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Global warming to increase flood risk on European railways

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Abstract

For effective disaster risk management and adaptation planning, a good understanding of current and projected flood risk is required. Recent advances in quantifying flood risk at the regional and global scale have largely neglected critical infrastructure, or addressed this important sector with insufficient detail. Here, we present the first European-wide assessment of current and future flood risk to railway tracks for different global warming scenarios using an infrastructure-specific damage model. We find that the present risk, measured as expected annual damage, to railway networks in Europe is approx. €581 million per year, with the highest risk relative to the length of the network in North Macedonia, Croatia, Norway, Portugal, and Germany. Based on an ensemble of climate projections for RCP8.5, we show that current risk to railway networks is projected to increase by 255% under a 1.5 °C, by 281% under a 2 °C, and by 310% under a 3 °C warming scenario. The largest increases in risk under a 3 °C scenario are projected for Slovakia, Austria, Slovenia, and Belgium. Our advances in the projection of flood risk to railway infrastructure are important given their criticality, and because losses to public infrastructure are usually not insured or even uninsurable in the private market. To cover the risk increase due to climate change, European member states would need to increase expenditure in transport by €1.22 billion annually under a 3 °C warming scenario without further adaptation. Limiting global warming to the 1.5 °C goal of the Paris Agreement would result in avoided losses of €317 million annually.

1 Introduction

Floods cause enormous damage globally, and it is projected that flood risks will further increase in the future due to socio-economic development and climate change (Alfieri et al. 2017; Hallegatte et al. 2013; IPCC 2013; Winsemius et al. 2016). In 2016 alone, hydrological

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hazards caused US$56 billion of global economic losses (Munich Re 2017). Recent flood events in Europe have demonstrated that losses to infrastructure can be substantial and can make up a large share of overall losses, amounting to up to 60% (Bubeck et al. 2011; Floodsite 2006; Thieken et al. 2016).

In addition to the high damage potential, transport infrastructure is classified as "critical infrastructure," i.e., their assets, systems, and networks are considered so vital for the functioning of a society that a disruption or failure of those functions can have a significant impact on the safety, security, economic, and/or social wellbeing, public health, or any combination thereof (Council of the European Union 2008; The White House 2013; United Nations 2015). Railway infrastructure, for instance, plays an important role in the climate-friendly transportation of freight and passengers across the European Union. According to the statistical office of the European Union (EUROSTAT), more than 415 billion passenger-kilometers were traveled,[1] and more than 416 billion ton-kilometers[2] were transported on national and international railway lines of the EU28 in 2015. Since transport of freights and passengers by rail considerably outperforms road and air transport in terms of greenhouse gas efficiency (IPCC 2014b), it is reasonable to assume that railway infrastructure becomes even more important in the future.

Recently, progress in estimating direct flood damage and risk at regional and global levels has been made, also due to advances in computational power and modeling (Hallegatte et al. 2013; Hirabayashi et al. 2013; Jongman et al. 2012b; te Linde et al. 2011; Ward et al. 2013; Winsemius et al. 2016). Such regional and global assessments are important, given the increased efforts to address disaster risk reduction and climate change adaptation across national boundaries. The EU Solidarity Fund, the EU Strategy on Adaptation to Climate Change, and the UN Sendai Framework for Disaster Risk Reduction 2015–2030 are examples of such initiatives (Council of the European Union 2002; European Commission 2013; United Nations 2015).

Despite the high damage potential of the infrastructure sector and its criticality, existing studies on regional and global flood losses have predominantly focused on the residential sector (Hallegatte et al. 2013; Jongman et al. 2012a; Winsemius et al. 2016), or more global estimates of affected population or gross domestic product (GDP) (e.g., Hirabayashi et al. 2013). Assessments that include infrastructure elements are largely lacking, possibly resulting in biased risk estimates, inadequate evaluations of the benefits of investments in risk reduction, and consequently in suboptimal disaster management and adaptation decisions (Bouwer et al. 2007; Kreibich et al. 2014). The few studies that included infrastructure in their modeling approach usually use one aggregate susceptibility function and one unit asset value for various but highly diverse infrastructure elements, or, are limited to local case studies (Jongman et al. 2012a; Kellermann et al. 2015; Kellermann et al. 2016b; Merz et al. 2010; te Linde et al. 2011). One of the few studies that examine the impacts of climate extremes on critical infrastructure in Europe is Forzieri et al. (2018). Based on a sensitivity matrix derived from an expert survey, spatial layers on assets, and loss records of the EM-DAT database, the impact of climate-related losses were assessed at a European scale. An infrastructure-specific damage model is not applied in this study. Also, Doll et al. (2014) assess the risk from weather extremes on railway infrastructure in several European regions. Their estimates are based on media and operator data for specific incidents that occurred between 2000 and 2010 in four

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[1] https://goo.gl/9MRfky, last accessed on 18th of January 2018

[2] https://goo.gl/qQipfq, last accessed on 18th of January 2018.

European countries, which are used to derive statistical measures of damage probabilities. This incidence-based approach requires no spatial mapping of flood hazards to railway infrastructure, and no infrastructure specific damage model is applied.

There are several reasons why modeling of damage to infrastructure is still in its infancy compared with other economic sectors. First, information about public infrastructure elements is often considered sensitive given their criticality, limiting data availability. Second, and closely related to the previous point, empirical damage data, commonly used for damage model development (Meyer et al. 2013), are largely lacking for the infrastructure sector (Merz et al. 2010). Third, because of their line features, elements of critical infrastructure, such as railway tracks, are substantially underrepresented in gridded land cover data, typically used for regional or global assessments (Hirabayashi et al. 2013; Jongman et al. 2014; Jongman et al. 2012b; Winsemius et al. 2016). A standard dataset for European-wide impact assessments is the Coordinated Information on the European Environment (CORINE) land cover dataset (see, e.g., Alfieri et al. 2015; Jongman et al. 2014), which has a spatial resolution of 100 by 100 m. From a gridded railway track map derived from the most comprehensive European-wide dataset of OpenRailwayMap,[3] only 2.4% of the network is coded as railway infrastructure in CORINE, despite its high resolution (see Supplementary Material Fig. S1 for an illustration).

In this paper, we address all of the abovementioned challenges associated with the modeling of flood risk to critical infrastructure at a regional scale. We apply a damage model that was specifically developed for assessing direct damage to railway infrastructure by using empirical damage data (Kellermann et al. 2015; Kellermann et al. 2016b) to assess current and future risk to railway tracks across Europe. To the best of our knowledge, this is the first European-wide assessment of current and future flood risk to railway infrastructure, using an infrastructure-specific damage model. To adequately and comprehensively capture the line-shaped features of railway tracks, the assessment makes use of the open-access dataset derived from OpenRailwayMap. Current and future flood hazard in Europe is obtained with the LISFLOOD-based pan-European flood hazard mapping procedure combined with ensemble projections of extreme stream flow for three different warming levels based on EURO-CORDEX RCP 8.5 climate scenarios (Alfieri et al. 2015).

Direct damage to railway tracks can result in subsequent indirect damage caused by disruptions of train traffic. During the flood of 2013, for instance, the train connection between Berlin, Germany, and important economic centers in Hanover, the Ruhr district, and Frankfurt (upon Main) was disrupted due to damage to railway assets for almost 5 months. As a result, more than 10,000 passenger trains and more than 3000 freight trains had to be diverted resulting in longer travel times. According to the Deutsche Bahn, about one third of the passengers chose alternative ways of transportation during this time (reported by Thieken et al. 2016). Such indirect losses are not included in our assessment. A quantification of indirect losses would require a detailed flow model of European train traffic, delay times resulting from different patterns of direct damage, insights into alternate routes and associated costs, which is beyond the scope of the current paper.

Our advances in the assessment of current and future flood risk to railway infrastructure are important for the development of effective disaster risk management and adequate climate change adaptation planning. This is particularly relevant because railways constitute critical infrastructure, and because losses to public infrastructure are usually not insured or even

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[3] http://www.openrailwaymap.org/

uninsurable in the private market (Zurich Insurance Group 2013). Inadequate consideration of the financial means required for relief and reconstruction, e.g., endowment of the European Solidarity Fund (Council of the European Union 2002), can thus negatively affect social and economic welfare (Bouwer et al. 2007; Jongman et al. 2014). To illustrate the policy implications of our analysis, the estimated risks are hence related to the current overall government expenditures on transport of the examined European countries and the EU's budget for enhancing the Trans-European Transport Network (TEN-T).

The reminder of the article is organized as follows. The methods and models applied in this article are presented in Sect. 2. Section 3 presents and discusses the findings with regard to current and future flood risk to railway infrastructure in Europe. Section 4 concludes and discusses the implications of our findings with respect to assessing and managing flood risk to railway infrastructures in Europe.

2 Methods

2.1 Climate inputs and flood hazard modeling

Seven EURO-CORDEX climate projections including historical (1970–2005) and future (2006–2100) projections with Representative Concentration Pathway (RCP) 8.5 were used as input to simulate river stream flow over the years 1970–2100. Projections of global mean surface temperature (GMST) under this scenario typically exceed 3 °C warming before 2100. Hence, the three considered specific warming levels (SWLs) could be analyzed in the same set of simulations and thus provide consistent results. We note, however, that impacts at the Paris target SWLs (1.5 and 2 °C) under the continued warming pathway considered here may differ from those under a stabilization pathway, because of the sensitivity of precipitation extremes to radiative forcing of greenhouse gases and aerosols (Lin et al. 2016). Climate projections were selected giving priority to driving global circulation models (GCMs) with high ranking in the performance evaluation of CMIP5 models carried out by Perez et al. (2014).

We produced continuous daily stream flow simulations with the Lisflood model, a distributed, physically based hydrological model (Burek et al. 2013; Van Der Knijff et al. 2010), run at 5 by 5 km^2 grid resolution. As input variables, we used 2 m temperature, precipitation, and potential evapotranspiration from each climatic projection. The latter was estimated using the Penman-Monteith equation calculated with daily mean 2 m temperature, wind speed, relative humidity, and solar radiation as input. The domain included in the hydrological simulations covers an area of 6.5 million km^2 and is calibrated at 693 stations across Europe against up to 8 years of daily observed discharge (Alfieri et al. 2016b). For each grid cell and climate projection, we fitted a Gumbel extreme value distribution on the series of 30 discharge annual maxima between 1976 and 2005, with the method of L-moments (Hosking 1990). A peak over threshold (POT) routine was used to select flood events simulated in the present and in the future climate. To this end, we calculated the return period of simulated discharges by inverting the analytical Gumbel distributions. High flow events with maximum return periods larger than the local value of flood protections, taken from (Jongman et al. 2014), are considered as flood.

Each flood event detected in the simulation period is assigned with an inundation area with the same return period taken from a set of European flood hazard maps at 100 by 100 m^2 resolution (Alfieri et al. 2014). Monetary impacts per grid cell are then estimated by forcing the

Table 1 Regional climate projections used in the flood analysis and corresponding year of exceeding 1.5, 2, and 3 °C warming

Institute	GCM	RCM	Driving ens member	1.5 °C	2 °C	3 °C
KNMI	EC-EARTH	RACMO22E	r1i1p1	2031	2046	2069
SMHI	HadGEM2-ES	RCA4	r1i1p1	2025	2037	2055
SMHI	EC-EARTH	RCA4	r12i1p1	2028	2042	2067
MPI-CSC	MPI-ESM-LR	REMO2009	r1i1p1	2031	2045	2068
CLMcom	MPI-ESM-LR	CCLM4–8-17	r1i1p1	2031	2045	2068
SMHI	MPI-ESM-LR	RCA4	r1i1p1	2031	2045	2068
CLMcom	EC-EARTH	CCLM4–8-17	r12i1p1	2028	2042	2067

railway-specific flood damage model "RAilway Infrastructure Loss" (RAIL) with the inundation depth and extent of each simulated flood. Extreme events are by definition rare; hence, flood impacts of the seven climate models are aggregated in space and time to increase the robustness of impact estimates. Quantitative analyses and comparisons between present-day conditions and future scenarios are performed on four representative 30-year time slices: the historical period (1976–2005) and three global warming levels of 1.5 °C, 2 °C, and 3 °C above preindustrial levels. The latter are estimated by taking the 30-year window centered on the year of exceedance of the different warming levels (taking the 20-year running mean) of the GCM corresponding to each EURO-CORDEX projection (see Table 1).

2.2 Modeling damage to railway networks

Flood damage to the European railway network was assessed using the RAIL model developed by Kellermann et al. (2015). RAIL is capable of estimating structural flood damage to the standard cross-section of a railway track and the resulting repair (replacement) costs. This is the first time the infrastructure-specific damage model is applied at the European scale. The damage model was applied before at the local and regional scale in Austria (Kellermann et al. 2015; Kellermann et al. 2016b).

Since gridded land cover data, such as CORINE, are not sufficiently detailed to capture line-shaped infrastructure elements (see Supplementary Material), the most comprehensive and publicly available dataset of railway infrastructure in Europe was derived from OpenRailwayMap. The dataset not only contains the main railway connections but also the multiple tracks present at switch yards or train stations. This dataset was used before also by other studies assessing flood risks to critical infrastructures in Europe (Forzieri et al. 2018). Since no spatial projections of future railway networks are available, OpenRailwayMap was used to estimate both, current and future flood risk.

Only direct (i.e., structural) damage to railway tracks was included in the modeling approach. Other railway-related infrastructure elements, such as railway stations, control centers, or bridges, were excluded from the analysis because of their large heterogeneity and/or the lack of empirical damage data that would be needed for model development.

In the RAIL model, structural damage is provided per 100 m track section affected by flooding. To this end, the entire European railway network was partitioned into 100-m track sections in a geographical information system (ArcGIS), and subsequently intersected with the various flood inundation scenarios (see Sect. 2.1). Depending on the flood depth occurring at each exposed track section, one out of three damage classes was assigned. The three damage classes distinguished in the RAIL model, which reflect different degrees of structural damage to the railway section, are depicted in (Fig. 1). The different damage classes were inferred from empirical evidence from the March River flooding of 2006 in lowland areas of Lower Austria (Kellermann et al. 2015). The damage classification is based on thresholds of relevant hydraulic impact parameters.

A standard cross-section of a railway track consists of the substructure, superstructure, catenary, and signals. For damage class one (left picture in Fig. 1), it is assumed that the track's substructure is (partly) impounded, but there is no or only little structural damage. For damage class two (middle), it is assumed that the substructure and superstructure of that track section are completely inundated, resulting in considerable damage at least to the substructure. For the highest damage class three (right picture in Fig. 1), additional damage to the superstructure, catenary, and/or signals must be expected. Damage class one is assigned for flood inundation levels up to 20 cm at the track section. In the default model, damage class two corresponds to water levels between 21 and 140 cm, and damage class three is assigned for water levels above 140 cm. The distribution of damage classes (totals and percentages) for each country across the different scenarios (return periods) is provided in the Supplementary Material (Fig. S2).

Subsequently, each damage class is assigned to standard repair costs (financial loss) based on figures provided by the Austrian Federal Railways (ÖBB) for 2008 price levels. These repair costs comprise costs of loss assessment and documentation, costs for track cleaning per running meter, and standard cross-section repair costs per running meter. The different cost types were individually combined for each damage class in accordance with the respective pattern of structural damage (Kellermann et al. 2015). For damage class one, this results in standard repair costs per 100 m segment of a single-tracked railway standard cross-section of €5.850 at 2008 prices. For damage class two, a damage of €67.775 was calibrated for Austria and for class three damage amounts to €351.100.

In a final step, the section-wise and damage class-dependent repair costs were aggregated across all track sections affected by the considered flood event. The aggregated repair costs from each flood scenario were then used to calculate the expected annual damage (EAD), which is a common risk metric in the context of natural risk assessments (Merz et al., 2009). All EAD values were corrected for inflation using inflation rates at the country level provided by EUROSTAT and reflect the 2015 price level. To account for differences between countries in terms of repair costs, losses were adjusted by using differences in GDP per capita provided by EUROSTAT (values of 2015).

To assess the robustness of our results, we carried out a sensitivity analysis altering the water levels (thresholds) used for assigning the different damage classes. In addition to the

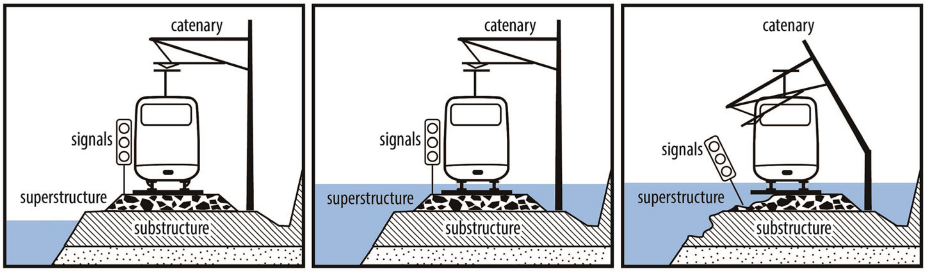

Fig. 1 Damage classes differentiated in the Railway Infrastructure Loss (RAIL) model (Adapted from: Kellermann et al. (2015))

default model run, we altered the thresholds to reflect a lower bound (= higher threshold for damage classes) and an upper bound (= lower thresholds for damage classes) for the respective damage classes. These thresholds provide a plausible range of water levels resulting in the respective damage classes. The adjusted threshold values are based on expert judgment of the railway operator and resemble the approach taken in Kellermann et al. (2016b). A table with the varying thresholds used for the three model runs is provided in the Supplementary Material (Table S1). The only parameter that was not varied in the sensitivity analysis is the cost value. This is because the cost values for damage class 1 and damage class 3 were taken directly from the standard cost table of the railway operator. Only the value of damage class 2 was empirically derived. Previous studies have shown that applying a scaling factor to a damage curve results in a respective scaling of the losses (Alfieri et al. 2016a).

2.3 Limitations

Flood loss and risk assessments are subject to considerable uncertainties (Apel et al. 2009; Merz et al. 2010). This holds also for the assessment of current and future flood risk to railway networks in Europe. Bias in damage estimates can result from the treatment of flood protection in the hydrological modeling. If the flood frequency exceeds the protection level (in terms of the design return period) at a given location, a failure of that flood protection is assumed. In reality, defense structures may not entirely fail but only be overtopped, which would likely result in lower flood extent and inundation levels. On the other hand, protection standards may fail also below their design protection standard.

As mentioned above, empirical damage data, which are needed for damage model development, calibration, and validation, pose a particular challenge as far as critical infrastructure is concerned. While the RAIL model was derived and calibrated using empirical damage data, independent datasets for model validation are currently still lacking (Kellermann et al. 2015; Kellermann et al. 2016b).

In our damage modeling approach, a uniform type of superstructures is assumed, i.e., ballast bed. While ballast beds are the dominant type of superstructure in Europe's railway network, some deviations exist for high-speed tracks. Due to their differences in construction characteristics and material, high-speed tracks are likely characterized by different damaging processes and replacement costs. However, information on variations in track structures is currently not available and could thus not be considered in the modeling approach. Moreover, damaging processes might differ for different flood types (e.g., flash floods versus slow rising river floods). Again, no empirical damage data are available that would allow for a more differentiated modeling approach.

We further assume constant exposure and vulnerability, hence present impacts of different warming levels on present railway assets. While this constitutes a common shortcoming of climate impact studies (IPCC 2014a), we consider the assumption of constant exposure less of an issue as far as railway infrastructure is concerned: substantial changes in the network cannot be expected in the examined time frames (see Table 1), given the longevity of this type of infrastructure, and the very long planning and construction times. For instance, the laying of 230 km new railway tracks between Berlin and Munich in Germany, which was completed in 2017, took 26 years.[4] Our assumption of a relatively stable network of railway lines is supported by data of the International Union of Railways. According to their statistics, the

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[4] https://inside.bahn.de/vde-8-schnellfahrstrecke/, last accessed on 22nd of January 2018.

length of railway lines in the EU (including Turkey) changed by just 1.1% between 2004 and 2016.[5] Given the increasing importance of climate-friendly transportation (IPCC 2014b), it seems dubious to extrapolate this small decreasing trend into the future. Moreover, an extrapolation of such a (small) overall trend provides no spatially explicit projection. Thus, we refrained from extrapolating an overall trend into the future, as, e.g., proposed by Bednar-Friedl et al. (2015) with respect to road infrastructure, which is a more dynamic type of infrastructure compared with railway lines.

Despite these limitations, we consider the current approach as a considerable advancement compared with previous studies, which commonly use one susceptibility function and financial loss value across various and highly diverse infrastructure sectors, and grossly underestimate exposed railway tracks due to the use of gridded land cover data (see Fig. S1).

3 Results and discussion

3.1 EAD for the historic period

Results show that estimated annual damage (EAD) to railway infrastructures in Europe is about €581 million Euro per year in the historic period 1976–2005, with the ensemble spread ranging from €403 million to €801 million. Results of the sensitivity analysis show that the estimated EAD values are fairly robust to alterations in the thresholds of water levels used to assign the three damage classes. This finding is in line with the results of Kellermann et al. (2016b). In comparison to the default EAD values (see Table S1), the model runs with the upper and lower bounds deviate by 8.7% (see Supplementary Material Table S2).

As there are no railway-specific loss databases to compare this number against, we put our results in the context of other studies examining flood risk in Europe. Jongman et al. (2014), who provide an estimate across various sectors including housing, industries, and a factor for infrastructure, estimated expected annual flood damage in the EU at €4.9 billion per year for the period 2000–2012. It should be noted, though, that the estimate for infrastructure in this study only comprised road infrastructure (Huizinga 2007; Jongman et al. 2012a). Alfieri et al. (2016b) estimate an average flood damage in Europe of €5.9 billion per year for the period 1990–2013. Both numbers compare well to observe average annual losses of €4.2 billion recorded in the NatCatSERVICE Database maintained by Munich Re for the period 2000–2012 (Jongman et al. 2014), and an average annual damage of approximately €5.4 billion estimated by the European Environment Agency (EEA) for the time period between 1998 and 2009 (European Environment Agency 2010). If we compare our estimate of €581 million to the €4.2 billion recorded by Munich Re and the €5.4 billion estimated by the EEA, damage to railway infrastructure represents a share of 13.8% and 10.8% of overall losses, respectively. These numbers compare well to the share of infrastructure losses reported for observed events. During the flood in 2002, damage to railway infrastructure in the heavily affected German federal state of Saxony amounted to 13% (Floodsite 2006). Based on specific incidents from weather events in four European countries, Doll et al. (2014) estimate annual damage to railway infrastructure in Europe at €305 million. When comparing this number to our estimate of €581 million, it should be noted that the study of Doll et al. (2014) uses a price level of 2010, a smaller set of countries, and does not comprise a spatial mapping of

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[5] https://uic.org/IMG/pdf/passenger-tonne-line-kilometers_timeseries-over-period-2004-2016.pdf

hazards and exposure. Moreover, Doll et al. (2014) takes the age structure of the infrastructure assets into account, which should result in lower values than the replacement costs applied in this study.

As mentioned above, we only estimated direct flood damage to railway tracks. However, railway networks represent critical infrastructure due to potentially cascading effects on mobility, safety, economic, and/or social welfare. These can be substantial, as indicated in the example of Germany in the introduction; hence, it is reasonable to assume that the economic losses are larger than the figures provided here. Moreover, railway tracks are potentially also affected by other natural hazards such as landslides, windstorms, or rail buckling (Dobney et al. 2009; Kellermann et al. 2016a).

The countries that face the highest flood risk to railway infrastructure in terms of absolute numbers for the historic period are, in descending order, Germany (165 million) and France (106 million), followed by Spain, Sweden, the Czech Republic, Italy, and the UK with EADs between 34 and 38 million (Fig. 2a and Table S3).

3.2 Assessment of vulnerability indicators

A different picture is obtained when the EAD is related to a country's length of the rail network and transport volumes (freight and passengers). As absolute losses are largely influenced by the size of the exposed network, these figures provide more meaningful insights into a country's vulnerability to flood losses to railways. In relation to the length of the rail network, annual losses per kilometer rail network amount to an average of €1080 in Europe for the historic period, with a standard deviation of €878. The highest relative annual losses in relation to the length of the network for the historic period are observed for North Macedonia (€3.272 per kilometer), Croatia (€2.920), Norway (€2.041), Portugal (€1.927), and Germany (€1.841), followed by the Luxembourg, Czech Republic, and Austria (Fig. 2b; Table 2). A high (or low) ranking in this category indicates a larger (or smaller) ratio between a country's EAD and the length of its railway network, when compared with the other countries. In terms of losses in relation to freight volumes, annual losses per thousand tons of transported goods amount to an average of €659 in Europe for the historic period (excluding Belgium due to missing information on freight volumes), with a standard deviation of €1.137. The countries with the highest annual losses in relation to freight volumes for the historic period are Ireland (€5.607 per freight ton), Greece (€2.983), North Macedonia (€1.395), Spain (€1.300), and France (€1.110) (see Table 2). A high ranking in this category indicates a relatively high ratio between a country's EAD and its national rail freight transport volumes (in comparison with the other countries). Annual losses in relation to passenger volumes amount to an average of €201 per thousand passengers in Europe for the reference period, with a standard deviation of €403 Euro. Here, the highest relative losses for the historic period are observed in North Macedonia (€2.138 per thousand passengers), Croatia (€508), Bulgaria (€274), Greece (€261), and Lithuania (€230) (see Table 2). A high ranking in this final category indicates a relatively high ratio between a country's EAD and its national passenger transport volumes (in comparison with the other countries).

A comparison of the three vulnerability indicators assessed in the current paper reveals no consistent pattern of vulnerable countries across the three indicators. While Germany has, e.g., a comparatively high value when EAD is compared to length and freight, it ranks rather low in terms of passengers given its high number of train users. Ireland, which ranks first in terms of EAD in relation to freight, ranks middle for the other two indicators. While there is no

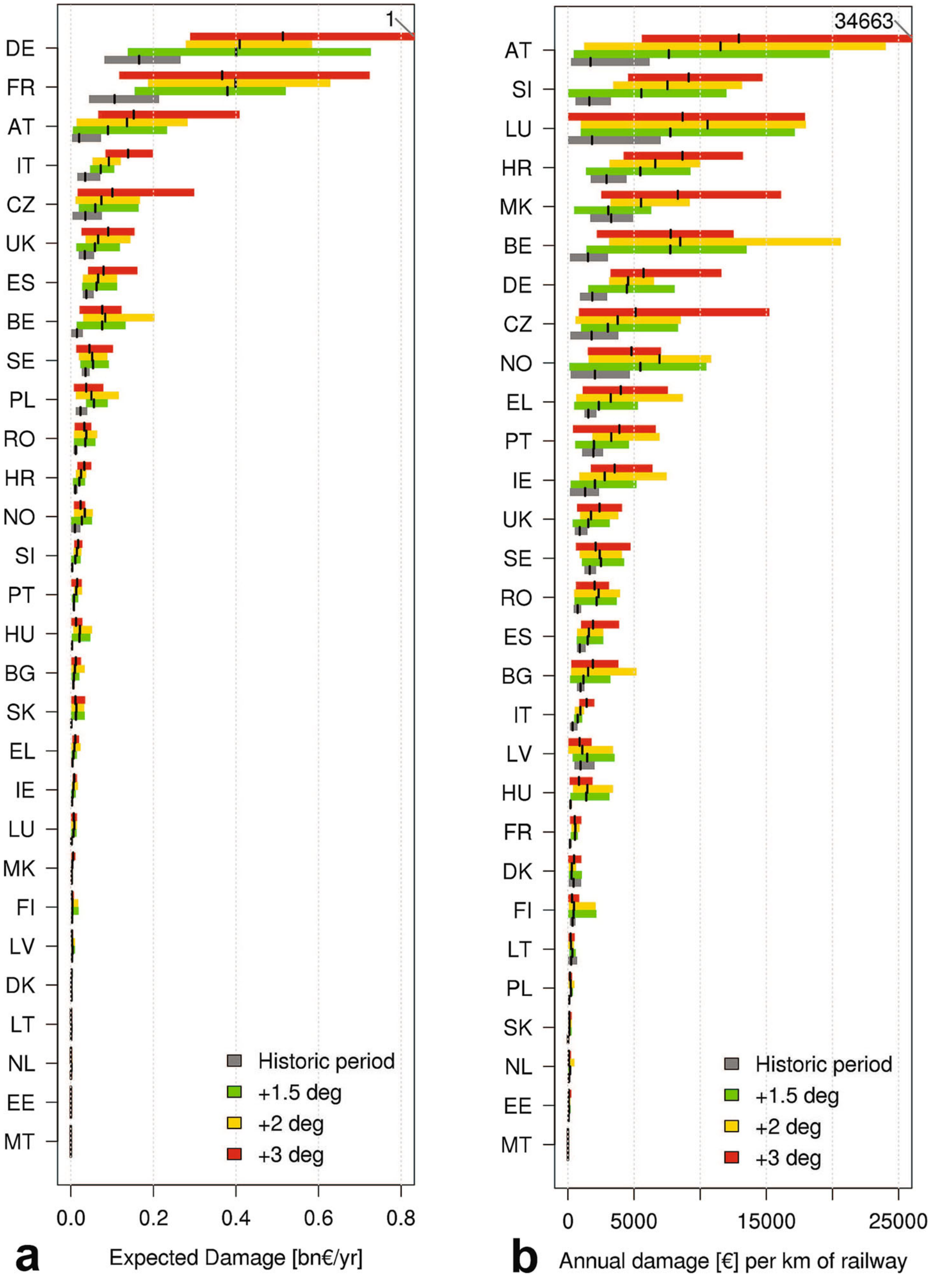


Fig. 2 **a**, **b** Country aggregated expected annual damage (billion Euro/year) and annual relative damage (based on length of the network) for the historic period and three warming scenarios (mean value and ensemble spread) using the Representative Concentration Pathway 8.5 scenario

Table 2 Expected annual damage related to the length of the rail network (per kilometer), freight volumes (per thousand tons), and passengers (per thousand passengers) for the historic period. The ranking of each country for each category is provided in brackets

	Length	Freight	Passenger
Belgium	1516 (12)	N/A	N/A
Bulgaria	953 (15)	421 (10)	274 (3)
Czech Republic	1789 (7)	362 (12)	200 (7)
Denmark	426 (19)	205 (17)	8 (25)
Germany	1841 (5)	450 (9)	62 (18)
Estonia	53 (27)	4 (27)	17 (24)
Ireland	1298 (13)	5607 (1)	76 (15)
Greece	1544 (11)	2983 (2)	261 (4)
Spain	902 (16)	1300 (4)	67 (16)
France	149 (24)	1110 (5)	85 (13)
Croatia	2920 (2)	1106 (6)	508 (2)
Italy	354 (20)	377 (11)	42 (20)
Latvia	956 (14)	52 (23)	168 (9)
Lithuania	245 (22)	18 (25)	230 (5)
Luxembourg	1822 (6)	284 (15)	66 (17)
Hungary	191 (23)	57 (22)	N/A
Malta	0 (29)	0 (28)	0 (26)
Netherlands	62 (26)	11 (26)	N/A
Austria	1711 (8)	201 (18)	84 (14)
Poland	98 (25)	105 (20)	89 (12)
Portugal	1927 (4)	687 (7)	59 (19)
Romania	735 (18)	215 (16)	194 (8)
Slovenia	1620 (10)	177 (19)	224 (6)
Slovakia	11 (28)	27 (24)	21 (22)
Finland	348 (21)	93 (21)	41 (21)
Sweden	1649 (9)	547 (8)	166 (10)
United Kingdom	893 (17)	349 (13)	19 (23)
Norway	2041 (3)	317 (14)	136 (11)
North Macedonia	3272 (1)	1395 (3)	2138 (1)
Average	1080	659	201
St. Dev.	878	1137	403

consistent pattern across the three indicators, they can be useful in different context and for different users.

3.3 Projections of future EADs

Direct flood risk to railway networks is projected to increase substantially due to climate change under different warming scenarios, yet, together with the associated uncertainty (Figs. 2a, b and 4). Based on ensemble means of seven climate scenarios (Alfieri et al. 2015), the EAD to European railways is projected to increase by 255% under a 1.5 °C (ensemble mean: €1.481 million; min: €1.000 million, max: €2.102 million), by 281% under a 2 °C (ensemble mean: €1.635 million; min: €1.241 million, max: €2.034 million), and 310% under a 3 °C warming scenario (ensemble mean: €1.799 million; min: €1.231 million, max: €3.206 million) (see Fig. 3). Accordingly, also the vulnerability indicators increase under the different warming scenarios. Relative risk in relation to the length of the network increases from an average of €1.080 for the historic period to €2.451 (SD = €2.411) under a 1.5 °C, €3.098 (SD = €3.242) under a 2 °C, and €3.373 (SD = €3.479) under a 3 °C warming scenario.

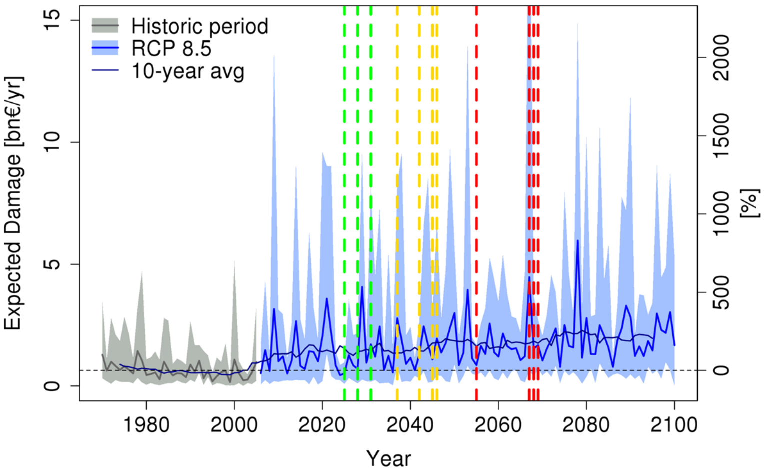


Fig. 3 Simulated damage to railway infrastructure per year, relative change from the historic period, and 10-year moving average (Europe-wide aggregated figures). Gray and blue shades show the ensemble spread given by the seven climate model realizations. Green, yellow, and red lines indicate when the specific warming levels are reached according to the regional climate projects as provided in Table 1

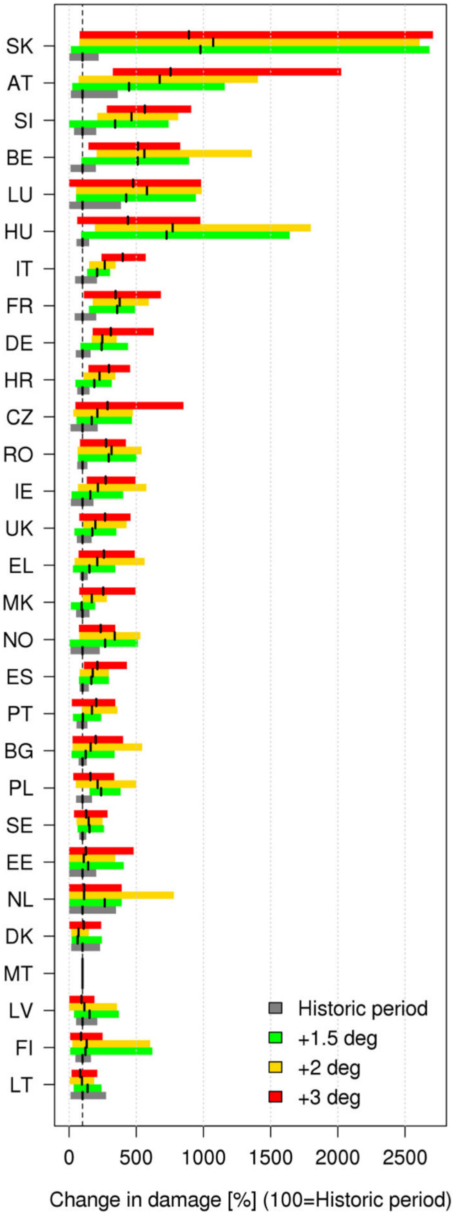
In line with the European-wide increase in risk, results per country show that flood risks steadily increase in many countries under the different warming scenarios. The largest increases in risk (in per cent) for the 3 °C warming scenario is projected for Slovakia, Austria, Slovenia, and Belgium (see Fig. 4). In some countries, such as, e.g., Belgium, France, Hungary, and Slovakia, the largest increase in risk is projected for a 2 °C scenario and would then be followed by stabilization or a decreasing trend for a three-degree warming scenario (see Fig. 4; Table S3). This pattern results from the hydrological projections, which foresee a stabilizing or decreasing trend for some countries following the two-degree warming scenario, especially in Eastern Europe (see also Alfieri et al. 2018). This is likely due to changes in the hydrological cycle at high-end warming levels, including reduced snow accumulation and melting, highlighting the non-linearity between global warming and its impacts in Europe. Similar patterns of flood hazards across Europe were also reported by Kundzewicz et al. (2017).

The change in relative EAD (in relation to the length of the network) across Europe according to the three warming scenarios is also spatially depicted in Fig. 5. It shows that relative risk (related to network length) is projected to increase under a 1.5 °C warming scenario mainly in central and south-eastern European countries as well as Norway, France, and Spain. Under the 2 °C degree warming scenario, relative risk further increases in several countries, including Belgium, Luxembourg, Austria, Hungary, North Macedonia, and Bulgaria. Under a 3 °C degree warming scenario, relative risk is projected to decrease mostly in Eastern Europe and to further increase in some central and south Eastern European countries as well as Portugal. No significant change in relative risk (related to length of the network) across the three warming scenarios is observed for example the Netherlands, Estonia, Slovakia, and Italy.

3.4 Implications for government expenditure in transport

In 2015, the European countries assessed in this paper spend on average 2.7% of their total government expenditure on the transport sector. With increasing damage to railway

Fig. 4 Percentage change in expected annual damage (100 = historic period) for the historic period and the three warming scenarios (mean value and ensemble spread)



infrastructure, governments would need to increase their expenditures in order to keep current levels of expenditure, assuming that flood protection levels remain unaffected by future investments in transport. To gain insights into the additional expenditures required, we also compared the EAD of the different scenarios to the total government expenditure in transport of the EU member states. To account for a possible short-term variability, we used expenditures in transport averaged over the period 2007 to 2015 (Table S4). Over this

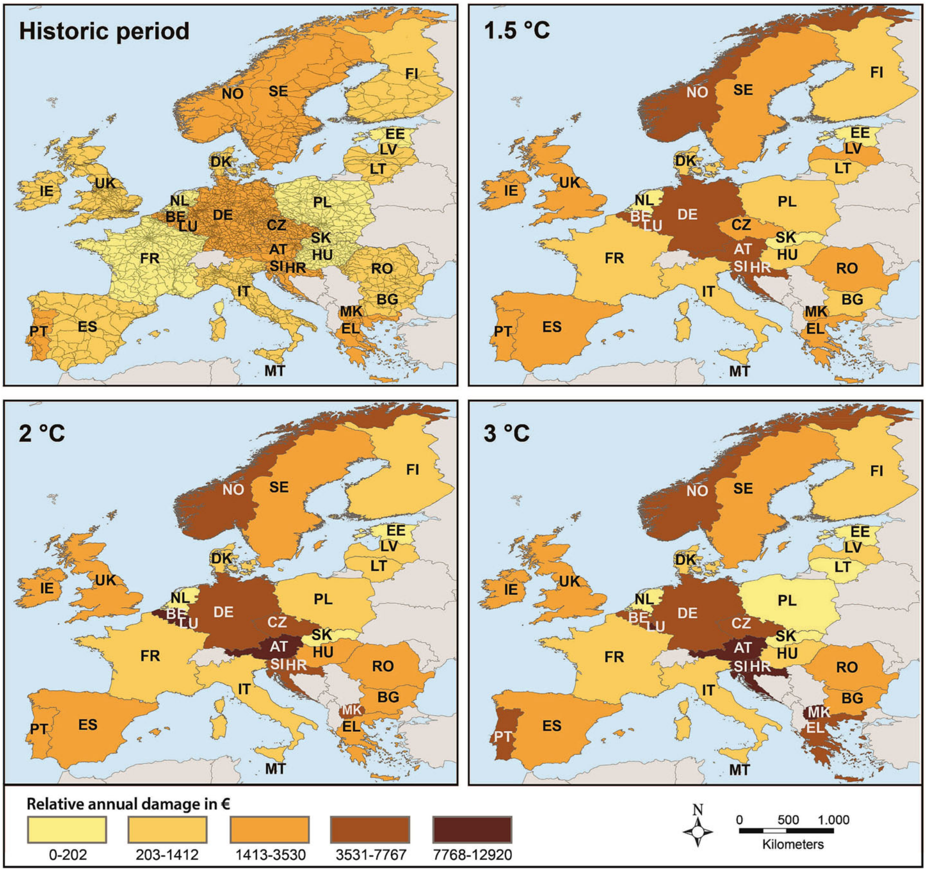


Fig. 5 Annual relative damage (related to length of the network at country level) for the historic period, 1.5 °C, 2 °C, and 3 °C warming level. The assessed network is depicted as a background layer for illustrative reasons in the historic period

period, the assessed European countries reported expenditures of €307 billion per year in the transport sector.[6] It must be noted that these expenditures comprise not only rail transport but also road, water, air, and pipeline and other transport. The analysis shows that in the historic period, the EAD of €581 million amounts 0.19% of the government expenditure in transport for the EU. This share would increase to 0.48% under a 1.5 °C, to 0.53% under a 2 °C, and to 0.58% under a 3 °C warming scenario. In order to cover the increasing risk in railway infrastructure, and to maintain current levels of funding for the transport sector, the countries would need to raise their expenditures by €1.22 billion per year under the 3 °C warming scenario (assuming that future investments would not affect flood protection levels). Limiting global warming to the ambitious 1.5 °C goal of the Paris Agreement would result in avoided losses of €317 million a year compared with the 3 °C warming scenario. If the 2 °C warming target would be reached, still €164 million of losses would be avoided compared to a world that warms by 3 °C.

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[6] Since no values were provided from Eurostat for North Macedonia, North Macedonia was excluded from this analysis as far as the analysis for expenditures in transport are concerned (see Table S3).

In the multi-annual budget from 2014 until 2020, the EU allocated investments of about €26.25 billion for enhancing the Trans-European Transport Network (TEN-T) (European Union 2013), which not only covers railways. The risk increase under a 3 °C scenario aggregated over a 6-year period would consume slightly more than one quarter of that amount. This emphasizes the need to (further) implement and improve integrated risk management solutions, and to account for increasing risks in public budgets.

4 Conclusions

Floods can cause substantial damage to critical transport infrastructure in Europe. In this study, we examined current and future flood risk to railway infrastructure at the European scale under different warming scenarios, using an infrastructure-specific damage model in combination with climate and hydrological modeling. Our findings show that current risk to railway networks is considerable and could increase substantially due to climate change. For the current situation, we estimated an average damage of €581 million per year. This risk could increase by up to 310% under a 3 °C warming scenario.

Our findings demonstrate that the examined European countries would need to considerably increase their expenditures on transport to cover for the additional risks induced by climate change, when assuming that flood protection levels remain constant: under a 3 °C warming scenario, approx. €1.22 billion extra per year would be required. In the Paris Climate Agreement, the global community has formulated the ambitious target to limit global warming to 1.5 °C. According to our findings, reaching this goal would avoid losses to railway infrastructure of €317 million per year compared with the 3 °C scenario. If the 2 °C warming target could be met, losses in the order of €164 million annually could be avoided in comparison with the 3 °C scenario.

Limitations and uncertainty of the current study, and thus future research needs, mainly relate to the scarcity of empirical damage data needed for the development, calibration, and validation of damage models. Currently, no such data are collected in most of the European member states, nor at the European level. A systematic collection of damage to railway infrastructure could significantly contribute to improving our understanding of damaging processes to railway infrastructure, the proportional share of different natural hazards to overall economic losses, and the enhancement of strategic risk management. Currently, information on railway accidents is collected based on Regulation (EC) 91/2003 of the European Parliament and of the Council on rail transport statistics. The statistics on rail safety are required by the European Commission "in order to prepare and monitor Community actions in the field of transport safety (EC 91/2003)." To enhance risk management of railway infrastructure also at the European level, this reporting system could be complemented with information on the impacts of natural hazards, which is currently not included. A better consideration of line-shaped features in gridded regional or global land use projections would help to overcome the shortcoming of using constant exposure in future works.

Future research could aim to complement this study by assessing direct damage with estimates of the indirect economic effects of interruptions of the railway networks due to flooding. This would require information on the time it takes to repair different structural damage to railway tracks, the amount of services normally provided during the time of interruption, and possible redundancies (alternative routes) in the system. Such an integrated approach would allow even more informed decisions about future risk reduction strategies. However, the presented study already illustrates that losses caused by natural hazards to transportation are a non-negligible amount to be considered in budgets and future risk management strategies.

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References

Alfieri L, Salamon P, Bianchi A, Neal J, Bates P, Feyen L (2014) Advances in pan-European flood hazard mapping. Hydrol Process 28:4067–4077

Alfieri L, Feyen L, Dottori F, Bianchi A (2015) Ensemble flood risk assessment in Europe under high end climate scenarios. Glob Environ Chang 35:199–212

Alfieri L, Feyen L, Di Baldassarre G (2016a) Increasing flood risk under climate change: a pan-European assessment of the benefits of four adaptation strategies. Clim Chang 136:507–521

Alfieri L, Feyen L, Salamon P, Thielen J, Bianchi A, Dottori F, Burek P (2016b) Modelling the socio-economic impact of river floods in Europe. Nat Hazards Earth Syst Sci 16:1401–1411

Alfieri L, Bisselink B, Dottori F, Naumann G, Roo A, Salamon P, Wyser K, Feyen L (2017) Global projections of river flood risk in a warmer world. Earth's Future 5:171–182

Alfieri L, Dottori F, Betts R, Salamon P, Feyen L (2018) Multi-model projections of river flood risk in Europe under global warming. Climate 6:6

Apel H, Aronica GT, Kreibich H, Thieken AH (2009) Flood risk analyses—how detailed do we need to be? Nat Hazards 49:79–98

Bednar-Friedl B, Wolkinger B, König M, Bachner G, Formayer H, Offenthaler I, Leitner M (2015) Transport in Steininger KW, König M, Bednar-Friedl B, Kranzle L, Loible W, Prettenthaler F (eds.) economic evaluation of climate change impacts. Development of a cross-sectoral framework and results for Austria. Springer International Publishing Sitzerland Berlin

Bouwer LM, Crompton RP, Faust E, Höppe P, Pielke RA Jr (2007) Confronting disaster losses. Science 318:753

Bubeck P, de Moel H, Bouwer LM, Aerts JCJH (2011) How reliable are projections of future flood damage? Nat Hazards Earth Syst Sci 11:3293–3306

Burek P, Van Der Knijff J, Roo A (2013) LISFLOOD - distributed water balance and flood simulation model. Revised user manual. Report EUR 26162 EN. Joint Research Centre

Council of the European Union (2002) COUNCIL REGULATION (EC) no 2012/2002 of 11 November 2002 establishing the European Union Solidarity Fund. Official Journal of the European Communities

Council of the European Union (2008) COUNCIL DIRECTIVE 2008/114/EC of 8 December 2008 on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection. Official Journal of the European Union

Dobney K, Baker CJ, Quinn AD, Chapman L (2009) Quantifying the effects of high summer temperatures due to climate change on buckling and rail related delays in south-east United Kingdom. Meteorol Appl 16:245–251

Doll C, Klug S, Enei R (2014) Large and small numbers: options for quantifying the costs of extremes on transport now and in 40 years. Nat Hazards 72:211–239

European Commission (2013) An EU strategy on adaptation to climate change COM(2013) 216, Brussels

European Environment Agency (2010) Mapping the impacts of natural hazards and technological accidents in Europe — an overview of the last decade. Copenhagen

European Union (2013) Regulation (EU) no 1316/2013 of the European Parliament and of the Council of 11 December 2013 establishing the Connecting Europe Facility, amending Regulation (EU)no

913/2013 and repealing Regulations (EC) no 680/2007 and (EC) no 67/2010. Official Joural of the European Union

Floodsite (2006) Guidelines for socio-economic flood damage evaluations

Forzieri G, Bianchi A, e Silva FB, Herrera MAM, Leblois A, Lavalle C, Aerts JCJH, Feyen L (2018) Escalating impacts of climate extremes on critical infrastructures in Europe. Glob Environ Chang 48:97–107

Hallegatte S, Green C, Nicholls RJ, Corfee-Morlot J (2013) Future flood losses in major coastal cities. Nat Clim Chang 3:802–806

Hirabayashi Y, Mahendran R, Koirala S, Konoshima L, Yamazaki D, Watanabe S, Kim H, Kanae S (2013) Global flood risk under climate change. Nat Clim Chang 3:816–821

Hosking JR (1990) L-moments: analysis and estimation of distributions using linear combinations of order statistics. J R Stat Soc Ser B Methodol:105-124

Huizinga HJ (2007) Flood damage functions for the EU member states. Implemented in the framework of the contract #382442-F1SC awarded by the European Commission – Joint Research Centre. HKV consultants

IPCC (2013) Climate change 2013: the physical science basis. Contribution of working group I to the Fith assessment report of the intergovernmental panel on climate change. United Kingdom and New York, Cambridge

IPCC (2014a) Climate change 2014: impacts, adaptation, and vulnerability. Part a: global and sectoral aspects. Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York

IPCC (2014b) Climate change 2014: mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change. United Kingdom and New York, Cambridge

Jongman B, Kreibich H, Apel H, Barredo J, Bates P, Feyen L, Gericke A, Neal J, Aerts JCJH, Ward P (2012a) Comparative flood damage model assessment: towards a European approach. Nat Hazards Earth Syst Sci 12: 3733–3752

Jongman B, Ward PJ, Aerts JCJH (2012b) Global exposure to river and coastal flooding: long term trends and changes. Glob Environ Chang 22:823–835

Jongman B, Hochrainer-Stigler S, Feyen L, Aerts JCJH, Mechler R, Botzen WJW, Bouwer LM, Pflug G, Rojas R, Ward PJ (2014) Increasing stress on disaster-risk finance due to large floods. Nat Clim Chang 4:264–268

Kellermann P, Schöbel A, Kundela G, Thieken AH (2015) Estimating flood damage to railway infrastructure – the case study of the March River flood in 2006 at the Austrian northern railway. Nat Hazards Earth Syst Sci 15:2485–2496

Kellermann P, Bubeck P, Kundela G, Dosio A, Thieken A (2016a) Frequency analysis of critical meteorological conditions in a changing climate—assessing future implications for railway transportation in Austria. Climate 4:25

Kellermann P, Schönberger C, Thieken AH (2016b) Large-scale application of the flood damage model railway infrastructure loss (RAIL). Nat Hazards Earth Syst Sci 16:2357

Kreibich H, van den Bergh JCJM, Bouwer LM, Bubeck P, Ciavola P, Green C, Hallegatte S, Logar I, Meyer V, Schwarze R, Thieken AH (2014) Costing natural hazards. Nat Clim Chang 4:303–306

Kundzewicz ZW, Pińskwar I, Brakenridge GR (2017) Changes in river flood hazard in Europe: a review. Hydrol Res 49:294–302

Lin L, Wang Z, Xu Y, Fu Q (2016) Sensitivity of precipitation extremes to radiative forcing of greenhouse gases and aerosols. Geophys Res Lett 43:9860–9868

Merz B, Elmer F, & Thieken AH (2009) Significance of" high probability/low damage" versus" low probability/high damage" flood events. Nat Hazards Earth Syst Sci 9(3):1033-1046

Merz B, Kreibich H, Schwarze R, Thieken A (2010) Review article “assessment of economic flood damage”. Nat Hazards Earth Syst Sci 10:1697–1724

Meyer V, Becker N, Markantonis V, Schwarze R, van den Bergh JCJM, Bouwer LM, 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 AH, Viavattene C (2013) Review article: assessing the costs of natural hazards – state of the art and knowledge gaps. Nat Hazards Earth Syst Sci 13:1351–1373

Munich Re (2017) TOPICS GEO. Natural catastrophes 2016. Analyses, assessments, positions Munich

Perez J, Menendez M, Mendez FJ, Losada IJ (2014) Evaluating the performance of CMIP3 and CMIP5 global climate models over the north-east Atlantic region. Clim Dyn 43:2663–2680

te Linde AH, Bubeck P, Dekkers JEC, de Moel H, Aerts JCJH (2011) Future flood risk estimates along the river Rhine. Nat Hazards Earth Syst Sci 11:459–473

The White House (2013) Presidential policy directive - critical infrastructure security and resilience. Office of the Press Secretary

Thieken AH, Bessel T, Kienzler S, Kreibich H, Müller M, Pisi S, Schröter K (2016) The flood of June 2013 in Germany: how much do we know about its impacts? Nat Hazards Earth Syst Sci 16:1519–1540

United Nations (2015) Sendai Framework for Disaster Risk Reduction 2015–2030. A/CONF.224/CRP.1., Van Der Knijff J, Younis J, De Roo A (2010) LISFLOOD: a GIS-based distributed model for river basin scale water balance and flood simulation. Int J Geogr Inf Sci 24:189–212

Ward PJ, Jongman B, Weiland FS, Bouwman A, van Beek R, Bierkens MF, Ligtvoet W, Winsemius HC (2013) Assessing flood risk at the global scale: model setup, results, and sensitivity. Environ Res Lett 8:044019

Winsemius HC, Aerts JCJH, van Beek LP, Bierkens MF, Bouwman A, Jongman B, Kwadijk JC, Ligtvoet W, Lucas PL, van Vuuren DP (2016) Global drivers of future river flood risk. Nat Clim Chang 6:381–385

Zurich Insurance Group (2013) European floods: using lessons learned to reduce risks. Zurich Insurance Group Zurich, Switzerland

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