Nat. Hazards Earth Syst. Sci. Discuss., 3, 2629–2663, 2015
www.nat-hazards-earth-syst-sci-discuss.net/3/2629/2015/
doi:10.5194/nhessd-3-2629-2015

Natural Hazards
and Earth System
Sciences
Discussions
Open Access

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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Received: 30 March 2015 – Accepted: 31 March 2015 – Published: 16 April 2015

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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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, a statistical modelling approach for estimating direct structural flood damage to railway infrastructure and associated financial losses is presented. Via a combination of empirical 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.

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, b). 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 $m^3 s^{-1}$ of the March in this section was exceeded nearly 13 times resulting in a peak flow rate of 1400 $m^3 s^{-1}$. 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, personal communication, 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 UK 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 aimed to develop a tool for the estimation of direct flood damage and losses to railway infrastructure by means of a probabilistic modelling approach derived from empirical damage data – the so called RAIL model (RAilway Infrastructure Loss). The RAIL model 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 various 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 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 Model development

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 and 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. 1. A railway track's standard cross-section consists of the elements substructure, superstructure, catenary and signals. The left box in Fig. 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.

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 most serious 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. 1).

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:

$$\text{Energy head } E = h + v^2/2g \tag{1}$$

$$\text{Intensity } I = v \cdot h \tag{2}$$

$$\text{Indicator for flow force IF} = h \cdot v^2 \tag{3}$$

with

h: water level [m]

v: flow velocity [m s^{-1}]

g: acceleration of gravity = 9.81 m s^{-2}

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. 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.

2.3 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 constituted as significant. 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. 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. 1). Table 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.

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 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, the model was iteratively adjusted to the real expenses.

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 (left) shows the damage curve in RAM for the land use type “Traffic”, which corresponds to the infrastructure sector.

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 (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 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.

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 points. 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 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, due to technical considerations, the 5 m buffer was neglected in retrospect as considered to be too narrow to represent the double-track standard cross-section of the Northern Railway adequately.

The summary statistics of the mean parameter values per damage class are illustrated by the boxplots in Fig. 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 Sect. 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 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.

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. 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. 1) and (2) the overall coefficient of variation (0.66) of the hydraulic data within the reference areas, which is relatively high.

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 significant correlations could be found (see Table 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. 2.3 and Table 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.

4 Application and evaluation

4.1 The March flood in 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. 2.4). 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 4. Additionally, the model results for the March flood data are cartographically mapped in Fig. 5 showing the inundation areas including water levels as well as classified damage at flood affected track segments.

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. 6 and Sect. 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. 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 Tables 4 and 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.

4.2 Flood scenarios

In a subsequent step, the damage model was applied to a set of hydraulic scenarios complying with synthetic 30, 100, 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 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 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 approximately EUR 283 000. Herein, the share of loss equals to 84.3 % for the low-probability events (HQ100–HQ300) and 15.7 % for the high/medium-probability events (HQ30–HQ100), respectively.

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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. Tables 6 (March flood) and 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 10–30 % 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.

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, personal communication, 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

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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.

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 Figs. 5 and 6) as well as a general accordance with inundation depths. Finally, however, the model could not be validated yet in terms of estimating flood damage reliably. Respective reviews, thus, are required when appropriate empirical data is available and further research also on potential sources of uncertainty is needed (see Sect. 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.

Acknowledgements. The authors gratefully acknowledge:

- The Austrian Federal Railways ÖBB for their substantial data supply.
- Raimund Heidrich from the engineering office *riocom* for his collaboration, data supply and advice concerning the hydraulic simulations of the March River.

The research leading to these results has received funding from the EU Seventh Framework Programme, through the project ENHANCE (Enhancing risk management partnerships for catastrophic natural hazards in Europe) under grant agreement no. 308438.

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Table 1. The upper row shows the combined standard costs per running metre (rm) of a double-tracked railway standard cross section. In order to quantify losses per damage point, the indicated costs have been multiplied, since a damage point in the model represents a track section of 100 m. Moreover, the repair costs for damage class 2 were calibrated by adding a coefficient of 0.25 (see Sect. 2.4). The cost value of EUR 702 200 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

Table 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 significance, which has been set to 0.5 within this study, are highlighted in bold type. Additionally, 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	**0.532**	**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)*

Table 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	0.319	0.079	−0.238	−0.136
	(0.015)	*(0.055)*	*(0.641)*	*(0.157)*	*(0.423)*
v	0.188	0.110	0.064	−0.332	−0.315
	(0.266)	*(0.517)*	*(0.705)*	*(0.045)*	*(0.058)*
I	0.300	0.170	−0.020	−0.302	−0.299
	(0.071)	*(0.314)*	*(0.909)*	*(0.069)*	*(0.072)*
IF	0.251	0.147	−0.111	−0.300	−0.308
	(0.134)	*(0.385)*	*(0.511)*	*(0.071)*	*(0.063)*
E	0.393	0.313	0.079	−0.232	−0.136
	(0.016)	*(0.059)*	*(0.641)*	*(0.166)*	*(0.423)*

Table 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	$\sum$
n	30	54	39	123
Repair costs	EUR 351 000	EUR 7 319 700	EUR 27 385 800	EUR 35 056 500

Table 5. Estimated frequencies of damage classes and resulting repair costs for different hydraulic scenarios.

		Damage class 1	Damage class 2	Damage class 3	$\sum$
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

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Table 6. Calculated monetary losses for the March flood in 2006 according to RAM and DSM.

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

Table 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

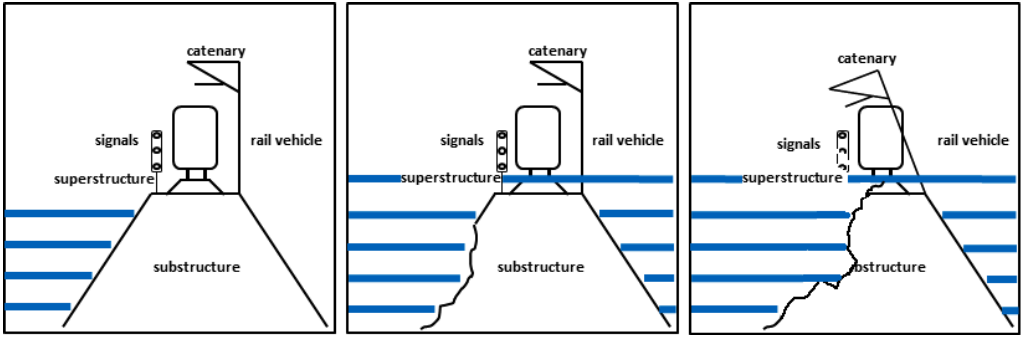

Figure 1. Damage classification scheme (adapted from Moran et al., 2010a).

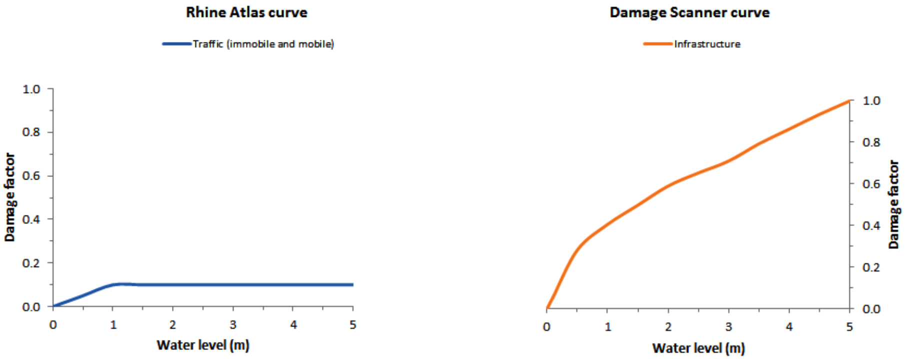

Figure 2. Damage curves used in the Rhine Atlas (left) and the Damage Scanner model (right) (adopted from Bubeck et al., 2011).

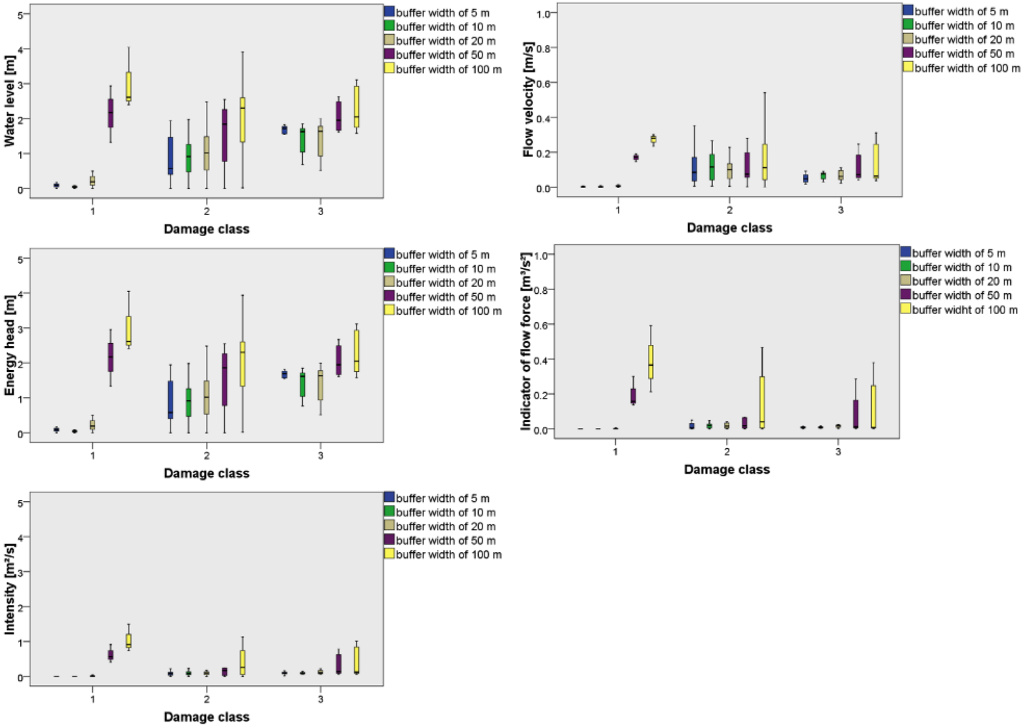

Figure 3. Box plots displaying the summary statistics of each impact parameter per damage class and for varying buffer widths.

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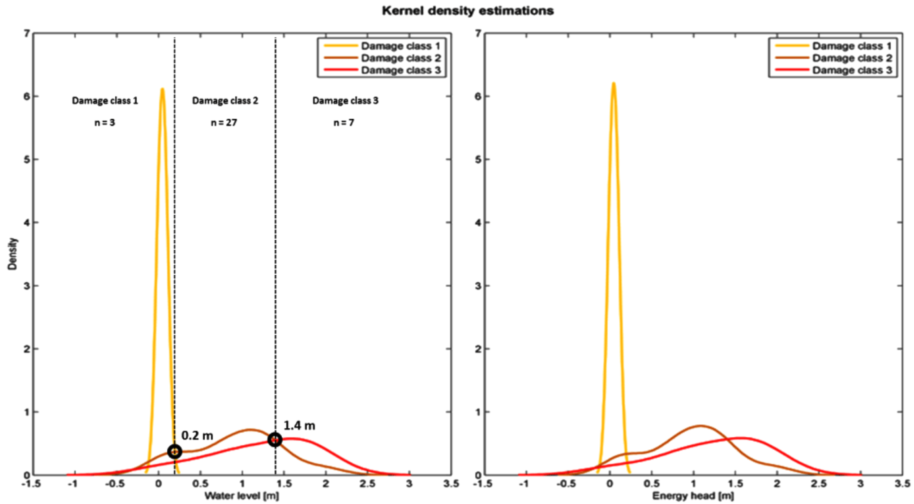

Figure 4. Kernel density plots for the impact parameters *h* and *E*. The parameter values at the marked graph intersection points determine the thresholds in the damage model to assign the most likely damage class to each track section. The derived values apply equally to both parameters.

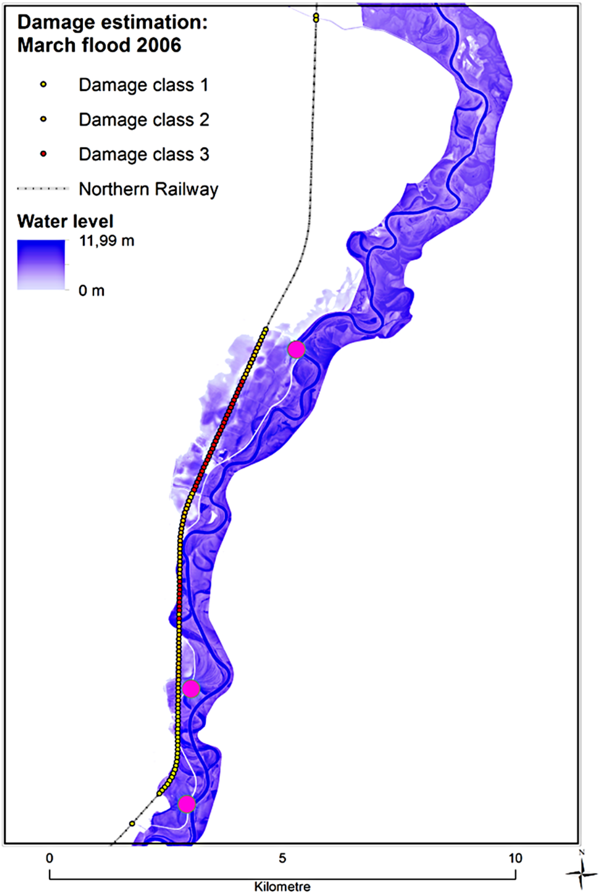

Figure 5. Estimation of damage potentials at the Northern Railway for the hydraulic conditions of the March river flood in 2006. During the event, three levee breaches occurred at three different locations along flood protection levee at the March River (see pink dots).

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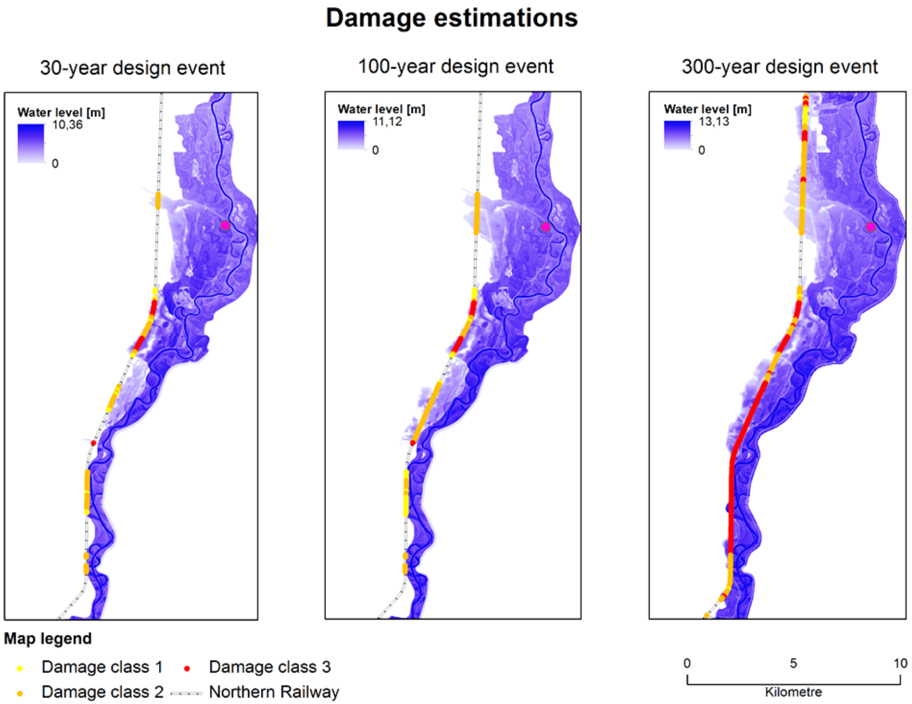

Figure 6. Estimation of damage potentials at the Northern Railway for three flood scenarios. The left map shows the model results for the hydraulic input of a synthetic 30 year event. The results for a synthetic 100 year event are illustrated in the middle map. The right map covers the results of the 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).