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"Everything should be made as simple as possible, but not simpler"

Albert Einstein

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Abstract

Natural hazards can have serious societal and economic impacts. Worldwide, around one third of economic losses due to natural hazards are attributable to floods. The majority of natural hazards are triggered by weather-related extremes such as heavy precipitation, rapid snow melt, or extreme temperatures. Some of them, and in particular floods, are expected to further increase in terms of frequency and/or intensity in the coming decades due to the impacts of climate change. In this context, the European Alps areas are constantly disclosed as being particularly sensitive.

In order to enhance the resilience of societies to natural hazards, risk assessments are substantial as they can deliver comprehensive risk information to be used as a basis for effective and sustainable decision-making in natural hazards management. So far, current assessment approaches mostly focus on single societal or economic sectors – e.g. flood damage models largely concentrate on private-sector housing – and other important sectors, such as the transport infrastructure sector, are widely neglected. However, transport infrastructure considerably contributes to economic and societal welfare, e.g. by ensuring mobility of people and goods. In Austria, for example, the national railway network is essential for the European transit of passengers and freights as well as for the development of the complex Alpine topography. Moreover, a number of recent experiences show that railway infrastructure and transportation is highly vulnerable to natural hazards. As a consequence, the Austrian Federal Railways had to cope with economic losses on the scale of several million euros as a result of flooding and other alpine hazards.

The motivation of this thesis is to contribute to filling the gap of knowledge about damage to railway infrastructure caused by natural hazards by providing new risk information for actors and stakeholders involved in the risk management of railway transportation. Hence, in order to support the decision-making towards a more effective and sustainable risk management, the following two shortcomings in natural risks research are approached: i) the lack of dedicated models to estimate flood damage to railway infrastructure, and ii) the scarcity of insights into possible climate change impacts on the frequency of extreme weather events with focus on future implications for railway transportation in Austria.

With regard to flood impacts to railway infrastructure, the empirically-derived damage model Railway Infrastructure Loss (RAIL) proved expedient to reliably estimate both structural flood damage at exposed track sections of the Northern Railway and resulting repair cost. The results show that the RAIL model is capable of identifying flood risk hot spots along the railway network and, thus, facilitates the targeted planning and implementation of (technical) risk reduction measures. However, the findings of this study also show that the development and validation of flood damage models for railway infrastructure is generally constrained by the continuing lack of detailed event and damage data.

In order to provide flood risk information on the large scale to support strategic flood risk management, the RAIL model was applied for the Austrian Mur River catchment using three different hydraulic scenarios as input as well as considering an increased risk aversion of the railway operator. Results indicate that the model is able to deliver comprehensive risk information also on the catchment level. It is furthermore demonstrated that the aspect of risk aversion can have marked influence on flood damage estimates for the study area and, hence, should be considered with regard to the development of risk management strategies.

Looking at the results of the investigation on future frequencies of extreme weather events jeopardizing railway infrastructure and transportation in Austria, it appears that an increase in intense rainfall events and heat waves has to be expected, whereas heavy snowfall and cold days are likely to decrease. Furthermore, results indicate that frequencies of extremes are rather sensitive to changes of the underlying thresholds. It thus emphasizes the importance to carefully define, validate, and—if needed—to adapt the thresholds that are used to detect and forecast meteorological extremes. For this, continuous and standardized documentation of damaging events and near-misses is a prerequisite.

Overall, the findings of the research presented in this thesis agree on the necessity to improve event and damage documentation procedures in order to enable the acquisition of comprehensive and reliable risk information via risk assessments and, thus, support strategic natural hazards management of railway infrastructure and transportation.

Zusammenfassung

Naturgefahren haben zum Teil gravierende Auswirkungen auf die Gesellschaft und die Wirtschaft der betroffenen Region. Weltweit ist etwa ein Drittel der finanziellen Verluste durch Naturereignisse auf Hochwasser zurückzuführen. Die Schäden an Eisenbahninfrastruktur haben dabei oft großen Anteil am Gesamtschaden. Hochwasser und andere Naturgefahren werden häufig durch Extremwetterereignisse, wie etwa Starkniederschläge oder Extremtemperaturen, ausgelöst. Im Zuge des Klimawandels rechnet man für die kommenden Jahrzehnte mit einer Zunahme in der Anzahl bzw. der Schwere einiger Naturereignisse.

Mit dem Ziel, die gesellschaftliche Widerstandsfähigkeit gegenüber Naturereignissen zu erhöhen, setzt man zur Gewinnung von Risikoinformationen auf sogenannte Naturrisikoanalysen. Die gegenwärtige Praxis konzentriert sich dabei meist auf die Analyse für einzelne Wirtschaftssektoren, wie etwa den Immobiliensektor. Der Transportsektor und insbesondere die Eisenbahninfrastruktur werden trotz der tragenden Rollen für die Wirtschaftskraft einer Gesellschaft jedoch weitgehend vernachlässigt. Zahlreiche Naturereignisse der letzten Jahrzehnte zeigten allerdings, dass Eisenbahninfrastruktur generell sehr schadensanfällig gegenüber Naturgefahren ist.

Ziel dieser Doktorarbeit ist es, das Management von Naturgefahren für den Schienensektor in Österreich durch die Bereitstellung von neuen Risikoinformationen zu unterstützen. Hierzu wurde zum einen ein neuartiges Schadenmodell zur Schätzung von Hochwasserschäden an Eisenbahninfrastruktur entwickelt. Zum anderen wurde unter Verwendung von regionalen Klimamodellen die klimawandelbedingte Änderung der Häufigkeiten von Extremwetterereignissen in Österreich untersucht und mögliche Auswirkungen auf den Eisenbahnbetrieb abgeleitet.

Die Forschungsergebnisse zeigen, dass das entwickelte Hochwasserschadenmodell „RAIL" in der Lage ist, potenzielle Schadenschwerpunkte entlang von Bahnlinien für großräumige Eisenbahnnetze zu identifizieren und damit einen wertvollen Beitrag für die gezielte Planung und Errichtung von technischen Hochwasserschutzmaßnahmen leisten kann. Ferner liefert die Untersuchung der Häufigkeitsentwicklung von Extremwetterereignissen bis zum Jahr 2040 wichtige Einblicke in die zukünftigen Herausforderungen für den Bahnbetrieb im Kontext des Klimawandels. Um aus zukünftigen Naturereignissen lernen zu können und somit ein tieferes Verständnis von Naturgefahrenprozessen und deren Auswirkungen auf Eisenbahninfrastruktur und –betrieb zu erlangen, wird die (Weiter-)Entwicklung und Anwendung von standardisierten Ereignis- und Schadendokumentationsverfahren empfohlen.

Contents

Acknowledgements **i**

Abstract **ii**

Zusammenfassung **iv**

Contents **v**

List of figures **viii**

List of tables **ix**

Chapter I - Introduction **1**

1.1 Background and motivation 2
1.2 Research questions and methods 8
1.3 Structure of the thesis 10

Chapter II - Estimating flood damage to railway infrastructure – the case study of the March River flood in 2006 at the Austrian Northern Railway **12**

2.1 Introduction 13
2.2 Model development 15
  2.2.1 Classification of structural damage 15
  2.2.2 Hydraulic impact data 16
  2.2.3 Derivation of the damage model 17
  2.2.4 Calibration of loss estimates 18
  2.2.5 Comparing the RAIL model to RAM and DSM 19
2.3 Statistical review and model adjustments 20
2.4 Application and evaluation 27
  2.4.1 The March flood of 2006 27
  2.4.2 Flood scenarios 29
  2.4.3 Results of the model comparison 31
2.5 Conclusions 33

Chapter III – Large-scale application of the flood damage model Railway Infrastructure Loss (RAIL) 35

3.1 Introduction 36
3.2 Data and methods 39
  3.2.1 The Mur River catchment 39
  3.2.2 The RAIL model 40
  3.2.3 Exposure analysis 41
  3.2.4 Damage estimation 42
  3.2.5 Sensitivity analysis 43
  3.2.6 The aspect of risk aversion 44
3.3. Results 44
  3.3.1 Damage and loss on the catchment scale 44
  3.3.2 Damage and loss on the operational level 46
  3.3.3 Sensitivity of RAIL estimates 49
  3.3.4 Impacts of risk aversion 50
3.4 Discussion 51
  3.4.1 Model limitations and uncertainties 52
  3.4.2 Insights for railway operation and natural hazard management 54
  3.4.3 Flood risk and climate change 56
3.5 Conclusions 57

Chapter IV - Frequency analysis of critical meteorological conditions in a changing climate - Assessing future implications for railway transportation in Austria 60

4.1 Introduction 61
4.2 The ÖBB weather warning and monitoring system 63
4.3 Data and methods 66
  4.3.1 Climate change signals for Austria 66
  4.3.2 Frequency analysis of CMCs in a changing climate 68
  4.3.3 Sensitivity analysis 69
4.4 Results 70
  4.4.1 A glance at Austria`s potential future climate 70
  4.4.2 Climate change impacts on the CMC frequencies 75
  4.4.3 How sensitive are CMC frequencies to changes in threshold values? 78

4.5 Discussion 80

4.6 Conclusions 84

Chapter V – Excursus 86

How can the performance of a weather warning system for railway operation be assessed empirically? 87

Chapter VI – Policy recommendations 91

6.1 Ongoing improvements of natural hazards management 92

6.2 Enhancing the management of risks arising from CMCs through an expansion of partnerships 93

6.3 Efforts to improve event and damage documentation procedures 94

6.4 Risk absorption by the federal government 95

6.5 Policy recommendation for the European level 96

Chapter VII – Synthesis and outlook 98

References 103

List of figures

Figure 1.1: Cooperation on three decision-making levels 7
Figure 2.1: Damage classification scheme 15
Figure 2.2: Damage curves 19
Figure 2.3: Box plots displaying the summary statistics 24
Figure 2.4: Kernel density plots 26
Figure 2.5: Estimation of damage potentials for the March river flood in 2006 28
Figure 2.6: Estimation of damage potentials for three flood scenarios 30
Figure 3.1: Risk management cycle and strategies of the ÖBB 37
Figure 3.2: The Mur River catchment 39
Figure 3.3: Estimation of damage potentials 45
Figure 3.4: Operational sections of the ÖBB railway subnetwork 47
Figure 4.1: Flowchart of procedures 66
Figure 4.2: Percentage difference of mean rainfall in the winter season 71
Figure 4.3: Percentage difference of mean snowfall in the winter season 72
Figure 4.4: Absolute difference of mean air temperature in the winter season 73
Figure 4.5: Percentage difference of mean rainfall in the summer season 74
Figure 4.6: Absolute difference of mean air temperature in the summer season 75

List of tables

Table 1.1: The most common natural hazards *6*

Table 2.1: Standard repair costs *18*

Table 2.2: Spearman`s rank correlation coefficients *21*

Table 2.3: Spearman`s rank correlation coefficients *23*

Table 2.4: Estimated frequencies of damage classes *27*

Table 2.5: Estimated frequencies of damage classes *31*

Table 2.6: Calculated monetary losses for the March flood *32*

Table 2.7: Calculated monetary losses for the synthetic flood scenarios *32*

Table 3.1: Estimated number of damaged track sections *46*

Table 3.2: Flood damage estimation *48*

Table 3.3: Expected Annual Damage (EAD) for different model settings. *50*

Table 3.4: Expected Annual Damage (EAD) for operational sections *51*

Table 4.1: Threshold criteria for Critical Meteorological Conditions (CMC) *64*

Table 4.2: List of model runs available for this study *68*

Table 4.3: List of RCM variables *68*

Table 4.4: Arithmetic mean values (m), standard deviations (s) and coefficients of variation (CV) *71*

Table 4.5: Changes in frequencies of critical meteorological conditions (CMCs) *76*

Table 5.1: Effectivity of Infra:Wetter *90*

Chapter I - Introduction

1.1 Background and motivation

Since the beginning of the 21st century an alarming number of natural disasters already took place all over the globe, and most of them had large impacts on societies (Guha-Sapir et al., 2013). For example, in 2012 alone, 900 natural disasters were recorded worldwide resulting in 9,500 fatalities as well as overall direct losses of US$ 160 billion (MunichRe, 2013). Among all the different types of natural hazards, floods are the most common one and the leading cause of fatalities worldwide (Doocy et al., 2013). Moreover, around one third of economic losses due to natural hazards are attributable to floods (Kron, 2005; Armanath et al., 2016). The situation is similar in Europe, where natural hazards caused nearly 100.000 fatalities, affected more than 11 million people and led to total economic losses of about EUR 150 billion in the period between 1998 and 2009 (EEA, 2011). Therein as well, flooding was the costliest hazard entailing losses of approx. EUR 52 billion (EEA, 2011). Recent events furthermore demonstrated that damage to transport infrastructure can contribute considerably to overall loss due to natural hazards. For example, by reviewing the recorded losses of the severe 2002 flood in Germany and the contributions of damage categories to total loss, the estimated share of damage to infrastructure alone amounted to around 31 % (Pfurtscheller and Thieken, 2013).

The majority of natural hazards (e.g. floods, droughts, mass movements, wild fires) are triggered by weather and climate-related extremes such as heavy precipitation, rapid snow melt, or extreme temperatures (Alcántara-Ayala and Goudie, 2010). Moreover, extreme weather events also have considerable damaging potential as, for instance, at a global level, more than 530.000 fatalities and economic losses of USD 2.17 trillion were inflicted in connection with more than 15.000 extreme weather events (Kreft et al., 2014). Across Europe, the figures are similarly alarming as the total reported economic damage caused by weather and climate-related extremes in the European Environment Agency (EEA) member countries[1] over the period 1980-2013 is almost 400 billion Euro (EEA, 2016). With regard to transport infrastructure, more than 1200 extreme weather events that caused direct or indirect damage to the national railway infrastructure (e.g., heavy precipitation, heat waves, or storms) occurred between 1990 and 2011 in Austria alone (Rachoy, 2012).

In the future, the majority of natural hazards triggered by weather extremes, and in particular floods, are projected to increase further in many parts of Europe as a consequence of climate change (Lehner et al., 2006; Dankers and Feyen, 2008; IPCC,

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[1] The European Environment Agency has 33 member countries, which are the 28 member countries of the European Union as well as the countries Iceland, Liechtenstein, Norway, Switzerland and Turkey (Status as of 2012).

2007; ESPON, 2013). However, the projections of changes in flood frequencies and magnitudes are still subject to considerable uncertainties, since e.g. only limited evidence can be produced from river discharge simulations due to the complexity of the causes of regional changes of river flooding (IPCC, 2012). Within Europe, the Alpine areas are constantly disclosed as being particularly sensitive to climate change (Schöner et al., 2011). For example, according to Eitzinger et al. (2009), Gobiet et al. (2009), and Strauss et al. (2013), a significant annual mean temperature rise of approximately 1.6 °C until 2040 is expected for this region. With regard to precipitation, the annual trend for Austria shows significant variations both in the seasonal and spatial pattern (Schmidli et al., 2002; Brunetti et al., 2006; PLANALP, 2013). In addition, climate change is also likely to alter the frequency, intensity, and spatiotemporal distribution of (at least some) extreme weather events such as intense rainfall or heatwaves (Beniston et al., 2007; IPCC, 2011; EEA, 2014), which will presumably also have serious implications on the current hazard (and risk) profile of Austria.

In general, natural (or disaster) risk can be understood as a function of the natural hazard, the exposure and the vulnerability of the element at risk (Merz and Thieken, 2004; Kron, 2005). Herein, the term "hazard" term stands for the probability and intensity of a natural event, the term "exposure" specifies whether the element at risk (e.g. humans or property) is located within the impact area of the respective hazard, and the term "vulnerability" again is a function of the (physical) susceptibility of the element and the resulting value of loss (Merz and Thieken, 2004; Kron, 2005). This interpretation of the terminology is used as the basis throughout the thesis at hand.

Experience over the last few decades clearly indicates the high vulnerability of modern societies to natural hazards and furthermore illustrates the necessity of enhancing its resilience. It also demonstrates that structural protection measures such as dykes are limited in reducing risks and, hence, a certain residual risk always remains. Consequently, and also due to climate and environmental change, natural hazard and risk management in Europe has shifted from pure technological and protective approaches towards more integrated risk management strategies including non-structural risk reduction measures such as spatial planning policies, private mitigation measures or monitoring and warning systems (Merz et al., 2010a). This more comprehensive approach yields an increase in the flexibility and, therefore, in the robustness of risk reduction measures with regard to future developments related uncertainties (Merz et al., 2010a). In the context of flood risk management, a prominent example is the European Floods Directive, which requires EU member states to assess flood risks on the catchment scale, develop flood hazard and risk maps, and draw up flood risk management plans for areas where significant flood risk exists (European Commission, 2007). Additionally, in order to account for climate change, all three steps of the analysis have to be updated every six years (European Commission, 2007).

The effective management of natural risks requires reliable and comprehensive risk information (Benson and Clay, 2004). Such information can generally be obtained through risk analyses, which aim at answering three questions (Kaplan and Garrick, 1981): 1) What can happen?, 2) How likely is it that it will happen?, and 3) If it does happen, what are the consequences? On the basis of such a risk analysis, a risk assessment can be performed in order to clarify the question of "what risk is (not) acceptable?" (DKKV, 2003). Finally, this enables to address further important issues of risk management: i) which measure can reduce the risk?, ii) what are the costs of possible measures?, and iii) is there an acceptable benefit in terms of risk reduction? (DKKV, 2003). Consequently, in order to develop effective risk reduction activities, related actors (e.g. government and business entities) are increasingly encouraged to draw on natural risk analysis approaches (UNICEF, 2013).

In a risk management context, and against the background that financial resources are limited, the reliable and comprehensive costing of natural hazards is of major importance e.g. for the development of effective risk reduction strategies (Meyer et al., 2013; Kreibich et al., 2014). The current approaches of cost assessments mostly focus on single sectors – e.g. flood damage models largely concentrate on the residential sector (Meyer et al., 2013). The transport infrastructure sector, however, is mostly neglected in natural hazards and risk research so far, since among other things knowledge of damage mechanisms as well as data for the development of appropriate model approaches is still scarce, and available approaches are still subject to very high uncertainties (Merz et al., 2010b).

However, transport infrastructure considerably contributes to economic and societal welfare, e.g. by ensuring mobility of people and goods (Pfurtscheller et al., 2011; Thieken et al., 2013), in particular in mountain areas. The European Alps, for instance, are a natural barrier for international freight transports from north to the south of Europe. Nevertheless, about 190 million tonnes of freight crosses the Alps per year (Permanent Secretariat of the Alpine Convention, 2010). Due to the high relief energy and the coincidence of multiple hazards in Alpine environments, usable areas for the construction and maintenance of infrastructure are very limited in the Alps. According to Tappeiner et al. (2008), only 17 % of the total area of the European Alps can be used for permanent settlement. In these areas, people, assets and infrastructure are hence highly concentrated. Hence, if the network is (partly) disrupted, alternative options for transportation are rarely available. Moreover, a mismanagement of land use that has allowed the location of settlements and/or commercial areas in flood-prone areas as well as developments that have induced a high mobility of working people and a high dependence of employees on commuting from valleys to centres has aggravated the vulnerability to natural hazards (Pfurtscheller et al., 2011) and emphasize the bottleneck function of transportation infrastructure in the Alps. In general, exposure and vulnerability of railway infrastructure in Austria is determined by a variety of drivers. The most important two are:

- Environmental setting: As railway tracks are immobile structures, their position in space does not change over time. Thus, there is direct and immediate coherency between localization of the respective element and its exposure to hazards. The relevance of different natural hazards for an infrastructure element is to a large part determined by the surrounding landscape (relief, geology, torrent and river network).

- Construction types: Railway infrastructure can significantly differ in terms of the quality of the structure and setup due to the time when it was built, although each type of construction usually implies the same track components (e.g. standard cross section, superstructure, switch points). The used building materials and their quality, the applied technology and the design characteristics, for instance, result in a unique performance of elements in case of a hazardous event occurs and therefore damage often highly varies. Hence, the construction type of a track section is an important factor regarding the assessment of its vulnerability to natural hazards. First insights on failure mechanisms of the railway infrastructure element "substructure" induced by flooding and seepage are given in Polemio and Lollino (2011). While existing railway lines have been built up typically upon older standards for track design, in case of renewal new standards have to be applied. This leads typically to higher costs when rebuilding a railway line after natural destructions.

Table 1.1 gives a general overview of the most common alpine hazards in Austria, including qualitative indications on their risk potential for persons (risk of harm), property (risk of damage) and catastrophe potential (after Hübl et al., 2011; adapted). Such natural hazards can cause substantial damage to railway infrastructure and pose a risk to the safety of passengers, as a number of examples demonstrate: In recent years, the ÖBB had to cope with economic losses on the scale of several million euros as a result of natural hazards (e.g. flooding in 2002, 2005 and 2013). Some events even led to fatal railway accidents, e.g. the disastrous avalanche event near Böckstein in the year 1909 caused 26 fatalities. Not least these recent experiences show that railway infrastructure and transportation is highly vulnerable to natural hazards.

Table 1.1: The most common natural hazards in Austria (after Hübl et al., 2011; adapted)

Type of natural hazard	person-related risk	damage-related risk	catastrophe potential
Flood	medium	very high	very high
Avalanche	very high	medium	high
Debris flow	high	medium	medium
Landslide	high	medium	medium
Rock fall	very high	low	low

Accordingly, risk analysis and management are important issues of railway operation in Austria, which is furthermore indicated by the fact that the Austrian Federal Railways (ÖBB) maintain an own department for natural hazard management being directly responsible for managing natural hazards and risks for railway infrastructure. Within this department, there are three levels of decision-making and, in addition, ÖBB Natural Hazard Management Department entered into partnerships and productive cooperation at different administrative levels, i.e. from the regional level to the national level, in order to better cope with the complex hazard profile of railway transportation in Austria (Otto et al., 2014) (see Fig. 1.1). In the context of event and crisis management, for example, this department is responsible for taking decisions on speed limits or track closures in case of natural events. Furthermore, for the long-term risk management, the planning and implementation of risk reduction measures is a principal task. In this regard, the ÖBB Natural Hazard Management Department follows two main strategies (Otto et al., 2014): One strategy focusses on structural risk reduction measures, i.e. planning, design, implementation and maintenance of technical protection measures such as embankments and torrent control structures. The second risk reduction strategy addresses the facts that 1) the implementation of technical protection measures is often not feasible for either economic reasons or aspects of nature and landscape conservation (Brauner, 2011), and that 2) technical measures are limited in ensuring a commensurate level of safety for railway operations in Alpine topography. Accordingly, the ÖBB also puts strong emphasis on non-structural, precautionary, and preparatory risk mitigation measures, i.e. monitoring and early warning systems with organisational measures such as speed limits and track closures in dangerous situations in order to mitigate (residual) risks from natural hazards.

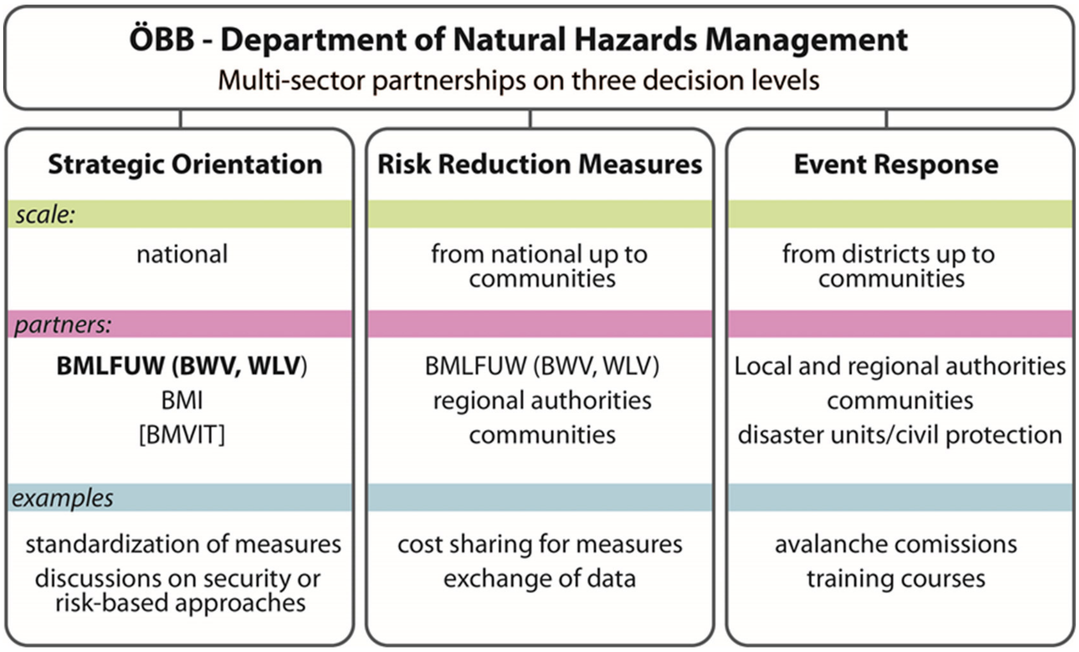

Figure 1.1: Cooperation on three decision-making levels. Source: Otto et al., 2014. (BMLFUW = Federal Ministry of Agriculture, Forestry, Environment and Water Management, BWV = Flood Control Management; WLV = Torrent and Avalanche Control; BM.I = Federal Ministry of the Interior; BMVIT = Federal Ministry of Transport, Innovation and Technology)

As outlined above, comprehensive and reliable risk information is needed for an effective risk management to secure and enhance the railway infrastructure and transport resilience to natural hazards. However, there is as yet only little (empirical) knowledge about damage to infrastructure as a result of natural hazards and only few studies on this issue are available, even though such damage can contribute considerably to the overall loss. Accordingly, Merz et al. (2010) pointed out that knowledge on damage mechanisms as well as crucial in-depth information and data for the development of appropriate model approaches is still scarce in the infrastructure sector, whereupon existing approaches are still subject to very high uncertainties. Kunert (2010) outlined that mainly unit loss assessments can be found in literature with regard to the infrastructure sector, whereas (empirical) flood damage functions have widely been used for loss estimation in the residential sector. As a consequence, damage to railway infrastructure is not or only insufficiently reflected in natural risk assessments so far (Bubeck et al., 2011).

Hence, in order to provide new risk information for the effective management of natural hazards to railway infrastructure with focus on floods and extreme weather, the following two main shortcomings are approached in this thesis:

- the lack of dedicated models to estimate flood damage to railway infrastructure as a basis for the planning and implementation of structural risk reduction measures;

- the scarcity of insights into possible climate change impacts on the frequency of critical meteorological conditions and resulting future implications for railway transportation in Austria.

1.2 Research questions and methods

The main objective of the research presented in this thesis is to overcome the shortcomings outlined in Section 1.1 by providing new risk information for actors and stakeholders involved in the risk management of railway infrastructure and transportation. This is done by dealing with the following research questions:

- What are the decisive hydraulic impact parameters for structural flood damage to railway infrastructure, and how can such damage be estimated?
- How reliable are estimates of flood damage to railway infrastructure, and how can they be used to enhance flood risk management strategies?
- To what extent may the frequencies of critical meteorological conditions for railway transportation change due to climate change, and how robust are these projections?
- What are the future implications for railway transportation in Austria in the context of climate change?

In order to support the strategic decision-making comprehensively, it is aimed to feed into both of the main risk reduction strategies currently followed by the ÖBB: With regard to structural risk reduction measures, the goal was to develop a flood damage model for the estimation of both structural damage to railway infrastructure and incurred direct economic loss. Such a tool should enable more targeted flood risk analyses for railway infrastructure and supports risk managers – among other things - in the strategic planning and prioritisation of technical protection measures. Regarding non-structural risk reduction measures, it was intended to deliver insights into possible climate change impacts on frequencies of extreme weather events jeopardizing railway operations in Austria. Such information facilitates the evaluation and, if necessary, the improvement of existing non-structural risk reduction measures such as a weather monitoring and warning system in terms of reliability and sustainability, in particular in the context of climate change.

In order to achieve the proclaimed goal to support and facilitate the decision-making in the management of natural hazards for railway transportation in Austria, a number of research methods were applied:

First, the demand for dedicated flood damage models for railway infrastructure was tackled through the assessment of empirically derived correlations between flood impacts and documented structural damage at affected track sections (Chapter 2). Via a combination of event data, i.e. photo-documented damage on the Northern Railway in Lower Austria caused by the March river flood in 2006, and simulated flood characteristics, i.e. water levels, flow velocities and combinations thereof, the correlations between physical flood impact parameters and damage occurred to the railway track were investigated and subsequently rendered into a damage model called Railway Infrastructure Loss (RAIL). Thereby, the particular aim was to develop a two-step model allowing a consideration of both structural damage types and direct economic loss (i.e. repair costs). Particularly the first step frequently is skipped in conventional risk analysis approaches as only (relative or absolute) monetary losses are computed. However, the localization of specific structural flood damage grades at specific track section and, coupled therewith, the possibility to identify risk hot spots along a railway track creates great added value for railway constructors and operators in terms of network and risk management. In addition, we investigated the relation between structural damage and flood impact not only on the basis of water levels, but also based on further hydraulic parameters, i.e. flow velocity, energy head, intensity and indicator of flow force, whereby the three latter ones are different combinations of water level and flow velocity.

Second, in order to obtain performance indicators, the robustness of the developed flood damage model RAIL was investigated. Therefore, a comparison of the RAIL model results with depth-damage curve based approaches for the infrastructure sector obtained from the Rhine Atlas damage model and the Damage Scanner model was performed (Chapter 2). Additionally, since the RAIL model implies a variety of model simplifications, which may involve significant model uncertainties and, hence, lead to potential misinterpretations, the sensitivity of the model results was analysed (Chapter 3). For this, the simplifications were modified based on two different variants and, subsequently, the flood damage was reestimated and compared in order to assess the appearing variances. Both of these strategies were also applied against the background that the RAIL model could not yet be properly validated due to lack of independent event and damage data.

Third, in pursuit of the goal of obtaining comprehensive information on potential flood risk hot spots as well as on expected flood damage for Austrian railway infrastructure, the RAIL model was applied i) on the local level (i.e. small test track) (Chapter 2), and ii) on the regional level (i.e. railway subnetwork located in the Mur River catchment) (Chapter 3) to estimate structural flood damage as well as resulting repair costs due to a 30-year, 100-year and 300-year flood scenario. The results of the large-scale application were furthermore used to calculate the expected annual damage (EAD) of the railway subnetwork, which is a common risk metric in the context of natural risk assessments (Merz et al., 2009). Additionally, the aspect of risk aversion was introduced and its impact on the risk quantifications was investigated (Chapter 3). The term risk aversion stands for the aversion towards catastrophes and distress, meaning that one natural event causing devastating damage and loss is much more strongly perceived and evaluated by the general public than numerous events causing in total the same amount of damage, while the damage of each event is comparatively small (BABS, 2003). In a final step of Chapter 3, the overall results were evaluated in terms of their applicability and benefit for the natural risk management of a railway operator as well as in terms of their sustainability in the context of climate change and possibly resulting changes in flood risk.

Fourth, with the aim of investigating a potential shift of the current multi-hazard profile (see Tab. 1.1) due to impacts of climate change, an ensemble of four high-resolution and bias corrected Regional Climate Models (RCM) for Europe containing a variety of precipitation and temperature-related parameters was evaluated. To account for the variability of possible projections, those four RCMs were selected on the basis that they represent the maximum difference in projected precipitation and temperature trends for Europe and thus likely consider the entire projection bandwidth provided by the given ensemble of simulations. Moreover, the robustness of the climate change signals was assessed using a simple approach suggested by the IPCC (2007), which proposes to check the matching rate of simulation results with respect to the direction of change.

Fifth, the projected frequencies of extreme weather events until 2040 are analysed and compared to the frequencies of the reference period (1961-1990) (Chapter 4). Based on a variety of predefined thresholds for different types of extreme weather events, the RCM simulations were assessed and occurrences of extreme weather events were counted on a daily basis.

Sixth, in order to obtain an indication of the sensitivity of the results, the frequency analysis of extreme weather events was repeated using a variety of modified threshold values. Thereby, all modifications are derived from internal discussions with railway experts and based on the premise that respective original thresholds are likely to be underrated and, consequently, less extreme thresholds can already pose similar risks to railway operations.

In general, the essential parts of the research presented in this thesis were conducted in a GIS environment as well as on the basis of the numerical programming language MATLAB.

1.3 Structure of the thesis

The research questions of this cumulative thesis are addressed by six Chapters, of which three Chapters are published in international peer-review scientific journals. In Chapter 2, the derivation of the empirical flood damage model RAIL on the basis of documented damage data of the March River flooding in 2006 at the Austrian Northern Railway is presented. This is followed by a large-scale application of the RAIL model in the Mur River catchment located in South Austria with the objective to obtain comprehensive risk information facilitating strategic flood risk management in the study area (Chapter 3). Chapter 4 elucidates the analyses on climate change impacts on the frequencies of extreme weather events in Austria and, furthermore, outlines the needs for information on the potential future implications for railway transportation. In the context of natural risk assessments, the validation of models for estimating damage and risk from natural hazards is essential for allowing statements about the reliability and accuracy of such tools. However, a proper validation is largely hindered by lack of appropriate data and, therefore, mostly neglected in natural risks research. Since required data for the validation of the concepts presented in this thesis is also missing, we at least propose an approach to investigate the effectiveness of a weather monitoring and early warning system to correctly forecast a railway operation incident (Chapter 5). Finally, some recommendations for future work and for the strategic level of the ÖBB natural hazard and risk management are given in Chapter 6, and overall conclusions are drawn in Chapter 7.

Chapter II - Estimating flood damage to railway infrastructure – the case study of the March River flood in 2006 at the Austrian Northern Railway

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Abstract

Models for estimating flood losses to infrastructure are rare and their reliability is seldom investigated although infrastructure losses might contribute considerably to the overall flood losses. In this paper, an empirical modelling approach for estimating direct structural flood damage to railway infrastructure and associated financial losses is presented. Via a combination of event data, i.e. photo-documented damage on the Northern Railway in Lower Austria caused by the March river flood in 2006, and simulated flood characteristics, i.e. water levels, flow velocities and combinations thereof, the correlations between physical flood impact parameters and damage occurred to the railway track were investigated and subsequently rendered into a damage model. After calibrating the loss estimation using recorded repair costs of the Austrian Federal Railways, the model was applied to three synthetic scenarios with return periods of 30, 100 and 300 years of March river flooding. Finally, the model results are compared to depth-damage curve based approaches for the infrastructure sector obtained from the Rhine Atlas damage model and the Damage Scanner model. The results of this case study indicate a good performance of our two-stage model approach. However, due to a lack of independent event and damage data, the model could not yet be validated. Future research in natural risk should focus on the development of event and damage documentation procedures to overcome this significant hurdle in flood damage modelling.

2.1 Introduction

Railway infrastructure plays a crucial role in ensuring transportation of people and goods and, thus, contributes to economic and societal welfare. River floods, however, pose a great threat to the network's reliability and continuously cause significant direct damage (Nester et al., 2008; Moran et al., 2010a, 2010b). In 2006, for example, a 100-year flood event occurred at the lower reach of the river March which is located at the border of (Lower) Austria and Slovakia. During this event, the average flow rate of 108 m³/s of the March in this section was exceeded nearly 13 times resulting in a peak flow rate of 1,400 m³/s. The maximum water level lasted for nearly 2.5 days and flow velocities were rather low (Godina et al., 2007). The flood affected an important connection line of the Austrian Federal Railways (ÖBB) between Vienna and the Czech Republic, the Northern Railway, along a section of around 10 km causing repair costs of more than EUR 41.4 million (Moran et al., 2010a; ÖBB-Infrastruktur AG, 2014) and a complete shutdown of passenger and freight operations for several months (Moran et al., 2010b). This event fully demonstrates the high vulnerability of railway infrastructure to floods. Hence, there is a clear need for valuable information on potential risk hot spots as well as on expected flood damage in order to support strategic decision-making in flood risk management.

Modelling flood damage to transportation infrastructure, however, is mostly neglected in natural hazards and risks research so far. Merz et al. (2010) indicated that knowledge on damage mechanisms as well as crucial in-depth information and data for the development of appropriate model approaches is still scarce in the infrastructure sector, whereupon existing approaches are still subject to very high uncertainties. Kunert (2010) outlined that mainly unit loss assessments can be found in literature, whereas (empirical) flood damage functions have widely been used for loss estimation in the residential sector. A popular example is the Multi-Coloured Manual (MCM) being the most advanced method for flood damage estimation within Europe (e.g. Penning-Rowsell and Chatterton, 1977; Penning-Rowsell et al., 1992, 2005, 2010, 2013; Jongman et al., 2012). Therein, direct flood damages in the transport infrastructure sector are only roughly estimated by a percentage share of property losses on the basis of empirical data of the summer floods in the United Kingdom in 2007 (Jongman et al., 2012). However, the focus of the MCM lies on the estimation of indirect losses due to traffic disruptions (e.g. additional travel time). A few established flood damage models, e.g. the Rhine Atlas damage model (RAM) or the Damage Scanner model (DSM), actually do also consider direct damage to infrastructure by use of depth-damage curves. Though, only aggregated CORINE land-use data containing a large variety of urban infrastructure and lifeline elements is used therein (Bubeck et al., 2011; Jongman et al., 2012). Due to the missing distinction into sub-classes in the CORINE Land Cover data, there is no detailed information on the share of damage to transport infrastructure in these model outputs. By reviewing the recorded losses of the Elbe flood of 2002 and the contributions of damage categories to overall losses, Bubeck et al. (2011) showed that both the RAM and the DSM significantly underestimate the share of damage corresponding to infrastructure, since the models result in a share of 1.6 % (RAM) and 2.1 % (DSM). However, the share of damage to infrastructure alone amounted to around 14 % (national) and 17 % (municipal) during the 2002 floods (Pfurtscheller and Thieken, 2013). With respect to the Elbe flood in 2002, the damage to municipal infrastructure even comprised about 20 % of overall losses (Bubeck et al., 2011). Since roads and bridges incurred the greatest share in the infrastructure sector during the Elbe flood, Bubeck et al. (2011) concluded that using land-use maps as input data consisting of aggregated information on asset values as well as coarse resolution only insufficiently reflect damage to linear structures.

The case study presented in this paper aims to develop a tool for the estimation of direct flood damage and losses to railway infrastructure derived from empirical flood damage data - the so called RAIL model (RAilway Infrastructure Loss). Using a photographic documentation of structural damage to the double-tracked Northern Railway line caused by the March River flooding of 2006, the damage information was classified into three different damage grades. Subsequently, the correlations of the (simulated) hydraulic impacts of the event and the damage grades were investigated. After identification of the most meaningful impact parameters, we performed a set of kernel density estimations to determine the decisive thresholds of impact parameter values leading to a specific structural damage class. Finally, the structural damage classes were linked to direct economic losses and, together with the parameter thresholds, rendered into a damage model. The resulting model RAIL is capable of estimating

- expected structural damage for the standard cross-section of railway track sections and

- resulting repair costs.

This two-stage approach allows a consideration of both structural damage types and direct economic losses. Particularly the first step provides new information on the occurrence of specific flood damage grades at exposed track sections. These can then be used for different risk management purposes, e.g. for the planning of (targeted) technical protection measures. The model development with the underlying data and statistics is described in detail in the following chapter. Then, the RAIL model is applied to reanalyse the losses due to the March flooding in 2006 as well as to estimate direct flood damage to the Northern Railway and respective financial losses in cases of a 30, 100 and 300-year flood event. Finally, the model performance is compared with the depth-damage curve based approaches of both the RAM and the DSM and initial conclusions for flood loss estimation in the railway transportation sector are drawn.

2.2 Model development

2.2.1 Classification of structural damage

Comprehensive research in modelling flood damage in the residential sector show the methodological expedience to distinguish between different object classes (e.g. building types) in the model framework (e.g. Kelman and Spence, 2004; Merz et al., 2004; Maiwald & Schwarz, 2008). Accordingly, considering the general importance of certain system components for rail operations, Moran et al. (2010a) differentiate between five main classes of rail infrastructure elements: standard cross-sections, bridges, station buildings, interlocking blocks and transformer substations. For each of these components different states of structural flood damage were determined in discussions with railway operators and engineers (see Moran et al., 2010a, b). For example, a revised version of the structural damage at standard cross-sections, which will be the focus of this paper, is depicted in Fig. 2.1. A railway track`s standard cross-section consists of the elements substructure, superstructure, catenary and signals. The left box in Fig. 2.1 illustrates the damage class 1, where the track`s substructure is (partly) impounded, but there is no or only little notable damage. In the middle box, the damage class 2 is depicted. The substructure and superstructure of the track section are fully inundated and significant structural damage at least to the substructure must be expected. Finally, the right box sketches the damage class 3. Additional damage to the superstructure, catenary and/or signals must be expected here and, most commonly, the standard cross-section of the affected track section needs to be completely restored. The classes are designed for the purpose of fast and practical in-field damage assessments and scaled ordinally by progression of damage.

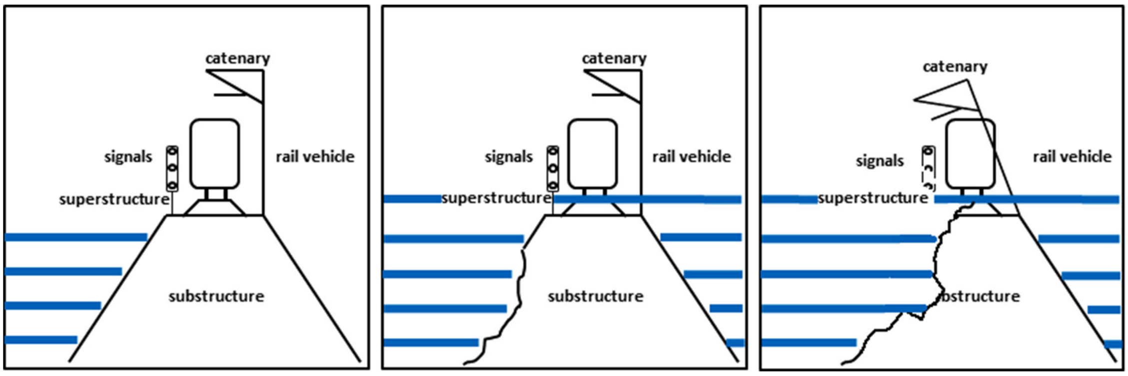

Figure 2.1: Damage classification scheme (adapted from Moran et al., 2010a).

Using the March River flood at the Northern railway in 2006 (see introduction) as an example, the occurrence of these three damage classes was mapped based on a photographic documentation of the Austrian Federal Railways (ÖBB). These nearly one hundred resulting photographs were used to evaluate and classify the structural damage at affected track sections. First, the damage patterns depicted in the photographs were georeferenced in the geoinformation system (GIS) ArcGIS 10.1 by means of distance markers along the Northern Railway track. Next, this damage data was assigned to point features, whereby each point represents a track segment with a length of 100 m and the highest damage pattern within each segment was decisive for the classification. In a final step, the generated damage points were each assigned to the damage class matching best, in accordance with the damage classification scheme (see Fig. 2.1).

2.2.2 Hydraulic impact data

The investigation of cause and effect relations between flooding and damage to railway standard cross-sections requires detailed information on the magnitudes of flood impact parameters at relevant damage spots. Similar to Kreibich et al. (2009), we investigated the relation between structural damage and five potential hydraulic impact parameters, i.e. water level, flow velocity, energy head, intensity and indicator of flow force, whereby the three latter ones are different combinations of water level and flow velocity using the following formulae:

Energy head $\mathrm{E} = h + v^2/2g$ (1)

Intensity $\mathrm{I} = v * h$ (2)

Indicator for flow force $\mathrm{IF} = h * v^2$ (3)

with

h: water level [m]

v: flow velocity [m/s]

g: acceleration of gravity = 9.81 m/s²

Since the above-mentioned event and damage documentation from the ÖBB provides no quantitative information on such flood characteristics, a transient hydraulic simulation of the March flood in 2006 was consulted. The simulation was calibrated on the basis of the March flood waves in 1997 and 1999. During the flood in 2006, three breaches occurred at different times along the flood protection levee at the March River (see Fig. 2.5), which partly influenced the waveform of the event and, thus, were also considered in the simulation. However, since only scarce information on the exact size of the breaches and their development over time was available, they could only be reproduced with limited accuracy (Humer and Schwingshandl, 2009a). The model validation was carried out by using recorded discharge data at the gauges Hohenau, Angern, Baumgarten, Marchegg and Dürnkrut as well as observed peak water levels along the river channel during the flooding in 2006. The temporal evolvement of the flood wave was reproduced very well (Humer and Schwingshandl, 2009a). The peak water levels were overestimated by the model by around 8 to 12 cm, depending on the reference gauge (Humer and Schwingshandl, 2009a).

Using the simulated water levels and flow velocities for the entire flood area on a 1 m grid as input data, the combined parameters (i.e. E, I and IF) were computed in ArcGIS 10.1 Raster Calculator.

2.2.3 Derivation of the damage model

The development of the flood damage model is essentially based on the significance of the correlation between the hydraulic flood impact and empirical damage patterns that occurred in 2006. Within the GIS, the Northern Railway is represented as a common linear feature. In order to account for the width of a multi-track standard cross-section and its potential impact area for floods, a spatial extension, i.e. a buffer zone, needs to be attached to each segment`s side facing the March River. Since this spatial limitation of causality is the decisive factor for the model`s validity, the buffer width has to be chosen sensibly. We therefore extracted hydraulic input data by using buffer widths of 5, 10, 20, 50 and 100 m in order to test the sensitivity of this factor to the significance of the correlations. By overlapping the buffer polygons with the hydraulic raster data of the March flood of 2006, those without at least a partial exposure to the simulated inundated area were excluded and the remaining polygons were taken as the relevant impact areas in the hydraulic simulation. Next, basic descriptive statistics were calculated for the extracted parameter values, whereby the respective mean values of all pixels of the five chosen flood impact parameters that (at least partly) overlap a buffer zone were further considered in the model development. In addition, the maximum values were also checked and differences will be briefly discussed.

The idea of the proposed flood damage model RAIL is to identify statistically significant correlations between different flood impacts and structural damage classes using the data basis described in the Sects. 2.1 and 2.2. Since the dependent variable (structural damage) is given on an ordinal scale, the nonparametric Spearman`s rank correlation coefficient (also: Spearman`s rho) was used to perform this analysis, whereby a correlation with a coefficient equal or superior to 0.5 was considered to be meaningful. Based on these criteria, the major purpose of our approach was to initially estimate the structural damage class to be expected for a given impact at exposed track sections. Since the damage classification (see Sect. 2.1 and Fig. 2.1) is discrete and distinct, the use of steady curve progressions (e.g. regression models) is not suitable to describe the damage evolution. Instead, it is striven to derive clear thresholds of parameter values for the assignment of an unambiguous damage class to each track segment granting sufficient validity of the model framework. Hence, we performed a set of kernel density estimations (KDE) to compute the empirical probability density distributions (Gaussian kernel) for the values of the impact parameters for each of the three damage classes. The intersections of the individual curves were subsequently used to determine the thresholds of parameter values in the RAIL model to assign the most likely structural damage class to each track segment.

In the final step of the model development, a financial loss was estimated for each structural damage class. Hereby, the following standard costs were considered: 1) costs of loss assessment/documentation, 2) cost for track cleaning per running metre (rm) and 3) standard cross-section repair costs per rm as defined by Austrian railway infrastructure experts (BMLFUW, 2008). These three cost types were individually combined for each damage class according to the corresponding damage pattern (see Fig. 2.1). Table 2.1 shows both the combined standard costs of a double-tracked segment per rm and the resultant costs for a 100 m track segment for all three damage classes.

Table 2.1: Standard repair costs per 100 m segment of a double-tracked railway standard cross-section. The costs of damage class 1 are attributable to damage documentation and cleaning of the track segment. The standard repair costs for damage class 2 were already calibrated by adding a coefficient of 0.25 (see Sect. 2.4). The cost value for damage class 3 complies with the overall damage potential of a 100 m track segment, including costs for damage documentation and cleaning.

	Damage class 1	Damage class 2	Damage class 3
Costs per 100 m segment	EUR 11,700	EUR 135,550	EUR 702,200

2.2.4 Calibration of loss estimates

Since the substructure is the most expensive system component of a railway standard cross-section, it requires special attention regarding its notably high weighting within the estimation of repair costs. In other words, the individual damage grade of the affected substructure can significantly bias the loss estimation, particularly because the underlying table of standard costs for the calculation only contains costs of full restoration providing no further graduation of costs for minor repairs (e.g. tamping of the substructure). However, if a track segment is classified to damage class 2, implying a substantial damage to the substructure, it is not fully assured that full restoration is definitely required. Our approach was, therefore, to calibrate the loss estimates by determining a proportional factor for damage to the substructure in damage class 2 on the basis of empirical loss data of the March

River flood in 2006. By knowing the exact length of the damaged track section, the individual damage grade of the track segments as well as the total repair costs of the ÖBB, the model`s boundary conditions could be set commensurate with the event. This was necessary as not all segments, which are exposed to flooding, were damaged during the March flood mainly due to effective flood protection measures. Now being applied with varying coefficients of cost calculation for the restoration of the substructure (damage class 2), the model was iteratively adjusted to the real expenses.

2.2.5 Comparing the RAIL model to RAM and DSM

Information on damage to the infrastructure sector has only been scarcely considered in flood damage modelling so far (see introduction). However, initial approaches are being implemented, for example, in the RAM and the DSM. The presented damage model RAIL was compared to these two models from ICPR (2001) and Klijn et al. (2007) in order to obtain comparative values and a further performance indication.

The RAM was developed for the International Commission for the Protection of the Rhine (ICPR, 2001; Bubeck et al., 2011). Derived from the empirical flood damage database HOWAS, the depth-damage functions were created to estimate direct tangible flood damage potentials for five re-classified CORINE land use classes depending on inundation depths (ICPR, 2001; Bubeck et al., 2011). Each of the functions is linked to a certain value of maximum damage (damage potential) in order to calculate the absolute loss per grid cell. The damage potential in the RAM was derived from gross underlying asset values as at 2001 (ICPR, 2001). Additional information on the RAM can be found e.g. in ICPR (2001) or Bubeck and de Moel (2010). Figure 2.2 (left) shows the damage curve in RAM for the land use type "Traffic", which corresponds to the infrastructure sector.

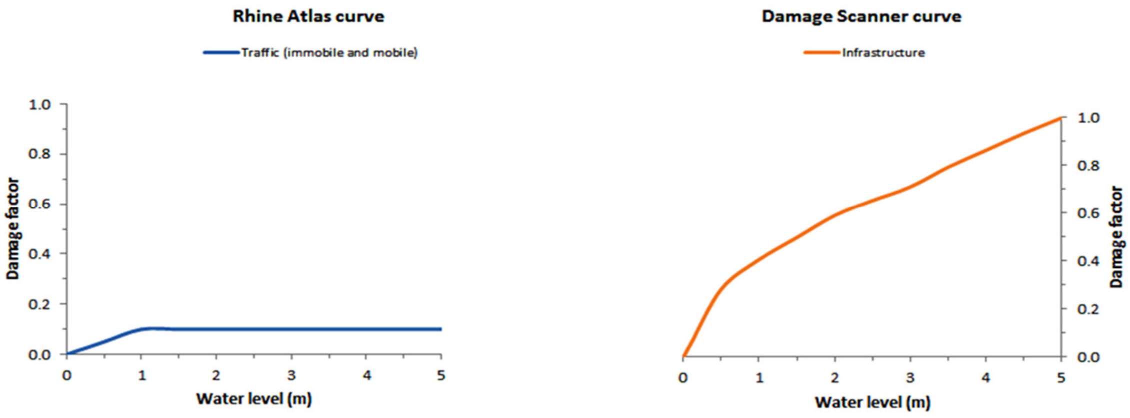

Figure 2.2: Damage curves used in the Rhine Atlas (left) and the Damage Scanner model (right) (adopted from Bubeck et al., 2011)

The DSM is based on the standard software for estimation of flood damage in the Netherlands, the Highwater Information System – Damage and Casualties Module (HIS-SSM) (Jongman et al., 2012). It was developed to obviate the disadvantage of the HIS-SSM model to require highly detailed input data on individual asset units. Due to limited availability of data on the object scale, the DSM uses only aggregated land-use data as inputs and is designed for estimations at the regional scale (Jongman et al., 2012). Differently from the RAM, this damage model has a more synthetic origin of development as its depth-damage functions are mainly derived from expert judgement, although some empirical information was used, too (Bubeck et al., 2011). Figure 2.2 (right) illustrates the damage curve shape for the land-use class "Infrastructure". Further information on the DSM is provided e.g. in Klijn et al. (2007) or Bubeck and de Moel (2010).

Both the RAM and the DSM estimate monetary losses by calculating the ratio of a predefined maximum damage depending on the particular inundation depths. In order to facilitate the comparison of RAM and DSM with the RAIL model, the two individual damage potentials for infrastructure were replaced by the ÖBB standard cross-section repair costs (see Table 2.1). Following the rationale that the damage potential of a railway track is a constant value, the model comparison is now based on the same price level. In a next step, the water levels from the hydraulic simulations were used as input for the infrastructure damage functions to calculate both total costs and respective difference factors to the RAIL model.

2.3 Statistical review and model adjustments

In this section, the results of the statistical review of the model setup and consequential model adjustments are presented.

The classification of structural damage on the basis of the photographic documentation (see Sect. 2.1) resulted in a sample size of 37 damage segments. After both the (dependent) variable damage class and the (independent) variables of flood impact were tested positive on normal distribution (Shapiro-Wilk test), the correlation coefficients were determined on the basis of Spearman`s rho. Table 2.2 provides all Spearman`s rho values resulting from the sensitivity analysis on buffer widths. The analysis revealed that both the strength and the direction of the correlation react very sensitively to the size of the area considered for potential flood impact. On the whole, it is notable that the correlation coefficients are strongly decreasing with increasing buffer width. However, there is a temporary increase in Spearman`s rho for the buffer width of 20 m for the parameters v, I and IF. From a width of 50 m the coefficients even begin to turn negative, which runs counter to the physical rationale of damage development. Solely the coefficients concerning the parameters h and E meet the defined threshold for at least some buffer widths, whereas the parameters v, I and IF are considerably below the threshold level of significance throughout all widths. The 5 m buffer obtained slightly higher coefficients than the 10 m variant. However, since the inner boundary of the buffers are set to the centre of the track lane, the buffer width of 5 m would be insufficient to cover the entire rail embankment and, thus, to enclose all elements of the cross-section adequately. Due to this technical consideration, the buffer width of 5 m was neglected in retrospect as considered to be too narrow to represent the double-track standard cross-section of the Northern Railway adequately.

Table 2.2: Spearman `s rank correlation coefficients between the dependent variable 'damage class' and each independent variable 'impact parameter' based on the mean values for varying buffer widths. The coefficients meeting the threshold level of meaningfulness, which has been set to 0.5 within this study, are highlighted in bold type. Additionally, the corresponding p-values (2-tailed, 5 % error) are provided in brackets and in italics.

	Damage class (n=37)				
Buffer width:	5 m	10 m	20 m	50 m	100 m
h	**0.532**	**0.5**	0.381	0.096	-0.066
	(0.001)	*(0.002)*	*(0.020)*	*(0.572)*	*(0.696)*
v	0.104	0.095	0.169	-0.106	-0.159
	(0.539)	*(0.578)*	*(0.318)*	*(0.531)*	*(0.347)*
I	0.334	0.323	0.399	-0.098	-0.172
	(0.043)	*(0.051)*	*(0.014)*	*(0.562)*	*(0.308)*
IF	0.261	0.090	0.216	-0.152	-0.239
	(0.119)	*(0.597)*	*(0.199)*	*(0.371)*	*(0.154)*
E	**0.532**	**0.505**	0.381	0.091	-0.066
	(0.001)	*(0.002)*	*(0.020)*	*(0.590)*	*(0.696)*

The summary statistics of the mean parameter values per damage class are illustrated by the boxplots in Fig. 2.3. Therein, only the median of h and E increases with increasing damage classes and, thus, is corresponding to the general logic of damage evolution. All other parameters are contradictory to it since the median values partly decrease with increasing damage. Furthermore, the boxplots clearly indicate a varying scatter range of the data as well as different natures of distribution for different buffer widths of the same parameter since both the lengths of the box plots and the position of the medians within the interquartile range diversify significantly. Considering these criteria, the 10 m buffer width features lower data scattering and lesser distributional skewness than widths of 20 m and higher. In damage class 1 and 2 the samples of 5, 10, and 20 m width are nearly normally distributed, whereas the widths of 50 and 100 m already show a distributional skewness in the data. In damage class 3, however, all boxplots indicate a skewed distribution of parameter values to a greater or lesser extent. Based on the shown characteristics, the buffer width of 10 m was selected for investigation of the parameters h and E, and the parameters v, I and IF are excluded from the further investigations.

As already described in Chapter 2, the identification of relevant flood impacts is based on transient hydraulic data, whereby the mean parameter values within the buffers were used for the model development. This method was chosen with the objective to reduce possible effects of very small-scale extremes in the high-resolution input data caused, for example, by cavities. On the other hand, maximum impacts might be more relevant for the extent of damage than mean values. Yet, in order to legitimise the use of mean values, the maximum values were also investigated. Table 2.3 provides the resulting correlation coefficients. In relative terms, the situation is similar to the findings on the basis of mean impacts, since h and E still show the highest correlation coefficients of all parameters and small buffer widths lead to better results than large buffer widths. In absolute terms, however, none of the combinations is meeting the defined threshold of significance of correlation and, thus, the maximum parameter values were not considered in the further course of this work.

Table 2.3: Spearman`s rank correlation coefficients between the dependent variable 'damage class' and each independent variable 'impact parameter' based on the maximum values for varying buffer widths. The corresponding p-values (2-tailed) are provided in brackets and in italics.

	Damage class (n=37)				
Buffer width:	5 m	10 m	20 m	50 m	100 m
h	0.398 *(0.015)*	0.319 *(0.055)*	0.079 *(0.641)*	-0.238 *(0.157)*	-0.136 *(0.423)*
v	0.188 *(0.266)*	0.110 *(0.517)*	0.064 *(0.705)*	-0.332 *(0.045)*	-0.315 *(0.058)*
I	0.300 *(0.071)*	0.170 *(0.314)*	-0.020 *(0.909)*	-0.302 *(0.069)*	-0.299 *(0.072)*
IF	0.251 *(0.134)*	0.147 *(0.385)*	-0.111 *(0.511)*	-0.300 *(0.071)*	-0.308 *(0.063)*
E	0.393 *(0.016)*	0.313 *(0.059)*	0.079 *(0.641)*	-0.232 *(0.166)*	-0.136 *(0.423)*

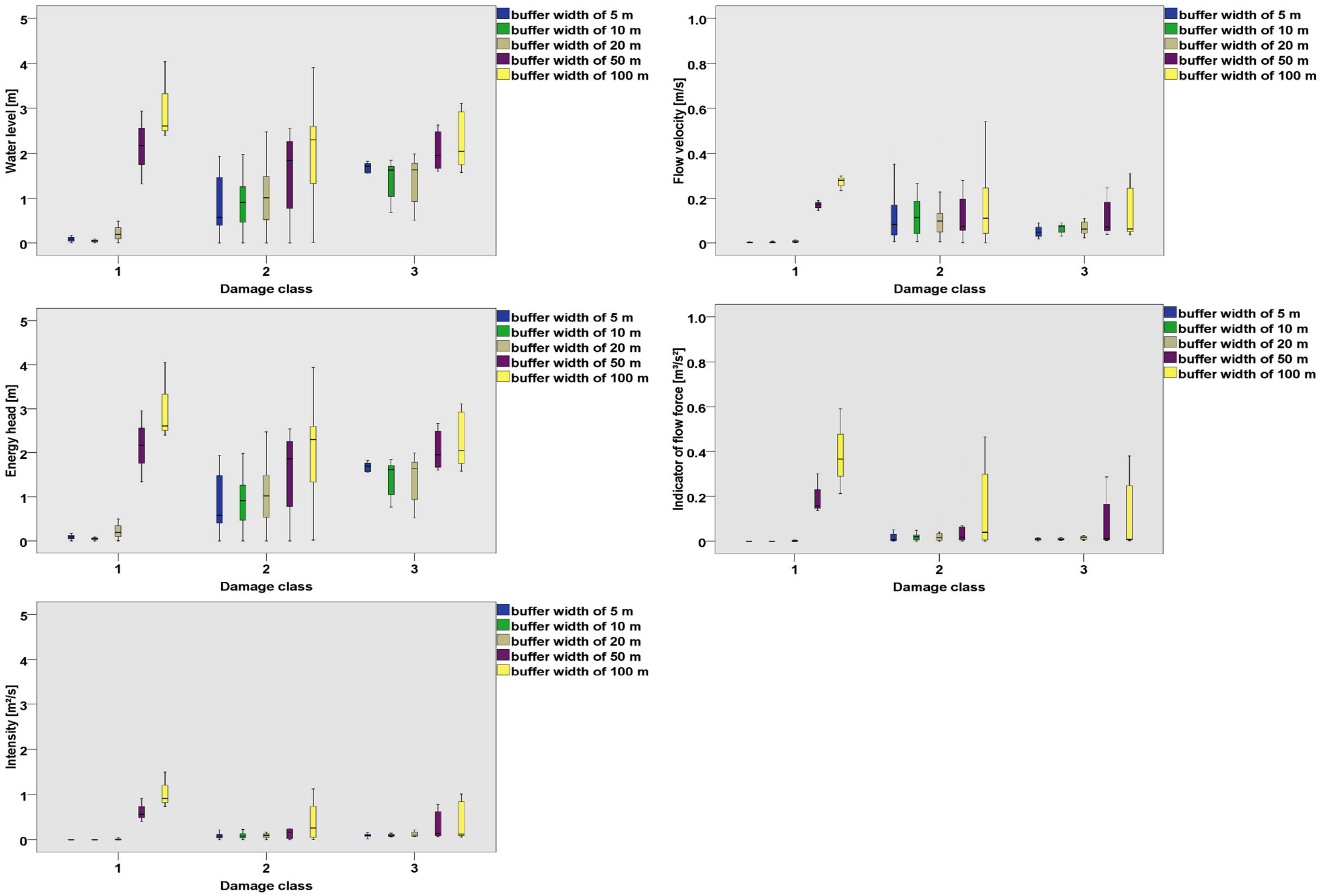

Figure 2.3: Box plots displaying the summary statistics of each impact parameter per damage class and for varying buffer widths

After identifying the impacts of concern and verifying the reference area, a KDE was performed for each parameter and damage class to derive probability-based thresholds of parameter values for the damage model. The resulting probability density plots are shown in Fig. 2.4. The black marks in the plot highlight the curve intersections being decisive for the threshold determination. It is apparent that there is almost no disparity perceptible between the curve shapes of the probability densities. As E has an additive interrelation to v - being very low for the March River flood in 2006 - its values only differ marginally from the inundation depths, which explains the close similarities of the graphs. Assessing the curve progressions also points to some characteristics in the data basis. First, differing shapes of the probability density curves are apparent showing a narrow shape for damage class 1 along with a broader span for the damage classes 2 and 3. Secondly, the curve amplitudes vary greatly between damage class 1 and damage class 2 and 3. This can be explained by 1) the very uneven sample sizes of the individual damage classes resulting from the classification of the photographically documented damage information according to the formulated scheme (see Fig. 2.1) and 2) the overall coefficient of variation (0.66) of the hydraulic data within the reference areas, which is relatively high.

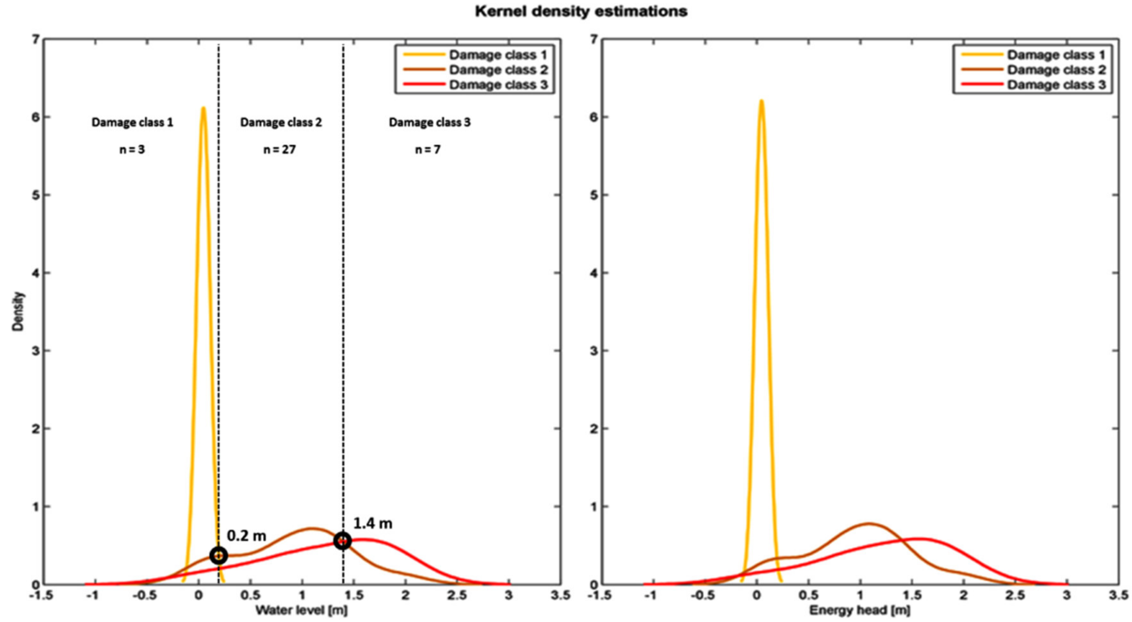

Figure 2.4: Kernel density plots for the impact parameters h and E. The parameter values at the marked graph intersection points determine the thresholds in the damage model to assign the most likely damage class to each track section. The derived values apply equally to both parameters.

Overall, a few questions still remain unanswered and some key assumptions concerning the model basis could not be validated so far. First, it was taken as granted that the correlations being investigated imply causality, although the possibility remains that unidentified parameters, certain preconditions of the test track structure or other unknowns could have been either the main cause of the damage occurrence or, at least, of partial influence. Indications thereof include the rather low correlation coefficients as the chosen impact parameters just reach the defined threshold of significance as well as the fact that data scattering is noticeably increasing and distributional skewness is arising in damage class 3. Second, there are other considerable impact parameters, such as significant flow velocities or duration of the flood impact. However, during the March River flood in 2006 only very low flow velocities occurred within the track`s impact area with the result that no meaningful correlations could be found (see Table 2.2). This parameter was therefore discarded in the model development. Both examples would presumably have at least some influence on damage patterns. Third, the data basis for loss estimation may contain considerable uncertainties. While the calculation of monetary losses is based on a table of standard costs for damage to individual infrastructure elements (see Sect. 2.2.3 and Table 2.1), its calibration was conducted using a single amount of total loss without detailed information on e.g. the composition of this amount, possible discounts or other price concessions. Finally, another source of uncertainty can be the missing information on the vertical extent of the track in GIS. The particular height of the track in relation to the surrounding area might change over course due to e.g. the substructure sectionwise being located below surface or, reciprocally, on existing railroad embankments. In such a case, the identified local water levels are significantly biased as their reference height is the ground level.

2.4 Application and evaluation

2.4.1 The March flood of 2006

The developed flood damage model RAIL was initially run with the hydraulic input of the March River flood of 2006 in order to evaluate its performance in loss estimation. For this, we compared the estimated total loss with recorded repair costs of the ÖBB incurred by this event. The results showed that the model overestimates the real loss by a factor of approximately 1.6, which indicated the need for further adjustments. Therefore, we calibrated the model by means of iteratively fitting its loss estimation in damage class 2 to the real expenses (see Sect. 2.2.4). The calibration resulted in a cost reduction of 75 % in this damage class. The overestimation bias of the RAIL model could thereby be reduced from the initial 60 % to approximately 2 %. The result of the (calibrated) loss estimation is provided in Table 2.4. Additionally, the model results for the March flood data are cartographically mapped in Fig. 2.5 showing the inundation areas including water levels as well as classified damage at flood affected track segments.

Table 2.4: Estimated frequencies of damage classes and resulting repair costs for the March flood in 2006.

	Damage class 1	Damage class 2	Damage class 3	∑
n	30	54	39	123
Repair costs	EUR 351,000	EUR 7,319,700	EUR 27,385,800	EUR 35,056,500

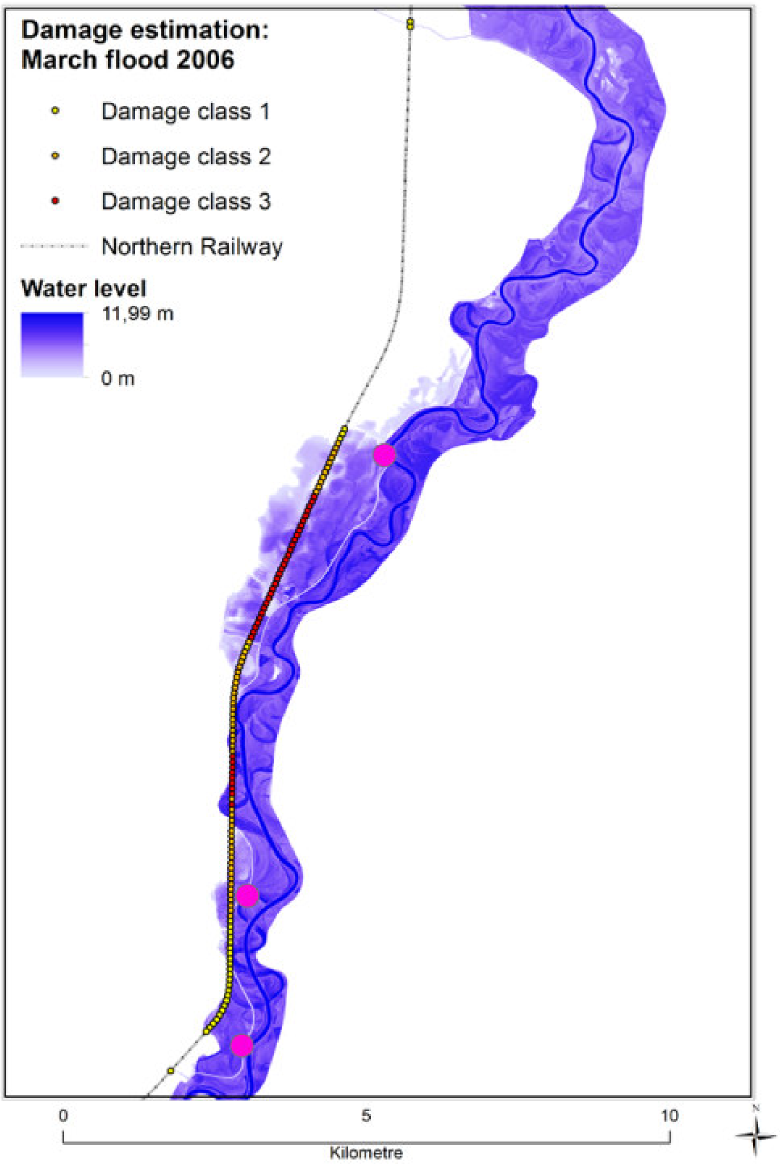

Figure 2.5: Estimation of damage potentials for the March river flood in 2006. During the event, three levee breaches occurred at three different locations along flood protection levee at the March River (see pink dots).

Although this event is classified as a 100-year event according to the observed discharge at the gauge Angern, the inundation area in the northern half of the river section considerably differs compared to the synthetic 100-year event (see Fig. 2.6 and Sect. 2.4.2). While the respective area has not been flooded in 2006, the synthetic scenario discloses wide-scale inundation in this section. This is due to the difference in the underlying assumptions of levee breaches in the simulations. The hydraulic remodelling of the real flooding in 2006 considers the three actual levee breaches that have occurred during the event (see Fig. 2.5), whereas the synthetic 100-year event simulation neglects these breaches, but includes a levee breach scenario at the March tributary Zaya (Humer and Schwingshandl, 2009b).

This naturally results in significant differences in the inundation areas as well as the hydraulic impact. Hence, there is greater exposure of the Northern Railway to the real event in 2006 and the respective total losses are more than 1.6 times higher than for the synthetic 100-year event (see Table 2.4 and 2.5). The results clearly indicate the strong sensitivity of the flood damage model on the hydraulic input and its underlying assumptions.

Furthermore, it should be noted that the March flood affected only slightly more than 10 km of the Northern Railway track, whereas the flood damage model states 12.3 km of exposure based on the hydraulic input. This discrepancy can have numerous reasons such as insufficiently detailed information on local flood characteristics or mobile/temporal flood protection measures not being considered in the setup of the hydraulic simulation. Regarding the latter point, massive efforts were made during the event by the local fire brigade, the Austrian Armed Forces, emergency services and the police (Bezirksfeuerwehrkommando Gänserndorf, 2006). In the aftermath of the March flood event, existing technical flood protection measures have been refurbished, extended and upgraded with state-of-the-art technology in order to achieve an appropriate level of protection (HQ100) for flood prone areas at the March River.

2.4.2 Flood scenarios

In a subsequent step, the damage model was applied to a set of hydraulic scenarios complying with synthetic 30-year, 100-year, and 300-year March River floods. The selected return periods play a major role in various natural hazard management strategies in Austria. For instance, the same return periods serve as a basis in the preparation of hazard zone maps by the Austrian Avalanche and Torrent Control (WLV). Figure 2.6 depicts the model results for the different synthetic scenarios sorted in ascending order according to maximum water levels. The maps show the individual inundation areas including water levels as well as the classified damage at flood affected track segments. Primarily induced by an increasing size of the inundation area as well as higher water levels, the Northern Railway is increasingly exposed with decreasing probability of flooding. As a consequence thereof, the number of affected track segments as well as the related damage potential is rising likewise. The model results on the estimation of monetary losses are shown in Table 2.5. Basically, the calculated costs amount to a plausible order and scale as the total costs increase for lower probability events. Although the uncertainties of estimations are not being quantified, the information on the order of loss magnitudes alone is already valuable for risk management.

Within the scope of risk assessments, the expected annual damage (EAD) is also a common risk metric. The EAD is defined as the annual monetary loss that is to be statistically expected on the basis of selected hazard scenarios. Considering the available scenario bandwidth (HQ30-HQ300) in this case study, the EAD amounts to EUR

839,721. Herein, the share of loss equals to 46 % for the low-probability events (HQ100-300) and 54 % for the high/medium-probability events (HQ30-HQ100), respectively.

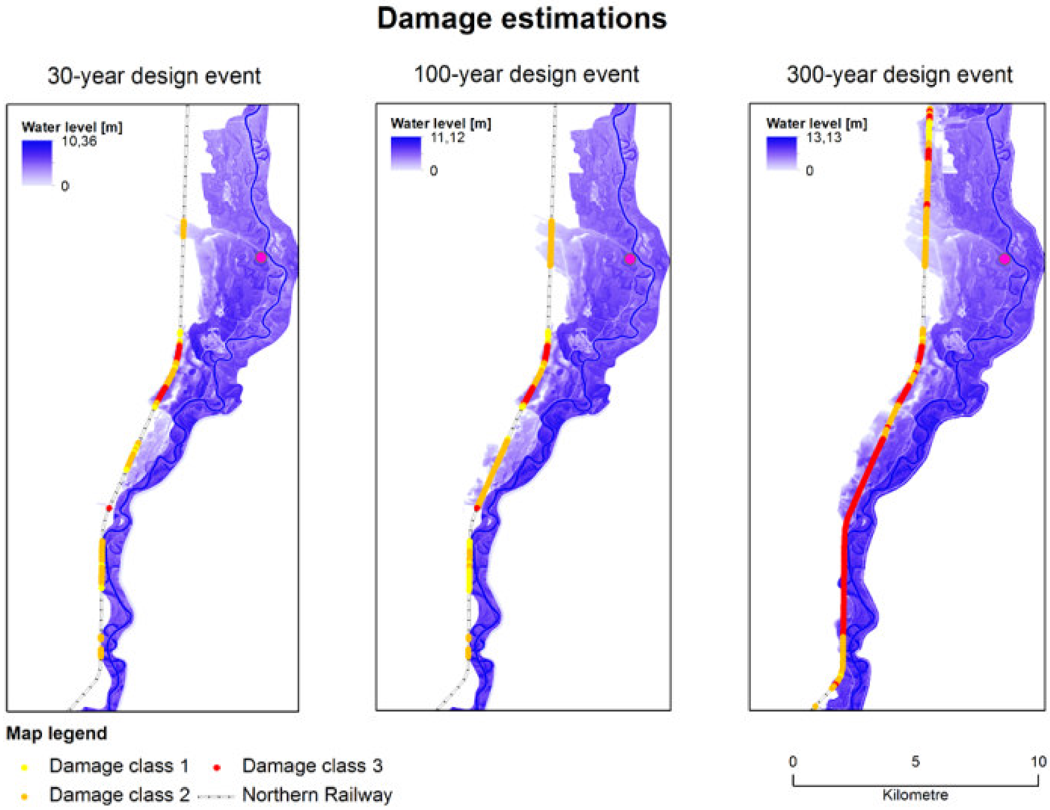

Figure 2.6: Estimation of damage potentials for three flood scenarios for the Northern Railway. The left map shows the model results for the hydraulic input of a synthetic 30-year event. The results for a synthetic 100-year event are illustrated in the middle map. The right map covers the results of the model application with the hydraulic input of a 300-year design event. In contrast to the hydraulic input of the March flood in 2006, the three levee breaches were not considered in these design events. Instead, a levee breach scenario at the March tributary Zaya was included (see pink dot). Hence, although the March River flood in 2006 was classified as a 100-year event, significant differences to the synthetic 100-year event can be identified (e.g. inundation area, local water levels).

Table 2.5: Estimated frequencies of damage classes and resulting repair costs for different hydraulic scenarios.

		Damage class 1	Damage class 2	Damage class 3	∑
HQ30	n	10	52	15	77
	Repair costs	EUR 117,000	EUR 7,048,600	EUR 10,533,000	EUR 17,698,600
HQ100	n	21	74	16	111
	Repair costs	EUR 245,700	EUR 10,030,700	EUR 11,235,200	EUR 21,511,600
HQ300	n	9	96	114	219
	Repair costs	EUR 105,300	EUR 13,012,800	EUR 80,050,800	EUR 93,168,900

2.4.3 Results of the model comparison

In the final part of the study, the RAIL model was compared with the depth-damage-curve based approaches of both the RAM and the DSM. Table 2.6 (March flood) and Table 2.7 (synthetic scenarios) show the results of loss estimation with RAM and DSM as well as the corresponding difference factors to the results of the RAIL model. As already mentioned in the introduction paragraph, the RAM and the DSM tend to underestimate damage to infrastructure for various reasons. The difference factors to the RAIL model fortify this finding, at least for railway infrastructure: The RAM estimations amount to only around a fourth of the losses compared to the results of the RAIL model. Although the DSM results are significantly better in line with our calculations, there is still a notable underestimation of around 10 % to 30 % of total losses except for the HQ100 scenario, where the costs are overestimated by around 10 %. Moreover, the absolute difference becomes stronger with rising event return period. Both comparative models seem to have no particular bias to high (or low) water levels, since there is no consistent increase (or decrease) in the difference factor with changing event probability and, associated therewith, alternating water level magnitudes.

Table 2.6: Calculated monetary losses for the March flood in 2006 according to the Rhine-Atlas Model (RAM) and the Damage Scanner Model (DSM).

RAM	Difference factor to RAIL	DSM	Difference factor to RAIL
EUR 8,099,812	4.3	EUR 29,162,547	1.2

Table 2.7: Calculated monetary losses for the synthetic flood scenarios according to RAM and DSM.

	RAM	Difference factor to RAIL	DSM	Difference factor to RAIL
HQ30	EUR 3,809,787	4.6	EUR 15,219,675	1.2
HQ100	EUR 5,643,006	3.8	EUR 23,178,842	0.9
HQ300	EUR 22,688,580	4.1	EUR 73,126,300	1.3

Indeed, the evaluation of the RAM and DSM via the difference factor is relativize by the fact that our developed approach of damage modelling to infrastructure could not have been validated yet due to lack of data. Nevertheless, the comparison of the RAM and DSM results for flooding in 2006 with the official repair costs of the ÖBB proves that the estimations are significantly biased, especially when considering that these reference costs refer only to the restoration of the railway standard cross-section (approx.. EUR 34.3 million) and do not include the repair costs of other railway infrastructure elements, which would imply additional costs of approximately EUR 7 million (Moran et al., 2010a; ÖBB-Infrastruktur AG, 2014). Hence, the findings of this comparison indicate the relevance of the level of detail in the input data that is used for the derivation of damage functions as well as the variety of exposed assets to be considered in the damage model. Since both the RAM and the DSM use aggregated land use data as input values, they are based on a certain degree of generalisation. Thus, the damage to railway infrastructure only marginally contributes to total damage as it is only one out of many damage categories with varying asset values and spatial configurations. Nevertheless, despite of their similar modelling approach, the DSM obtains far better loss estimates in our case study. This can be explained by the fact that the DSM damage function better reflects the real damage evolution with respect to railway infrastructure. In contrast, the RAM curve does not sufficiently differentiate between certain assets of infrastructure. Instead, the approach is based on a rough average of direct tangible losses over the entire land use class also including comparatively low assets, which adversely affects the loss estimations solely for expensive infrastructure elements such as railway system components.

2.5 Conclusions

The purpose of the approach presented in this paper was to initially estimate the expected structural damage for a given flood impact at exposed track sections. This step frequently is skipped in existing flood damage models as only (relative or absolute) monetary losses are computed. However, the localization of significant structural damage potentials at specific track section and, coupled therewith, the identification of risk hot spots creates great added value for railway constructors and operators in terms of network and risk management. Such information allows, for example, the targeted planning and implementation of (technical) risk reduction measures. In this regard, the model performance already proves expedient as the mapped results plausibly illustrate the high damage potential of the track section located closely adjacent to the course of the river March (see Fig. 2.5 and 2.6) as well as a general accordance with inundation depths.

Basically, the RAIL model cannot only be applied to estimate flood damage and related costs for specific railway lines, but also to an entire railway network provided the following two conditions are met: First, the general construction characteristics of the infrastructure must be similar to the ones of the Austrian Northern Railway. Accordingly, slab tracks (i.e. high-speed railway lines), for example, are not suitable to be investigated by RAIL since their construction design is significantly different from the design of the Northern Railway line and, hence, the derived correlations of flood impact and resulting damage are no longer valid. Second, since the RAIL model was derived from flood impacts caused by rather low flow velocities, i.e. static river flooding, and has not yet been tested for other flood types such as flash floods, it is assumed that the RAIL mode is in a first instance valid for lowland rivers. This aspect needs to be considered for an application to a broader railway network being at risk of flooding, particularly in countries with complex topography. In Austria, for example, around 65% of the national territory is located in Alpine areas mainly characterized by high relief energy and steep slopes. In such topography, fluvial natural events often show hydraulic characteristics being significantly different to static river flooding, e.g. regarding the flow velocity. Further cases and data are needed to adapt the RAIL model to such conditions.

The RAIL model could not yet be validated by an independent data set. Respective reviews, thus, are required when appropriate empirical data is available and further research also on potential sources of uncertainty is needed (see Sect. 2.3). On the latter point we intend to put special emphasis on the flow velocity v as this parameter is considered to also have substantial impact on railway infrastructure above a certain magnitude. Its investigation was not suitable so far due to the fact that the March flood in 2006 – being classified as a static river flood - was characterised by very low flow velocities. Therefore, testing the model`s performance in estimating structural damage caused by a dynamic flood event with high flow velocities is striven.

Further reviewing the model`s loss estimation is another issue of concern. Although the approach was calibrated to real expenses due to flooding in 2006, a verification of the loss estimation accuracy against independent loss events is still missing due to data scarcity. Nevertheless, its comparison to the RAM and DSM loss estimations for the available scenarios points out that our presented approach is well under way. The most obvious difference between the RAIL model and the established tools lies in the model characteristics itself. While our approach is developed and specified only for railway infrastructure, the other two models focus on flexibility in application in a generalized manner, which of course affects their model accuracy for selective applications.

Overall, the findings of this study show that the development of reliable flood damage models is heavily constrained by the continuing lack of detailed event and damage data. Future research in natural risk should focus on the development of event and damage documentation procedures to overcome this significant hurdle in flood damage modelling.

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Chapter III – Large-scale application of the flood damage model Railway Infrastructure Loss (RAIL)

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Abstract

Experience has shown that river floods can significantly hamper the reliability of railway networks and cause extensive structural damage and disruption. As a result, the national railway operator in Austria had to cope with financial losses of more than EUR100 million due to flooding in recent years. Comprehensive information on potential flood risk hot spots as well as on expected flood damage in Austria is therefore needed for strategic flood risk management. In view of this, the flood damage model RAIL (RAilway Infrastructure Loss) was applied to estimate (1) the expected structural flood damage and (2) the resulting repair costs of railway infrastructure due to a 30-, 100- and 300-year flood in the Austrian Mur River catchment. The results were then used to calculate the expected annual damage of the railway subnetwork and subsequently analysed in terms of their sensitivity to key model assumptions. Additionally, the impact of risk aversion on the estimates was investigated, and the overall results were briefly discussed against the background of climate change and possibly resulting changes in flood risk. The findings indicate that the RAIL model is capable of supporting decision-making in risk management by providing comprehensive risk information on the catchment level. It is furthermore demonstrated that an increased risk aversion of the railway operator has a marked influence on flood damage estimates for the study area and, hence, should be considered with regard to the development of risk management strategies.

3.1 Introduction

The railway transportation system in Austria is of major importance for the European transit of passengers and goods from north to south and east to west. In addition, the railway lines are essential for the accessibility of lateral alpine valleys and, thus, contribute to economic and societal welfare. However, experience has shown that river floods can significantly hamper the reliability of railway networks and cause extensive structural damage to parts of the infrastructure and disruption in the network (Nester et al., 2008; Moran et al., 2010a, b; Kellermann et al., 2015). Particularly in recent years, the national railway operator in Austria, the Austrian Federal Railways (ÖBB), had to cope with financial losses of more than EUR 100 million due to flooding. For example, the 100-year Morava River flood in Lower Austria in 2006 washed parts of the Northern Railway (Nordbahn) away and caused repair costs of more than EUR 41.4 million (Moran et al., 2010a; ÖBB-Infrastruktur AG, personal communication, 2014) and a complete shutdown of passenger and freight operations for several months along the Austrian Northern Railway (Moran et al., 2010b; Kellermann et al., 2015). The severe flooding in central Europe in May and June 2013 had even more serious consequences for the ÖBB, costing a total of more than EUR75 million (ÖBB Infrastruktur AG, 2014), caused by heavy direct damage at multiple track sections as well as extensive service disruptions, including loss due to further rainfall-triggered events (e.g. debris flows, torrential processes). Such events clearly show that railway infrastructure and service are highly vulnerable to floods and furthermore point out the importance of a comprehensive flood risk management.

Given the significance of flood hazards as well as other natural hazards, e.g. debris flows and extreme weather events (e.g. Fuchs et al., 2015; see Fig. 3.1), the ÖBB maintains its own department for natural hazard management and additionally cultivates partnerships with various stakeholders at different administrative levels. Figure 3.1 provides a schematic overview of the ÖBB risk management cycle and the most important partners involved. In the context of risk reduction, the ÖBB follows two main strategies (Otto et al., 2014; see Fig. 3.1). One strategy focusses on structural risk reduction measures, i.e. planning, design, implementation and maintenance of technical protection measures such as embankments and torrent control structures. This strategy is mainly applied to reduce risks from avalanches, rock falls and torrents, particularly in alpine areas, but also in lowland river catchments, where appropriate. However, the implementation of technical protection measures is often not feasible either for economic reasons or due to aspects of nature and landscape conservation (Brauner, 2011). Moreover, technical measures are limited in ensuring a commensurate level of safety for railway operations in Alpine topography (Kellermann et al., 2016a). Hence, in recent years, natural hazard and risk management has shifted from pure technological and protective approaches towards a more integrated risk management strategy including a variety of non-structural measures in order to mitigate (residual) risks from natural hazards. Accordingly, the second main risk management strategy of the ÖBB also puts strong emphasis on non-structural, precautionary and preparatory risk mitigation measures, i.e. monitoring and early warning systems with organizational measures such as speed limits and track closures in dangerous situations (Kellermann et al., 2016a).

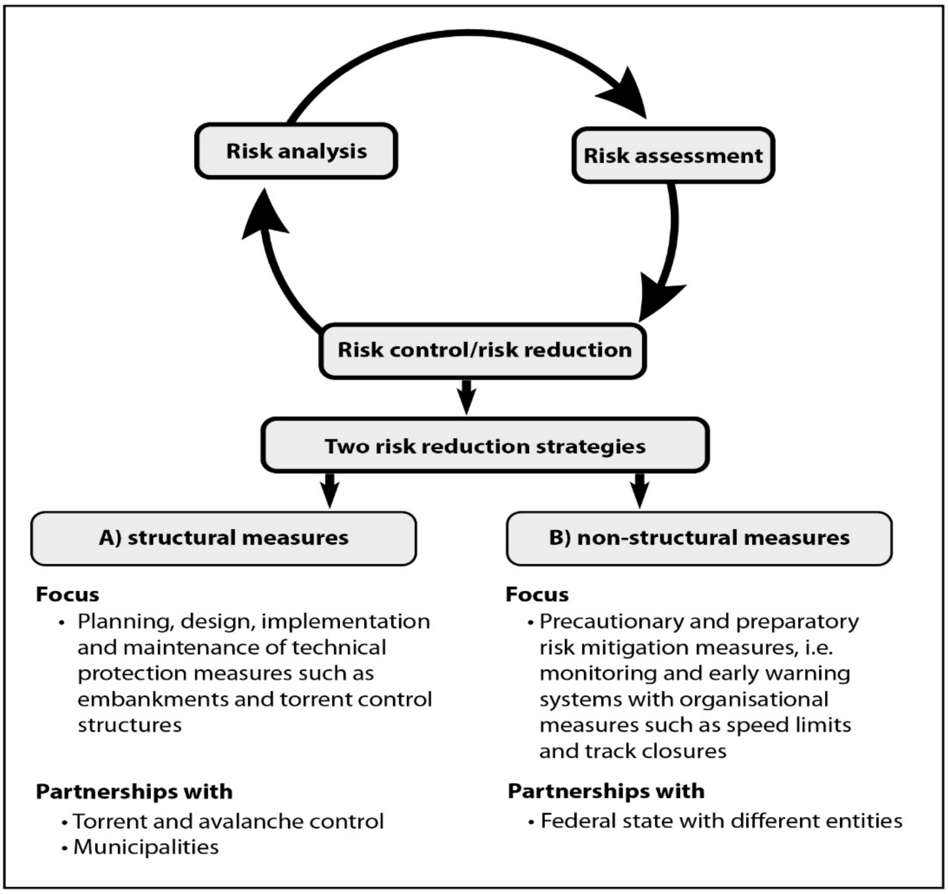

Figure 3.1: Risk management cycle and strategies of the ÖBB

To support strategic flood risk management and decision-making with a focus on structural measures, reliable information on potential flood risk hot spots as well as on expected flood damage is needed. However, modelling flood damage to transportation infrastructure is either neglected in natural hazards and risks research or only roughly estimated by a fixed percentage share of property losses – as practised, for example, in the Multi-Coloured Manual (MCM) (e.g. Penning-Rowsell and Chatterton, 1977; Penning-Rowsell et al., 1992, 2005, 2010, 2013). Although a few established flood damage models such as the Rhine Atlas damage model (RAM) (ICPR, 2001) and the Damage Scanner model (DSM) (Klijn et al., 2007) consider direct flood damage to infrastructure by dedicated depth–damage curves, their estimations are based only on aggregated, low-resolution CORINE land cover data containing a large variety of urban infrastructure and lifeline elements (Bubeck et al., 2011; Jongman et al., 2012). As a consequence, the model outputs of RAM and DSM only insufficiently reflect damage to linear structures and furthermore provide no detailed information on the individual shares of damage to transport infrastructure (Bubeck et al., 2011).

Kellermann et al. (2015) aimed at closing the gap of more targeted flood risk analyses for the railway transportation sector by developing a flood damage model for the estimation of both structural damage to railway infrastructure and incurred direct economic losses, i.e. repair costs. This model, named RAilway Infrastructure Loss (RAIL), was derived from empirical, i.e. photo-documented, flood damage data collected during and after the Morava River flood in Lower Austria in 2006. The model RAIL is capable of estimating (1) the expected structural damage for the standard cross section of railway tracks using water depths as a basis and (2) resulting repair costs. This two-step approach allows us to estimate not only direct economic loss, which is a widespread research practice, but also structural damage types. The latter capacity of the RAIL model enables the user to obtain new information on the occurrence of specific grades of structural flood damage at individual track segments and, hence, to identify potential hot spots of flood risk at railway tracks and to support the decision-making with regard to flood risk management tasks, e.g. the strategic planning and prioritization of technical protection measures. A similar approach was implemented by Maiwald and Schwarz (2014a, b) for residential buildings damaged by river floods. A comparative study of methods to assess the physical vulnerability of structures is given in Papathoma-Köhle (2016).

So far, a large-scale estimation of flood damage explicitly to railway infrastructure is still missing, since both appropriate flood damage models and suitable exposure data were lacking. However, such risk information is needed for comprehensive flood risk assessment, as well as for support of the decision-making within railway operations management. The objective of the study at hand was to fill this research gap. Thus, the RAIL model was applied to the Austrian railway subnetwork located in the Mur River catchment and the model uncertainties of RAIL were investigated by analysing the sensitivity of the model results to the modification of the key assumptions in the model framework. In a subsequent step, three different degrees of risk aversion of the ÖBB were assumed and implemented in the calculation of the expected annual flood damage in order to investigate its impact in the risk quantification. In the context of natural risk management, the term "risk aversion" indicates the aversion of the railway operator (or also the general public) towards catastrophes and distress (BABS, 2003). Accordingly, the implementation of risk aversion in the risk quantification of flood risk for railway infrastructure allows putting special emphasis on the ultimate premise of the ÖBB to ensure safety of passengers and personnel (see Eisenbahngesetz §19b, 2016). Finally, since climate change might have a certain impact on future flood risk in Austria and, hence, relativize the risk information obtained in this study, related research findings were briefly evaluated. In doing so, we aim at obtaining indications on the sustainability of the current flood risk characterization as well as respective management approaches.

3.2 Data and methods

3.2.1 The Mur River catchment

The Mur River catchment was selected as an application area for the RAIL model due to (1) availability of both digital elevation model and hydraulic simulation data, (2) an appropriate spatial scale for a large-scale test approach and (3) the significant importance of the regional infrastructure subnetwork for the ÖBB railway service (see Sect. 3.2.4). The Mur River is the main river of the province of Styria located in southern Austria (see Fig. 3.2). Originating in the Salzburg Alps, the Mur runs through the province of Styria and its capital Graz, crosses the borders to Slovenia, Croatia and Hungary and empties into the Drau River after a total water course length of approx. 453 km (thereof approx. 350 km in Austria) (Fartek et al., 2001). Draining an area of approx. 10 340 km^2 of Austrian national territory, the average flow of the Mur at the gauge Mureck is 147 m^{3}s^{-1} and the highest ever measured flow reached 1251 m^{3}s^{-1} in August 2005, which corresponds approximately to a 10-year flood event (BMLFUW, 2013). The flow of a 100-year flood event was estimated to 1800 m^{3}s^{-1} (Fartek et al., 2001).

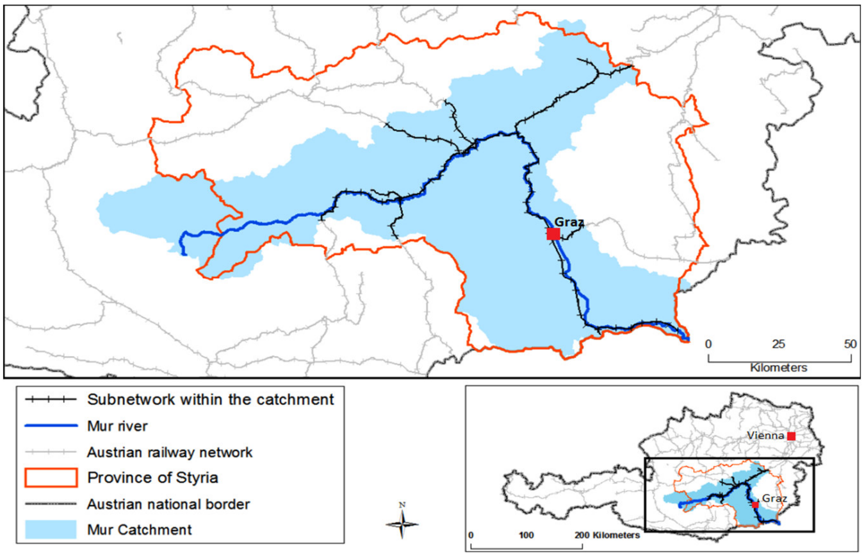

Figure 3.2: The Mur River catchment including the railway subnetwork under consideration

3.2.2 The RAIL model

The flood damage model RAIL was empirically derived from the Morava River flood event in 2006 at the Austrian Northern Railway and designed to estimate both structural damage at a railway track's standard cross section and the resulting repair costs (see Sect. 3.3.1). A railway track's standard cross section consists of the elements substructure, superstructure, catenary and signals. Depending on the water level at exposed track sections, different degrees of structural flood damage can be expected at one (or more) of those elements. In order to estimate these, the RAIL model distinguishes three structural damage classes. The classes are designed for the purpose of fast and practical in-field damage assessments and scaled ordinally (Kellermann et al., 2015). In damage class 1, the track's substructure is (partly) impounded, but no or only little notable damage is expected. When being classified as damage class 2, the substructure and superstructure of the affected track section is fully inundated and significant structural damage at least to the substructure must be expected. Consequently, additional damage to the superstructure, catenary and/or signals is expected in damage class 3 and, hence, the standard cross section of the affected track section is assumed to be completely restored.

For the estimation of the financial losses due to the repair of damaged track sections, the following standard costs were considered (Kellermann et al., 2015): (1) costs of loss assessment/documentation, (2) cost for track cleaning per running metre (rm) and (3) standard cross section repair costs per rm as defined by Austrian railway infrastructure experts (BMLFUW, 2008). These three cost types were individually combined for each damage class according to the corresponding structural damage pattern. Therefore, the standard repair costs for a damage class 1 amount to EUR 11 700, the costs for damage class 2 are EUR135 550 and the costs for damage class 3 total EUR 702 200, whereby all values refer to a 100m section of a double-tracked railway line. For single-tracked railway lines, these values have to be adapted.

The substructure is the most expensive element of a railway standard cross section and, hence, has a notably high weight within the estimation of repair costs. Therefore, the damage grade of a damaged substructure can significantly bias the loss estimation, since the defined standard repair costs only consider a full restoration providing no further graduation of costs for minor repairs (e.g. tamping of the substructure). However, since it is not assured that a full restoration of the substructure is required when a track section is classified as damage class 2, the loss estimates had to be calibrated (Kellermann et al., 2015). Hence, a proportional factor for damage to the substructure in damage class 2 was determined on the basis of the empirical damage data of the Morava River flood in 2006. This approach resulted in a cost calibration factor for damage class 2 amounting to 0.25. More detailed information on the RAIL model can be found in Kellermann et al. (2015).

3.2.3 Exposure analysis

Comprehensive flood hazard information, i.e. area-wide data on water depths at affected track sections, is required to apply the RAIL model at the catchment scale. In the framework of the implementation of the European Floods Directive (European Union, 2007, Directive 2007/60/EC), a series of flood hazard maps that basically meet those data requirements were produced for Austria. More detailed information on Austria's flood hazard maps can be found in BMLFUW (2015). The maps are also publicly accessible via the web-GIS tools Wasserinformationssystem Austria (WISA) (http://wisa.bmlfuw.gv.at).

However, the flood hazard maps are not sufficient as input data for the RAIL model for two reasons. First, the flood hazard maps are produced on a spatial scale of 1 : 25 000. This scale is seen as being inadequate to provide detailed spatial information on linear structures such as railway lines. Second, the flood hazard maps feature a rather low information level with respect to water depths, since this decisive flood impact parameter is only provided on the basis of three categories of water depths, i.e. <0.6, 0.6–1.5 and >1.5 m. Using this classification for water depths, it is not possible for the RAIL model to determine the resulting structural damage class at affected track segments unambiguously. However, to achieve an appropriate level of detail for issuing targeted flood warnings for the railway service and for analysing flood risks in the railway infrastructure network, the ÖBB planned to reanalyse and improve the available flood hazard information by the following approach: first, taking the Austrian flood hazard maps as reference, an exposure analysis was performed by superimposing the Austrian railway network with the designated inundation areas for flood return periods of 30, 100 and 300 years using a GIS. Thereby the network is subdivided into track sections of a length of 100 m each, which follows the standard distances between the waypoints along a railway track (i.e. the chainage) and, hence, is in accordance with the standard dimensioning approach used in railway infrastructure planning and design. In a second step, the degree of potential affectedness of the exposed track sections was further analysed by determining the height difference of the altitude of the top edge of the relevant track section and the water level line – the so-called freeboard. However, since the Austrian flood hazard maps are inappropriate for this purpose due to the coarse vertical resolution of water depths, a set of hydraulic simulations delivering an appropriate vertical resolution of water depths was used by the ÖBB to calculate the freeboard values.

On the basis of the exposure analysis approach described above, the degree of potential affectedness of the regional railway subnetwork (i.e. the freeboard) was determined for exposed track sections. Since the freeboard values each represent a 100m track section, they are in accordance with the design of the RAIL model, which uses the same track section length as a spatial reference for flood damage estimates.

3.2.4 Damage estimation

In order to estimate structural flood damage to railway infrastructure and resulting repair costs for a 30-, 100- and 300- year flood in the Mur catchment, the RAIL model developed by Kellermann et al. (2015) was applied (see Sect. 3.1). Therefore, the freeboard values derived from of the ÖBB exposure analysis (see Sect. 3.2.3) were considered as input. However, the RAIL model uses absolute water depths to estimate structural flood damages to the rail track (Kellermann et al., 2015).

Hence, since the freeboard values only give a relative indication of the hazard potential and provide no absolute values of water depths and since the original hydraulic simulations were not provided for use in this study, the data had to be converted accordingly. For this purpose, due to the necessity of determining the absolute construction height of the affected track sections referring to the ground level and due to the fact that no elevation profiles were accessible, assumptions had to be made about the standard construction characteristics of the railway subnetwork in the Mur catchment. A rail track consists of two major structures: the substructure and the superstructure. According to the ÖBB technical code for conventional track systems in Austria, the standard construction height for the superstructure is 50 cm. For the construction height of the substructure, however, no standard is defined, since this parameter is dependent on a variety of local terrain characteristics such as soil bearing capacity and ground inclination (Rahn, 2007). For example, on soils having a low loadbearing capacity, the construction height of the rail track's substructure must be kept low to avoid structural instabilities. With increasing ground inclinations, however, the height of the substructure must necessarily increase in order to obtain an inclination-free track layout. As a general principle and not least to save bulk material and thus costs, the height of the substructure (or rail embankment) should be kept as low as possible. According to Rahn (2007), a common construction height in a lowland area with an average soil bearing capacity is in the range of 1 m. Considering the standard construction heights of both the substructure (i.e. 1 m) and the superstructure (i.e. 50 cm) as constantly given in the study area, we used the resulting total construction height of the railway subnetwork of 1.5m as a basis for the conversion of freeboard values into absolute water depths.

First, the derived water depths were fed into the RAIL model and both the structural damage and the resulting repair costs (or direct economic loss) caused by the given flood scenarios were estimated for the entire railway subnetwork situated in the Mur catchment. The estimated structural damage classes were then cartographically mapped and the repair costs were used to calculate the expected annual damage (EAD), which is a common risk metric (Merz et al., 2009). The EAD is defined as the average monetary loss that is to be statistically expected each year and is estimated on the basis of selected discrete hazard scenarios with different probabilities. It is calculated as follows (Merz et al., 2009):

$$EAD = \sum_{j=1}^{m} \Delta P_j D_j \qquad (1)$$

where D_j and P_j are the average flood damage and the exceedance probability increment for the j-th interval, respectively, and m is the number of probability increments (Merz et al., 2009):

$$D_j = \frac{1}{2}\left(D(h_j) + D(h_{j+1})\right) \qquad (2)$$

$$\Delta P_j = P(h_j) - P(h_{j+1}) \qquad (3)$$

Since the EAD has been criticized for underrepresenting extreme events (see Merz et al., 2009), risk aversion is considered as described in section 3.2.6.

In a second step, the RAIL model was separately applied to five predefined operational sections within the subnetwork and the individual EAD values were recalculated in order to provide more targeted risk information. Those operational sections were selected by consideration of important network junctions and marked out by major rail stations with in the Mur catchment railway subnetwork. To assess the relative importance of operational sections, the number of trains running on each section was used as an indicator. Therefore, the track utilization figures of 2013 for the ÖBB railway network serves as a basis. The data contain the daily mean number of trains running on each operational section, whereby all types of train used in Austria (e.g. regional trains, express trains, freight trains) are considered. By sorting the numbers in descending order, a ranking of the importance of the operational sections within the study area was established. Hence, the operational section with the highest volume of train traffic in 2013 was classified as the most important one. The resulting ranking of importance of operational sections was then compared to the ranking resulting from their individual EAD values in order to identify potential lacks of prioritization in the implementation of risk reduction measures.

3.2.5 Sensitivity analysis

The flood damage model RAIL implies two key assumptions in the model application, namely (1) the constant construction height of the substructure of 1m (see Sect. 3.2.4) and (2) the cost calibration factor of 0.25 for the loss estimates referring to damage class 2 (see Sect. 3.2.2 and Kellermann et al., 2015). Since these simplifications may involve significant model uncertainties and, hence, lead to potential misinterpretations, the sensitivity of the model results was analysed. For this, both factors of uncertainty were modified based on two variants: modification variant A stands for the "best case" variant, where the assumed standard construction height of the substructure was increased from 1 to 1.2m and the cost calibration factor was decreased from 0.25 to 0.2. In modification variant B, the substructure height was decreased from 1 to 0.8m and the cost calibration factor was increased from 0.25 to 0.3, which is equivalent to a "worst case" model variant. The EAD was recalculated on the basis of each variant and resulting values were compared in order to assess the appearing variances.

3.2.6 The aspect of risk aversion

According to BABS (2003), one natural event causing devastating damage and loss is much more strongly perceived and evaluated by the general public than numerous events causing, in total, the same amount of damage, while the damage of each event is comparatively small. Against the background that the ultimate premise of the railway operator is to ensure safety of passengers and personnel and, hence, to prevent people being exposed to natural hazards (Thieken et al., 2013), different degrees of risk aversion were assumed and implemented in the calculation of the EAD in order to investigate its impact on the risk quantification.

In accordance with BABS (2003), three different risk aversion factors, i.e. 10, 50 and 100, were added as weighting factors to the computation of the share of EAD of the low probability events (HQ100–HQ300). Expressed mathematically, the solution of the variableD_j for $\Delta P_j = 0.0067$ (see Equation 2 and 3) was separately multiplied with each risk aversion factor and the EAD was recalculated (see Equation 1).

3.3. Results

3.3.1 Damage and loss on the catchment scale

In a first step, the potential damage and loss of the Austrian railway subnetwork within the Mur catchment were investigated. Using the derived water depths as input (see Sect. 3.2.3 and 3.2.4), the RAIL model was applied to produce scenario-based estimates of the structural damage at flood-affected track sections as well as direct monetary losses in terms of repair costs. The model estimates on structural damage are mapped in Fig. 3.3 showing the classified damage for each 100m track section. The maps indicate that significant damage has to be expected not only for long stretches along the course of the Mur River (see Figs. 3.2 and 3.3) but also at track sections being located adjacent to certain tributaries: for example, it is estimated that the Liesing River flowing into the Mur River in the north of the study area also causes extensive damage, i.e. in most cases classified as damage class 3, already on the basis of a 30-year flood scenario. The flood damage maps furthermore reveal that both the number of affected track sections and the share of higher damage classes increase with decreasing flood event probability.

The total number of potentially damaged track sections per damage class and per flood scenario as well as resulting repair cost estimates are given in Table 3.1. It is striking that the proportion of track sections classified as damage class 3 is very high already for the 30-year flood scenario. This ratio changes only slightly with decreasing event probability, since the increase in the number of track sections classified as damage class 1 or 2 then outweighs the increase in the damage class 3. However, the absolute number of affected track sections classified as damage class 3 remains the highest in all scenarios.

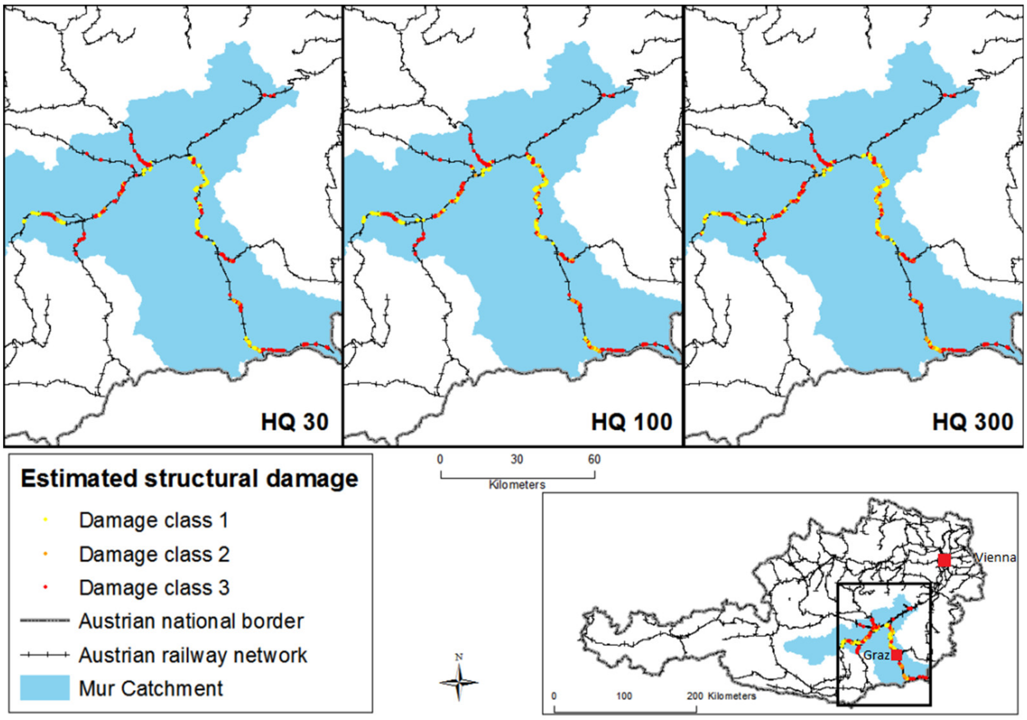

Figure 3.3: Estimation of damage potentials The map shows the RAIL model results for synthetic flood events of return periods of 30 years (left), 100 years (middle) and 300 years (right).

The large proportion of track sections encountering heavy structural damage is also reflected in the resulting repair costs of the infrastructure, since the overall costs of damage class 3 for all flood scenarios account for more than 93 % (see Tab. 3.1). Considering the available scenario bandwidth (HQ30-HQ300) for this RAIL application, the EAD for the entire railway subnetwork amounts to EUR 8,780,000 (rounded to three significant digits), wherein the loss proportion of the low-probability events (HQ100-HQ300) equals to 25 % and 75 % for the high-/medium-probability events (HQ30-HQ100). Accordingly, the share of three-quarters of high-/medium probability events in the EAD corroborates the results obtained from the flood damage maps which also demonstrate a high (structural) damage potential for this event intensity.

Table 3.1: Estimated number of damaged track sections per damage class and per flood scenario as well as related repair costs on the Mur catchment level. The EAD is rounded to three significant digits.

	Damage Class 1	*Damage Class 2*	*Damage Class 3*	*Total*	
No. of affected sections	175	36	364	575	HQ 30
Repair costs	2,047,500 €	4,879,800 €	255,600,800 €	262,528,100 €	
No. of affected sections	297	118	404	819	HQ 100
Repair costs	3,474,900 €	15,994,900 €	283,688,800 €	303,158,600 €	
No. of affected sections	321	183	457	961	HQ 300
Repair costs	3,755,700 €	24,805,650 €	320,905,400 €	349,466,750 €	
			EAD	8,780,000 €	

3.3.2 Damage and loss on the operational level

With the aim of providing more targeted information on the risk potentials, the railway network under study was further differentiated into operational sections by means of important network junctions as well as major rail stations (see Sect. 3.2.4). Figure 3.4 shows the five operational sections identified by these two selection criteria. It has to be noted that, as indicated in the map, some parts of the network (e.g. two sections in the north of the study area) are no longer taken into consideration in this step of the analysis, since either (at least) one selection criterion is not fulfilled or the operational section is not entirely located within the catchment area. After the identification of important operational sections, the EAD values were calculated for each section.

The change of the investigation level leads to more detailed insights regarding the shares of structural damage classes as well as the distribution of losses within the railway subnetwork (see Tab. 3.2). First, it emerged that the large proportion of damage class 3 identified on the network level, does not apply to all operational sections. In particular, the section Bruck a. d. Mur – Graz particularly shows segments with are classified as damage class 1 (i.e. with no or only little notable structural damage), whereas the damage classes 2 and 3 occur relatively seldom. However, the opposite can also be found: the section Bruck a. d. Mur – Mürzzuschlag shows no damage meeting the criteria for damage class 1 and 2 for all scenarios, but only track sections exhibiting damage class 3 (see Tab. 3.2). The largely differing structural damage patterns are also reflected in the individual EAD values, ranging from 110,000 EUR to

2,690,000 EUR (rounded to three significant digits).

A further objective of this study was to investigate the potential need for action in terms of risk reduction measures by comparison of the grade of track utilization of individual operational sections and their specific risk potential (see Sect. 3.2.4). Therefore, the operational sections were ranked 1) on the basis of their individual train numbers of 2013, and 2) on the basis of their EAD values. The resulting ranking is depicted both in Table 3.2 and Figure 3.4. Interestingly, the comparison shows that the ranking of EADs is ordered mirror-inverted to the ranking of track utilization. Hence, for example, the operational section Unzmarkt – St. Michael is ranked No. 1 with respect to its EAD value and shows the lowest rank with respect to the track utilization, whereas the section showing the highest rank of utilization, i.e. the section St. Michael – Bruck a. d. Mur, is ranked last in terms of its EAD value.

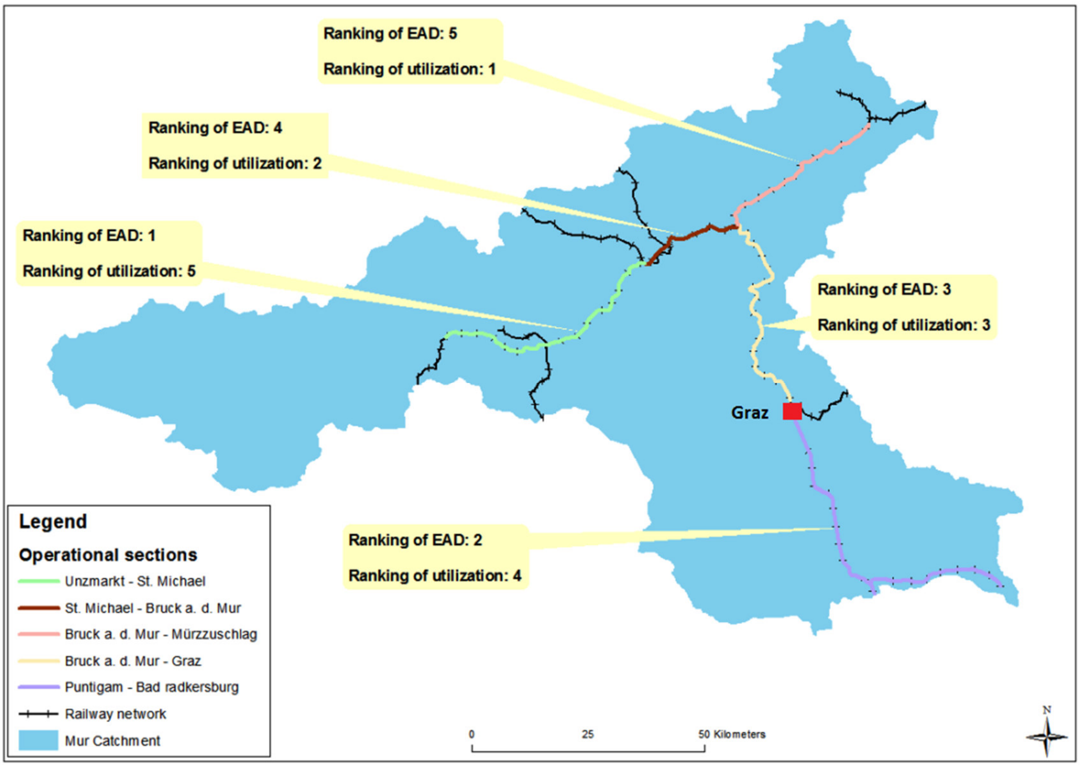

Figure 3.4: Operational sections of the ÖBB railway subnetwork. The yellow boxes provide the individual rankings according to the EAD value and the track utilization figure of 2013.

Table 3.2: Flood damage estimation on the level of selected operational sections. The table furthermore provides the individual rankings according to the EAD as well as the track utilization figure of 2013.

		Damage Class 1	*Damage Class 2*	*Damage Class 3*	*Total*	*Flood scenario*	*Rank of EAD*	*Rank of utilization*
Unzmarkt - St. Michael	*No. of affected sections*	31	16	112	159	HQ 30	1	5
	Repair costs [€]	362,700	2,168,800	78,646,400	81,177,900			
	No. of affected sections	59	38	123	220	HQ 100		
	Repair costs [€]	690,300	5,150,900	86,370,600	92,211,800			
	No. of affected sections	56	56	140	252	HQ 300		
	Repair costs [€]	655,200	7,590,800	98,308,000	106,554,000			
	EAD				**2,690,000 €**			
St. Michael - Bruck a. d. Mur	*No. of affected sections*	1	0	7	8	HQ 30	4	2
	Repair costs [€]	11,700	0	4,915,400	4,927,100			
	No. of affected sections	2	0	8	10	HQ 100		
	Repair costs [€]	23,400	0	5,617,600	5,641,000			
	No. of affected sections	6	1	9	16	HQ 300		
	Repair costs [€]	70,200	135,550	6,319,800	6,525,550			
	EAD				**164,000 €**			

Bruck a. d. Mur - Mürzzuschlag	*No. of affected sections*	0	0	5	5	HQ 30	5	1
	Repair costs [€]	0	0	3,511,000	3,511,000			
	No. of affected sections	0	0	5	5	HQ 100		
	Repair costs [€]	0	0	3,511,000	3,511,000			
	No. of affected sections	0	0	7	7	HQ 300		
	Repair costs [€]	0	0	4,915,400	4,915,400			
	EAD				**110,000 €**			
Bruck a. d. Mur - Graz	*No. of affected sections*	93	3	30	126	HQ 30	3	3
	Repair costs [€]	1,088,100	406,650	21,066,000	22,560,750			
	No. of affected sections	167	26	44	237	HQ 100		
	Repair costs [€]	1,953,900	3,524,300	30,896,800	36,375,000			
	No. of affected sections	190	49	61	300	HQ 300		
	Repair costs [€]	2,223,000	6,641,950	42,834,200	51,699,150			
	EAD				**981,000 €**			
Puntigam - Bad Radkersburg	*No. of affected sections*	30	14	96	140	HQ 30	2	4
	Repair costs [€]	351,000	1,897,700	67,411,200	69,659,900			
	No. of affected sections	25	45	108	178	HQ 100		
	Repair costs [€]	292,500	6,099,750	75,837,600	82,229,850			
	No. of affected sections	32	49	115	196	HQ 300		
	Repair costs [€]	374,400	6,641,950	80,753,000	87,769,350			
	EAD				**2,340,000 €**			

3.3.3 Sensitivity of RAIL estimates

In order to get insights in the sensitivity of the RAIL estimates, the two key assumptions for the model application were modified in two different variants and, subsequently, the EADs of the operational sections were recalculated (see Sect. 3.2.5). The resulting values of both variants and, in order to facilitate the comparison, also the EAD values resulting from the original model assumptions are depicted in Table 3.3. The application of variant A, i.e. the increase in the assumed standard construction height of the substructure from 1 m to 1.2 m along with the decrease in the cost calibration factor for damage class 2 from 0.25 to 0.2 (see Sect. 3.2.5), led to a reduced EAD in most cases. Conversely, the modification of the key model assumptions towards more unfavourable preconditions, i.e. a decrease in the standard construction height from 1 m to 0.8 m along with an increase in the cost calibration factor for damage class 2 from 0.25 to 0.3, results in augmented EAD values. However, there are two exceptions, namely the operational sections "Bruck a.d. Mur - St. Michael" and "Bruck a.d. Mur - Mürzzuschlag", for which the modifications show no effect and can thus be regarded as rather robust. In general, the comparison of the EAD resulting from the modifications with the default EAD values reveals no marked deviations ranging from approx. 4 % to approx. 10 % in relative terms, and from 99,000 EUR to 160,000 EUR in absolute terms. Accordingly, the apparent low sensitivity of results indicates a robust estimation of flood damage by the RAIL model, at least in this study area.

Table 3.3: Expected Annual Damage (EAD) for different model settings. Modification variant A comprises of an assumed substructure height of 1.2 m and a cost calibration factor of 0.2. Modification Variant B comprises of an assumed substructure height of 0.8 m and a cost calibration factor of 0.3. All values are rounded to three significant digits.

	Expected Annual Damage (EAD)		
	Modification A	*Default settings*	*Modification B*
St. Michael - Unzmarkt	2,590,000 €	2,690,000 €	2,850,000 €
Bruck a.d. Mur - St. Michael	164,000 €	164,000 €	164,000 €
Bruck a.d. Mur - Mürzzuschlag	110,000 €	110,000 €	110,000 €
Bruck a.d. Mur - Graz	919,000 €	981,000 €	1,080,000 €
Puntigam - Bad Radkersburg	2,210,000 €	2,340,000 €	2,490,000 €

3.3.4 Impacts of risk aversion

In a final step of the study, the impact of risk aversion on the estimation of flood risks was investigated in order to put special emphasis on the ultimate premise of the ÖBB to ensure safety of passengers and personnel. In detail, three different risk aversion factors were implemented in the calculation of the EAD values, whereby only the lower probability events, i.e. the HQ100-HQ300 scenario bandwidth, were of relevance (see Sect. 3.2.6). Table 3.4 presents the results for all risk aversion factors. It can be seen that the consideration of risk aversion against low probability (or high impact) events by adding a weighting factor leads to an extensively increased EAD value for all operational sections within the Mur catchment. In detail, the risk aversion factor 10 already caused an increase of more than three times the default value, whereas the factor 50 even brought an increase of more than tenfold, and the factor 100 led an the increase in the EAD value of well over 25 times the default value. In view of the fact that the HQ100-HQ300 scenario bandwidth accounts for a proportion of only 25 % of the EAD on average (see Sect. 3.3.1), the consistently large increases underline the considerable influence of the aspect of risk aversion on flood risk estimates for the study area, in particular with regard to the development of risk management strategies.

Table 3.4: Expected Annual Damage (EAD) for operational sections and for varying risk aversion factors.

	Expected Annual Damage (EAD) [€]			
Operational section	*Default settings*	*Risk aversion factor 10*	*Risk aversion factor 50*	*Risk aversion factor 100*
St. Michael - Unzmarkt	2,690,000	8,600,000	35,200,000	68,300,000
Bruck a.d. Mur - St. Michael	164,000	500,000	2,160,000	4,200,000
Bruck a.d. Mur - Mürzzuschlag	110,000	400,000	1,500,000	2,900,000
Bruck a.d. Mur - Graz	981,000	3,100,000	15,400,000	25,200,000
Puntigam - Bad Radkersburg	2,340,000	7,400,000	30,100,000	58,400,000

3.4 Discussion

In this study, flood damage to railway infrastructure was estimated on the large scale (i.e. the catchment level) with the objective of obtaining new flood risk information for railway infrastructure and, consequently, supporting strategic planning and decision-making of the ÖBB with regard to structural protection measures. For this, both the structural damage and resulting repair costs were estimated for the railway subnetwork located in the Mur catchment on two different spatial scales, i.e. the catchment level and the operational level, using the flood damage model RAIL. As a further goal, the sensitivity of estimates of the economic flood loss as provided by the

EAD was analysed by a modification of the key model assumptions. Three different degrees of risk aversion were furthermore implemented in the calculation of the EAD in order to investigate its impact on the flood damage estimates in the study area and, hence, on the potential decision-making in a risk management context.

Different aspects of the achieved results are discussed in this section. First, the limitations of the flood damage model RAIL and associated uncertainties are reflected in order to allow a sound interpretation and evaluation of the results presented thereafter. Accordingly, the potential benefits for a railway operator from the given information basis are portrayed and recommendations for action are outlined next. Finally, the achieved risk information is briefly discussed against the background of climate change and possibly resulting changes in flood risk.

3.4.1 Model limitations and uncertainties

In general, the case study demonstrates that the RAIL model can be applied to estimate flood damage to railway infrastructure in larger areas (e.g. river catchments, national territories). This can be done if the following conditions are met: 1) the general construction characteristics of the railway infrastructure must be the same as (or very similar to) the characteristics of the Northern Railway, on the basis of which the RAIL model was derived (Kellermann et al., 2015). Accordingly, slab tracks (i.e. high-speed railway lines), for example, are not suitable to be investigated by RAIL without amendments since their construction design is significantly different from the design of the Northern railway line and, hence, the derived correlations of flood impact and resulting damage would be no longer valid. Different empirical data would be needed to adapt the RAIL model to such types of railway tracks. 2) The RAIL model was derived from flood impacts caused by rather low flow velocities, i.e. river floods occurring in flat areas, which was the case at the March river flood in Lower Austria in 2006. However, around 65% of Austria is located in Alpine areas mainly characterized by high relief energy and steep slopes. In such topography, fluvial natural events often show hydraulic characteristics being significantly different to river flooding, in particular with regard to the flow velocity. Accordingly, since the RAIL model has not yet been tested for varying flood types, it is assumed that the RAIL model is in a first instance valid for lowland rivers and, hence, might be limited in estimating flood damage on the national level of a country like Austria providing a high topographic complexity (Kellermann et al., 2015). Indeed, the Mur catchment also features considerable portions of land with complex topography – first and foremost in the western part of the catchment area – and, hence, may obviously introduce uncertainties in the RAIL model estimates. Therefore, the robustness of the model results was tested.

The main model uncertainties of RAIL lie in the two key assumptions made within the model design, which are 1) the construction height of the railway substructure and 2) the cost calibration factor for the estimation of economic loss linked to damage class 2 (see Sect. 3.2.5 and 3.3.3). The first assumption had to be made in order to convert the available impact data, i.e. the freeboard values, from relative water levels to absolute water depths being the required input data format for the RAIL model. It can be assumed that fixing the construction height to a constant value involves uncertainties, since in reality the substructure height can vary significantly within larger areas, in particular in complex topographic areas. The second assumption rests on the empirical damage data of the March flood event in 2006 at the Austrian Northern Railway. In principle, this empirical factor represents the average of observed damage to the substructure of the Northern Railway (Kellermann et al., 2015). However, it may change for different study areas due to e.g. changing flood event or rail track construction characteristics, and, thus, may also entail epistemic uncertainty. In order to analyse the potential impact of the uncertainties described above, the sensitivity of results was investigated by modifying the key model assumptions. Results show that the modifications only lead to marginal variations of the estimates and, hence, suggest a certain degree of robustness (see Sect. 3.3.3). A closer look at the results further reveals that the construction height of the substructure has an overall higher influence on the loss estimates in comparison to the cost calibration coefficient, which on the one hand confirms that assuming a fixed construction height might considerably bias the results and, on the other hand, endorses the practicality of the cost calibration factor. It should be noted though that the presented sensitivities of results can only be presumed as being valid for the study area at hand, since the individual impact of all factors of uncertainty may change markedly in other study areas. For example, the damage class 2 may be better represented in other large-scale damage patterns and, hence, the influence of the calibration coefficient could increase substantially.

Initially, the RAIL model was derived on the basis of preliminary work of Moran et al. (2010a), who distinguished between five different structural damage classes to estimate the degree of flood damage for exposed track sections. The (statistical) results, however, were not satisfactory on the basis of such a detailed classification. Hence, after discussing and evaluating the initial results with railway experts, we revised the classification of Moran et al. (2010a) and reduced the number of categories from five to three with the aim to focus on structural damage to the substructure being the most important and expensive element of the standard cross-section. This approach led to a markedly increase in the statistical correlations of flood impact and structural damage and, furthermore, confirms the supposition that a finer classification of structural (and economic) damage is not required, since from the engineering perspective there is no significant difference between certain grades of damage to the track, e.g. minor, medium and major erosion damage to the substructure. In case the railway track`s substructure is (at least somehow) damaged, the train service is disrupted and the segment has to be repaired.

The uncertainty entailed by a fixed construction height of a substructure could theoretically be removed by revising the model approach. Hence, instead of using absolute water depths as the decisive flood impact parameter, the RAIL model could be newly derived on the basis of relative water levels. However, impact data providing freeboard values of railway infrastructure for a given flood scenario are usually not available, wherefore the scope of application of the RAIL model in practice would be very limited. It is therefore appropriate to initially strive for a validation of the RAIL model in order to clarify its performance in different areas. This would require a better and comprehensive documentation of damaging flood events.

Additionally, flood damage should also be estimated for more dynamic flood events and subsequently validated on the basis of documented damage in order to obtain targeted performance indicators of the damage model for higher flow velocities. Due to data scarcity, however, this validation tasks could not yet be implemented.

3.4.2 Insights for railway operation and natural hazard management

A particular added value of the RAIL model is seen in its two-step modelling approach, i.e. the estimation of both, structural damage at exposed track sections and resulting repair costs. The estimation of structural damage is usually neglected in existing flood damage models, i.e. only (relative or absolute) monetary losses are computed. However, the localization of significant structural damage potentials at specific track sections and, coupled therewith, the identification of risk hot spots is valuable information for railway constructors and operators in terms of network and risk management. Such information allows e.g. the targeted planning and implementation of (technical) risk reduction measures. For instance, the flood damage maps for the Mur River catchment clearly show a considerable increase in both the number of affected track sections and the share of higher damage classes with decreasing flood event probability. Furthermore, besides the main risk areas along the course of the Mur River, additional risk areas along certain tributaries can be easily identified (see Fig. 3.3 and Sect. 3.3.1).

To effectively prioritize the implementation of technical protection measures at the risk hot spots identified, decisive aspects such as the EAD or the importance of affected operational sections could be used as a basis. In the study at hand, the EADs were computed on the operational level, ranked in ascending order and compared to the equally ranked track utilization figure of the respective section (reference year 2013) in order to assess the current prioritization of risk reduction measures (see Sect. 3.3.2). The comparison of the rankings indicates that–from a risk management perspective–the (past) prioritization of risk reduction measures reflects the exposure to floods, as for the operational sections showing a comparatively high EAD only relatively low track utilization was recorded, and vice versa (see Tab. 3.2). In other words, the most important sections with regard to their specific train frequencies already present comparatively low economic flood risks, whereas the sections that are faced with higher risk values (i.e. EAD values) only have a comparatively minor relevance with respect to railway service.

Besides economic risks, however, there are further substantial aspects to be considered in the decision-making process. Herein, safety for passengers and personnel is the key premise for a railway operator. Three degrees of increased risk aversion were thus implemented in the estimation of the EAD in order to investigate their impact on the risk quantification and, in particular, to provide a revised foundation for decision-making with regard to the implementation of risk reduction measures (see Sect. 3.2.6). Results show that the consideration of a risk aversion factor of 10 already induces a triplication of the EAD value of all operational sections, although the overall share of low-probability events only amounts to 25 % in the Mur River catchment (see Tab. 3.4, Sect. 3.3.1 and 3.3.2). The increase in EAD values is on a similar scale for the risk aversion factors 50 and 100. As the findings show, risk aversion has a strong impact on the economic risk of railway infrastructure in the Mur catchment – and probably also in the rest of Austria. Hence, the consideration of risk aversion against low-probability flood events in the context of risk management is seen as expedient as it gives new incentives for the planning and implementation of risk reduction measures.

In recent years, the railway operation in Austria had to cope with serious financial losses as a result of flooding and other natural hazards. The March flood event in Lower Austria in 2006, for instance, caused direct economic losses of more than EUR 41 million (Moran et al., 2010a; ÖBB Infrastruktur AG, 2014, Kellermann et al., 2015), and the severe flooding in May and June 2013 in large parts of Austria even led to costs of more than EUR 75 million (see Sect. 3.3.1). As the examples demonstrate, natural events can cause serious economic loss and, hence, require appropriate risk-financing solutions. Therefore, the superordinate institution of the Austrian (state-owned) railway operator, i.e. the Federal Ministry of Transport, Innovation and Technology (BMVIT), offers a risk compensation mechanism that aims at enabling the railway operator to better cope with the economic impacts of natural hazards. In other words, the BMVIT sporadically accumulates financial reserves, which may be drawn upon by the railway operator in case of disastrous natural events. A review of recent annual reports of the railway operator reveals that such hazard-related funds were provided in 2006 (no amount specified), in 2013 (EUR 18.4 million) and in 2014 (EUR 7.2 million) to support the recovery from damage caused by natural events.

In order to illustrate the potential benefit of comprehensive risk information for the development as well as for the evaluation of risk compensation strategies, a simple thought experiment can be carried out: If we assume that the exposure of the Austrian railway network to flooding is equal (or very similar) to the exposure of the subnetwork within the Mur catchment, the flood risk information obtained for the Mur catchment can be used to estimate the theoretical annual demand of the railway operator for risk compensation of the entire railway network in Austria. More specifically, the EAD of the subnetwork can be extrapolated on the basis of the ratio between the length of the entire railway network of Austria (approx. 5841 km) and the length of the subnetwork (approx. 408 km). In terms of figures, the resulting ratio of approx. 14.3 can be used as a multiplier for the EAD value of the subnetwork (see Tab. 3.1), which results in an EAD value of approx. EUR 125.7 million of the entire railway network of Austria. A comparison of this value with the actual demand in recent years (see above) indicates a realistic dimension of the RAIL model estimates. Furthermore, the substantial amount of potential annual economic loss provides important indications of the decision-making towards an enhanced risk financing strategy, in particular with regard to climate change and possible consequences. This aspect will require close attention and might become of growing importance, as climate change could jeopardize the sustainability of current flood risk management practices.

3.4.3 Flood risk and climate change

The hypothesis that frequencies of river floods in Europe may increase in the future due to climate change is widely discussed among scientists (Hall et al., 2014; Blöschl et al., 2015). Lehner et al. (2006) as well as Dankers and Feyen (2008), for example, concluded that the frequency (and magnitude) of flooding in large parts of Europe is projected to increase in future, i.e. in the period 2071-2100 using the period 1961-1990 as reference. In particular, flash and urban floods, triggered by local intense precipitation events, are likely to be more frequent throughout Europe (Kundzewicz et al., 2006; Christensen and Christensen, 2007;). In accordance therewith, the study on future frequencies of (hydro-) meteorological extremes in Austria by Kellermann et al. (2016a) revealed an increase in the frequency of heavy rainfall events (≥ 100 mm/24 h) until 2040. However, the IPCC (2012) stated that the projections of changes in flood frequencies (and magnitudes) are subject to considerable uncertainties, since e.g. only limited evidence can be produced from river discharge simulations due to the complexity of the causes of regional changes of river flooding. Furthermore, future trends of climatic extremes cannot be projected with sufficient reliability, in particular with respect to heavy rainfall, which considerably contributes to rain-generated local flooding in most cases (Hanel and Buishand, 2010; IPCC, 2012).

Blöschl et al. (2011b) presented a study addressing the issue of changing flood frequencies in Austria due to climate change. According to them, the above-mentioned complexities and uncertainties also apply on the national level, which makes a reliable projection of future trends nearly impossible against current knowledge. Therefore, they used five different ´if-then´ scenarios to describe possible future trends in Austria. For example, one scenario is based on the assumption that the intensity of convective rainfall events will increase in future (2021-2050, in comparison to 1976-2007), and another one implies a rising snow line in the same period. In order to consider the regional complexities of flood generation, the Austrian territory was divided into ten regions taking into account the hydro-climatic situation and, subsequently, every region was analysed individually each represented by a typical, yet hypothetical area of approx. 500 km². Therein, one region is considered as being representative for the Mur river catchment. Blöschl et al. (2011b) concluded that, in general, the consistency of trend analyses for Austria depends heavily on the underlying observation period, which indicates that the high natural variability of flooding in the past may remain significantly higher than the expected impacts due to climate change. With regard to the Mur river region, no significant trends in the time series of flood events of the Mur River and its tributaries were identifiable. However, the consideration of the scenario of increasing convective rainfall intensities led to an increase in the magnitude of a 100-year flood by around 7 %, whereas the other scenarios have no significant influence (Blöschl et al., 2011b). Accordingly, the question rises whether (and to what extent) this 7 % increase might bring implications for the current flood risk situation in the catchment. This question cannot be answered unambiguously due to the above mentioned uncertainties in the projection of climate extremes. However, since research provides some indications for an increase both in the frequency of heavy rainfall (see Kellermann et al., 2016a) and floods (see Lehner et al., 2006; Dankers and Feyen, 2008), an exacerbation of the current flood hazard profile in Austria must be considered. Consequently, the damage and loss estimates presented in the study at hand might be no longer representative and, if no action is taken, the costs due to flood events must be expected to rise in the future.

3.5 Conclusions

The main objective of this study was to provide information on potential flood risk hot spots as well as on expected flood damage on the large scale in order to support strategic flood risk management and decision-making of the Austrian railway operator ÖBB. Therefore, the flood damage model RAIL was applied to estimate structural damage as well as direct economic loss to railway infrastructure in the Mur River catchment. The risk information obtained was then investigated in terms of its sensitivity to changes in model assumptions and, furthermore, evaluated while also taking into consideration different degrees of risk aversion.

The mapped results of the damage estimation (see Fig. 3.3 and Sect. 3.3.1) indicate that the RAIL model is basically capable of identifying and localizing risk hot spots at larger spatial scales. Such information can create added value for a railway operator, for example, with regard to supporting the planning and implementation of structural risk reduction measures (e.g. embankments). Further possible application fields of RAIL within flood risk management include the calculation of EAD values on the operational level (see Tab. 3.2 and Sect. 3.3.2). As the study demonstrated, the potential economic loss of an operational section, in conjunction with the individual importance, can be used to effectively prioritize the implementation of such measures or to assess the current status of prioritization, respectively. Finally, the RAIL model also allows the user to investigate the impact of risk aversion on the quantification of risk and, thus, to revise the basis for decision-making with regard to costs and benefits of implementing risk reduction measures. Indeed, the results show that the consideration of risk aversion has a marked impact on the economic flood risk of railway infrastructure in the study area (see Tab. 3.4 and Sect. 3.3.4). Against the background that the key premise of the ÖBB is to ensure safety for passengers and personnel, the risk-adjusted EAD values can be a key argument within decision-making processes.

Looking at the results of the sensitivity analysis (see Tab. 3.3 and Sect. 3.3.3), it appears that the model uncertainties of RAIL are at an acceptable level as the loss estimates revealed no marked sensitivity to the modification of the two key assumptions within the model application. Accordingly, since the results can be regarded as rather robust, an application on the national level is striven for in order to enlarge and strengthen the information basis for risk management of railway infrastructure in Austria.

However, the validity of the results could not yet be properly assessed due to the lack of documented damage and loss data from the Mur River catchment. Although the ÖBB already established an event and damage documentation system for natural hazards in Austria, the given data quality is still not sufficient to provide detailed and process-oriented information on the impacts of flooding (and other hazards) and, hence, hampers the model validation. Therefore, in order to afford a deeper understanding of natural hazards and damaging processes as well as in order to facilitate the derivation of reliable flood damage models, future risk management activities should put special emphasis on the enhancement of standardized event and damage documentation procedures.

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Chapter IV - Frequency analysis of critical meteorological conditions in a changing climate - Assessing future implications for railway transportation in Austria

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Abstract

Meteorological extreme events have great potential for damaging railway infrastructure and posing risks to the safety of train passengers. In the future, climate change will presumably have serious implications on meteorological hazards in the Alpine region. Hence, attaining insights on future frequencies of meteorological extremes with relevance for the railway operation in Austria is required in the context of a comprehensive and sustainable natural hazard management plan of the railway operator. In this study, possible impacts of climate change on the frequencies of so-called critical meteorological conditions (CMCs) between the periods 1961–1990 and 2011–2040 are analyzed. Thresholds for such CMCs have been defined by the railway operator and used in its weather monitoring and early warning system. First, the seasonal climate change signals for air temperature and precipitation in Austria are described on the basis of an ensemble of high-resolution Regional Climate Model (RCM) simulations for Europe. Subsequently, the RCM-ensemble was used to investigate changes in the frequency of CMCs. Finally, the sensitivity of results is analysed with varying threshold values for the CMCs. Results give robust indications for an all-season air temperature rise, but show no clear tendency in average precipitation. The frequency analyses reveal an increase in intense rainfall events and heat waves, whereas heavy snowfall and cold days are likely to decrease. Furthermore, results indicate that frequencies of CMCs are rather sensitive to changes of thresholds. It thus emphasizes the importance to carefully define, validate, and—if needed—to adapt the thresholds that are used in the weather monitoring and warning system of the railway operator. For this, continuous and standardized documentation of damaging events and near-misses is a pre-requisite.

4.1 Introduction

The railway transportation system of the Alpine country Austria plays an important role in the European transit of passengers and goods. In total, 11.7 million tons of goods were transported across the Austrian Alps in 2013, which is 28% of the total volume recorded for the inner Alpine Arc (UVEK, 2013). In addition, railway lines are essential for the accessibility of lateral Alpine valleys and thus contribute to their economic and societal welfare. The harsh mountainous nature of the Eastern Alps, in which around 65% of the national territory of Austria is situated (Permanent Secretariat of the Alpine Convention, 2010), poses a particular challenge to railway transport planning and management. Relief energy and steep slopes limit the space usable for permanent settlements and infrastructure (e.g., amounting to 15%–20% of the whole Alpine Convention territory) (Price, 2009). Hence, railway lines often follow floodplains or are located along steep unsteady slopes, which considerably exposes them to flooding and in particular to Alpine hazards (e.g. debris flows, rockfalls, avalanches, or landslides).

The majority of (Alpine) natural hazards are triggered by extreme/severe (hydro-) meteorological events such as heavy precipitation, rapid snow melt, or extreme temperatures (Alcántara-Ayala and Goudie, 2010). More than 1200 weather events that caused direct or indirect damage to Austria's railway infrastructure (e.g., heavy precipitation, heat waves, or storms) occurred between 1990 and 2011 Rachoy, 2012). In this context, direct damage is generally understood as damage resulting from physical contact with the relevant natural event (e.g., structural damage to railway tracks), whereas indirect damage, such as service disruptions, occurs spatially or temporally outside the actual event (Kreibich et al., 2014).

Since meteorological, hydrological, and geological extremes can have great hazard potential for damage to railway infrastructure as well as for posing risk to the safety of passengers, they are of major importance for the risk management of railway transportation in Austria. However, the implementation of technical protection measures is often not feasible for either economic reasons or aspects of nature and landscape conservation (Brauner, 2011). Moreover, technical measures are limited in ensuring a commensurate level of safety for railway operations in Alpine topography. Hence, in recent years, natural hazard and risk management has shifted from pure technological and protective approaches towards a more integrated risk management strategy including a variety of non-structural measures in order to mitigate (residual) risks from natural hazards. Accordingly, the risk management strategy of the Austrian railway network operator, the Austrian Federal Railways (ÖBB), puts great emphasis on non-structural, precautionary, and preparatory risk mitigation measures, particularly with regard to weather monitoring and warning as well as immediately adapting operations in case of extreme weather events. In cooperation with a private weather service provider, a weather monitoring and warning system was implemented in 2005 along the Austrian railway network to provide current data and forecasts of a set of meteorological parameters to the local railway staff. Furthermore, thresholds for key weather phenomena, such as extreme low or high air temperature and very intense precipitation, were defined in order to identify imminent weather extremes putting railway operation at risk—so-called critical meteorological conditions (CMCs). These CMCs are extreme weather events with the potential to have a large-scale effect on railway operations requiring coordinated action on behalf of the ÖBB. In practice, they are derived from 72-hour-forecasts to allow sufficient time for the implementation of damage reducing measures.

Experiences from the heavy rainfall event in 2013 in the Central Alps showed that the system generally performed well even under extreme conditions. However, climate change is likely to alter the climatic conditions and thus might present new challenges in terms of weather monitoring and warning response.

Since the European Alps are constantly disclosed as being particularly sensitive to climate change (Schöner et al., 2011), recent studies on climate change in Europe increasingly focused on this region. The analyses on future temperature trends consistently show a marked increase in mean air temperature in all regions (e.g., Hollweg et al., 2008; Eitzinger et al., 2009; Gobiet et al., 2009; Smiatek et al., 2009; Loibl et al., 2011; Blöschl et al., 2011a; Strauss et al., 2013; Zimmermann et al., 2013). According to Eitzinger et al. (2009), Gobiet et al. (2009), and Strauss et al. (2013), a significant annual mean temperature rise of approximately 1.6 °C until 2040 is expected. Zimmermann et al. (2013) estimate a temperature increase of 1.8 °C to 4 °C for the period 2051–2080 (A1B scenario) using the average conditions from 1961–1990 as reference, whereby the least warming in the winter season and the highest warming during summer is shown. With regard to precipitation, the annual trend for Austria shows significant variations both in the seasonal and spatial pattern (Schmidli et al., 2002; Brunetti et al., 2006; PLANALP, 2013). In addition to these changes, climate change is also likely to alter the frequency, intensity, and spatiotemporal distribution of (at least some) extreme weather events such as intense rainfall or heatwaves Beniston et al., 2007; IPCC, 2011; EEA, 2014). These changes will presumably have serious implications on the current hazard (and risk) profile of Austria, which consequently might also challenge the natural hazard management for railway transportation. Rising temperatures and extended heatwave periods, for instance, increase problems of rail buckling and thermal comfort for passengers in trains during the summer (EEA, 2014). In the winter season, however, less extreme cold events can reduce related damages to infrastructure (e.g., point failures) and service disruptions. Intense rainfall events, as a further example, can cause various direct damages to railway infrastructure (e.g., structural damage caused by erosion), which would consequently also pose an imminent impact to railway operations.

Hence, in order to support decision-makers in the comprehensive and sustainable natural hazard management, we investigate possible changes in the frequencies of CMCs due to climate change and future implications for railway transportation in Austria. The upcoming section of this paper briefly presents the weather monitoring and warning system being implemented and operated by the ÖBB natural hazards management in cooperation with a private weather service provider to address the risks from CMCs and related Alpine hazards. In Section 4.3.1 and Section 4.4.1, we look at the seasonal climate change signals for air temperature and precipitation between the periods 1961–1990 and 2011–2040 using simulations of four Regional Climate Models (RCMs). The RCM ensemble was subsequently used to evaluate the projected changes in the frequencies of CMCs (Section 4.3.2 and Section 4.4.2). Section 4.3.3 and Section 4.4.3 present the methods and results of the sensitivity analysis of CMC frequencies by varying some threshold values. Finally, the results are discussed and consequences for the risk management for Austrian railway transportation, as well as potential adaptation and mitigation strategies, are outlined (Section 4.5 and Section 4.6).

4.2 The ÖBB weather warning and monitoring system

To cope with the risks arising from CMCs, the ÖBB Natural Hazards Management Department initiated a partnership with the private weather service provider UBIMET GmbH in 2005 to develop and implement a dense weather monitoring and early warning system along the Austrian railway network—the so-called "Infra:Wetter". The system combines data from both its own and external weather stations, radars, and satellites, as well as local and global weather projections with detailed information on the entire railway network in Austria. On this basis, current data and forecasts of a set of important meteorological parameters like temperature, wind speed, precipitation, snowfall, and the snow line can be provided at the local level. The main features of Infra:Wetter are (1) both short (i.e., hours) and mid-term (i.e., up to three days) weather warnings and forecasts along individual railway lines; (2) on demand (mid-term) forecasts of weather-related hazards (e.g., occurrence of flash floods, snow drifts, black ice, thunderstorms, fire) and (3) detailed long-term forecast (i.e., up to seven days) of the general weather development (Eisenbach, 2013). The issuing of an alarm by the early warning subsystem of Infra:Wetter is based on a variety of threshold values for relevant CMCs. For instance, more than 100 mm of rainfall or 20 cm of snowfall in the Alps within 24 h are classified as a critical meteorological condition possibly impacting the railway operation. An overview of currently applied thresholds for CMCs being relevant for this study is provided in Table 4.1a. These thresholds were jointly defined by the ÖBB and the private weather service UBIMET on the basis of expert knowledge.

Table 4.1: Threshold criteria for Critical Meteorological Conditions (CMC). Section (a) shows the original threshold criteria for CMCs for railway transportation in Austria. In Section (b), the modified threshold criteria used for the sensitivity analysis are depicted.

(a)		**(b)**	
Critical Meteorological Condition (CMC)	**Threshold Criteria**	**Critical Meteorological Condition (CMC)**	**Threshold Criteria**
Very intensive rainfall—Alps	≥100 mm/24 h	*Very intensive rainfall—Alps*	≥80 mm/24 h
Very intensive rainfall—Lowlands	≥ 60 mm/24 h	*Very intensive rainfall—Lowlands*	≥50 mm/24 h
Intensive rainfall with high antecedent soil moisture	Precipitation sum of ≥100 mm within max. three preceding days, and precipitation event with an intensity of ≥50 mm/24 h on the fourth day	*Intensive rainfall with high antecedent soil moisture - variant 1*	Precipitation sum of ≥100 mm within max. five preceding days, and precipitation event with an intensity of ≥50 mm/24 h on the sixth day
		Intensive rainfall with high antecedent soil moisture—variant 2	Precipitation sum of ≥80 mm/max. three preceding days, and precipitation event with an intensity of ≥25 mm/24 h on the fourth day
First heavy seasonal snowfall (September, October)—Alps	≥20 cm/24 h	*First heavy seasonal snowfall (September, October)—Alps*	≥15 cm/24 h
First heavy seasonal snowfall (September, October)—Lowlands	≥10 cm/24 h		
Extreme cold	≤−20 °C	*Extreme cold*	≤−15 °C
Heat wave	≥+35 °C, duration of at least five days	*Heat wave*	≥+35 °C, duration of at least three days

In the case that a threshold exceedance can be forecast at least 72 h in advance (thus allowing sufficient pre-warning and reaction time), a weather warning is issued and a plan of procedures is implemented (see Figure 4.1). First, it is classified into one of five different alarm levels. Subsequently, potentially affected railway sectors are identified and an internal meeting with the general management is held in order to decide on the adequate plan of emergency measures. If such a contingency plan is already available for the respective situation, its measures are implemented. If no contingency plan is available for this situation, a regional weather warning is issued and consultations with the engineering department in charge take place. If threshold values are exceeded, or a weather warning has been issued for an event with a lead time of less than 72 h, a weather alarm is issued and an incidence command is installed that decides on operational safety precautions, such as speed limits, track closures, or temporary mitigation measures. For instance, in the case that heavy snowfall is predicted, measures such as a revised planning of human resources and provision of winter services or the preheating of switch points can be taken to ensure the operability of the network. In addition, the weather warnings are continually reviewed and daily reports of possible weather-related problems are provided to the first train of the day on remote tracks. The system is also used to analyze which parts of the rail network were affected by CMCs such as extreme rainfall, heavy snowfall, or heat waves so that the operation managers can be informed about potential problems and impose temporary speed limits, where necessary. The weather monitoring system, in combination with the early warning system, thus aims to facilitate the demands for a reliable provision of services and to meet the top priority of the operator in order to achieve a maximum possible level of safety for passengers and staff.

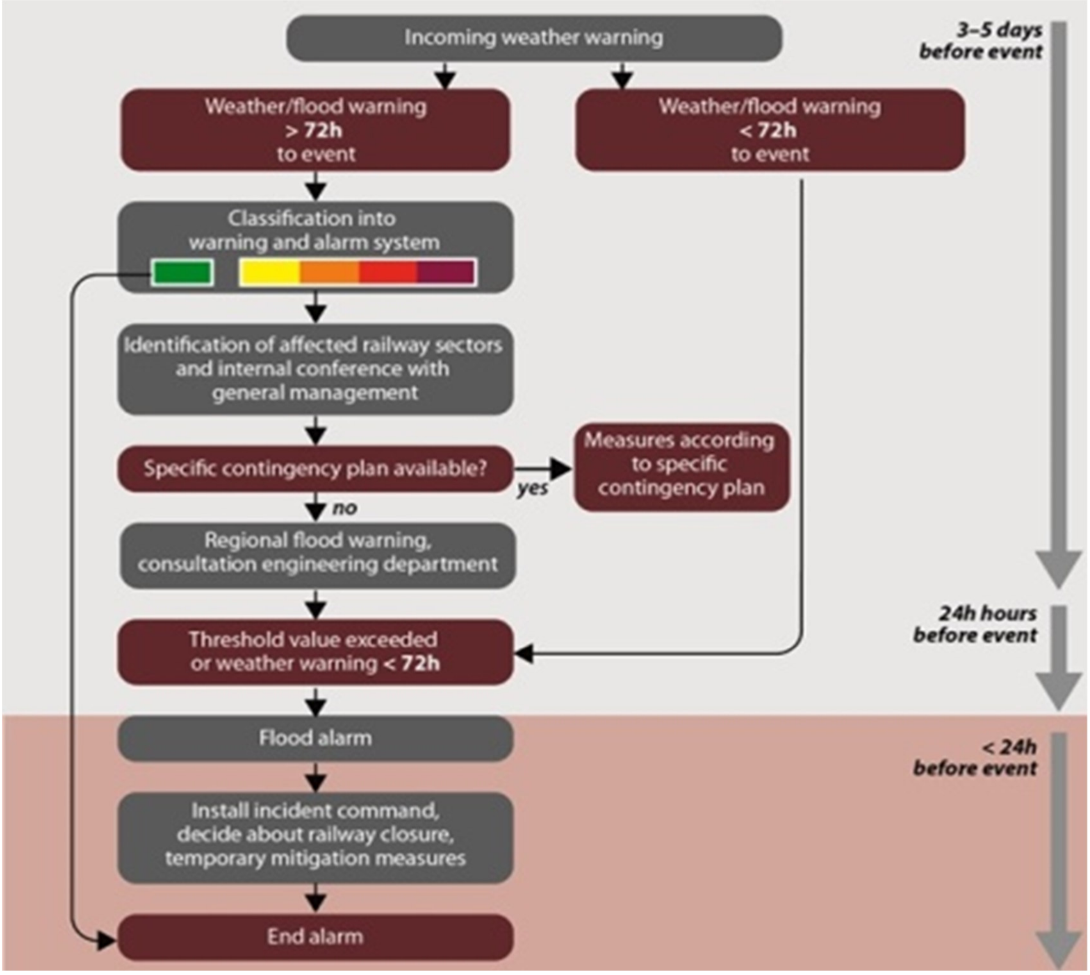

Figure 4.1: Flowchart of procedures in case a threshold value for a CMC is exceeded and a weather warning (and/or flood warning) is issued. (Source: ÖBB)

Between 2006 and 2014, 499 weather warnings were issued (excluding storms and thunderstorms) (Rachoy, 2015). Heavy snowfall events accounted for the greatest proportion of warnings (273) followed by heavy rain (226). According to the ÖBB damage database for railway service and infrastructure, damage related to extreme rainfall events accounted for approximately 37% of all entries from 1991 to 2011 (Rachoy, 2012). Therefore, rainfall-related CMCs rank among the most important ones for risk management of railway infrastructure. In the same period, snowfall and snowdrift events had a 17% share of all damaging events (Rachoy, 2012) and have thus also been of major importance for ÖBB risk management.

4.3 Data and methods

4.3.1 Climate change signals for Austria

Climate change signals at a national or regional scale are generally investigated by means of RCMs instead of Global Circulation Models (GCMs), since their spatial resolution is much higher and complex topography as well as heterogeneous land cover is finer-scaled and, hence, better represented (Dosio and Parulo, 2011). RCMs result from either statistical or dynamical downscaling procedures of GCM results and are associated with a number of uncertainties regarding spatial resolution and temporal accuracy of the obtained results Thermeßl et al., 2010). However, in recent years the variety and number of simulations were enlarged, related uncertainties were mostly identified, and the model quality has been improved accordingly Montesarchio et al., 2014). Thus, the level of confidence in RCMs has grown especially for mean temperature and precipitation projections, but also with regard to extremes IPCC, 2013).

To investigate the climate change signals for Austria, an ensemble of high-resolution RCM simulations for Europe, which has been produced within the EU-project ENSEMBLES (http://www.ensembles-eu.org), was accessed. Since all simulations represent a realization of an equally probable future, there is no criterion to choose only one simulation as the most suitable for the Alpine region or Austria. To account for the variability of possible projections, four RCMs were selected that represent the maximum difference in projected precipitation and temperature trends for Europe and thus likely consider the entire projection bandwidth provided by the given ensemble of simulations (Dosio et al., 2012). Table 4.2 specifies the model runs available. Dosio et al. (Dosio et al., 2012) showed that the KNMI-model roughly represents the average of the twelve RCMs regarding precipitation and temperature trends in Europe, whereas the DMI-model tends to be rather warm and dry, while the METO-HC-model tends towards cold and wet conditions. Moreover, the MPI-model was added in order to enlarge the ensemble of climate models, which finally led to a selection of four models (see Table 4.2). The RCM datasets have been bias corrected by Dosio et al. (2011) prior to the study at hand. All available climate variables and underlying data specifications are listed in Table 4.3.

According to the Intergovernmental Panel on Climate Change (IPCC) (2007), climate model projections on mean air temperature based on different emission scenarios diverge only marginally in the near future (i.e., by 2050). These magnitudes are, however, significantly different for the rest of the projection period (2050–2100). Considering this, we selected the periods 1961–1990 (reference period) and 2011–2040 (projection period) as the basis for our analyses in order to allow for the availability of only data referring to the A1B scenario and thus increase the representativeness of this case study. Another justification lies in the fact that, from the ÖBB natural hazard management perspective, the near future is more of a concern with regard to non-structural risk management than the far future.

Table 4.2: List of model runs available for this study (adapted from Dosio et al. (2012). The selected models are highlighted in bold characters. (For a full description of the Institutes` and model acronyms see, e.g., Christensen et al. (2010))

Institute	RCM	Driving GCM	Emission scenario
METO-HC	**HadRM3Q0**	**HadCM3Q0**	**A1B**
MPI-M	**REMO**	**ECHAM5**	**A1B**
C4I	RCA3	HadCM3Q16	
ETHZ	CLM	HadCM3Q0	
KNMI	**RACMO2**	**ECHAM5-r3**	**A1B**
SMHI	RCA	BCM	
SMHI	RCA	HadCM3Q3	
SMHI	RCA	ECHAM5-r3	
DMI	HIRHAM5	BCM	
DMI	HIRHAM5	ARPEGE	
DMI	**HIRHAM5**	**ECHAM5**	**A1B**
CNRM	RM5.1	ARPEGE	

Table 4.3: List of RCM variables considered in this study and data specifications. Bias correction was conducted by Dosio et al. (2011).

Variable	Definition	Specifications
pr	Bias-corr. rainfall (mm)	Spatial resolution: 25*25 km Spatial coverage: Europe Temporal resolution: daily time step
psno	Bias-corr. snowfall (cm)	
tavg	Bias-corr. mean air temperature (°C)	
tmax	Bias-corr. maximum air temperature (°C)	
tmin	Bias-corr. minimum air temperature (°C)	

4.3.2 Frequency analysis of CMCs in a changing climate

The core of this study was to assess the climate change-related alteration of frequencies of CMCs until 2040. The underlying threshold criteria for CMCs were directly drawn from the weather monitoring and warning system Infra:Wetter (see Section 4.4.2 and Table 4.1a) and applied to the individual RCM simulation runs. It must be noted that the original list of CMCs contains further thresholds (i.e., criteria of snow-breakage, floods, and storms). Due to RCM data availability constraints, however, an analysis of these CMCs is currently impossible and they are, therefore, neglected in this study. The analyses on very intensive rainfall and intensive rainfall with high antecedent soil moisture were conducted on the basis of the pr variable, the heat wave frequencies were assessed using the tmax variable, the extreme cold threshold is referring to the tmin variable, and the psno variable was used to quantify the CMC frequencies regarding first heavy seasonal snowfall (see Table 4.3). While the RCM datasets were used on a seasonal basis concerning climate signals in Austria, the CMC frequency analyses now are referring to the entire time period, with one exception: The criterion for first heavy seasonal snowfall is truncated to only early seasonal events (i.e., September and October), since these are of particular interest for railway operation purposes with regard to the commencement and coordination of railway winter services. Another exception is made for the regionalization of CMC occurrences. Due to the insufficient resolution of the available RCMs (25 km), the frequency analyses are not consistently differentiated by specific regions (e.g., federal states, operational sections), but mainly provide information at the national level. The CMCs for very intensive rainfall and first heavy seasonal snowfall, however, are applied separately for the Alpine area and the lowlands of Austria in order to account for the differing threshold criteria for each of these greater areas (see Table 4.1a).

In a first step of the frequency analyses, the absolute number of days of threshold exceedance in the individual RCM datasets for both the reference period and the projection period were quantified for each CMC. Next, the percentage change of threshold exceedances as compared to the reference period was analyzed. Finally, the mean percentage change over all model-specific CMC frequencies was computed on the basis of (1) the mean of the model-specific absolute number of days of threshold exceedance in the reference period; (2) the mean of the model-specific absolute number of days of threshold exceedance for the projection period.

4.3.3 Sensitivity analysis

In order to obtain an indication of the sensitivity of the results, the frequency analysis was repeated using modified threshold values. Table 4.1b displays the new threshold criteria of the meteorological extremes under consideration. The very intensive rainfall criteria have each been modified towards a reduction of the rainfall intensity for both regions. With respect to the criteria for intensive rainfall accompanied by high antecedent soil moisture, we likewise defined two new variants that both intended to reduce the intensity of underlying precipitation events. The sensitivity of first heavy seasonal snowfall was tested by decreasing only the threshold value for the Alpine region by 25%, since the threshold value for the Austrian lowland is being considered as already appropriate. Extreme cold days were redefined by changing the minimum air temperature from initially −20 °C to −15 °C. Finally, we modified the heat wave criteria with respect to the required duration of the event to be "critical". All modifications are derived from internal discussions with railway experts and based on the premise that respective original CMCs are likely to be underrated and, as such, less extreme thresholds can already pose similar risks to railway operations.

4.4 Results

4.4.1 A glance at Austria`s potential future climate

The following section presents the seasonal climate signals for air temperature and precipitation for Austria in order to provide a general overview of the characteristics of the RCM datasets used for the subsequent frequency analyses (see Sections 4.3.2 and 4.4.2), and to assess the robustness of the climate change signals.

Figure 4.2 depicts the mean percentage difference of rainfall in the winter season as projected by the selected RCMs. Three out of four models project a maximum increase in rainfall varying between around 14%–19% for the central and eastern part of Austria, whereas for the country's western part the rainfall is likely to decrease by up to around 9%. Regarding the spatial patterns, the DMI-model, the KNMI-model, and the MPI-model agree quite well. The METO-HC-model, however, is contradictory to the other models, since it indicates an opposite spatial trend in rainfall. In order to further evaluate the depicted signals, the percentage averages of rainfall change for Austria are specified in Table 4.4. Herein, the average changes show a marginal increase of approximately 5%–10% for the models DMI, KNMI, and MPI, whereas the METO-HC-model is likewise contradictory by calculating a slight decrease of around 4%. According to IPCC (2007), a simple approach to assess the robustness of climate change signals is to check the matching rate of simulation results with respect to the direction of change. They define a signal direction as being "likely" if more than 66% of all results agree in the respective direction. Following this approach, the mean rainfall in the winter season in Austria can be considered as likely to (marginally) increase until 2040.

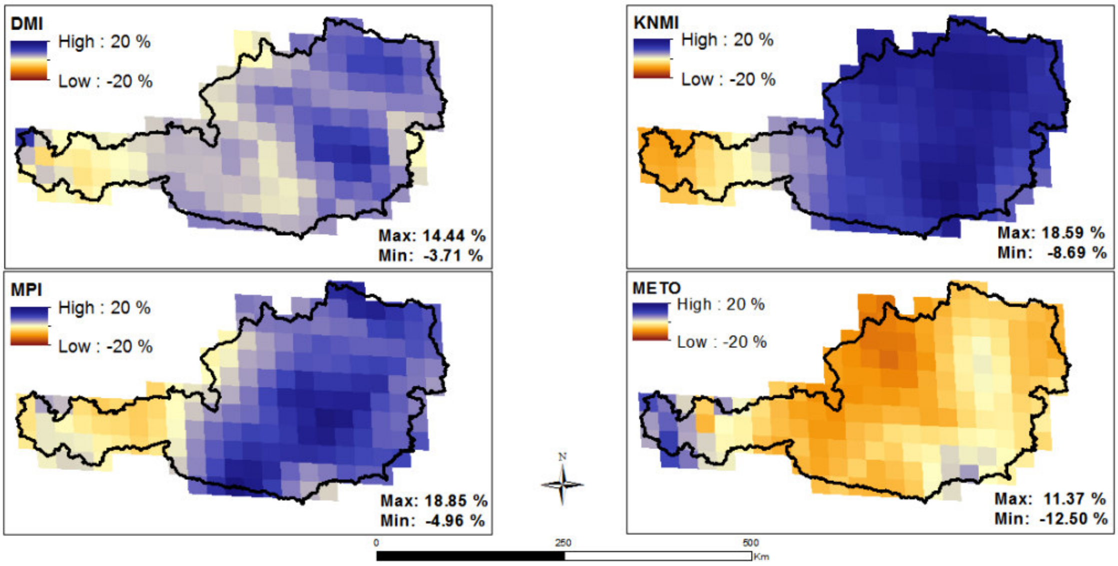

Figure 4.2: Percentage difference of mean rainfall in the winter season (DJF) between the periods 1961-1990 and 2011-2040.

Table 4.4: Arithmetic mean values (m), standard deviations (s) and coefficients of variation (CV) of changes in temperature and precipitation in Austria according to the different RCM results (DJF: winter season; JJA: summer season).

	DMI			KNMI			MPI			METO-HC		
Temperature [K] DJF	0.67	0.06	0.09	0.98	0.09	0.09	1.17	0.19	0.16	2.16	0.09	0.04
Temperature [K] JJA	0.22	0.15	0.69	1.00	0.07	0.07	0.92	0.08	0.09	1.07	0.05	0.05
Rainfall [%] DJF	4.79	3.46	0.72	10.21	6.83	0.66	7.11	5.63	0.79	-4.25	4.76	1.11
Rainfall [%] JJA	9.55	6.01	0.62	-3.92	2.47	0.62	2.82	4.59	1.62	7.74	3.47	0.44
Snowfall [%] DJF	-5.26	6.06	1.15	-6.89	4.27	0.61	-8.80	4.99	0.56	-32.43	10.91	0.33
	m	s	CV	m	s	CV	m	s	CV	m	s	CV

Figure 4.3 illustrates the projected trends of mean snowfall in winter. All four models agree in a moderate to strong decrease in snow precipitation throughout most of Austria until 2040. The METO-HC-model again stands out, since its calculated average is substantially lower than the other ones, however, the standard deviation is also the highest one in the model set

of this study (see Table 4.4). Although the projected maximum relative decrease in snow quantity between the selected periods is varying considerably over all models ranging from approx. −18% to −48%, the climate change signals show a robust negative direction when assessed by the approach of IPCC (2007).

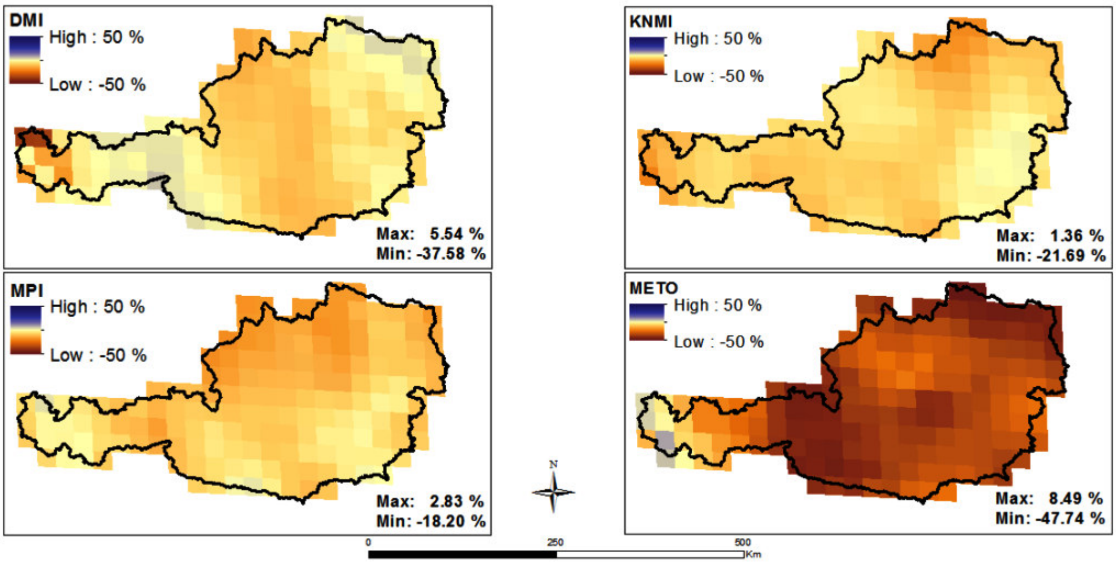

Figure 4.3: Percentage difference of mean snowfall in the winter season between the periods 1961-1990 and 2011-2040.

The changes in absolute mean air temperature in the winter season until 2040 are illustrated in Figure 4.4. As clearly indicated by the climate signal maps, all RCMs show an increase in air temperature throughout Austria. While the DMI-model is showing the smallest increase, ranging from approximately 0.5 K to more than 0.8 K, the KNMI-model and the MPI-model both compute a maximum increase in air temperature amounting to approximately 1.1 K and 1.4 K, respectively. The METO-HC-model behaves again exceptionally, since its results show a significantly stronger increase in mean temperature in winter season than the other models, varying between approximately 1.8 K and 2.4 K. Regarding the spatial patterns, the projections mostly agree that the lowland areas of Austria (i.e., the east of the country), experience the largest relative increase, whereas for the Alpine region a comparatively lower increase can be expected. Looking at the statistics, the model`s mean values are ranging from approximately 0.7 K (DMI) to 2.2 K (METO-HC), accompanied by moderate standard deviations spanning from 0.06 K (DMI) to 0.2 K (MPI), which finally leads to low variation coefficients in the data. In conclusion, the findings on the increase in mean air temperatures in Austrian winter seasons until 2040 are considered to be robust in the IPCC terminology.

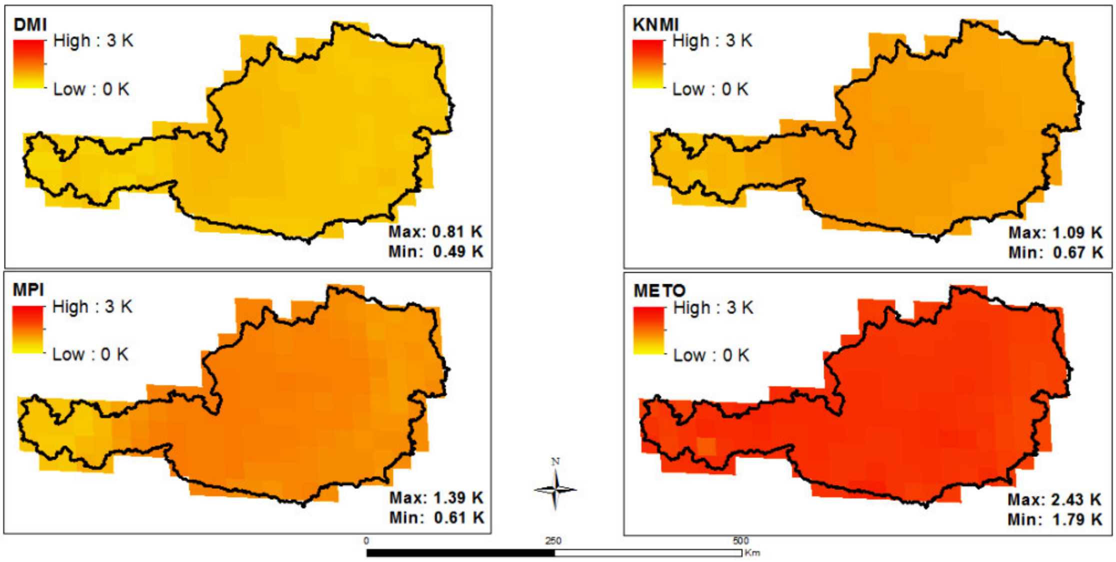

Figure 4.4: Absolute difference of mean air temperature in the winter season (DJF) between the periods 1961-1990 and 2011-2040.

In the summer season (JJA) only rainfall is considered, since snowfall rarely occurs or in extremely low quantities even in the high mountainous regions of Austria. The percentage differences of mean rainfall for JJA based on the RCM selection are illustrated in Figure 4.5. The models disagree in the direction as well as the quantities of projected changes in Austria, since the mean percentage changes range from around −4% (MPI) to −12% (METO-HC) in the negative direction, and from around 2% (KNMI) to 34% (DMI) in the positive direction. Furthermore, there is only scarce consistency in the projections with respect to the depicted spatial patterns of changes. The DMI-model and the METO-HC-model indicate an overall increase in summer rainfall, whereas the KNMI-model and the MPI-model assume an overall decrease. Looking at the regional level reveals further disagreements particularly in the high Alpine area of Austria (i.e., in the far west). These discordances are also reflected in the basic statistics of the data sets (see Table 4.4). Therein, the DMI-model and the METO-HC-model show a positive arithmetic mean value of percentage change, whereas the other two models indicate an overall negative direction. Thus, the model ensemble does not give robust information on the development on summer rainfall until 2040.

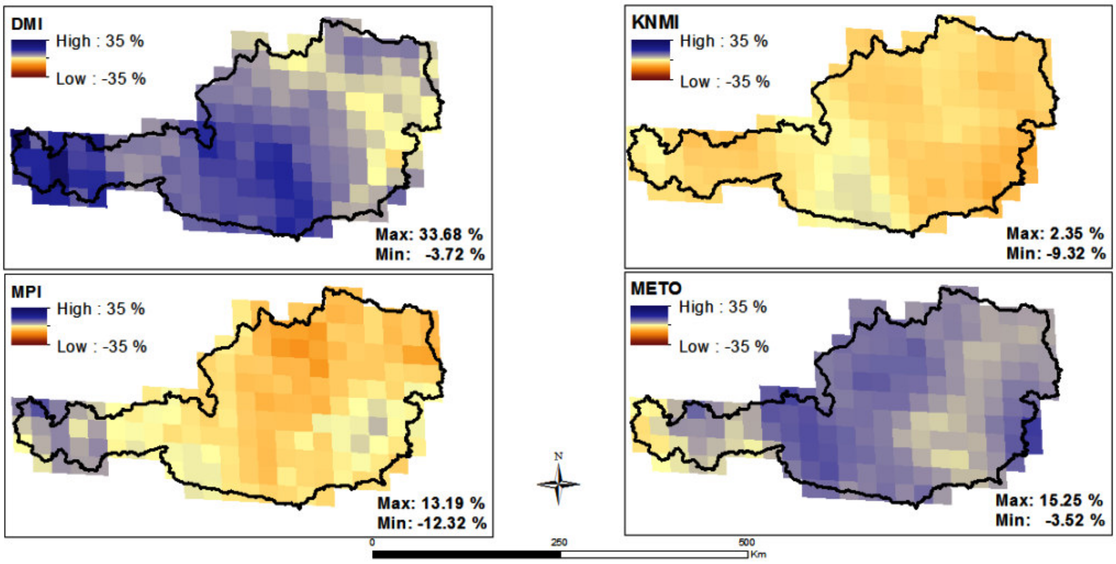

Figure 4.5: Percentage difference of mean rainfall in the summer season (JJA) between the periods 1961-1990 and 2011-2040.

Finally, the results of the analysis for mean air temperature change in the summer season are displayed in Figure 4.6. The general trend observed in the winter season is also obvious here, since all model results show an increase throughout the country for the summer season until 2040. Herein, the DMI-model is showing the greatest span ranging from no changes to a maximum increase of more than 1.3 K, however, large parts of the Austrian territory only face a very small increase in mean air temperature. The results of the remaining three models are closely related, as their projected bandwidths are of a similar nature ranging from roughly 0.8 K to 1.3 K. Reviewing the statistics likewise shows a significant temperature rise in three out of four models amounting to around 1 K. Since the respective coefficients of variation are far below 1, only marginal data scattering is indicated. The DMI-model, however, breaks ranks by stating a lower increase of approximately 0.2 K on average, although the coefficient of variation is considerably higher for these data. Nevertheless, following the IPCC (2007) guidelines, the projected increase in mean air temperature in the summer season can be described as robust.

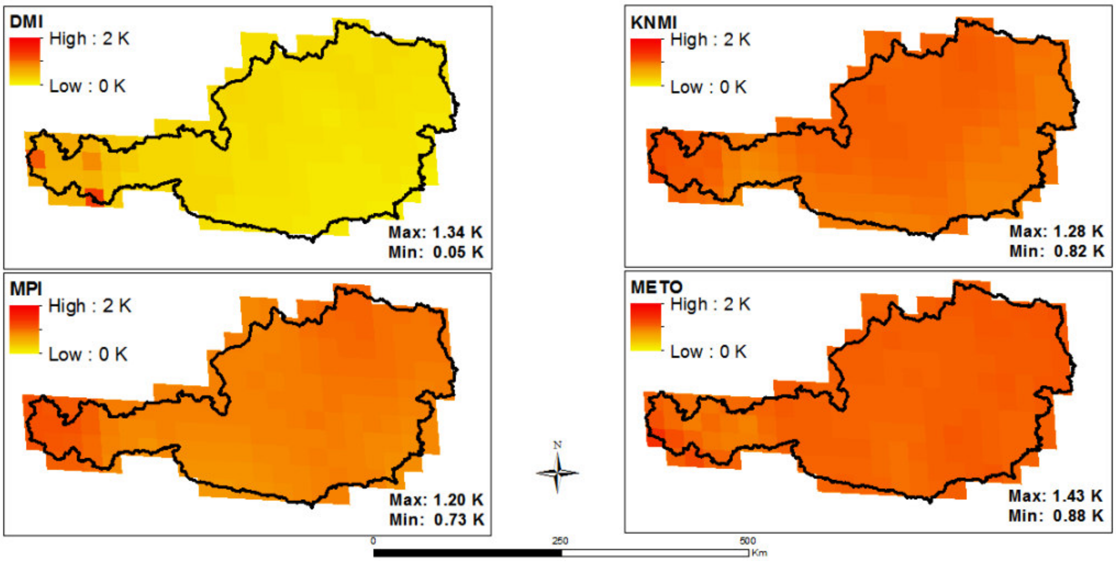

Figure 4.6: Absolute difference of mean air temperature in the summer season (JJA) between the periods 1961-1990 and 2011-2040.

4.4.2 Climate change impacts on the CMC frequencies

In the next step, possible impacts of climate change on the frequencies of CMCs in the projection period were investigated. Table 4.5a shows the detailed results for all RCMs and every CMC. On average, the very intensive rainfall frequency (≥100 mm/24 h) undergoes a relative change of +36% in the Alpine region, which clearly indicates a significant increase in days with extreme rainfall events for the future period. This finding is also reflected in the individual model results, since all changes in frequencies show a positive direction. This also applies for the Austrian lowlands (≥60 mm/24 h), since a strong relative increase of 70% on average is calculated. Considering the absolute number of days with critical rainfall in the reference period, the DMI-model indicates a conspicuously high value for the Alpine region, whereas the other three models widely agree in the total number of events. In this respect, the model outcomes for the lowland area are more balanced.

The results for the frequency analysis of intensive rainfall accompanied by high antecedent soil moisture draw a different picture. The DMI-model, indeed, stands out again by indicating exceptionally high event occurrences in the reference period compared to the other RCMs in the ensemble. However, in contrast to the results for the CMC very intensive rainfall, two specific disparities can be identified: (1) the intensive rainfall accompanied by high antecedent soil moisture frequency seems to remain more or less the same showing a marginal decrease of 5% on average and (2) the models disagree in the direction of change.

Table 4.5: Changes in frequencies of critical meteorological conditions (CMCs). Section (a) shows the changes in frequencies of CMCs (see Table 4.1a) between the reference period 1961–1990 and the projection period 2011–2040 based on individual RCM simulations. The mean relative change of the individual CMC frequency for the projection period is calculated on the basis of the absolute mean values of all model results for both periods (see text for the abbreviations). In Section (b), the changes in frequencies of CMCs resulting from the modification of the threshold criteria (see Table 4.1b) are depicted. The mean relative change of the individual CMC frequency for the projection period is calculated on the basis of the absolute mean values of all model results for both periods.

(a)				**(b)**			
Critical Meteorological Condition (CMC)	**Regional Climate Model (RCM)**	**Number of CMCs in the Reference Period (1961–1990)**	**Relative Change of Frequencies in the Future Period (2011–2040)**	**Critical Meteorological Condition (CMC)**	**Regional Climate Model (RCM)**	**Number of CMCs in the Reference Period (1961–1990)**	**Relative Change of Frequencies in the Future Period (2011–2040)**
Very intensive rainfall—Alps	DMI	65	17%	*Very intensive rainfall—Alps*	DMI	106	19%
	KNMI	1	100%		KNMI	6	83%
	METO	2	200%		METO	2	1050%
	MPI	1	900%		MPI	7	300%
	mean	**17**	**36%**		**mean**	**30**	**55%**
Very intensive rainfall—Lowlands	DMI	3	233%	*Very intensive rainfall—Lowlands*	DMI	11	118%
	KNMI	6	17%		KNMI	12	42%
	METO	7	86%		METO	14	114%
	MPI	7	29%		MPI	21	5%
	mean	**6**	**70%**		**mean**	**15**	**60%**

Critical Meteorological Condition (CMC)	**Regional Climate Model (RCM)**	**Number of CMCs in the Reference Period (1961–1990)**	**Relative Change of Frequencies in the Future Period (2011–2040)**	**Critical Meteorological Condition (CMC)**	**Regional Climate Model (RCM)**	**Number of CMCs in the Reference Period (1961–1990)**	**Relative Change of Frequencies in the Future Period (2011–2040)**
Intensive rainfall with high antecedent soil moisture	DMI	78	−9%	*Intensive rainfall with high antecedent soil moisture-variant 1*	DMI	100	−10%
	KNMI	2	−50%		KNMI	4	−25%
	METO	1	300%		METO	2	200%
	MPI	2	50%		MPI	2	500%
	mean	**21**	**−5%**		**mean**	**27**	**-2%**
				Intensive rainfall with high antecedent soil moisture-variant 2	DMI	175	12%
					KNMI	23	−26%
					METO	19	42%
					MPI	26	19%
					mean	**61**	**12%**
First heavy seasonal snowfall—Alps	DMI	37	−43%	*First heavy seasonal snowfall—Alps*	DMI	81	−42%
	KNMI	33	30%		KNMI	59	22%
	METO	54	−17%		METO	95	−21%
	MPI	76	−4%		MPI	131	−24%
	mean	**50**	**−9%**		**mean**	**91**	**−20%**
First heavy seasonal snowfall—Lowlands	DMI	4	−75%				
	KNMI	1	0%				
	METO	4	25%				
	MPI	8	−50%				
	mean	**4**	**−35%**				
Extreme cold	DMI	206	−16%	*Extreme cold*	DMI	825	−19%
	KNMI	178	−20%		KNMI	817	−19%
	METO	486	−33%		METO	904	−52%
	MPI	165	−73%		MPI	1264	−19%
	mean	**259**	**−34%**		**mean**	**953**	**−27%**
Heat wave	DMI	0	-	*Heat wave*	DMI	4	225%
	KNMI	0	-		KNMI	3	133%
	METO	1	100%		METO	7	814%
	MPI	2	1150%		MPI	7	0%
	mean	**1**	**933%**		**mean**	**5**	**333%**

With respect to first heavy seasonal snowfall in the early seasons until 2040, the CMC frequency analyses show a slight overall decrease of 9% in the Alps. Three out of four models agree in the decline of heavy snowfall in September or October. Contrary to the two previous precipitation criteria, however, the KNMI-model now behaves exceptionally instead of the DMI-model by indicating a relative increase of around 30%. Another peculiarity is that the individual reference values show a certain convergence compared to the previous precipitation-related indicators. In the Austrian lowlands, future first heavy seasonal snowfall frequencies overall are markedly decreasing by around −35%. Interestingly, the METO-HC-model now suggests a positive direction in the frequency alteration of first heavy seasonal snowfall, whereas the KNMI-model shows no change at all. The underlying numbers of events in the reference period are, as expected, considerably lower than those for the Alpine region.

The days of extreme cold are likely to decrease in Austria in the projection period, since the mean percentage change is amounting to approximately −34%. All RCMs show the same tendencies, however, both the individual absolute values and the percentage changes differ markedly. Despite the indicated decrease, the CMC extreme cold seems to remain the most frequent extreme weather event in the projection period.

Finally, an extreme mean relative increase in heat wave events of approximately 933% is projected until 2040. This high amount is, however, due to the low absolute number of such events in the reference period. Furthermore, all RCMs agree with respect to the direction of change, which demonstrates a high robustness of the results. Since the DMI-model and the KNMI-model showed no events in the reference period, the calculation of corresponding relative change of these frequencies is mathematically not possible. In total, although heat waves only play a very minor role for natural hazards management so far, they are likely to become more important in the future.

4.4.3 How sensitive are CMC frequencies to changes in threshold values?

The threshold criteria for the CMCs as shown in Table 4.1a were modified according to Table 4.1b and the frequency analysis was conducted again with the aim to obtain an indication of the impacts of threshold modification on the changes of frequencies of extreme weather events until 2040 (see Section 4.3.3). Table 4.5b provides the respective results for all modified CMCs. The reduction of the intensity for very intensive rainfall by 20 mm led to a considerable increase in the mean percentage change of 55% in future frequencies in the Alps. The underlying reference values also increased except for the METO-HC-model, which suggests the same number of events in the reference period by simultaneously signalizing a much higher increase in future frequencies compared to its results based on original thresholds. Regarding very intensive rainfall in the lowlands, the reference values likewise increased consistently, however, the mean relative change shows a lower increase in the future frequency compared to the original results.

The threshold criteria for the CMC intensive rainfall accompanied by high antecedent soil moisture were modified in two different ways (see Table 4.1b). The results for the modification variant 1, which comprises an increase in the maximum number of days to reach the threshold of precipitation to be defined as critical antecedent rainfall, show only a marginal change both in the mean percentage change and the reference values in comparison with the previous findings. Furthermore, the initial order of magnitudes of the reference values among the different models in principle remained the same, since the DMI-model still states an exceptional high number of past events. The model-specific frequency changes, however, were significantly altered. Now, the MPI-model suggests the highest relative increase in intensive rainfall events accompanied by high antecedent soil moisture while maintaining the number of past events. The modification variant 2 is premised on a reduction of the precipitation sum of antecedent rainfall as well as a halving of the precipitation sum of the final rainfall event. As a result, considerable differences are revealed in the magnitudes of both the number of past events and the percentage change until 2040 as compared to the results based on the original criteria. While the former markedly increased in all models, the latter even changed the direction from a very small decrease to a notable increase in the frequency of approximately 12%. On the model level, the KNMI-model is now the only RCM that still issues a decrease in the frequency for the projection period, whereas the DMI-model joined the estimation of the METO-HC-model and the MPI-model with respect to the direction of change.

Critical snowfall events in the early season were only modified for the Alpine area (see Section 4.3.3). The reduction of the event intensity led to a marked increase in the number of events in the reference period in all four RCMs. The mean percentage changes in the projection period, however, retained their individual direction of change, whereby the KNMI-model is still the only RCM indicating an overall positive trend in the future frequency of snowfall events. Furthermore, the mean percentage change over all models significantly changed towards a stronger decline of CMCs in comparison to the values resulting from the original threshold, which is mainly due to the considerable variation of the MPI-model.

The decrease in the intensity of extreme cold events had a strong impact on the registered CMCs in the reference period in all RCMs as all absolute values have multiplied. However, the mean relative changes until 2040 almost remained the same in the DMI-model and the KNMI-model. Changes are more significant in the METO-HC-model, which depicts a stronger decrease in the future frequency of around 19%, and the MPI-model, which suggests a difference of more than 50% towards a lower decrease of the future frequency. Overall, the mean percentage change of extreme cold occurrences based on the modified threshold criteria is marginally lower than the original mean estimation.

Finally, looking at the averaged results for heat wave shows (1) a quintupled number of events in the reference period; and (2) a less sharp rise in the future frequency amounting to 333%. In contrast to the previous results (see Section 4.4.2 and Table 4.5a), all individual RCM simulation runs now contain a certain number of events in the reference period. Interestingly, the MPI-model, which initially calculated the highest increase in heat wave events for the future period, now concludes that there will be no change in their frequency.

4.5 Discussion

The main objective of this study was to analyze possible climate change impacts on frequencies of extreme weather events jeopardizing railway operations in Austria. For this, the RCM ensemble simulations for two periods (i.e., 1961–1990 (reference period) and 2011–2040 (projection period)) were used in order to (1) investigate the projected changes in the occurrence of critical meteorological conditions (CMCs) for railway transportation and (2) test the sensitivity of frequencies of extreme weather events for varying threshold criteria. The climatic elements of air temperature and precipitation are the decisive factors for relevant extreme weather events, wherefore the respective climate change signals as well as the robustness of the directions of change are characterized and discussed first. All analyses presented in this paper may involve a considerable degree of uncertainty, mainly because the underlying RCMs possess only limited validity—in particular in the complex topography of Alpine regions (Strauss et al., 2013; Frei et al., 2006; Schiermeier, 2010), where small-scale orographic conditions and related influences on weather dynamics cannot be fully reproduced. This aspect must be considered in drawing conclusions based on the provided results.

The investigation of projected mean changes of air temperature and precipitation as provided by the selected RCM ensemble yielded different results. First, the recurrent deviations of the METO-HC results in comparison to the rather similar signals provided by the other three RCMs are striking. This general observation can be explained by the fact that the climate produced RCM largely reflects the climate variability of the driving GCM (Hostetler et al., 2011). Hence, since the METO-HC model is the only model in the ensemble driven by the GCM "HadCM3Q0", whereas the other three models are driven by the GCM "ECHAM5" (see Table 2), the different characteristics of these two GCMs are also reflected to a certain extent in the results of the RCMs.

With respect to changes in rainfall, the simulations rather disagree either in seasonal and in spatial patterns except for the broad agreement in a marginal increase in mean rainfall in the winter season. Accordingly, the investigation of precipitation change revealed no robust tendency in the direction of change. The marked deviations in the RCMs clearly indicate that there is still high uncertainty in the model projections related to rainfall, which is also reflected in the high value of the coefficients of variation of the data. These results are in broad agreement with several previous studies on precipitation under climate change in Europe, which likewise have discovered substantial variations and disagreements of rainfall trends both in terms of seasonal and spatial patterns (e.g., Schmidli et al., 2002; Brunetti et al., 2006)). The snowfall signal, however, draws a different picture, since the selected RCMs widely agree in a significant decrease in snowfall quantities for most of the area of investigation until 2040. Results on temperature signals are even more unambiguous with respect to the direction of change towards a significant rise in air temperature for both seasons and the whole of Austria. The latter findings equally concur with other studies on climate change in Europe, and particularly the Alps, which likewise show a significant increase in mean air temperature in all seasons and in all regions (e.g., Hollweg et al., 2008; Eitzinger et al., 2009; Gobiet et al., 2009; Smiatek et al., 2009; Loibl et al., 2011; Blöschl et al., 2011a; Strauss et al., 2013; Zimmermann et al., 2013).

Extreme rainfall events rank among the most important meteorological hazards for risk management of railway transportation in Austria (see Section 4.2). Besides the considerable damaging potential of this event type itself, (very) intensive rainfall is furthermore an important trigger for other natural hazards such as (flash) floods, torrential processes, and debris flows.

The frequency analysis indicates a significant increase in intensive rainfall in the projection period (+36%). By reducing the threshold, the number of past events noticeably increased in all RCM results. Additionally, these changes led to an even higher increase in future frequency in the Alpine region, whereas the frequency in the lowlands is projected to experience a slightly lower increase. Although such analyses are subject to a variety of limitations and uncertainties, all RCMs give indications towards a considerable increase of extreme rainfall events in the projection period. This finding is also confirmed by several related studies, which also come to the conclusion that the frequencies and intensities of extreme rainfall events must be expected to rise in Europe and, depending on the season, also in the Alps (EEA, 2012, 2014; IPCC, 2013). The projected change in the precipitation-related risk is likely to intensify problems such as overloading of the drainage systems leading to (flash) flooding and/or scouring of track lines and other infrastructure elements.

The CMC intensive rainfall with high antecedent soil moisture is closely linked to the previous rainfall indicator, since unfavourable high antecedent soil moisture is mostly a result of either continuous rainfall or a couple of rainfall events occurring in a close sequence. Hence, a change in rainfall frequencies, sums, and/or intensities mostly has an effect on the soil moisture conditions in the affected region. Rainfall-related extreme events are therefore considered to have a significant impact on the hazard profile confirming the strong need of consideration with regard to natural risks management. Based on the original CMC threshold, the frequency shows a marginal decrease of 5% in the projection period. We modified this specific CMC according to two different variants (see Table 4.1b). The first variant considered a reduction of precipitation intensity in the preceding time. In this case, the result related to projected frequencies shows only marginal sensitivity to the modification. A different picture emerges for the second modification variant, in which the intensity of the final precipitation event was reduced. Although the mean relative increase in the frequency for the projection period is manageable, the reference value is distinctively higher than in the previous results. Similar to the effects associated with preceding rainfall-related threshold modifications, an aggravation of the risk, at least in susceptible areas, must be taken into account in the future.

With a 17% share of all damaging events between 1991 and 2011 (Rachoy, 2012), first heavy seasonal snowfall events are also of certain importance for ÖBB risk management. Looking at the projected frequencies of this CMC shows a slight (Alps) to significant (Lowlands) decrease. The reduction of the critical threshold value in Alpine areas led to a further decrease from the initial −9% to −20%. This shows a certain sensitivity of the CMC occurrence to changes in the threshold criteria. Nevertheless, since there is a robust signal in the RCM ensemble towards a considerable mean temperature increase in the projection period, as well as a decrease of mean snowfall, the projections for the direction of future first heavy seasonal snowfall event frequencies are considered to be generally robust as well. Hence, the likely changes can be considered as having an overall positive effect on railway operations. Winter services, for instance, will probably be somewhat relieved at the beginning of future winter seasons, since switch malfunctions caused by snow fall or snow drift potentially decrease—at least during September and October.

Extreme cold is the by far most frequent meteorological extreme in the study area. This CMC can cause frost damage to infrastructure elements such as the freezing of switch points, which can lead to significant service disruptions and associated costs. The frequency of extremely cold days is likely to decrease markedly by around one third when applying the original CMC thresholds. This result is in accordance with the projected increase in mean air temperature in the winter season (see Section 4.4.1). However, besides the positive effects for railway infrastructure maintenance and winter services, this change might also have negative effects. A reduction of frost days could, for instance, lead to the thawing of permafrost and thus cause destabilizations of masses of rocks and debris, for example—especially in areas showing a particular susceptibility to mass movements (Felderer et al., 2013). Subsequently, an increase of hazardous landslide and debris flow-related events must be taken into account. Warmer temperatures in winter can also cause unfavourable wet snow that is able to generate serious snow loads (e.g., on trees or catenary). Such loads, in turn, can cause significant direct or indirect damage to railway infrastructure and services (Felderer et al., 2013).

Heat waves have been of comparatively low importance in the ÖBB natural hazards management so far. Since 1991 only two damaging heat waves (in 1994) have been recorded in the ÖBB damage database, which amounts to less than 1% of all critical meteorological events (Rachoy, 2012). Since the frequency analyses indicate a high relative increase until 2040, management of heat waves is likely to become more important in the projection period. The reduction of the CMC-threshold from five to three days caused a considerably less strong relative increase in heat wave frequencies until 2040 compared to the initial criterion. However, the reference values are considerably higher, meaning that in absolute terms heat waves of shorter duration occur more frequently both in the reference and in the projection period. In general, the sensitivity analysis demonstrated a high sensitivity of the models with regard to this CMC threshold. Potential future implications of the projected increase of heat wave frequencies are, for example, (1) thermal stress for passengers, staff, tractive units (Hoffmann et al., 2016), and electronic infrastructure elements such as signals Lindgren et al., 2009); (2) increasing risk of wild fires EEA, 2014); and (3) increasing risk of rail buckling Dobney et al., 2009). On the first aspect, heat waves can overstress, inter alia, the air-conditioning systems in trains and thus cause significant thermal stress in particular to elderly passengers and infants. Secondly, high temperatures and dry weather conditions increase the risk of wild fires along tracks due to flying sparks occurring during the braking procedure of trains, which can cause considerable service disruptions. The last implication poses a great threat to railway operation due to the high risk of derailment as well as significant costs caused by speed restrictions. Using the south-east region of the UK as an example, Dobney et al. (2009) showed that railway infrastructure is already at risk of severe rail buckling within a temperature range of approx. 25 °C and 39 °C (ambient air temperature) depending on the condition of the track. The risk is assumed to significantly increase with the increase in the duration of high temperatures. The exceptionally hot summer in 2015 in Europe might provide more empirical data to derive representative thresholds for heat stress on railway infrastructure.

4.6 Conclusions

The frequency analysis of extreme weather conditions in a changing climate revealed a noticeable to strong alteration of the current hazard profile in Austria. Notwithstanding the fact that climate change impacts can also have positive effects on some sectors (e.g., winter service), the occurrence of the most relevant type of CMC analyzed (i.e., very intensive rainfall events) is likely to increase significantly in the future, which, overall, leads to new challenges for the ÖBB natural hazards management. If no action is taken, the costs due to extreme weather events must be expected to rise in the future. Based on historical experiences (e.g., from the extreme rainfall event in 2013), the weather monitoring and warning system Infra:Wetter proved to be a rather cost-effective non-structural risk mitigation measure. However, the modification of the thresholds for the identification of CMCs revealed that frequencies of extreme weather events are quite sensitive to changes of this decisive factor. In the context of climate change, this result emphasizes the importance to carefully define and constantly adapt and validate the thresholds in order to optimize the effectiveness as well as the adaptive capacity of a weather monitoring and warning system. Since the necessary data for an empirical evaluation of the threshold are currently not available in respect to data quality and temporal coverage, the importance of continuously collecting detailed event and damage data following a standardized procedure is striking. Event documentation including "near misses" can enable risk managers to better understand and learn from historical events and thus adapt natural hazards management according to future changes. For example, a comprehensive data basis would facilitate a reliable assessment of expected impacts in a quantitative way (e.g., estimation of expected damages and/or service disruptions in the projection period).

While the ÖBB already collects detailed damage data due to natural hazards, and currently further elaborates this system, no such reporting exists in many other European member states or at the European level. The existence of a European damage database for natural hazards could, however, significantly contribute to improving the understanding of damaging processes to railway infrastructure, the proportional share of different natural hazards to overall losses, and thus to the development of strategic risk management. For instance, a risk assessment of the Trans-European Transport Network (TEN-T) could provide guidance on where to invest European Community funds in risk reduction. This appears especially important given the substantial investments of EUR 26.25 billion into transport infrastructure up to 2020 (European Commission, 2013). In order to enhance risk management of railway infrastructure at the European level as well, the reporting system according to Regulation (EC) 91/2003 of the European Parliament and of the Council on rail transport statistics could be complemented with information on the impacts of natural hazards. These statistics on rail safety are required by the commission "in order to prepare and monitor Community actions in the field of transport safety" (EC 91/2003). While accidents resulting from collisions, derailments, accidents involving level crossings, accidents to persons caused by rolling stock in motion, fires in rolling stock, and 'others' are accounted for, damage due to natural hazards is currently not an individual category. How and what type of information to include in such a European database could be informed by the experience gathered by national railway operators such as the ÖBB.

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Chapter V – Excursus[2]

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[2] It was initially planned to publish this chapter as part of the research article "Frequency analysis of critical meteorological conditions in a changing climate - Assessing future implications for railway transportation in Austria" by Kellermann et al. (2016), and discarded afterwards due to a referee comment. However, since it fits well into the broader scope of this thesis, it was integrated as an excursus.

How can the performance of a weather warning system for railway operation be assessed empirically?

The precise detection of CMCs that potentially cause (direct or indirect) damage to the railway network is a crucial factor for the performance of a related weather monitoring and early warning system. On the one hand, accurate warnings are needed to implement appropriate (non-structural) risk reducing measures (e.g. speed limits or track closures). On the other hand, 'false' alarms can disrupt or delay train traffic unnecessarily with negative economic and potentially reputational effects for the railway operator. As it was already mentioned in Chapter IV (Sections 4.1 and 4.2) of this thesis, the CMC thresholds applied for Infra:Wetter were defined using expert judgement and not empirical data. However, an empirical evaluation of thresholds would further substantiate their adequacy, providing valuable insights for operators of a weather monitoring and early warning system. Hence, we propose to investigate the congruence of dates of occurrence individual threshold exceedances (i.e. days with specific extreme weather conditions) and dates of occurrence of (Alpine) hazard-related incidents for railway operation (e.g. damages to the railway track, speed limits). We argue that the congruence of event dates is a measure for the effectiveness of the system to correctly forecast a railway operation incident taken the congruence of the respective event locations as granted.

To quantify this effectiveness of each individual threshold to differentiate between extreme weather and non-hazardous situations, we suggest applying the so-called "probability of detection" method (POD) – also known as "hit rate" – according to Jolliffe and Stephenson (2003):

$$\text{POD} = \frac{a}{a+c} = \hat{p}(\hat{x} = 1 | x = 1) \quad (1)$$

with:

$a =$ Number of days with railway incidents that have been observed and correctly indicated by a CMC,

$c =$ Number of observed incidents that are not indicated by a CMC,

$\hat{p} =$ Conditional probability.

The POD is a sample estimate of the conditional probability of the event (i.e. incident) being forecasted (by a CMC) given that the event was observed (Jolliffe and Stephenson, 2003). A comprehensive performance analysis also requires studying the number of false alarms. For this, the "probability of false detection" should be determined. This probability, also called "false alarm rate" (FAR), is the proportion of non-occurrences that were incorrectly forecasted (Jolliffe and Stephenson, 2003).

$$\text{FAR} = \frac{b}{b+d} = \hat{p}(\hat{x} = 1 | x = 0) \quad (2)$$

with:

$b =$ Number of days of CMC occurrences, where no railway incident was observed,

$d =$ Number of days showing neither a CMC, nor a railway operation incident,

$\hat{p} =$ Conditional probability.

A recent article by Sättele et al. (2016) presents a three-step framework approach to evaluate a broad field of early warning system designs for natural hazards. Following the signal detection theory, Sättele et al. (2016) herein adopt a similar approach to quantify the effectiveness of semi-automated systems (such as Infra:Wetter) by calculating the reliability of the system using a classifier (e.g. a predefined threshold) to distinguish critical events from non-occurrences. Using two case studies as an example, they show that the approach can provide valuable support for decision-makers to optimize their risk mitigation strategies.

However, for an accurate assessment, a detailed, consistent and long-term (longitudinal) damage data base would be required. Such data bases with a high level of detail in terms of damage caused by natural hazards are currently not available for railway infrastructure in Europe. Even the ÖBB, which has invested considerably in event and damage documentation over recent years, does not dispose such a detailed longitudinal damage data base. At present, the ÖBB event and damage database provides data on the date, type and location (i.e. track section) of railway operation incidents and/or damage to railway infrastructure caused by natural events since 1991. A limitation of this dataset for empirically evaluating CMC thresholds, however, is that the type of natural event causing a reported incident is not distinctly identifiable, since several event types are aggregated into joint event categories. For example, the event types "debris flow", "mud flow" and "rock fall" constitute a common category of causes. Hence, the ambiguity in the data hinders a clear assignment of specific CMCs and resulting railway operation incidents. Further uncertainties occur from the fact that damage data are often lacking or, if existing, have not been consistently reported over the entire time period. Particularly in the 1990s, the rules and criteria to insert entries in the database have not been very clear leading to fuzzy or even false entries. For example, incidents that were not caused by natural hazards, such as damage or accidents caused by wild animals (game crossing), were also inserted into the damage database and were not separated from the natural hazard-related incidents. Consequently, although the ÖBB damage documentation procedure can already be regarded as best practice, there is still potential and need to further enhance the approach to make it suitable for the suggested analysis. Cases in point include the refinement of the classification of causes of incidents, so that a more in-depth analysis of potential causal chains between extreme weather events, Alpine hazards, and damage to railway infrastructure and service is possible. Another proposal for improvement is to comprehensively document the observed damage patterns, e.g. via photographs, to gain more in-depth insights into damaging processes.

In order to demonstrate the suggested methodological approach to assess the performance of an early warning system such as Infra:Wetter empirically, we performed an example application using the existing ÖBB damage database as input (see Tab. 5.1). The dates of CMC occurrences were determined using the ERA-Interim global atmospheric reanalysis (Dee et al., 2011). Since an appropriate interpretation of the results is hindered due to the outlined data limitations, they are not further discussed in this thesis.

Table 5.1: Effectivity of Infra:Wetter - Exemplary congruence table. First, we identified the dates of CMC threshold exceedance in the ERA-Interim reanalysis for the period from 1991 until the end of 2013. Subsequently, we filtered out all entries in the ÖBB damage database that are relevant for an investigation of a relationship to the CMCs considered in this study. Finally, the required variables for equation (1) and (2) were quantified and both the POD and FAR were calculated.

	CMC	Incident			
Very intensive rainfall		Yes	No	Total	**POD = 0.171 FAR = 0.367**
	Yes	57	33	90	
	No	277	8034	8311	
	Total	334	8067	8401	
Intensive rainfall with high antecedent soil moisture	CMC	Incident			**POD = 0.129 FAR = 0**
		Yes	No	Total	
	Yes	43	0	43	
	No	291	8067	8358	
	Total	334	8067	8401	
First heavy seasonal snowfall	CMC	Incident			**POD = 1 FAR = 0.685**
		Yes	No	Total	
	Yes	17	37	54	
	No	0	8347	8347	
	Total	17	8384	8401	
Extreme cold	CMC	Incident			**POD = 0.055 FAR = 0.589**
		Yes	No	Total	
	Yes	16	23	39	
	No	276	8086	8362	
	Total	292	8109	8401	
Heat wave	CMC	Incident			**POD = 0 FAR = [ ]**
		Yes	No	Total	
	Yes	0	0	0	
	No	2	8399	8401	
	Total	2	8399	8401	
Combined	CMC	Incident			**POD = 0.2 FAR = 0.489**
		Yes	No	Total	
	Yes	100	96	196	
	No	399	7806	8205	
	Total	499	7902	8401	

Chapter VI – Policy recommendations[3]

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[3] This Section represents a revised and adapted version of the ENHANCE project report "Deliverable 7.5: Case study synthesis and policy recommendations - Case study: Building railway transport resilience to alpine hazards" by Kellermann et al. (2016). Large parts of this report are published as a book chapter of the "ENHANCE synthesis book".

Apart from the synthesis and outlook provided in the concluding Chapter of this thesis (Chapter 7), the presented research findings are initially viewed in a broader context. Accordingly, some ongoing improvements are presented, and a variety of general ideas and policy recommendations are made in the course of this Chapter. These contents are partly based on external information obtained from several consultations and interviews[4] conducted with the ÖBB Natural Hazards Department and associated stakeholders.

6.1 Ongoing improvements of natural hazards management

The weather monitoring and early warning system Infra:Wetter is the main non-structural risk reduction measure maintained and applied by the ÖBB Natural Hazards Management (see also Chapter 4.2 of this thesis). The system was established in 2006 in the aftermath of a major flood event in 2005, and stress-tested for the first time in June 2013, when extreme rainfall resulted in floods and debris flow events obstructing and interrupting train transportation in large parts of Austria. Experiences of this stress test show that the system generally performed well also under extreme conditions: The event was predicted with a sufficient warning time and operational measures such as track closures and temporary speed limits reduced the risk to passengers and staff. However, those experiences also revealed potential for improving internal risk and crisis management. One aspect that was identified by ÖBB officials was the need for clearly defined responsibilities during such a long-term event. Being an infrastructure manager with a complex organisational structure, it is important for the ÖBB to have a clear picture of the persons in charge at different levels of the organisation. At the beginning of an event, this is usually the head of the organisational unit responsible for taking decisions at the respective level. However, in case of a longer-lasting crisis, as it was the case in 2013, it is important to share responsibilities and to appoint and communicate deputies that are available in times when the head of the division is not available. In order to strengthen the social capital internally, strategic plans were developed that shall further improve the effectiveness of the crisis management and the preparedness of the responsible staff. For instance, it was decided to appoint an officer in charge on the spot during future events of such a magnitude.

An organised and structured hazard management depends on regular training and continuous education of personnel. For instance, the ÖBB established its own avalanche warning service and commissions that consist of trained avalanche specialists. These experts evaluate the avalanche risk

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[4] Further information on the interviews as well as a full list of interviewees is given in Otto et al. (2013).

and give advice to decision makers. Based on their advice, the track managers then decide whether the railway service will continue operation, or, if there will be restrictions or even track closures. Against the background of the good experiences made with this system, the Natural Hazard Management section of the ÖBB started a project to set up similar institutions for hydrological hazards, such as floods and torrential processes. These commissions shall ensure an effective and regulated workflow during crisis situations and a legal basis for imposing safety measures, which is immensely important for the field staff as well as for the decision-makers. If critical decisions are taken by commissions, this would also mean an improvement for ÖBB staff members in terms of liabilities for these decisions. Clear regulations regarding the legal liability of these commissions for certain decisions, such as false alarms, would further improve legal certainty. Although the field personnel showed an enormous work effort to bring the situation under control during the event in 2013, such structured operating instructions help to further optimise and accelerate decision-making processes for an even quicker response during extreme weather events.

To enhance the ability of the ÖBB to implement (temporary) speed limits or stop trains also as far as small-scale convective weather events are concerned, it was furthermore proposed that each train should be equipped with a GPS system so that it can be readily located.

6.2 Enhancing the management of risks arising from CMCs through an expansion of partnerships

In addition to internal improvements of the risk and crisis management (see Section 6.2.1 of this thesis), the flood event of 2013 was also a trigger for the ÖBB to further enhance risk management by establishing and strengthening cooperation with additional external partners from the public sector as well as from the university and industry sector. For instance, the hydrographic services of the federal states of Austria maintain a dense hydrographic monitoring system throughout the country and are also responsible for issuing regional flood warnings. To make best use of this information resource, specific thresholds for inundation levels posing a risk to railway infrastructure, for instance in the Salzburg region, were defined and integrated into early warning module of Infra:Wetter. Based on these thresholds, the hydrographic services can provide railway-specific flood warnings to the ÖBB.

The 2013 event furthermore revealed that a good knowledge of the situation on the ground throughout the duration of the event is very important. While the state of flood protection measures and embankments is usually well known due to their good visibility, the situation for torrents is different: catchment areas are difficult to monitor, because the amount of debris is constantly changing in the course of such an intense rainfall event. Moreover, there is also the risk of drift-wood blockage, which can heavily impair the protective action of torrent control measures. Hence, to also improve this aspect of risk management, a pilot project that is concerned with the optimisation of the current observation of torrential catchments, e.g. with drones, was set up by the ÖBB in collaboration with the University of Natural Resources and Life Sciences (BOKU) in Vienna.

Also the EU Floods Directive (European Commission, 2007) provided impetus to the ÖBB to develop additional and more context-specific flood risk maps, which localize track sections prone to flooding. The maps that were produced for the Floods Directive are usually not of sufficient detail as far as rail infrastructure is concerned. For instance, tunnels under the railway tracks or bridges are not reflected correctly and, as a result, the flood risk maps might wrongly report an inundation of railway infrastructure at the relevant sections. Moreover, to reflect the exact height of the railway tracks, a very detailed digital elevation model (DEM) is needed giving their linear feature. To better account for the specific features of the railway network and to improve the level of detail, the maps of the Floods Directive are currently being enhanced by the ÖBB in collaboration with the hydraulic engineering company riocom on the basis of high-resolution DEMs. The resulting maps illustrate the flood plains with a return period of 30, 100 and 300 years and take the specific details of the railway network into account. Consequently, such revised and improved versions of flood risk maps help to create specific flood risk management plans as well as to establish flood monitoring and early warning systems where they are useful and needed. This is also demonstrated by the findings of the large-scale application of RAIL (Chapter 3 of this thesis), where these improved and railway infrastructure-specific flood exposure data was used as a basis.

In order to further enhance risk management and strategic planning, the knowledge on the hazard side could be complemented by establishing new or expanding the existing partnerships in terms of impact assessments, which is mostly neglected in the current ÖBB risk management practice. For example, deeper insights into damage potentials and processes as well as knowledge on expected annual loss occurring from individual natural hazards such as flood and debris flow events would considerably facilitate the optimization of risk management, e.g. regarding the targeted planning and prioritisation of risk reduction measures.

6.3 Efforts to improve event and damage documentation procedures

At present, the ÖBB damage reporting and documentation system comprises three steps. All incidents that occur during railway operations are reported directly by the train conductor and recorded in the internal database on Railway Emergency Management (REM). This includes incidents due to natural hazards but also other reasons such as for instance deer crossing. As incidents are also recorded from moving trains, identifying the exact reason for an incidence is not always an easy task. Therefore, incidents are examined further by the ÖBB and, subsequently, are included in the damage database. Those events that are considered as serious and thus worth registration are further examined and verified by ÖBB staff and then included in the ÖBB accident statistics. In this data base, it is also specified whether the incident occurred due to a natural hazard and what type of natural hazard.

However, in the current classification scheme, several natural hazards that are characterised by different damaging processes to railway infrastructure are integrated into a single category. For instance, one category comprised the alpine hazards debris flow, landslide and rock fall. This makes is difficult to use these databases to gain insights into the specific damaging processes of these hazards. A good understanding would be needed, though, to develop impact and risk models that are capable of supporting risk-based decision making.

In order to enable the assessment of natural hazards impacts and to better quantify damaging processes, the ÖBB Natural Hazards Department currently works on restructuring the reporting system in such a way that insights into damaging processes from different natural hazards can be drawn. Moreover, it was considered to also include ‘near-misses’, i.e. documentations of events that nearly caused damage or operation events, and their reasons in the data base.

6.4 Risk absorption by the federal government

Natural hazards can be associated with substantial damage that makes additional funding from the federal government necessary. A review of recent annual reports of the ÖBB reveals that additional funds were provided by the government in 2006 (no amount specified), in 2013 (€18.4 million) and in 2014 (€7.2 million) to support the recovery from damage caused by natural events (see Section 3.4.2 of this thesis). With the projected increase in the frequency and intensity of at least some CMCs (see Chapter IV of this thesis), also the demand for additional finance from the budget earmarked by the ministry for calamities or extra subsidies according to the Bundesbahngesetz could rise. These dynamics are currently not taken into account by the risk-absorbing mechanism, which builds upon past experiences in terms of costs due to natural hazards.

To better account for the dynamics of CMCs associated with global warming, but also to consider changes in exposure and vulnerability of railway infrastructure, a periodic review of the earmarked budget reserved by the responsible ministry is recommended. Based on this revision, it could then be decided whether the risk-absorbing finances or procedures in general need to be adjusted. Such a dynamic component was, for instance, integrated in the European Floods Directive (European Commission, 2007) in Article 14 No. 1-3. Herein, fixed intervals of six years for a revision of preliminary risk assessments, flood hazard and risk maps and risk management plans are prescribed. Such periodic revisions could have positive effects with regard to the financial capital of the ÖBB Natural Hazards Management and related partnerships on risk reduction.

Moreover, providing comprehensive risk information for the entire national railway network for the current situation as well as future scenarios could also support the optimization of risk absorption mechanisms with regard to effectivity and sustainability. As shown in Chapter III of this thesis, the flood damage model RAIL is capable of providing appropriate risk information, i.e. expected annual damage (EAD), on the large scale and, hence, could be one of the building blocks of a risk-informed decision making.

6.5 Policy recommendation for the European level

The thesis at hand repeatedly pointed to the importance of damage data for an effective risk management: for instance, damage data can be used to derive railway-specific damage models (such as the RAIL model), which can be used to calculate EAD for floods that are able to support decision-making processes in risk management, and to facilitate the evaluation of different risk reduction strategies. Moreover, a detailed and consistent long-term damage database could be used to assess the adequacy of thresholds defined in an early warning system and to inform risk absorption mechanisms provided by national governments.

As already argued in Chapter V of this thesis, the ÖBB already puts great emphasis on the documentation of damage to railway infrastructure due to natural hazards as well as on the continuing amendment of these procedures. In doing so, the ÖBB plays a pioneering role in Europe as no comparable system exists in other EU member states. However, the establishment and maintenance of a pan-European event and damage database would significantly contribute to improving the understanding of damaging processes to railway infrastructure, the proportional share of different natural hazards to overall losses and the enhancement of strategic risk management. The specific need to fill this knowledge gap even on the global level is also confirmed and highlighted by the Sendai Framework for Disaster Risk Reduction adopted by the United Nations member states during the Third UN World Conference on Disaster Risk Reduction (United Nations, 2015). Therein, four priorities as well as seven global targets are formulated to be achieved within the near future (United Nations, 2015). With regard to critical infrastructure, one global target aims at "*the substantial reduction* *of disaster damage to critical infrastructure and disruption of basic services […] including through developing their resilience by 2030".* Reaching this and other goals requires first and foremost a solid understanding of disaster risk, which is addressed in Priority 1 of the framework: "*Policies and practices for disaster risk management should be based on an understanding of disaster risk in all its dimensions of vulnerability, capacity, exposure of persons and assets, hazard characteristics and the environment. Such knowledge can be leveraged for the purpose of pre-disaster risk assessment, for prevention and mitigation and for the development and implementation of appropriate preparedness and effective response to disasters"* (United Nations, 2015)*.*

So far, information on railway incidents on the European level is based on the EU regulation (EC) 91/2003 and, therefore, limited to accident categories such as train collisions and derailments. However, no information is provided on natural hazards and their impacts, or even on damaging processes. Hence, in order to enhance risk management of railway infrastructure also at the European level, this reporting system should be complemented with appropriate information on the impacts of natural hazards. How and what type of information to include in such a European database could be informed by the experience gathered by national railway operators such as the ÖBB.

Chapter VII – Synthesis and outlook

Experience over the last few decades has clearly shown that natural hazards can significantly hamper the reliability of railway networks and cause extensive structural damage and disruption. As a result, the national railway operator in Austria had to cope with financial losses of several million euros due to natural hazard impacts in recent years. Such amounts clearly demonstrate the high vulnerability of railway infrastructure and transportation to natural hazards. Hence, comprehensive and sustainable risk information is indispensable for an effective management of natural hazards and risks in Austria, which is also indicated by the fact that the ÖBB has an own department for natural hazards management and furthermore fosters partnerships on risk reduction with various stakeholders at different administrative levels.

As outlined in Chapter 1, in order to address the risks stemming from the most important natural hazards in the context of railway operations, i.e. floods and extreme weather events, the objective of this thesis was to support and facilitate the decision-making in the management of natural hazards by providing new risk information as well as tools for targeted risk analyses. Herein, it was aimed to feed into both of the main risk reduction strategies currently followed by the ÖBB, i.e. structural and non-structural risk reduction measures.

In the context of the risk management strategy with focus on structural measures, the flood damage model RAIL was developed that is able to estimate both structural flood damage to railway infrastructure and associated direct economic loss (Chapter 2) using the decisive impact parameters "water level" and "energy head" as a basis. The particular added value for railway constructors and operators such as the ÖBB is that this tool enables the localization of significant structural damage potentials at specific track section and, coupled therewith, the identification of risk hot spots. Such information allows, for example, the targeted planning and implementation of (technical) risk reduction measures. The results of the risk assessment for the March River indicate that the model performance proves expedient as the mapped results plausibly illustrate the high damage potential of the track sections located closely adjacent to the course of the river as well as a general accordance with the inundation depths. Moreover, the estimates of the associated economic loss amount to a plausible order and scale. However, the findings also show that the development of reliable flood damage models for infrastructure is heavily constrained by the continuing lack of detailed event and damage data. As a further consequence of this lack of primary data, the RAIL model is only applicable to standard cross sections, whereas other infrastructure elements such as bridges or interlocking blocks are currently not included. Moreover, it is assumed that the RAIL model is in a first instance valid for lowland rivers, since it is derived from flood impacts caused by static river flooding. Further cases and data, thus, are needed to i) adapt the RAIL model to different hydraulic characteristics (e.g. higher flow velocities), and ii) perform a model validation. Furthermore, the railway operator ÖBB already proclaimed their interest in a transfer of the RAIL model to other natural hazards than floods, with emphasis on debris flows. However, since only hazard data but no empirical damage data are currently available, this purpose affirms the need for better and more comprehensive documentation procedures.

Chapter 3 is dedicated to the acquisition of flood risk information for Austrian railway infrastructure on a larger scale. In view of this, the RAIL model was applied to estimate flood damage and loss due to a 30-year, 100-year and 300-year flood in the Mur River catchment and the sensitivity of the results to the key model assumptions was analysed in order to obtain indications on the model robustness. Additionally, the impact of risk aversion was investigated, and some light was shed on the sustainability of current flood risks in the context of climate change. With reference to the research questions formulated in Chapter 1 of this thesis, the findings indicate that the RAIL model is capable of supporting decision-making in risk management by providing comprehensive risk information on the catchment level. The apparent low sensitivity of results furthermore signalizes an acceptable robustness of flood damage estimations delivered by RAIL, at least in this study area. Hence, taking into account the given model limitations, the RAIL model could also be applied to even larger scales, e.g. the national or the European level, to estimate flood damage for infrastructure. For example, as already suggested in Chapter 4.6, an assessment of flood damage and risk to the Trans-European Transport Network (TEN-T) could provide important risk information and, thus, guidance on where to invest European Community funds in risk reduction. To the best of our knowledge, flood risk assessments for railway infrastructure on the national level, European level or even beyond do not yet exist, but would certainly attract the interest of various actors and entities related to natural risks management. The results presented in Chapter 3 moreover demonstrated that an increased risk aversion of the railway operator has a marked influence on the estimates for the study area. Against the backdrop that the safety of passengers and personnel is the unique premise for a railway operator, the consideration of risk aversion against low-probability flood events in the context of risk management is seen as expedient as it gives new incentives for the planning and implementation of risk reduction measures. Especially in the context of climate change and possible consequences, the sustainability of current flood risk management practices could be jeopardized and, hence, the underlying strategies should be reconsidered. For example, conventional cost-benefit analysis approaches for structural risk reduction measures could be broadened by the application of multi-criteria analyses, wherein particular weight is attributed to risk aversion.

Since the implementation of technical protection measures is often not feasible for either economic reasons or aspects of nature and landscape conservation and technical measures are furthermore limited in ensuring a commensurate level of safety for railway operations in Alpine topography, the ÖBB puts great emphasis on non-structural, precautionary, and preparatory risk mitigation measures. In this context, the key element is the weather monitoring and early warning system "Infra:Wetter". Since knowledge and information are the key issues of this non-structural risk reduction measure, the major objective of the research presented in Chapter 4 was to gain new insights into possible climate change impacts on frequencies of critical meteorological conditions (CMC) jeopardizing railway operations in Austria. With reference to the guiding research questions of this thesis, the analysis gave robust indications of a noticeable to strong alteration of the current hazard profile in Austria. Apart from certain positive effects on some sectors (e.g. winter service), most of the projected shifts, in particular with regard to very intensive rainfall events, are likely to lead to new challenges for the ÖBB natural hazards management. Consequently, an increase of heavy rainfall events is likely to intensify problems such as overloading of the drainage systems leading to (flash) flooding and/or scouring of track lines and other infrastructure elements. If no action is taken, the costs caused by extreme weather events must be expected to rise in future. Such actions could involve the comprehensive implementation of adaptation measures, e.g. the redesign of drainage systems or the adaptation of existing construction standards for railway lines using revised design events for natural hazards as a basis. Furthermore, the current maintenance standards for railway infrastructure could be reviewed and – if appropriate – adapted towards increased system resilience. The results of the sensitivity analysis indicate that frequencies of CMCs are rather sensitive to changes of thresholds. This aspect emphasizes the importance to carefully define, validate, and—if needed—to adapt the thresholds that are used in a weather monitoring and warning system of the railway operator in order to optimize its effectiveness as well as its adaptive capacity. However, since the necessary data for an empirical evaluation of the thresholds in use are currently not available in respect to data quality and temporal coverage, the importance to continuously collect detailed event and damage data following a standardized procedure is striking. This is underlined by the brief analysis presented in Chapter 5.

Chapter 5 addresses the importance of assessing the effectivity of a threshold-based weather monitoring and early warning system such as Infra:Wetter to precisely detect CMCs that potentially cause a railway operation incident. Accordingly, against the background that the thresholds in use are derived from expert judgements, a proposal for an empirical evaluation of the performance of such a system to correctly forecast a railway operation incident caused by a CMC is made. Using the existing ÖBB damage database as input, an example application was performed in order to demonstrate the suggested methodological approach. However, due to the fact that this damage database does not dispose of sufficiently detailed longitudinal damage data required for an accurate evaluation, the presented results allow no conclusions about the actual effectivity of Infra:Wetter. This shortage again highlights the importance of comprehensive event and damage documentation. In conclusion, although the ÖBB damage documentation procedure is a trailblazer within the European infrastructure sector (and possibly worldwide), there is still room for improvement towards a better and more in-depth understanding of potential causal chains between extreme weather events, Alpine hazards, and damage to railway infrastructure and service.

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