.1007/s00703-007-0262-7, 2007.

Guzzetti, F., Peruccacci, S., Rossi, M., and Stark, C. P.: The rainfall intensity–duration control of shallow landslides and debris flows: an update, Landslides, 5, 3–17, https://doi.org/10.1007/s10346-007-0112-1, 2008.

Hervás, J., Günther, A., Reichenbach, P., Chacón, J., Pasuto, A., Malet, J.-P., Trigila, A., Hobbs, P., Maquaire, O., Tagliavini, F., Poyiadji, E., Guerrieri, L., and Montanarella, L.: Recommendations on a common approach for mapping areas at risk of landslides in Europe, in: Guidelines for Mapping Areas at Risk of Landslides in Europe. Proceedings Experts Meeting, Ispra, Italy, 23–24 October 2007. JRC Report EUR 23093 EN, edited by Hervás, J., Office for Official Publications of the European Communities, Luxembourg, 2007.

Horn, B. K. P.: Hill shading and the reflectance map, Proceedings of the IEEE, 69, 14–47, https://doi.org/10.1109/PROC.1981.11918, 1981.

Imbery, F., Plagemann, S., and Namyslo, J.: Processing and analysing an ensemble of climate projections for the joint research project KLIWAS, Advances in Science and Research, 10, 91–98, https://doi.org/10.5194/asr-10-91-2013, 2013.

IPCC: Climate Change: The IPCC Scientific Assessment (1990), Cambridge University Press, 1990.

IPCC: IPCC Second Assessment – Climate Change 1995, Cambridge University Press, 1995.

IPCC: IPCC Special Report on Emission Scenarios: A Special Report of IPCC Working Group III, Cambridge University Press, 2000.

IPCC: Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II, and III to the Third Assessment Report of the Integovernmental Panel on Climate Change, Cambridge University Press, 2001.

IPCC: Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007.

IPCC: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, Cambridge University Press, 2012.

IPCC: Climate Change 2013 – The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, https://doi.org/10.1017/CBO9781107415324, 2014a.

IPCC: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2014b.

Jaedicke, C., Van Den Eeckhaut, M., Nadim, F., Hervás, J., Kalsnes, B., Vangelsten, B. V., Smith, J. T., Tofani, V., Ciurean, R., Winter, M. G., Sverdrup-Thygeson, K., Syre, E., and Smebye, H.: Identification of landslide hazard and risk 'hotspots' in Europe, Bulletin of Engineering Geology and the Environment, 73, 325–339, https://doi.org/10.1007/s10064-013-0541-0, 2014.

Jóhannesson, T., Jónsson, T., Källén, E., and Kaas, E.: Climate change scenarios for the Nordic countries, Climate Research, 5, 181–195, https://doi.org/10.3354/cr005181, 1995.

Keiler, M., Knight, J., and Harrison, S.: Climate change and geomorphological hazards in the eastern European Alps, Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, 368, 2461–2479, https://doi.org/10.1098/rsta.2010.0047, 2010.

Kellermann, P., Schöbel, A., Kundela, G., and Thieken, A. H.: Estimating flood damage to railway infrastructure – the case study of the March River flood in 2006 at the Austrian Northern Railway, Natural Hazards and Earth System Sciences, 15, 2485–2496, https://doi.org/10.5194/nhess-15-2485-2015, 2015.

Koetse, M. J. and Rietveld, P.: The impact of climate change and weather on transport: An overview of empirical findings, Transportation Research Part D: Transport and Environment, 14, 205–221, https://doi.org/10.1016/j.trd.2008.12.004, 2009.

Loveridge, F., Spink, T., O'Brien, T., Briggs, K., and Butcher, D.: The impact of climate and climate change on infrastructure slopes with particular reference to southern England, Quarterly Journal of Engineering Geology and Hydrogeology, 43, 461–472, 2010.

M., P.-K. and T., G.: The role of vegetation cover change for landslide hazard and risk, in: The Role of Ecosystems in Disaster Risk Reduction, edited by Renaud, G., Sudmeier-Rieux, K., and Estrella, M., pp. 293–320, 2013.

Matulla, C., Groll, N., Kromp-Kolb, H., Scheifinger, H., Lexer, M., and Widmann, M.: Climate change scenarios at Austrian National Forest Inventory sites, Climate Research, 22, 161–173, https://doi.org/10.3354/cr022161, 2002.

Matulla, C., Scheifinger, H., Menzel, A., and Koch, E.: Exploring two methods for statistical downscaling of Central European phenological time series, International Journal of Biometeorology, 48, 56–64, https://doi.org/10.1007/s00484-003-0186-y, 2003.

Matulla, C., Hollósi, B., Andre, K., Gringinger, J., Chimani, B., Namyslo, J., Fuchs, T., Auerbach, M., Herrmann, C., Sladek, B., Berghold, H., Gschier, R., and Eichinger-Vill, E.: Climate Change driven evolution of hazards to Europe's transport infrastructure throughout the twenty-first century, Theoretical and Applied Climatology, https://doi.org/10.1007/s00704-017-2127-4, 2017.

McBean, G. A.: Coping with Global Environmental Change: Need for an Interdisciplinary and Integrated Approach, in: Coping with Global Environmental Change, Disasters and Security: Threats, Challenges, Vulnerabilities and Risks, edited by Brauch, H. G., Oswald Spring, Ú., Mesjasz, C., Grin, J., Kameri-Mbote, P., Chourou, B., Dunay, P., and Birkmann, J., pp. 1193–1204, Springer Berlin Heidelberg, Berlin, Heidelberg, https://doi.org/10.1007/978-3-642-17776-7_73, 2011.

Meyer, V., Becker, N., Markantonis, V., Schwarze, R., van den Bergh, J. C. J. M., Bouwer, L. M., Bubeck, P., Ciavola, P., Genovese, E., Green, C., Hallegatte, S., Kreibich, H., Lequeux, Q., Logar, I., Papyrakis, E., Pfurtscheller, C., Poussin, J., Przyluski, V., Thieken, A. H., and Viavattene, C.: Review article: Assessing the costs of natural hazards – state of the art and knowledge gaps, Natural Hazards and Earth System Sciences, 13, 1351–1373, https://doi.org/10.5194/nhess-13-1351-2013, 2013.

Natural Earth: Vector Data Set, v3.0.0.0, https://github.com/nvkelso/natural-earth-vector, last access: 21 August 2017, 2017.

Nestroy, O.: Soil sealing in Austria and its consequences, Ecohydrology & Hydrobiology, 6, 171–173, https://doi.org/10.1016/S1642-3593(06)70139-2, 2006.

Neuhäuser, B. and Terhorst, B.: Landslide susceptibility assessment using "weights-of-evidence" applied to a study area at the Jurassic escarpment (SW-Germany), Geomorphology, 86, 12–24, https://doi.org/10.1016/j.geomorph.2006.08.002, 2007.

OSM: Highway tag usage, https://wiki.openstreetmap.org/wiki/Key:highway, last access: 21 August 2017, 2017.

Panagos, P.: The European soil database, GEO: connexion, 5, 32–33, 2006.

Panagos, P., Liedekerke, M. V., Jones, A., and Montanarella, L.: European Soil Data Centre: Response to European policy support and public data requirements, Land Use Policy, 29, 329 – 338, https://doi.org/10.1016/j.landusepol.2011.07.003, 2012.

Panagos, P., Ballabio, C., Borrelli, P., Meusburger, K., Klik, A., Rousseva, S., Tadić, M. P., Michaelides, S., Hrabalíková, M., Olsen, P., Aalto, J., Lakatos, M., Rymszewicz, A., Dumitrescu, A., Beguería, S., and Alewell, C.: Rainfall erosivity in Europe, Science of The Total Environment, 511, 801 – 814, https://doi.org/10.1016/j.scitotenv.2015.01.008, 2015.

Persichillo, M. G., Bordoni, M., Meisina, C., Bartelletti, C., Giannecchini, R., Avanzi, G. D., Galanti, Y., Cevasco, A., Brandolini, P., Galve, J. P., and Barsanti, M.: Slope Angle as Indicator Parameter of Landslide Susceptibility in a Geologically Complex Area, in: Landslides and Engineered Slopes. Experience, Theory and Practice. Proceedings of the 12th International Symposium on Landslides (Napoli, Italy, 12-19 June 2016), edited by Aversa, S., Cascini, L., Picarelli, L., and Scavia, C., pp. 1605–1612, CRC Press, Berlin, Heidelberg, https://doi.org/10.1201/b21520-199, 2016.

Persichillo, M. G., Bordoni, M., and Meisina, C.: The role of land use changes in the distribution of shallow landslides, Science of The Total Environment, 574, 924–937, https://doi.org/10.1016/j.scitotenv.2016.09.125, 2017.

Peruccacci, S., Brunetti, M. T., Gariano, S. L., Melillo, M., Rossi, M., and Guzzetti, F.: Rainfall thresholds for possible landslide occurrence in Italy, Geomorphology, 290, 39–57, https://doi.org/10.1016/j.geomorph.2017.03.031, 2017.

Petitta, M., Pregnolato, M., Pedoth, L., and Schneiderbauer, S.: Relationship between landslide processes and land use-land cover changes in mountain regions: footprint identification approach., Geophysical Research Abstracts, 17, 2015.

Pfurtscheller, C.: Regional economic impacts of natural hazards – the case of the 2005 Alpine flood event in Tyrol (Austria), Natural Hazards and Earth System Sciences, 14, 359–378, https://doi.org/10.5194/nhess-14-359-2014, 2014.

Pfurtscheller, C. and Thieken, A. H.: The price of safety: costs for mitigating and coping with Alpine hazards, Natural Hazards and Earth System Sciences, 13, 2619–2637, https://doi.org/10.5194/nhess-13-2619-2013, 2013.

Pfurtscheller, C. and Vetter, M.: Assessing entrepreneurial and regional-economic flood impacts on a globalized production facility, Journal of Flood Risk Management, 8, 329–342, https://doi.org/10.1111/jfr3.12102, 2015.

Postance, B., Hillier, J., Dijkstra, T., and Dixon, N.: Extending natural hazard impacts: an assessment of landslide disruptions on a national road transportation network, Environmental Research Letters, 12, 014 010, http://stacks.iop.org/1748-9326/12/i=1/a=014010, 2017.

Promper, C., Puissant, A., Malet, J.-P., and Glade, T.: Analysis of land cover changes in the past and the future as contribution to landslide risk scenarios, Applied Geography, 53, 11–19, https://doi.org/10.1016/j.apgeog.2014.05.020, 2014.

Reichenbach, P., Busca, C., Mondini, A. C., and Rossi, M.: The Influence of Land Use Change on Landslide Susceptibility Zonation: The Briga Catchment Test Site (Messina, Italy), Environmental Management, 54, 1372–1384, https://doi.org/10.1007/s00267-014-0357-0, 2014.

Schlögl, M. and Laaha, G.: Extreme weather exposure identification for road networks – a comparative assessment of statistical methods, Natural Hazards and Earth System Sciences, 17, 515–531, https://doi.org/10.5194/nhess-17-515-2017, 2017.

Sidle, R. C. and Ochiai, H.: Landslides: Processes, Prediction, and Land Use, American Geophysical Union, https://doi.org/10.1029/WM018, 2013.

Terhorst, B.: Periglacial cover beds and soils in landslide areas of SW-Germany, CATENA, 71, 467–476, https://doi.org/10.1016/j.catena.2007.03.021, rates and Time Scales of Pedogenic Processes in Natural and Man-Affected Soil Systems, 2007.

Van Den Eeckhaut, M., Hervás, J., Jaedicke, C., Malet, J.-P., Montanarella, L., and Nadim, F.: Statistical modelling of Europe-wide landslide susceptibility using limited landslide inventory data, Landslides, 9, 357–369, https://doi.org/10.1007/s10346-011-0299-z, 2012.

von Storch, H., Zorita, E., and Cubasch, U.: Downscaling of Global Climate Change Estimates to Regional Scales: An Application to Iberian Rainfall in Wintertime, Journal of Climate, 6, 1161–1171, https://doi.org/10.1175/1520-0442(1993)006<1161:DOGCCE>2.0.CO;2, 1993.

Wilson, M. F. J., O'Connell, B., Brown, C., Guinan, J. C., and Grehan, A. J.: Multiscale Terrain Analysis of Multibeam Bathymetry Data for Habitat Mapping on the Continental Slope, Marine Geodesy, 30, 3–35, https://doi.org/10.1080/01490410701295962, 2007.