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Damage functions for transport infrastructure

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Abstract

Purpose – Damage functions constitute an essential part of the modelling of critical infrastructure (CI) performance under the influence of climate events. This paper aims to compile and discuss publications comprising damage functions for transport assets.

Design/methodology/approach – The research included the collection of contemplable literature and the subsequent screening for damage functions and information on them. In conclusion, the derived damage curves and formulae were transferred to a unified design.

Findings – Damage functions for the transport sector are scarce in the literature. Although specific damage functions for particular transport assets exist, they mainly consider infrastructure or transport in general. Occasionally, damage curves for the same asset in different publications vary. Major research gaps persist in wildfire damage estimation.

Research limitations/implications – The study scope was restricted to the hazards of fluvial floods and wildfires. Despite all efforts, this study did not cover all existing literature on the topic.

Originality/value – This publication summarises the state of the art of research concerning transport asset damage functions, and hence contributes to the facilitation of prospective research on CI performance, resilience and vulnerability modelling.

Keywords Critical infrastructure, Climate impact, Damage curve, Damage function, Natural hazard, Transport asset

Paper type Literature review

Introduction

Climate change and its consequences are currently in broad discussion. "Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes" (IPCC, 2007). Field *et al.* (2012) expected extensive effects on infrastructure from climate events. This is where research gaps emerged. According to Mehrotra *et al.* (2011), these involved research on quantifying expected climate impacts on transport networks and users:

> Infrastructure is an understudied area of direct tangible damage. Many studies have ignored it altogether, although evidence indicates that damage to infrastructure can constitute a large proportion of the overall damage total (Hammond and Chen, 2014).

Recently, the modelling of interdependent critical infrastructure (CI) networks and their behaviour during climatic events gained attention. The modelling of asset performance

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required a characterisation of the connections between hazards and losses. Damage functions depict the said correlation, and thereby constitute an essential part of the modelling. This literature review collected and discussed existing damage functions for transport assets, with the objective to facilitate future research in interconnected CI performance modelling. The paper introduces the EU-CIRCLE project, which this research affiliates to. Further, it defines the terminology of CI damage assessment, provides an overview of relevant literature and displays exemplary curves for specific assets.

The EU-CIRCLE project

This research is affiliated to the pan-European project EU-CIRCLE. The project obtained funding by the European Commission DG - Connect in the Horizon 2020 Framework Programme in the period 2015-2018:

> EU-CIRCLE's scope is to derive an innovative framework for supporting the interconnected European Infrastructure's resilience to climate pressures, as well to generate scientifically truthful and validated knowledge on the potential impacts of climate (EU-CIRCLE consortium, 2016).

The central part of the research was the modelling of CI behaviour affected by natural hazard events, regarding the interdependencies within linked CI networks. The modelling of hazard-induced damages and losses utilised damage functions as input. Various functions from the literature were selected to characterise the behaviour of assets appendant to different infrastructure sectors.

The modelling results were implemented in five case studies:

(1) electrical grid and highways affected by extreme droughts and forest fires, South France;
(2) electrical grid disruption due to forest fires, Cyprus;
(3) impacts from coastal floods on roads, railways and buildings, the UK;
(4) cyclone impacts on electrical grid, Bangladesh; and
(5) sewage and electricity disruption due to fluvial floods, Germany.

The multiplicity of transport assets required the selection of an asset sample regarding the relevance for the case studies, to conduct the case study modelling within the project timeframe. The comparison of the modelling results with real historic data of similar incidents allowed the calibration of the modelling and the applied damage functions. The developed EU-CIRCLE framework enables modellers to conduct the modelling for multi-hazard events and interconnected networks of different CI sectors.

Research methodology

The research took place as a secondary research. The majority of publications were in English language. In addition, the collection included papers in German and Dutch from publication references. The search for papers accessed the following search engines and databases:

- Google;
- Google Scholar;
- Citavi Online Search;
- Karlsruhe Virtual Catalog;
- ScienceDirect;

- ResearchGate;
- IEEE Xplore;
- Semantic Scholar;
- SpringerLink;
- Scopus;
- ScienceOpen;
- ASCE Library; and
- Wiley Online Library.

The following keywords were entered in various combinations:

- damage/loss/vulnerability function/curve;
- flood/wildfire damage/loss;
- (transport) infrastructure;
- critical infrastructure;
- natural hazard;
- damage/loss estimation/assessment; and
- infrastructure design standards.

Further publications found in the reference lists of papers augmented the sample. The literature collection contained 327 papers in total. The screening process involved three rounds (confer Figure 1). The terms of reference were pertinent to EU-CIRCLE case studies 1 and 5, confining the regarded hazards to wildfire and fluvial floods. In total, 166 papers were discarded in the first round. About 106 publications did not pass the second screening for information on damage functions. Finally, 29 papers remained after the third screening, as they contained damage curves utilisable for the modelling of transport infrastructure affected by flood or wildfire. Transferring the damage functions from the literature into a unified design ensured comparability and avoided biases.

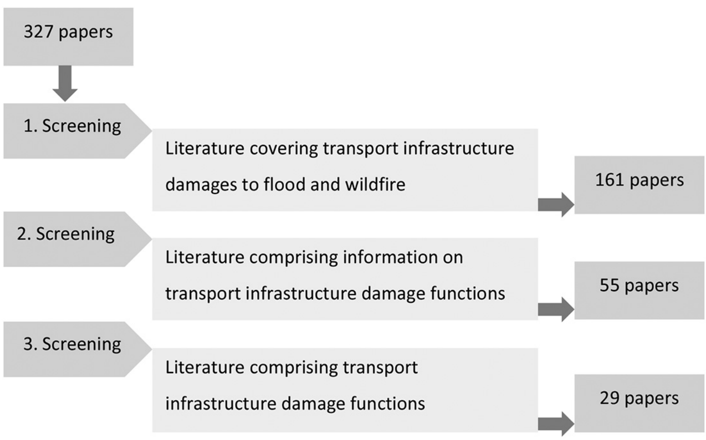


Figure 1.
Literature review screening process

Terminology and definitions

Critical infrastructure

Country governments worldwide defined the term "critical infrastructure" differently. The German Federal Ministry of the Interior (2008) defined CI:

> [. . .] as organizations and institutions of central importance for the country and its people whose failure or functional impairment would lead to severe supply bottlenecks, significant disruption of public security or other dramatic consequences.

The US Government referred to:

> [. . .] systems and assets, whether physical or virtual, so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety, or any combination of those matters (Francis and Bekera, 2014).

Johansson and Hassel (2010) and Larsen *et al.* (2008) provided and discussed further definitions.

Damage

Defining damage, Vanneuville *et al.* (2005) referred to material losses consequent on hazardous events. In the literature, a high consensus according to the differentiation of damage categories was discernible (see Figure 2) (Emergency Management Australia, 2003; Lange *et al.*, 2015; Admiraal, 2011; Merz *et al.*, 2010; Bubeck; Thieken *et al.*, 2005; Garrote *et al.*, 2016; Messner *et al.*, 2007; van der Sande, 2001):

- *Direct damages*: Resulting from direct contact with the hazard.
- *Indirect damages*: Resulting from the event, but not its direct impact.

Both categories contain sub-categories:

- *Tangible damages*: Specifiable in monetary terms.
- *Intangible damages*: Difficult to assess in monetary terms.

Recent publications attempted to assess operational damages (Thieken *et al.*, 2016). "Many case studies have applied a percentage of direct damage as representative of the indirect damage [. . .], which is a rather coarse assumption" (Olesen *et al.*, 2017). Taylor *et al.* (2006) and Matsushima *et al.* (2007) approached the inclusion of inconveniences and losses from reduced road network accessibility.

Difficulties appeared in the monetisation of intangible damages. The assessment of direct damages necessitated the monetary estimation of asset values (Jenelius and Mattsson, 2015). These describe the maximum damage "for a virtual scenario in which everything is destroyed" (Deckers *et al.*, 2010). The literature research revealed two options for maximum damage determination (Albano *et al.*, 2015; Merz *et al.*, 2010):

	Direct	Indirect
Tangible	Structural damage (e.g. to infrastructure)	Operational damage (e.g. traffic disruption)
Intangible	Fatalities Injuries, Diseases	Inconveniences (e.g. due to time loss)

Figure 2. Differentiation of damages

(1) replacement costs; and
(2) depreciated/repair costs.

Replacement costs tended to overestimate damages, because they included infrastructure improvements after restoration (Meyer and Messner, 2005). Penning-Rowsell *et al.* (2005), Messner *et al.* (2006), Bubeck and Moel (2010) and Merz *et al.* (2010) recommended the use of depreciated values.

Besides few recommendations in Donovan and Brown (2005) and Zybach *et al.* (2009), approaches for wildfire and smoke loss estimation in the transport sector were unavailable in the literature.

Damage functions

Prahl *et al.* (2016) and Prahl (2016) defined damage functions as "mathematical relation between the magnitude of a (natural) hazard and the average damage caused on a specific item". Bubeck, Bubeck and Moel (2010) and Jongman *et al.* (2012) provided comparable definitions.

The literature presented damage functions either as mathematical calculations or as graphs.

Jongman *et al.* (2012) distinguished relative and absolute damage functions. Figure 3 contrasts advantages and disadvantages of both function types. Absolute damage functions allocate monetary losses to hazard severity. Merz *et al.* (2010) proposed the use of "standard costs for length units (e.g. km railway, km road)". The preceding research depicted relative damage either as percentage or as proportion of the maximum possible damage.

Garrote *et al.* (2016), Olesen *et al.* (2017), Chen *et al.* (2016), Bubeck, Hammond (2014), Dutta and Herath (2001) and van der Sande (2001) coincided relating to two approaches for the construction of damage curves:

(1) *Empirical approaches*: "use damage data collected after flood events" (Merz *et al.*, 2010).

Surveys with large samples were conducted for the collection of information on property types, hazard severity and damages. A subsequent regression analysis revealed typical depth damage functions for different assets (Messner *et al.*, 2007).

(1) *Synthetic approaches*: are "based on hypothetical damage estimates by experts through what-if-analysis" (Gerl *et al.*, 2016).

Synthetic assessment approaches examined standardised assets (Messner *et al.*, 2006). The synthetic functions were calibrated in consideration of real recorded damages. Figure 4 summarises the advantages and disadvantages of both approaches.

	+	−
Relative damage	• Available data on values • Independent from market values	• Value estimation causes uncertainties
Absolute damage	• No value estimation necessary	• Regular calibration necessary • Dependent on market values

Source: Confer Merz *et al.* (2010)

Figure 3. Advantages and disadvantages of absolute and relative damage functions

Estimations of thresholds for flood damages were noticeable in the literature. Simply put, CI assets are resilient to certain hazard severities. Vanneuville *et al.* (2003) determined a flood inundation threshold of 50 cm for roads and railways.

Design criteria further influence the resilience of CI assets. "Agency policy and standards generally define the design event based on consideration of the nature of the structure, the roadway, or of the transportation facility served" (Federal Highway Administration, 2016).

Albano *et al.* (2015) identified uncertainties of damage functions due to insufficient data and simplifications in the modelling. Scorzini and Leopardi (2017), Moel and Aerts (2011) and Bubeck *et al.* (2011) compared several damage models and discovered large deviations between them. Notaro *et al.* (2014) examined the influences of different damage functions by applying them to the same area. According to Messner and Meyer (2005), uncertainties emerged due to the omission of indirect effects. A profound examination of uncertainties was provided by Wagenaar *et al.* (2016).

In the literature, produced damage functions were mostly based on historic event data, which made them less suitable for different areas. To find damage functions that best represent the considered area, Wagenaar *et al.* (2016) recommended attaining damage functions from other models or the combination of various functions into one damage curve. Prahl *et al.* (2016) introduced an attempt for the adaption of existing damage functions to other hazards.

Damage functions derived from the literature

Overview of pertinent literature

Tables I and II contain the publications providing information on damage functions, hazard–damage relations and damage functions themselves for transport assets. These papers passed screening rounds 2 and 3.

Infrastructure in general

The majority of damage functions in the literature addressed infrastructure in general. Meyer and Messner (2005), ICPR (2001, 2016) and Moel and Aerts (2011) contained the Rhine Atlas damage function for transport (Figure 5). Bubeck, Vanneuville *et al.* (2006) and Klijn *et al.* (2007) provided the damage scanner curve (see Figure 6). Bubeck and Moel (2010), Bubeck *et al.* (2011), Moel and Aerts (2011) and Kellermann *et al.* (2015) contained both. The resulting damages in these examples differed broadly. While the Rhine Atlas function reached 10 per cent damage at 1 m inundation depth and further remained constant, the damage scanner function reached a total damage at 5 m. This elucidated the variety of damage modelling outcomes determined by the applied damage curve. Messner and Meyer (2005), van der Sande (2001), van der Sande *et al.* (2003), Hammond *et al.* (2014), Genovese (2006), Mittelstädt and Gönnert *et al.* (2004) provided further functions for infrastructure and transport in general. Few publications contained formulae to compute losses. Dutta and

	+	−
Empirical approach	• Real data • Mitigation considered	• Often poor quality data • Extrapolation causes uncertainties
Synthetic approach	• Producible for each asset and hazard • Applicable to any area	• Regular calibration • Dependent on market values • Mitigation not considered

Source: Confer Merz *et al.* (2010)

Figure 4. Advantages and disadvantages of empirical and synthetic flood damage models

Chen *et al.* (2016), Garrote *et al.* (2016), Gerl *et al.* (2016), Jongman *et al.* (2012), Messner *et al.* (2006), Messner *et al.* (2007), Olesen *et al.* (2017), Wagenaar *et al.* (2016)	Function estimation
Chen *et al.* (2010)	Impacts of high temperatures on asphalt
Chen *et al.* (2015)	Course of functions
Hammond *et al.* (2014)	Function estimation, variables
Hardy (2005)	Indicators/variables for fire damage
International Joint Commission (2000)	Function estimation, formula for CI damages
Jofré *et al.* (2010)	Behaviour of asphalt and concrete in fire
Mattsson and Jenelius (2015)	Schematic damage function
Merz *et al.* (2010)	Function estimation, approach discussion
Mostafaei *et al.* (2014), Pool (2016), Wright *et al.* (2013)	Structural damage to bridges due to fire
Lee and Kim (2018)	Schematic function for precipitation
Penning-Rowsell *et al.* (2005)	Operational damages
Prahl (2016), Prahl *et al.* (2016)	Adaption of functions
Pregnolato *et al.* (2017)	Formulae for operational damages on roads
Reese and Ramsay (2010)	Flood impacts on roads
US Department of Agriculture (2013)	Schematic of wildfire damage functions; indirect, intangible losses

Table I.
Literature containing information on damage functions

Herath (2001) and Dutta *et al.* (2001) contained equations for the estimation of system disruption losses, marginal costs and delay costs. Hammond *et al.* (2014) proposed formulae for time and fuel consumption losses.

Roads and railways

Functions for wildfire damage were unobtainable. Chen *et al.* (2010) and Jofré *et al.* (2010) examined the behaviour of asphalt, asphalt binder and concrete affected by fire. The available functions for flood damage concerned structural damages. Figures 7 and 8 contain exemplary flood damage curves for roads. Tariq *et al.* (2013) and Huizinga *et al.* (2017) contained further damage functions.

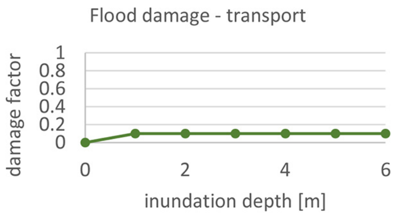
Various references contained joint roads and railways damage functions. Figure 9 illustrates the damage function from Kok *et al.* (2004). Vanneuville *et al.* (2003) introduced a function (see Figure 8), which is also contained in Deckers *et al.* (2010), Vanneuville *et al.* (2005), Verwaest *et al.* (2008) and Kellens *et al.* (2013). Flood damage functions for roads and railways were the most consistent functions in the literature. Hammond *et al.* (2014), Pregnolato *et al.* (2017) and Jenelius and Mattsson (2015) approached the estimation of operational damages emerging from road closure (Figure 10).

Bridges

The research did not reveal damage functions for bridges. The Department of Homeland Security FEMA (2013) emphasised a low probability of bridge failure due to flooding, because design standards required resilience to standardised flood events. The structural damage of bridges depends on bridge type, technical equipment, structural features and position in the infrastructure network. Mostafaei *et al.* (2014) examined fire damage to bridges based on reported incidents. They concluded that a collapse, equivalent to total damage, occurred after short fire duration when the bridge was directly affected. Alutaibi (2017) assumed that “the level of damage is influenced by several factors such as wind speed and direction, and fuel type and load”.

Alutaibi (2017)	Formulae for fire damage
Bubeck *et al.* (2011), Bubeck and Moel (2010)	Flood damage for mobile and immobile traffic and infrastructure
Deckers *et al.* (2010):	Flood damage for roads and railways
Dutta and Herath (2001)	Formulae for system and disruption losses of infrastructure, marginal costs and delay costs due to flood
Dutta *et al.* (2001)	Flood damage for infrastructure: system damage, disruption loss, marginal and delay
Genovese (2006)	Flood damage for infrastructure
Gönnert *et al.* (2004):	Flood damage for trade and traffic
Hammond *et al.* (2014)	Flood damage for transport and transport services; formulae for velocity attenuation; for economic losses of fuel consumption, time consumption of private cars and motor coaches
Huizinga *et al.* (2017)	Flood damage for roads in Europe
ICPR (2001, 2016)	Formula for flood damage to mobile and immobile traffic
Kellens *et al.* (2013)	Flood damage for roads
Kellermann *et al.* (2015)	Flood damage for mobile and immobile traffic and infrastructure
Klijn *et al.* (2007)	Flood damage for infrastructure
Kok *et al.* (2004)	Flood damage for airports, roads and railways
Messner and Meyer (2005)	Flood damage for traffic + telecommunications
Meyer and Messner (2005)	Formula for flood damage to immobile traffic
Mittelstädt	Flood damage for traffic and communication
Norwegian Geotechnical Institute (2014)	Flood damage for roads and bridges
Moel and Aerts (2011),	Formula for flood damage to immobile traffic
Penning-Rowsell *et al.* (2013)	Evacuation travel cost, flood damage for roads and railways
Tariq *et al.* (2013)	Flood damage for roads
van der Sande *et al.* (2003)	Flood damage for roads
van der Sande (2001)	Flood damage for roads
Vanneuville *et al.* (2003, 2005)	Flood damage for roads and railways
Vanneuville *et al.* (2006)	Flood damage for gasoline stations, train stations and airports
Verwaest *et al.* (2008)	Flood damage for roads and railways

Table II. Literature containing specific damage functions and formulae



Source: ICPR (2016)

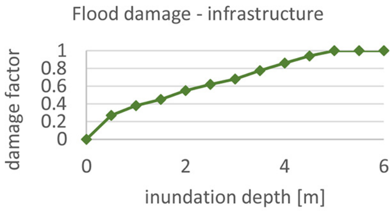
Figure 5. Rhine Atlas flood damage function for mobile and immobile transport

Gasoline stations and train stations

Vanneuville *et al.* (2006) developed flood damage functions for industry (see Figure 9), which the authors applied to gasoline stations, airports and train stations, disregarding the structural and operational differences between these assets. Damage curves for indirect or intangible losses were unavailable. The research also did not reveal damage functions for wildfire damages.

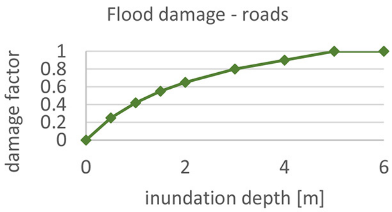
Airports

Kok *et al.* (2004) developed a flood damage function for airports (Figure 11). Vanneuville *et al.* (2006) also applied the damage function for industry (see Figure 12). Both curves estimated direct tangible losses. In comparison, the damage function of Kok *et al.* (2004) showed a fast damage growth reaching maximum damage at 3.5 m inundation depth. Functions for indirect or intangible damages were non-existent. The review did not reveal damage functions for wildfire damages.



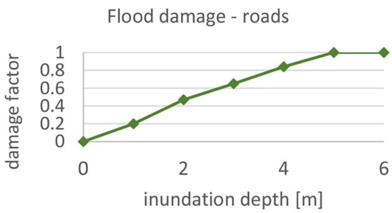
Source: Moel and Aerts (2011)

Figure 6. Damage scanner flood damage function for infrastructure



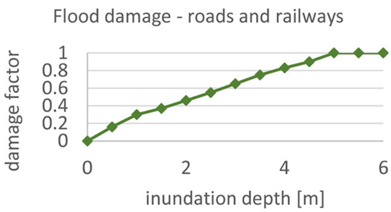
Source: Huizinga *et al.* (2017)

Figure 7. Flood damage function for roads in Europe



Source: van der Sande (2001)

Figure 8. Flood damage function for roads



Source: Kok *et al.* (2004)

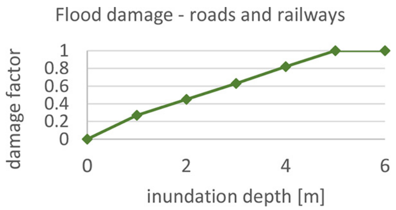
Figure 9. Flood damage function for roads and railways

Conclusions

The literature screening revealed several publications comprising damage functions for transport assets. Precedent publications contained several damage functions for infrastructure in general. However, profound information on included assets was rarely available, whereby the application of general functions for the modelling at asset level ought to be considered carefully. Several insurance organisations possessed knowledge on damage estimations for CI. However, this knowledge was mostly proprietary and inaccessible.

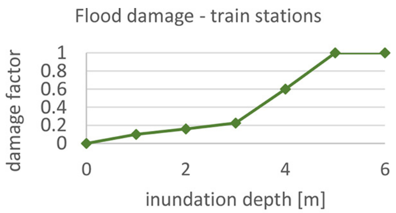
Mentionable was the lack of consistent approaches to estimate wildfire severity. The review results corroborated the conclusion in Howard (2014) that most literature estimated particular fires or group of fires and lack generality. Further research on the estimation of losses from wildfire needs to broaden the existent investigations on the factors that influence fire damage.

Inundation depth was the most frequently applied variable for flood severity. Although Merz *et al.* (2010) confirmed the multiplicity of influencing variables, they found no ample approach for including them in damage modelling. Messner and Meyer (2005) considered these variables as often disregarded due to their correlation with inundation depth. The literature review confirmed the need to include different hazard variables, as done by Kreibich *et al.* (2009). Lately, research started to pay particular attention to damages from



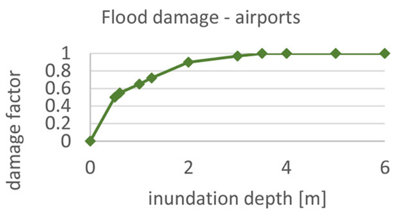
Source: Vanneuville *et al.* (2003)

Figure 10. Flood damage function for roads and railways



Source: Kok *et al.* (2004)

Figure 11. Flood damage function for agriculture, recreation and airports



Source: Vanneuville *et al.* (2006)

Figure 12. Flood damage function for industry, gas stations, train stations and airports

pluvial flooding, which still appeared to be sparsely examined (Vanneuville *et al.*, 2016; Weerasinghe *et al.*, 2018; Lee and Kim, 2018; Melvin *et al.*, 2017).

More thorough research needs to take more assets and hazards into account. Furthermore, research gaps remained concerning interdependent infrastructure systems and their performance in multi-hazard events. With lack of monitoring and management, they introduce new risks and societal consequences (Kaewunruen *et al.*, 2016). Moreover, approaches for the estimation of cascading effects in interconnected transport infrastructure (Wang *et al.*, 2018; Ouyang, 2014; Setola and Geretshuber, 2009; Trucco *et al.*, 2012; Huang *et al.*, 2014; Laugé *et al.*, 2015; Dudenhoefer *et al.*, 2006) need more profound examination. Existent damage estimation approaches primarily assessed direct damages. Indirect and intangible damages were often addressed, but not further estimated, mostly due to lack of data or knowledge. As the assessment of indirect and intangible damages came into focus, methodologies for their measurement need further development.

This literature review summarised the current state of the art in flood and fire damage estimation for transport assets. It gleaned damage curves scattered in various publications into an overview. The research results aimed to encourage and facilitate further damage estimations and CI network modelling. The development of frameworks for the modelling at the asset level as in the EU-CIRCLE project is important for flood damage forecasting and the enhancement of transport asset resilience, as well as the safety for network users.

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