Analysis Of The Risk Of Transport Infrastructure Disruption From Extreme Rainfall

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ABSTRACT: Transport infrastructure networks are increasingly vulnerable to disruption from extreme rainfall events due to increasing surface water runoff from urbanization and changes in climate. The impacts of such disruptions typically extend far beyond the original disaster footprint, because of the increased interconnection and spatial extent of modern infrastructure systems. This paper presents an integrated assessment methodology to quantify the flooding risks from extreme rainfall, measured in terms of expected travel time across the road network. The method is driven by a probabilistic rainfall weather generator that can simulate time series of current and future rainfall. This is integrated with a high resolution urban flood model, CityCAT, to provide information on depth and velocity of floodwater. This hazard layer is combined with empirical analysis of vehicle speeds during a flood, to perturb a transport accessibility model to determine the impact of a given event on journey times. The study assessed the potential impact of flooding on the network performance in relation to macroscopic urban travel times using Newcastle-upon-Tyne (UK) as a case study. Results showed relevant delays for two different hazard scenarios, for a maximum of 24 minutes and 42 minutes respectively. The impacts are significant and implementation of a probabilistic risk-based approach will provide a rational means to prioritise adaptation measures to reduce delays in these circumstances.

1. INTRODUCTION AND MOTIVATION

The scientific consensus on global climate change (Doll et al. 2014a, Doll et al. 2014b, IPCC 2014) is that the general trend is towards increasing temperatures with warmer winters, dryer summers, and rising sea levels, together with unusual weather patterns and a higher number of floods. Climate change is expected to lead to increased frequency and intensity extreme weather events and associated natural hazards (Stewart and Deng 2014). Moreover, the magnitude of the impacts of such natural phenomena is even further amplified in urban environments due to the high concentrations of people and assets (Hall et al. 2009).

Transport infrastructure networks are vital to cities, forming the backbone of commerce, social interaction, and access to services. Any disruptions to such networks could cause much wider effects since other lifeline systems (e.g.: emergency services, communications) rely on them for the movement of people and equipment during restoration and repairs (Dalziell and Nicholson 2001). Thus, the robustness of these networks is fundamental to efficiently maintain the functionality of the whole infrastructure system. To face this issue, new tools must be established to assist in increasing the resilience of these networks.

This paper specifically addresses the resilience of transport networks to flooding, examining the potential impact of extreme rainfall events on the performance of the road network in UK. At a macro scale, evaluating the disruption in urban travel caused by such flooding results one of the most relevant factors of impact assessment (Suarez et al. 2005).

The methodology described in this paper comprises a spatial model based on the well-established combination of hazard, exposure and vulnerability. The estimation of the hazard is achieved through a spatial "weather generator", and a flood model. The exposure is obtainable through multiple GIS datasets (e.g. national spatial data products). The vulnerability is assessed through a damage curve, developed by the authors, delivering a tangible appraisal of the impact.

The model is run for several scenarios with differing magnitude. This study focuses on the flood risk to urban transportation, although the framework can also be applied to other weather-related phenomena and infrastructure. Such methodology is based on data and resources usually available for most metropolitan areas in US and Europe.

2. BACKGROUND

There have been a number of studies examining the impact of weather events on urban transportation infrastructure, however they are limited to disruptions on traffic flow due to ice, snow, precipitation, and wind (Agarwal et al. 2005; Hooper et al. 2012; Jaroszweski et al. 2010; Koetse and Rietveld 2009; Kyte et al. 2001; Tsapakis et al. 2013). Surprisingly few studies investigated the impact due to flooding, but those that did focussed on road closures or car accidents, without considering free-flow speed and travel time (Chang et al. 2010; Penning-Rowsell et al. 2013; Suarez et al. 2005).

In relation to infrastructure flood damage, Merz et al. (2010) highlighted the scarcity of well-established models and data. Available models tend to employ simple approaches or are based on few data. Moreover, model validation is rarely performed and model transferability rarely proven. Finally, emphasis is often placed on hazard assessment rather than damage assessment, considered additional to risk analysis.

Floods reduce network's efficiency and performance by increasing travel times, which is disruptive to personal and business journeys (Hooper et al. 2013). Since a flooded link in the transport network does not imply its complete closure, an approach is needed which considers reductions in speed at differing flood levels, giving a more realistic interpretation of the impact.

This paper aims to address such limitations by illustrating an integrated model, combining climate simulations, spatial analysis, and vulnerability relationships. The approach includes simulations of commuters flow on urban transport networks under several hazard scenarios. By assigning a monetary value to trips time and delays, flooding impact is expressed in terms of cost. The validation of the model is an on-going process through real traffic and rainfall data from major events.

3. TRANSPORT ANALYSIS MODELING OF NEWCASTLE-UPON TYNE

3.1. Study Area

Newcastle-upon-Tyne was selected for this study due to availability of historical data on past events that provide a basis for calibration. Most notably 50 mm rainfall fell over the city in two hours in the afternoon of 28th June 2012. Flooding events caused by such summer meteorological conditions are expected to occur with greater frequency (Kendon et al. 2014) in the future. Since this study is focused on commuting journeys, observed census journey-to-work data was chosen for analysis, allowing assessment of impacts at peak travel times. As the 28th June disruptions occurred in peak hours, causing severe transport disruption and closing many routes, this presented an opportunity for validation of a model of such impacts.

3.2. Transport modelling

A model to assess the impact of extreme flood-related events on the urban transport network was developed, examining disruptions due to flooding of roads. The approach consists of a spatial model, which combines deterministic loss models and probabilistic risk assessment techniques (Figure 1). This framework integrates the hazard maps output from an urban flood model with the transport network model.

Commuter journeys are determined between origin census wards and a destination ward (assumed in this case to be the central ward with highest employment) based on free flow speed. The first stage consists in running the model under normal settings (i.e. speed limits imposed by UK traffic laws), providing a baseline simulation. The model is then re-run for a set of probabilistic hazard scenarios, to be compared to the baseline data. Outputs from the flood model (see below) are used to calculate impacts on the transport network; this impact is translated into free flow speed reduction and consequent redistribution of the flows. A vulnerability curve (described in section 3.2.3) relating car safety speed to water depth has been developed to obtain this result. Thus, additional travel time due to flooding impacts can be computed.

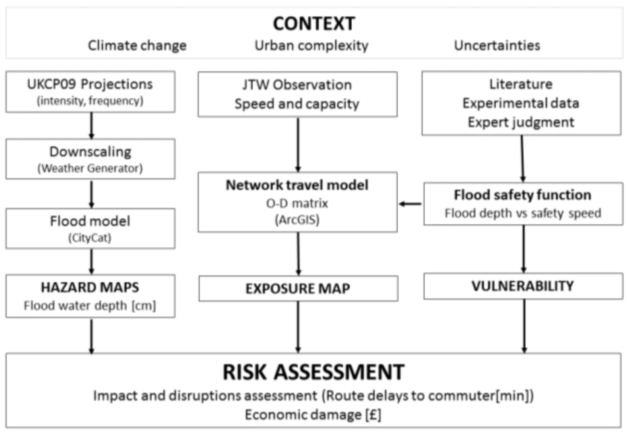

Figure 1. The integrated risk-based approach developed to assess flooding impacts on transport network.

3.2.1. Hazard modelling

The hazard is represented by floodwater depth and determined by simulating surface water flooding. The spatial footprints of the simulated flood event produce a time series of hazard maps showing water depths (in metres). Flood depth has been chosen as the most significant key metric in relation to transport network disruption, in accordance with the literature (Kreibich et al. 2009; Merz et al. 2010).

The first stage of this process consists of climate downscaling using an Urban Weather Generator (UWG). The UWG is a tool that generates statistically-plausible hourly time series of rainfall variables on a 5km grid, consistent with the overarching 25km resolution UKCP09 climate projections (Kilsby et al. 2011). It couples a stochastic rainfall model with change factors in accordance to the probabilistic outputs from UKCP09 (Jones et al. 2009), for the baseline and climate change scenarios up to 2099. For this reason it is functional for a probabilistic modeling study (Coulthard et al. 2012).

In the second stage, the outputs from UWG are used to drive the City Catchment Analysis Tool (CityCAT) software, which produces floodwater depths. CityCAT is a 2-d hydrodynamic flood model based on the evaluation of infiltration of pervious areas. In recent years Cloud computing has made possible the simulation of a large number of ensembles, allowing assessment of the uncertainty and variability of extreme rain events in the present and future conditions (Glenis et al. 2013). Simulations can be undertaken on current climatic conditions or future scenarios, based on the rainfall duration and return period. By considering the specific flooding event likelihood, such simulations can be integrated in a probabilistic rather than deterministic framework.

For this study, two different scenarios were chosen for initial testing prior to simulating a larger range of events in the probabilistic approach described above. The first scenario is defined by the peak of a 10-year return period event of 60 minutes duration, the second, more severe, scenario being 200-year return period and 60 minutes duration (Figure 2).

Digital Terrain Models (DTMs) are utilized as inputs to the hazard modeling stage to generate the underlying topography, and UK Ordnance Survey MasterMap Data describes the features of the built environment. The process of including buildings, soil porosity, and other characteristic parameters allows more realistic simulation of flow paths in urban areas. This allows scenarios of present urban development, as well as future pathways such as trends in urbanisation.

3.2.2. Exposure modelling

As the study highlights the impacts on the commuters in terms of disruption to their journeys, a model of network trips was developed using a Geographic Information System (ArcGIS). The model uses a simple all-or-nothing trip assignment routine to load journey-to-work (JTW) observations from the 2011 UK census onto network models in GIS.

The network, defined as link and nodes, was constructed from a selection of public data source

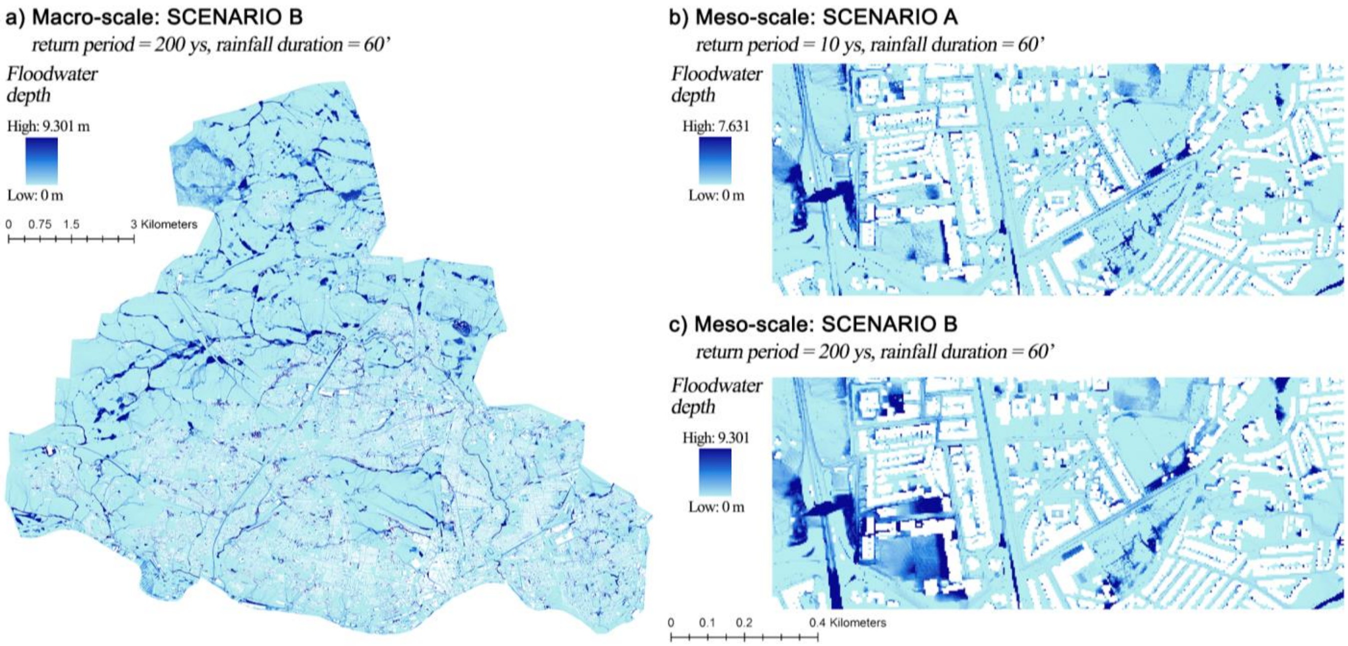

Figure 2. Examples of hazard maps obtained from the CityCAT model, at different scales.

(e.g. Ordnance Survey ITN and Meridian data) supplemented with speed and capacity information.

The JTW trips are calculated as least cost routes between origin and destination location according to the shortest time. By overlaying the CityCAT water depth and the ArcGIS network, impacts are assessed. If a link experiences a time delay due to the presence of water, the journey is recalculated according to the least-cost alternative route. Therefore, the disruption is calculated as increased time (delay) required to achieve the journey.

3.2.3.Vulnerability modelling and impact

Vulnerability curves represent a consistent method for flood risk assessment. However, little research explains in detail the methodology of their construction and their application (Merz et al. 2010). This paper presents a curve developed by the authors, with a practical application in the case study.

In order to explore the coincidence of the hazard outputs with the spatial locations of the network, the floodwater depths simulated by CityCAT must be associated with safe travelling speed for cars (safety speed) through a function. The safety speed is the velocity considered safe for travelling through a specific water level.

In order to overcome the definition of flooding threshold in binary terms (e.g. declaring a road closed or opened whether it is flooded or not), a curve that relates water depth (between 0 and a critical flood depth where the road is impassable) to safe driving car speed has been advanced (Figure 3).

The fragility curve has been developed by combining data from experimental reports (Morris et al. 2011), safety literature (Great Britain Department for Transport and Agency 1999), experimental data (Galatioto et al. 2014), analysis of videos of cars driving through floodwater, and expert judgment (e.g. Automobile Association). The maximum threshold for safe driving, stopping, and steering (without aquaplaning) is identified as 30 cm.

An upper and lower confidence interval are considered, to include uncertainties due to driving characteristic and behaviour (e.g. type of car, asphalt or tire, behaviour of the driver, visibility). Further research is needed to include uncertainties associated to each flood depth level and different type of cars.

The values R^2 (0.95) and the adjusted value of R^2 (0.94), from the performed regression analysis calculations, suggest that there is a good fit to the data. The Analysis of Variance (ANOVA) tests of R^2 and of the coefficients confirmed the validity of the Regression output.

The curve represents the safety function that relates floodwater depth and free flow speed. By overlaying the hazard map with the road network, road segments that intersect flooded areas are defined and their modelled flood depth measured. For such segments, the free flow speed is re-computed, according to the relation between flooding water depth and safety speed defined above through the safety function.

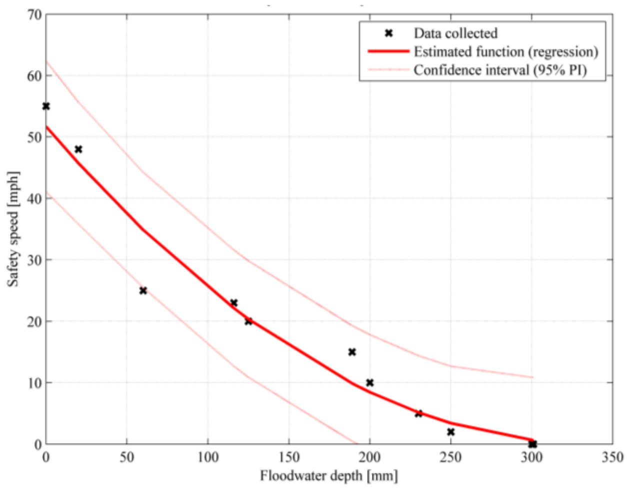

Figure 3. Representation of the safety driving speed as a function of the flooding water depth, analysed through a Quadratic Least Squared Regression.

3.2.4. Risk modelling

Hazard, exposure and vulnerability are combined in the model in order to explore the extent of the impact experienced on commuting transport routes. Using the new disrupted free-flow speeds calculated above, new travel times are calculated within the origin-destination matrix. The impact on travellers can be assessed by comparing the perturbed travel times with undisrupted ones, i.e. the delay in the journeys with respect to the baseline. The total damage in terms of Person-Minutes can be calculated from the number of journeys using a specific route (known from the JTW table). By assigning a monetary value to the delay time, the total cost of the disruption can computed. Generalized costs C can be assessed through Eq. 1, considering the distance D and the time T needed for it (Ford et al. 2015):

$$C = aD + bT \tag{1}$$

where a and b are the distance coefficient and the time coefficient respectively.

After Dawson and Hall (2006), the disruption risk due to flooding is given by Eq. 2:

$$R = \int \rho(w) D(w) dw \tag{2}$$

where $\rho(w)$ is the probability of a given rainfall w, and $D(w)$ is the disruption associated with it.

Given N simulations of the hazard of loading, l, the expected annual disruption from flooding, R, can be computed as a function of the disruption of each event, $D(l_k)$ and the probability of occurrence, $P(l_k)$:

$$R = {}^{1}/_{N} \sum_{k=1}^{N} D(l_k) P(l_k) \tag{3}$$

A preliminary analysis has been run in Tyne and Wear (in North East England) to demonstrate how the analysis can be used to assess the disruptions to commuter journeys due to flooding. The analysis conducted is based on the comparison between the pre-event and post-event travel time maps. The storm is assumed to fall only on Newcastle City Council area, but travel times are modeled for the wider Tyne and Wear transport region. Newcastle city centre has been adopted as a prototype case study but other UK cities are likely to be tested, including London.

4. RESULTS AND DISCUSSION

4.1. Findings

Journey times consistent with UK speed limits (assuming free flow conditions) were compared with perturbed journeys using speeds from the safety function described above. For the case study, the results regarding the delays in traveling journeys were significant (Figure 4). Scenario A (60' rainfall duration, 10 years return period) gave a maximum flood depth at a point critically chosen on the network of 0.13 m on the network and a maximum delay of 24 min. Scenario B (60' rainfall duration, 200 years return period) yielded a water depth at the same point of 0.86 m and a maximum delay of 42 min.

These results show that, even using simple assumptions about network behaviour (see below), significant delays can be measured and the need for adaptation highlighted. Adaptation options can be assessed in the model, for example through adjustments of land use and building characteristics in CityCat, and comparison between scenarios can

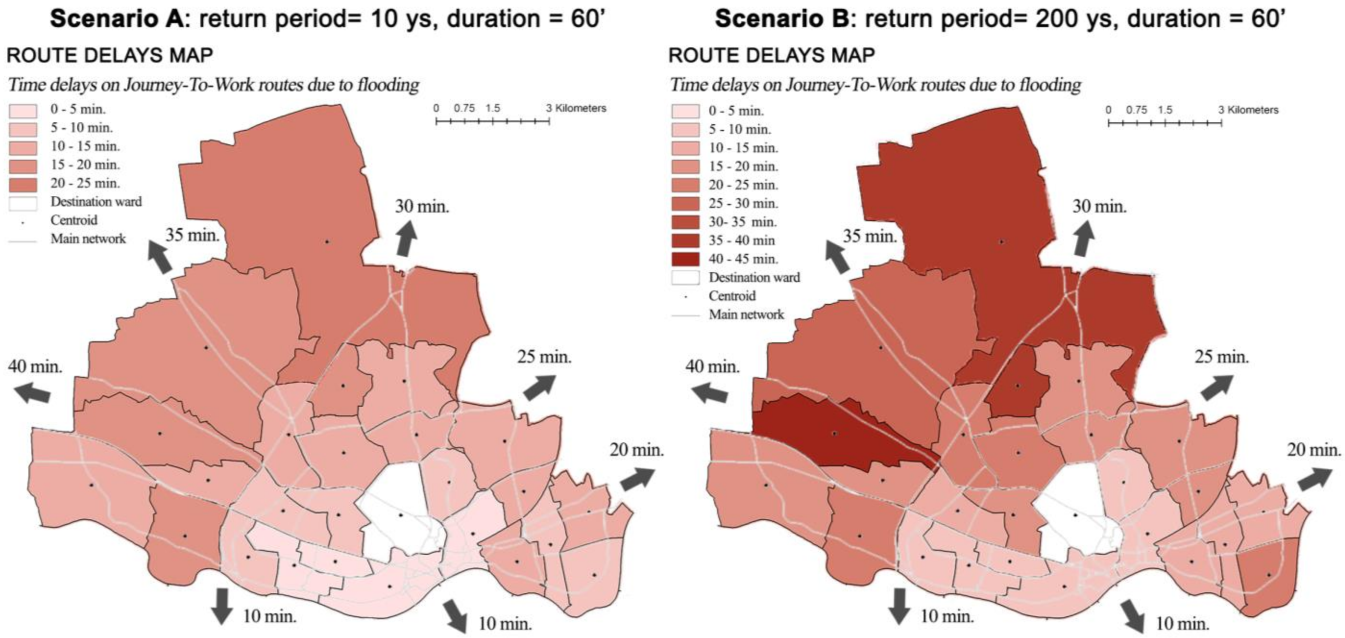

Figure 4. Final results for the prototype study case in Newcastle.

determine the cost-effectiveness of the solution considered. Topography, permeability, and surface flow processes are the main factors that influence urban catchment and drainage systems. Reducing pervious areas or enhancing rain-water collection through SUDs solutions (e.g.: green roofs, natural corridors, rain water gardens) could help to integrate risk management into urban planning and design.

4.2. Limitation and critical discussion

Due to the very complex nature of the study and to the broad scale of the model, some assumption were necessary which the authors feel are justified given the macro scale of the analysis. General considerations include:

- in the transport model, people are assumed to be aware of the disruptions, and to have perfect knowledge of the network; all commuters will choose the shortest route. Only private vehicles are considered, thus public transport excluded. Moreover, no differentiation regarding road characteristics (e.g.: pavement, drainage) or car types was advanced at this stage;
- the representation of the urban area is simplified into census wards and their centroids, which are assumed as trip origins and destinations. No complex interactions are considered, as JTW trips are assumed only towards the central wards.
- the model incorporates congestion effects (e.g. roads becoming busy), but does not account for traffic lights, queuing, and possible accidents.

Given these assumptions, results should be compared relatively rather than in absolute. Nevertheless, the analysis offers an interdisciplinary view on a complex problem, presenting a specific indication of flood impacts on transport network, and provides basis for further studies.

Although the study is site-specific, techniques and data are easily available so that the approach is transferable to other contexts. This approach can be applied to present conditions as well as future scenarios including potential adaptation strategies, allowing the examination of impacts alongside socio-economic and climate change. Whilst this study focuses on the flood risk to the road network, the framework can also be applied to other weather-related phenomena facilitating the systematic analysis of their direct and indirect impacts.

4.3. Further research

The proposed method examines the impacts of extreme weather floods on urban transport infrastructure, through network spatial analysis, climate simulations, and a safety function. Such methodology could be led in numerous research directions, depending on interest.

Firstly, a complete range of hazard scenarios with different severity and frequency will be simulated (e.g.: over a wide range of return periods, intensities and durations), in order to evaluate a broader variety of disruptions within a probabilistic risk framework described by Equation 3.

In this study, the flood analysis was restricted to the city boundary of Newcastle-upon-Tyne, introducing some approximation in the outcomes. Additionally, only flood depth is considered, whereas flood velocity is assumed minimal (as is the case for wind, visibility, driver behavior, and other circumstances that can influence dynamics which are not examined). Next steps could extend the existing framework by overcoming such restrictions.

The next stage of the model will consist in testing different “soft” adaptation measures (e.g.: SUDs, green/blue roofs), aiming at the reduction of the impact. At the same time, the most vulnerable nodes and links of the network can be identified and analysed, allowing the testing of hard flood-defences measures (e.g.: drainage improvement, node strengthening). This portfolio of assets will lead to a cost-benefit analysis of all the possible options.

Finally, the methodology could be adapted to explore other hazard impacts, different types of infrastructure networks and potentially cascading failures between infrastructure systems.

5. CONCLUSIONS

The increasing number and impact of environmental disasters highlight the important role that the concepts of risk and resilience play for both current-day and future society.

This study detailed an integrated analysis investigating the flooding impact on free flow speed on urban road networks. The proposed methodology combined climate simulations and spatial representations together with a safety speed function. By overlaying in GIS spatial data regarding exposure, hazard thresholds from CityCAT, and a vulnerability curve, different levels of disruptions to commuting journeys on road networks were evaluated.

Newcastle-upon-Tyne (UK) was adopted as prototype to investigate the disruption on urban traffic due to flooding, in the form of time delays of commuter journeys caused by reduction in free flow speed or re-routing. Two scenarios were presented with differing magnitudes, to test combination of severity and intensity. The result showed significant delays in traveling journeys, for a maximum of 24 minutes and 42 minutes respectively. The work in this paper is leading towards a systematic tool, which could provide decision-makers with more relevant risk-based information.

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