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Risks and consequences of weather hazards on railway infrastructure

Keywords

weather hazards, risk assessment, hazard management, climate change, railway systems

Abstract

Weather-related hazards are already among the factors most frequently causing disturbances for railways. Flooding and storm are considered major threats to the system. Climate change might in the long run produce new kinds of hazards and threats to the railway system, but the climate change will principally involve a strengthening of the already known threats, in terms of increased frequency as well as increased intensity. Based on examples of natural hazards' impact on railways, possible approaches of vulnerability assessment are described which could also address potential consequences of climate change. In order to reduce the effects of weather hazards technical countermeasures are necessary, but also an appropriate risk management as, e.g., required for flooding in the European Union.

1. Introduction

A railway network is a complex system of different and interacting infrastructures including earthworks, civil structures, track structure, signaling and catenary installations and rail operations (train services, management of stations).

Disruptions in a railway system can have severe consequences, such as direct damage and indirect loss. Floods represent one of the most important natural hazards, and cause at least one-third of the total losses due to all natural hazards in the world. China is a country prone to flood hazards. Two-thirds of the Chinese land area faces the threat of floods [14].

A flood can be defined as a temporary covering of land by water outside its normal confines according to the definitions of the FLOODsite project [12].

Floods are natural phenomena which cannot be prevented. However, some human activities (such as the reduction of the natural water retention by land use) and climate change contribute to an increase in the likelihood and adverse impacts of flood events. It is desirable to reduce the risk of adverse consequences, especially for infrastructure associated with floods.

Throughout the centuries, Europe has suffered from many floods. Despite many efforts to protect against floods, it has proven impossible to eradicate them completely. For this reason attention in Europe has shifted in the past decades from protection against floods to managing flood risks.

Following the 2002 floods in the Danube and the Elbe, the European Community's Council of Ministers launched a European initiative on flooding. This resulted in October 2007 in the publication of a directive on flood risk management [11]. Article 14 of this directive requires:

1. The preliminary flood risk assessment, or the assessment and decisions referred to in Article 13(1), shall be reviewed, and if necessary updated, by 22 December 2018 and every six years thereafter.
2. The flood hazard maps and the flood risk maps shall be reviewed, and if necessary updated, by 22 December 2019 and every six years thereafter.
3. The flood risk management plan(s) shall be reviewed, and if necessary updated, including the components set out in part B of the Annex, by 22 December 2021 and every six years thereafter.
4. The likely impact of climate change on the occurrence of floods shall be taken into account in the reviews referred to in paragraphs 1 and 3.

However, effective flood prevention and mitigation requires, in addition to coordination between Member States of the European Union, cooperation with third countries.

Risks for infrastructure, rolling stock and other rail assets are [29]:

- high temperatures resulting in rail buckling, expansion of swing bridges, overheating of electrical equipment in location cases or overhead line sag,

- excess precipitation and flooding resulting in earthworks failure, scour of bridges, risk to signaling systems and electronic equipment or track circuits failures,
- drought leading to earthworks failure due to desiccation or movement of overhead lines (OHL) due to soil shrinkage around foundations,
- heavy snow leading to traction motor failures due to snow ingress or trees falling onto tracks and OHL,
- high winds leading to overhead line equipment damage from fallen trees other and objects,
- lightning which damages electronic equipment, and
- sea level rise and storm resulting in coastal erosion of earthworks, structures and tracks as well as damage to sea walls.

2014 will go down in history as the year with no summer. This did not appear to be the case initially as the early weeks of June were warm and dry. Then the temperatures fell and the rain started. Over the entire summer, e. g most regions of Switzerland experienced rainfall at levels ranging between 110 and 140 percent above the norm; in some places they reached as much as 200 percent.

In addition to the problem of flood risk, the railway network is exposed to a number of other natural hazards such as rockfalls and landslides with an average of 85 incidents per year on the French rail network, of which approximately 25% are associated with flooding [2]. Also in Switzerland the persistent precipitation resulted in floods and sometimes even landslides.

Climate-related events are already among the factors most frequently causing disturbances for railways. Flooding and storm events are considered major threats to the system. Climate change might in the long run produce new kinds of events and threats to the railway system, but the climate change will principally involve a strengthening of the already known threats, in terms of increased frequency as well as increased intensity.

A long time horizon is used in the planning process for new investments in railway infrastructure. Typically, railways are expected to operate at full capacity for a 60-year period but looking in more detail, the lifetime of different installations can be substantially longer, up to 100 years for culverts and bridges. The combination of a long time horizon in planning and design and an increasing demand for rail traffic in the future raises many questions regarding how adaptation to climate change can be accounted for in the planning, design and management of railways [20].

2. Examples of the impact of weather hazards on railways

Several examples all over the world show the potential consequences of flooding as one typical climate-related event for railways. In the following, flooding examples from Europe and Asia and consequences are described in more detail underlining the need for an appropriate hazard assessment.

In June 2013, several parts of Central Europe were hit by large-scale flooding. Particularly Southern and Eastern Germany were affected, but also other countries such as Austria, Switzerland, Czech Republic, Poland, Hungary, Slovakia, Croatia and Serbia. The flooding in Germany was caused by heavy rain persisting over several days in combination with wet catchments; a strong rainfall anomaly in May had led to very high soil moisture over large parts of Germany. Almost all rivers in Germany showed high water levels. Severe flooding occurred especially along the Danube and Elbe rivers, as well as along the Elbe tributaries Mulde and Saale. In 45 % of the German river network peak flows exceeded the 5-year flood discharge [33].

Using an adapted method described in [35] that determines and assesses large-scale flooding based on discharge data from 162 gauges from all over the country, the flood of June 2013 can be regarded – in hydrological terms – as the most severe flood in Germany over at least the past 60 years [24].

The enormous hydrological severity was caused by widespread and intense rainfall on very wet soils due to exceptionally high rainfall in the month preceding the event. Although the hydrological severity of the flood 2013 is at least twice as high as the severity of the flood 2002, the damages in 2013 are expected to be significantly lower than in 2002. Generally, it is assumed that the improvements in flood risk management since 2002 have prevented higher damage [24].

Flood discharges above a 5-year return period were observed in many rivers reaches in Germany between 21 May 2013 and 20 June 2013. Over a length of approximately 1400 km in the river network even 100-year flood discharges were exceeded [34].

One company that has been considerably affected by the flood event of 2013 is the Deutsche Bahn AG. In June 2013, mudslides as well as the submergence or under-washing of tracks led to a variety of interferences of the normal rail traffic (see *Figure 1*). Thus, the morning of 3 June 2013 saw 60 route closures and interferences, of which approximately 25 were in Bavaria and approximately 30 in Thuringia and Saxony. In the afternoon, further restrictions were reported on up to 15 routes. These could be lifted to some extent in the subsequent days. From 8 June 2013, when the flood attained the middle reaches of the Elbe, this number increased to 17 routes.

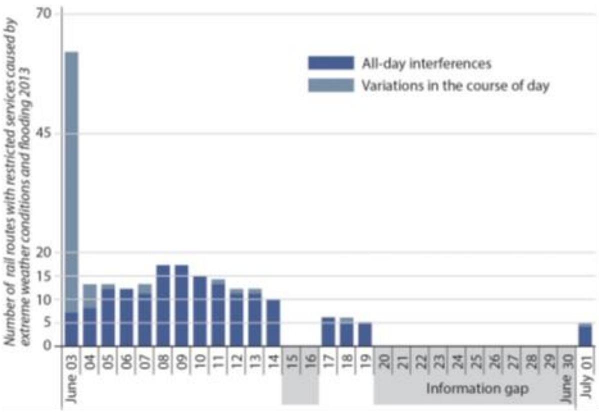

Figure 1. Number of train routes with disruptions or interferences caused by extreme weather conditions (low-speed routes, platform or route closures; information source: German Deutsche Bahn AG survey maps detailing interferences caused by extreme weather, in part updated several times a day)

In the medium term, primarily long-distance traffic had to bear the brunt of the flood after the dyke breach at Fischbeck on 10 June 2013 resulted in the flooding of an approximately 5 km long stretch at the town of Stendal. This meant that the high-speed rail line between Berlin and Hanover had to be interrupted until 4 November 2013, i.e. for almost 5 months [5]. For this reason, important connections between Berlin and the Ruhr district, Cologne and Bonn, as well as between Berlin and Frankfurt (am Main) were affected. A replacement timetable with diversions was deployed but led to travel time extensions of 30–60 min and resulted in the fact that one third of the travelers from and to Berlin choose flights, busses or their own cars [6].
The potential for disruption to transport infrastructure and the services it supports is of particular concern in countries like that have under-invested in their transport operations for many decades. This has been well illustrated by several recent incidents when sections of the railway network in UK were forced to close for weeks after embankments and cuttings became damaged after heavy rain [4].
The majority of overtopping events causing damage to infrastructure have taken place at the most exposed section of line at King Harry’s Walk, Dawlish, where top of the sea defences are only 4.9 m above ordnance datum.
Perhaps most famously, winter storms in February 2014 breached the sea wall in several places along a coastal stretch of the London to Penzance railway line at Dawlish, in Devon, leaving the railway tracks completely unsupported (see *Figures 2 and 3*) and closing the line for 2 months [26].

Figure 2. The breach in the sea wall near King Harry’sWalk at Dawlish, Devon, on7 February 2014

Figure 3. Investigation of the damages according to [26]

In-sea sensors provide information to railway staff in advance of severe overtopping events in order to allow them to close the line before it becomes dangerous to passing rail traffic. The events of February 2014 amounted to a spectacular example of restrictions, when the in-sea sensors returned the most extreme warning possible.
In India, thousands of rail bridges/culverts are more than 100 years old, and many of them are prone to floods due to change in hydrological conditions and river regime. During the last decade, many bridges are affected by flash floods in the country causing damage to lives and property. A flash flood is caused by heavy or excessive rainfall in a short period of time, generally less than 6 hours.
Such a flood devastated the Machak River during the midnight of 4 August 2015 due to heavy rainfall in the

catchment. As the slopes were steep in the upstream catchment area, the lag-time of the peak flood was found to be less and washed off the Machak rail culvert without any alert [9].

As a consequence of this hazard, two passenger trains in the Indian state of Madhya Pradesh have derailed minutes apart on a flooded bridge. The first train derailed, then simultaneously on the neighbouring line from the opposite direction, another train was coming. That train also encountered a flash flood situation. So it almost happened simultaneously on neighbouring tracks.

Extreme weather events have occurred frequently in Malaysia over the past decade. The most devastating natural disasters experienced in Malaysia are floods and landslides.

The destructive flood in southern peninsular of Malaysia, which occurred in two events back to back in December 2006 and January 2007, is known as Typhoon Utor. The massive flood in Kota Tinggi Johor started when the Northeast monsoon brought heavy rain through a series of storms. The series of floods were unusual as the 2006 average rainfall return period was 50 years, while 2007 had more than a 100-year return period. Local weather changes are among the natural causes that triggered the flash flood [32].

Asia has suffered more landslides compared to other world regions due to its climate nature [30]. There are many factors that can trigger landslides including changes in slope geometry, water level, rainfall intensity, and loading. However, the major cause of landslides in Malaysia is high precipitation.

Also Japan has its experiences traffic disruptions caused by natural hazards [25].

Heavy rain (427 mm for 2 days) resulted in landslide and flooding in Niigata in July 2004, strong wind (over 30 m/s) lead to a derailment of the train and falling from the bridge in Hyogo in December 1986 and – as further example – high waves led to a coastal erosion and collapse of a shore protection wall in December 2000.

3. Approaches of vulnerability assessment

In [4] the likely impact of rising sea levels on the Dawlish to Teignmouth stretch of the London to Penzance railway line was investigated by using a 'semi-empirical' modelling approach (see, for example, [28]) that involved two stages. The first was to establish an empirical relationship between sea-level rise and overtopping events along the railway line, assuming decadal-scale sea-level change to be the physical driver of such events. The post-1975 relationship between sea-level rise and overtopping events was then extrapolated to 2100 in accordance with modelled projections of future sea-level rise [21] to estimate the likely impact of this trend on the functioning of the line.

In all sea-level change scenarios, we expect the number of overtopping events to increase as the century progresses, and these are likely to impinge upon the ability of Network Rail and the train operating companies to run a reliable service along the line within a couple of decades. Even in the event of a significantly strengthened sea wall, it is reasonable to expect ongoing disruption because of continuing periodic overtopping of the sea defences.

An overarching risk assessment process based on ISO 31000 [16] is described in [13] and is helpful to infrastructure managers who want to assess the infrastructure related risks due to natural hazards. The process uses generic definition of sources, hazards, objects of the network and the network itself.

As the events form the initiating event to the event upon which a value is placed forms a causal chain it is convenient to think of them in the form of an event tree, where each chain of events is represented by a path in the event tree.

To build the tree it is necessary to determine the intensity measures to be used to define the events to be investigated, *e.g.,* the water height above which a flood event is considered to have occurred. At each branch in the event tree a decision is required to determine the value of the intensity measures, which allow classification of the event. The number of intensity measures used to describe the events depends on the problem being investigated and the level of detail required in the analysis [13]. A very simple example is given in *Figure 4.*

As it can be seen from this simple example, there is an infinite number of ways to represent reality. Due to this, particular care needs to be used in the development of an appropriate system representation. The necessary detail to be used depends on the specific problem and the level of detail desired. If events at any level or complete ranges of the values of intensity measures are excluded, it should be explicitly explained and documented why, because in the following risk assessment, the risk coming from those hazards cannot be taken into account.

In order to estimate the likelihood of each subsequent event in the causal chain of events appropriate models of the relationship between them are to be developed.

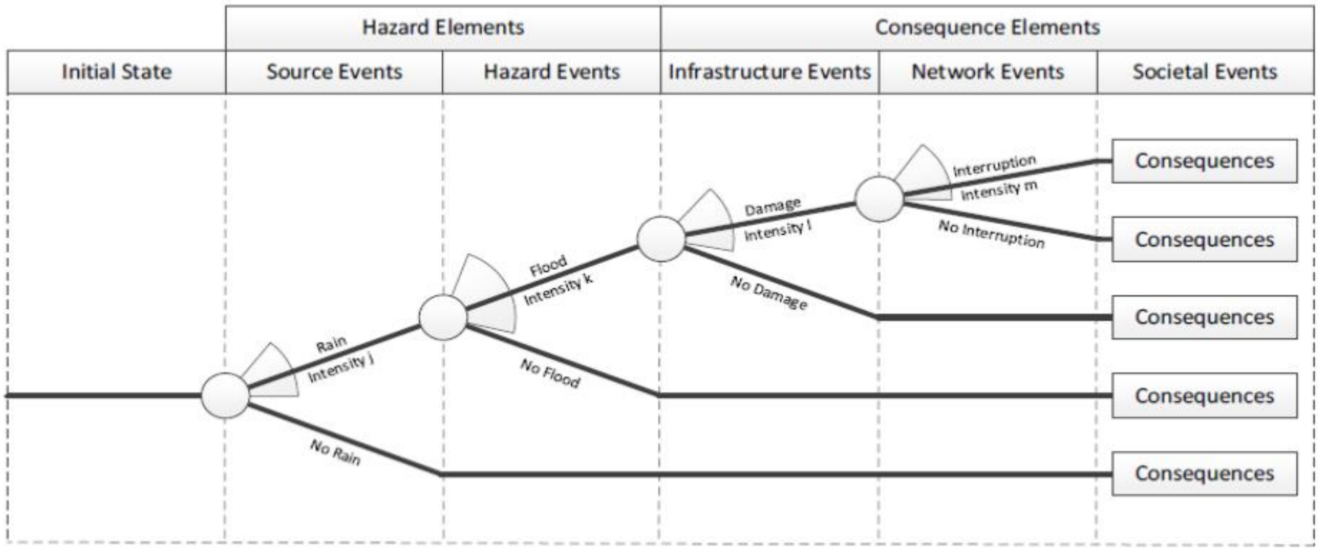

Figure 4: Example of a simple event tree for the risk assessment of infrastructure networks.

For example, in order to determine the amount of water coming in contact with a bridge during a flood, it is necessary to model how the water which falls as rain reaches the river, taking into consideration, e. g., the amount of water that seeps into the ground or held in temporary retention ponds [13].

One of the main objectives are to identify the key parameters for generating flood risk and to avoid over complexification of the exercise by integrating a large number of input criteria to perform the evaluation.

It is envisaged that the results of this preliminary assessment will be used in a more detailed analysis during later stages of the project**.** *Figure 5* presents the three components of risk [2].

Due to the different types of flood risk under consideration, the large study area (400 km of railway line) and the requirement to analyze a large quantity of information, it was decided at an early stage in the project to use of a geographic information system (GIS) based model.

Flood sources associated with small catchments are typically short duration surface water runoff events and mudslides whereas the larger catchments (<10 km^2) will tend to generate longer duration events. This characterization of flood risk in terms of catchment size is the first stage of the flood risk evaluation process and is subsequently refined by integrating other factors in the later stages. The grouping of flood risk sources in terms of catchment size allows different flood sources to be mapped in the GIS model.

The GIS model RiskVIP has been constructed through the assessment of three distinct components of risk: vulnerability (assessment of the susceptibility of the railway infrastructure to flood conditions),intensity (capacity of a catchment to generate a flood flow) and probability (probability of a rainfall event). The model RiskVIP allows the evaluation of flood risk to be undertaken at different scales and will aid in targeting precise reaches of railway line to be studied in more detail. It is a tool which can aid in the management of flood risk on the railway network, optimising for example the maintenance program of drainage structures, ensuring monitoring and inspections are targeted at problem reaches, identifying areas where civil works are necessary and improving the overall resilience of the railway system [2].

A comprehensive methodology to quantitatively assess the railway system vulnerability under floods using historical data and GIS technology is proposed in [14]. This methodology includes a network representation of the railway system, the generation of flood event scenarios, a method to estimate railway link vulnerability, and a quantitative vulnerability value computation approach.

A method to analyze the vulnerability of road networks under area-covering disruptions is presented in [17]. In that method, the road network is covered using a grid of uniformly shaped and sized cells, where each cell represents the spatial extent of a disrupting event.

However, this approach can also be used for railway networks.

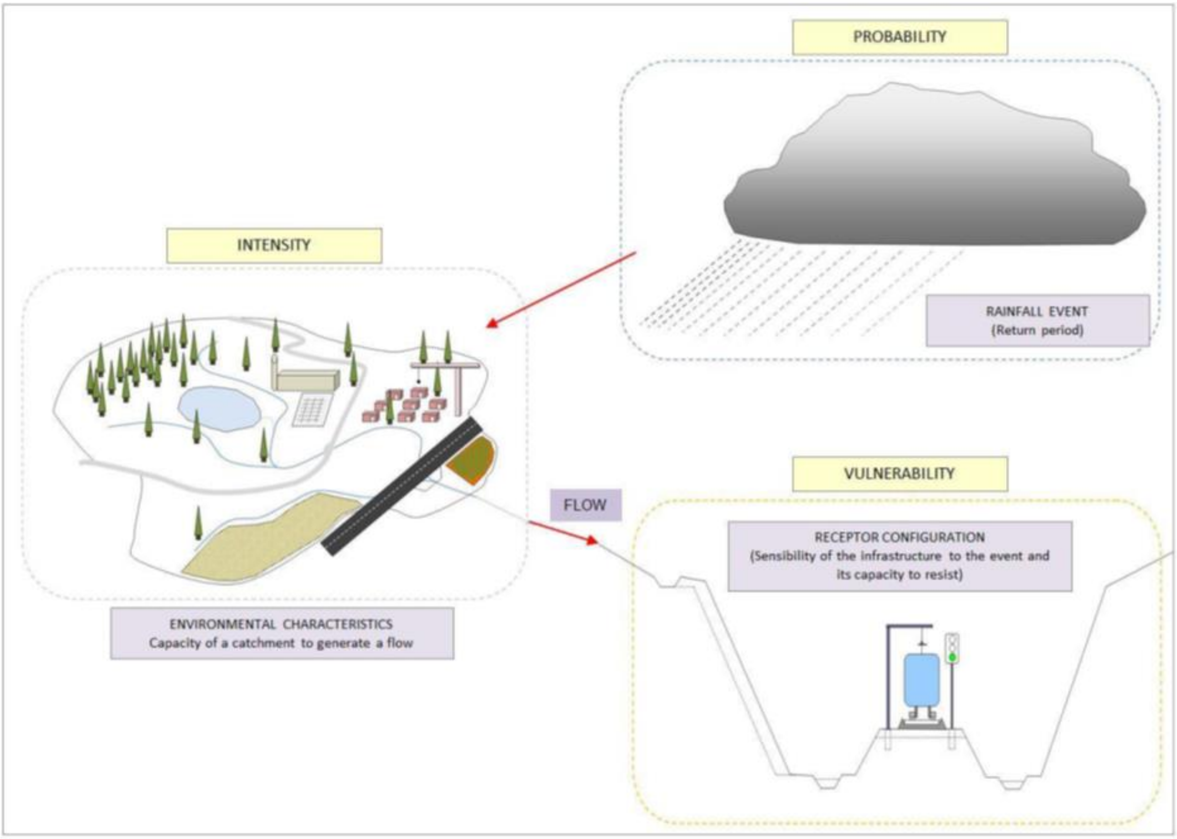

Figure 5. RISK VIP model

The aforementioned vulnerability studies are aimed at different systems and different types of hazards, but illustrate a common modeling framework. This framework includes the following steps:

- modeling the hazards of concern to generate a hazard scenario,
- estimating component failure probabilities under the hazard scenario,
- comparing each component failure probability with a uniformly distributed random number to produce a damage event which describes the damage state of each component; and
- modeling and analyzing system performance response under the initial component damage or the specific event, and computing the system performance drop under the event, which is labeled the vulnerability.

The procedure is repeated under different events using the random number. The average computed vulnerability value across the events is regarded as the vulnerability under that specific hazard in this framework is applied to propose an approach to quantitatively assess the vulnerability of a railway system under flood hazards by using historical flood data and GIS technology [14]. This method consists of four parts that are illustrated using the Chinese railway system (CRS):

- a network representation of the CRS is provided and some of its topological properties are discussed,
- flood event scenarios are generated through Monte Carlo simulation using historical flood event data for the past 30 years in China,
- the railway link vulnerabilities are estimated based on flood-induced railway disruption event data for the past 30 years, and
- the concept of railway service disruption is introduced and used to quantify the railway system vulnerability.

The flood type varies from region to region, such as river floods in flatlands, melting snow floods in high altitudes, and mountain floods. Different types of floods affect the railway system in different ways. Additionally, the occurrence of floods is affected by many factors such as rainfall per hour, geological conditions, and terrain situations. Currently, only the data of each historical flood event occurrence time and location is available. Hence, a simple probabilistic model to generate flood scenarios is used. A flood event scenario is generated using Monte Carlo probabilities of each province in a particular month.

The average monthly flood-induced vulnerability of the CRS network (CRSN) is computed using the Monte Carlo simulation procedure (see *Figure 6*).

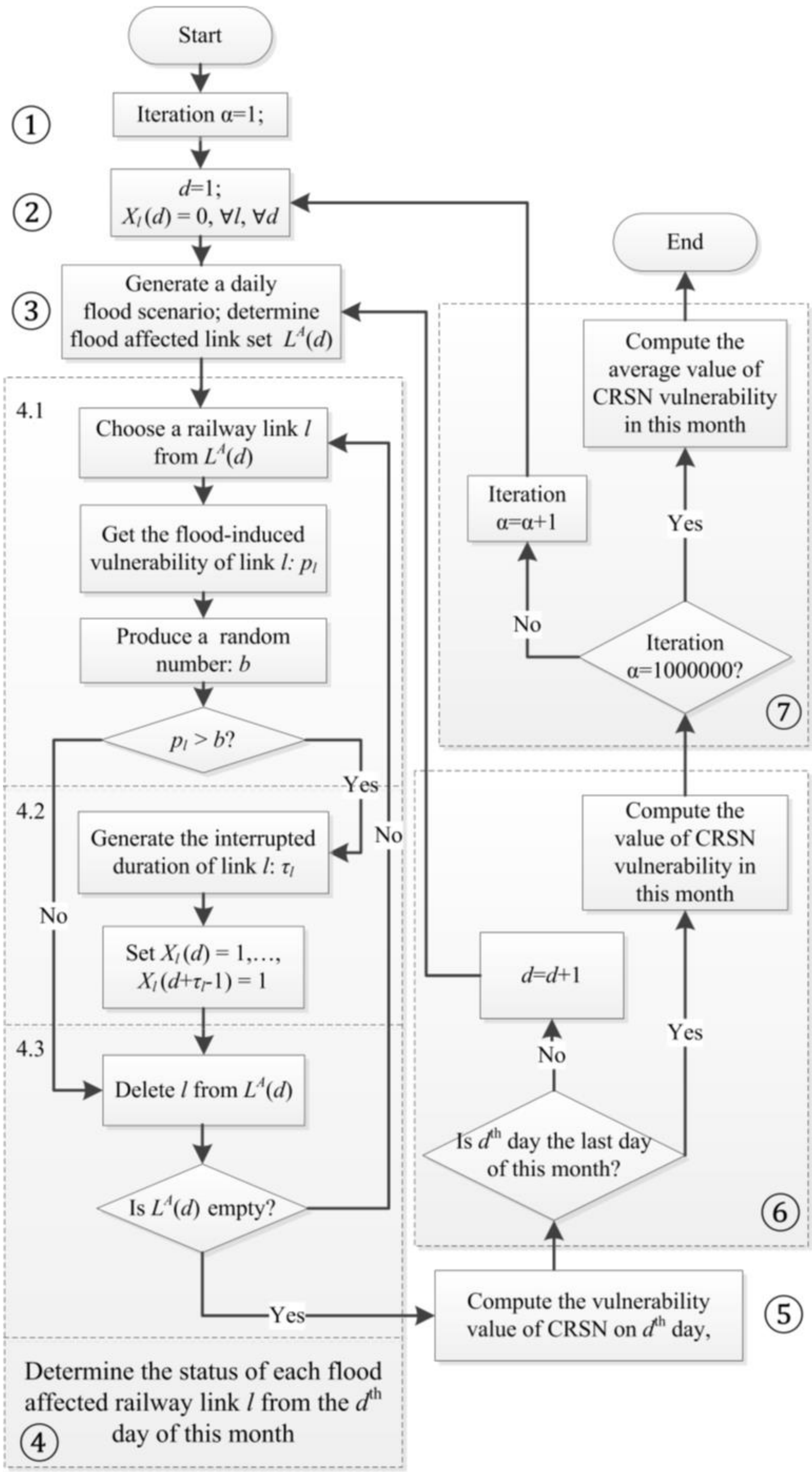

Figure 6. Flow chart for the approach to compute the average monthly CRSN vulnerability [14]

To generate a flood event scenario for a province, a uniformly distributed random number within [0, 1) is produced and compared with the daily flood occurrence probability of the province. If the random number is larger than or equal to that daily flood occurrence probability, the flood is assumed not to occur in that province; otherwise, the flood is assumed to occur.
In railway systems, the railway links are usually very long and easily exposed to flood events, especially in large flat geographical terrains.
The steps of the Monte Carlo simulation procedure are summarized below [14]:
Step 1: Set the Monte Carlo iteration counter α=1.
Step 2: Initialize the interruption status profile of all links to 0 for the month of interest, that is, none of them are interrupted or $X_l(d) = 0$ for all l and d. Set the start time d=1, which is the first day of a month.
Step 3: Generate a daily flood scenario and determine the flood affected link set $L^A(d)$ under this scenario.
Step 4: Determine the status of each flood affected railway link l from the d^{th} day of this month.
Step 5: Compute the CRSN vulnerability value on the d^{th} day of this month.
Step 6: If the value of d indicates that it is the last day of this month, compute the value of the CRSN vulnerability in this month as the summation of the corresponding daily values, and go to Step 7. Otherwise, update the day counter, d = d + 1, and repeat Steps 3-6.
Step 7: Update the Monte Carlo iteration counter. If α is less than 1,000,000, $\alpha = \alpha+1$ and go to Step 2. If it is equal to 1,000,000, compute the average value of the CRSN vulnerability in this month over the 1,000,000 Monte Carlo simulations.

4. Potential consequences of climate change

Climate change may be one of the greatest threats the planet is facing. It has been recognized that climate change presents a significant and indeed imminent challenge for transport. Rising sea levels, increased frequency/intensity of extreme storm waves and surges, droughts, increased temperatures and heat waves, cooler winters, extreme precipitation events and river floods, as well as the melting of permafrost pose serious threats transport infrastructure and services.
Globally, the atmosphere and the ocean are becoming increasingly warmer, the amount of ice on the earth is decreasing over the oceans, and the sea level has risen. The average increase in global temperature (combined land and surface) between the 1850–1900 period and the 2003–2012 period was 0.78 ◦C (0.72 to 0.85), see [31] for more details.
According to the observations of the Intergovernmental Panel on Climate Change [15], the evidence for rapid climate change is compelling:

- global temperature rise,
- sea level rise,
- warming oceans,
- shrinking ice sheets,
- declining Arctic sea ice,
- glacial retreat,
- extreme events,
- ocean acidification, and
- decreased snow cover.

A rise in the sea level will automatically affect the reading of the 100-year flood level, which, e.g., the Malaysian design standard normally adopts when designing a platform level bridge. There are many consequences for railway infrastructure due to hot and dry weather and the obvious example is the risk of buckling. According to Network Rail, the definition of buckling is the extent of track deformation constituting a reportable buckle that would render the line unfit for the passage of trains at line speed and/or necessitates emergency remedial work to a running line under cover of either a temporary restriction of speed or closure of the line. Buckling is very treacherous as it could cause derailment of the train and end up in the disruption of railway operation services.
In [1] changes for the 2050s in the southern part of England are predicted as follows:

- A rise of about 1.5 ◦C in the average winter temperature and of 2.5 ◦C for the average summer temperature.
- Average winter rainfall to increase by around 15% and average summer rainfall to decrease by around 25%.
- The 20 year return period daily rainfall will increase by around 10 to 15% in the winter and decrease by about the same amount in the summer.
- The 20 year daily wind speed will increase by around 5% in the winter and decrease by the same amount in the summer.

Three potential climate change categories can be defined:

- hotter, drier summers,
- warmer, wetter winters, and
- increased frequency of extreme storms.

5. Countermeasures to reduce the effects of natural hazards

In [7] an extensive list of possible adaptation measures to protect infrastructure against extreme weather effects is developed.
The compiled strategies revealed that almost all the

suggested adaptation measures are state of the art for new rail infrastructure assets in those European regions, where such measures are already regarded as essential to protect infrastructure against specific weather events.

They include the following measures:

- switch protection [7],
- pile construction for buildings with technical equipment [23]),
- cooling of signals and installation of fans to keep electronic equipment functional during periods of extreme heat,
- increased (preventive) maintenance activities (infrastructure and existing protection systems) (see [20] and [30]),
- vegetation and land use regulations along rail tracks (see [20] and [22]),
- installation of (automatic) monitoring systems such as anemometer, water and rain gauge, rail temperature gauge, landslide detectors (see [1], [20] and [25].

6. Concluding remarks

A railway that is safe and more resilient to the effects of weather is an important vision for the future [3]. This could be achieved by identification of high risk sites with a particular focus on drainage, earthworks, structures and vegetation management. Increased spatial and temporal resolution for rainfall information would allow the development of better vulnerability mapping techniques and lead to more accurate rainfall risk assessment and prediction tools. Geographic Information Systems could be used to support the identification and mapping of sensitive hotspots [29].

In a vulnerability analysis results for the railway infrastructure the most critical asset impacts are in terms of signaling, monitoring, heating and traction systems, whereas when interdependent infrastructures are considered electricity and telecommunications networks have the biggest impact on railway operations.

In the flood vulnerability analysis one can see that even though there are only a small number of assets exposed to flooding, their impacts on the network functionality are substantial.

Vulnerability also depends on the habituation of regions to specific events. The more often specific events occur, the better the infrastructure is equipped to handle these events. This applies especially to those events relevant for the Alpine region like floods, landslides and avalanches, harsh winters with prolonged and intensive frost periods as discussed in [10] and [22]).

The vulnerability results highlight the importance of considering quantity and spatial extents of assets, which influence the spread of failures; and the specific locations of assets, which influence the disruptions of network flows [27].

In addition, an appropriate warning system, an infrastructure that is able to withstand the impact also of future increasing weather conditions, a rapid recovery from the impacts of adverse and extreme situations, and an improved performance and safety during adverse and extreme weather conditions are important preconditions.

While, e.g., the ÖBB in Austria 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 [18].

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.

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