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Assessment of the impacts of extreme weather events upon the pan-European infrastructure to the optimal mitigation of the consequences

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Abstract

A number of extreme weather events (EWEs) have made the resilience of the critical infrastructure of priority concern for infrastructure owners, operators and other decision makers. In this context, the European research project RAIN has studied the EWEs and their impacts upon land-based infrastructure in Europe, and developed a Risk-Based Decision Making Framework with the final goal of mitigating the consequences. This paper presents the main findings of the RAIN project, such as established thresholds for EWEs in the face of a changing climate, decision support tools for infrastructure owners and operators, crisis coordination and response planning based on recent cases, risk-based decision making, technical solutions for risk mitigation, and their implementation considering the current status of European infrastructural elements and networks. The outputs of RAIN aid decision making in the long term, securing new robust infrastructure development and protection of existing infrastructure against climate change and more frequent occurrence of extreme weather.

Keywords: Land-based transport networks; Extreme weather events; Vulnerability; Resilience; Risk-based decision making; Risk mitigation.

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1. Introduction

Nogal et al (2016a) presents the conceptual approach behind the European research project RAIN (Risk Analysis of Infrastructure Networks in response to extreme weather). The multidisciplinary vision presented, involving aspects as diverse as climatology, transportation, or sociology, provides an operational analysis framework that identifies critical infrastructure (CI) components impacted by extreme weather events and helps to determine the measures that minimise the impact of these events on the EU infrastructure network. The project focusses on land transport networks, and the energy and telecommunication systems to identify cascading and inter-related effects.

The general framework of the RAIN project is depicted in Figure 1. It consists of five inter-related modules, namely, (a) *hazard identification*, to identify the most potential harmful hazards impacting the CI; (b) *analysis of vulnerabilities* of the CI, based on past transport infrastructure failures and the current means of protecting them; (c) *risk-based analysis framework* for single events and cascading effects of single or multiple hazard events. The cascading effects consider the interdependency identified in critical transport, energy and telecom infrastructure; (d) *societal, security and economic impacts* of CI failure; and (e) *strategies for mitigation and adaptation* to the potential impacts of extreme weather to improve the resilience of the existing infrastructure networks.

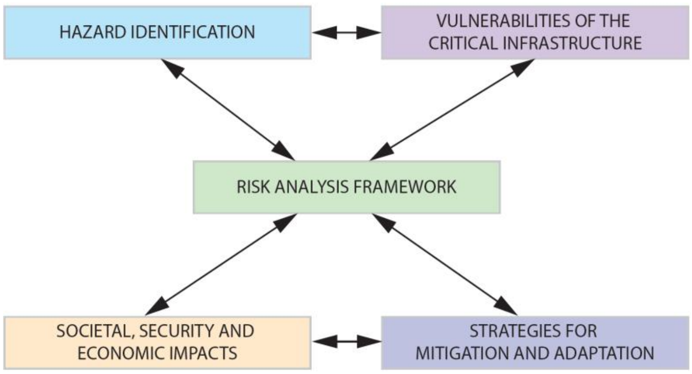

Fig.1 General Framework of the RAIN project

The aim of this paper is to present the main insights of the RAIN project, as a result of the development and implementation of the presented conceptual approach. Special attention is paid to the potential role of the infrastructure managers and emergency managers on improving the resilience of the land-based transportation networks.

Other relevant aspects discussed in this paper are the intensity thresholds used to characterize an event as an extreme, which is presented in Section 2, taking into account regional differences in vulnerability and climate. The conclusions obtained from the elicitation of infrastructure managers, policy makers and other stakeholders regarding the vulnerability and resilience of the European CI is presented in Section 3. The applicability of the risk-based analysis framework, which has been benchmarked against two case studies at two different geographical scales, is shown in Section 4. In Section 5, aspects regarding technical, logistical and response strategies for mitigation and adaptation to the impacts of extreme weather are discussed, including the analysis of the current state of the early-warning systems. Finally, some conclusions are drawn in Section 6.

This paper presents some of outputs of the RAIN project. The interested reader is referred to http://rain-project.eu for further information.

2. Extreme Weather Events. Thresholds and projections

An extreme weather event (EWE) occurs when the value of the weather or climate variable is above a threshold near the upper ends of the range of observed values of the variable (Barros et al., 2012). Given the classical engineering design criteria, which are based on safety coefficients related to specific return periods and their corresponding probability of occurrence, the threshold is associated with an intensity that leads to significant consequences in the built environment. Therefore, the definition of the thresholds to consider a climatic event as "extreme" must consider a number of factors such as infrastructure type and geographical area. For example, the same amount of snowfall will cause different impacts in the North or in the South of Europe. The same is true for extreme wind speeds, as building codes and practices are generally adapted to the local wind climate, resulting, e.g., in higher construction standards in coastal and mountainous areas than elsewhere. For some hazards, thresholds are best expressed relative to known local climatology as a return interval in the present climate.

In order to define sound thresholds to address the problem across Europe, 28 semi-structured interviews with stakeholders were conducted (Holzer et al. 2015). These stakeholders include managers of infrastructure and emergency managers. On the basis of the interviews, literature study, meteorological analyses, and a review of thresholds used by weather services, the following thresholds were defined (Table 1).

Table 1. Summary of thresholds defined and used in the RAIN project.

Hazard	**Intensity Threshold 1**	**Intensity Threshold 2**
Windstorm	50-year event	-
Heavy rainfall	10-year event	-
River flood	100-year event	-
Coastal flood	100-year event	-
Tornado	Any tornado	-
Lightning	Any lightning	-
Large hail	Hail diameter ≥ 2 cm	Hail diameter ≥ 5 cm
Thunderstorm wind	25 m/s (90 km/h)	32 m/s (115 km/h)
Crown snow load		
Heavy snowfall	6 cm / 24 h	25 cm / 24 h
Blizzard (snow storm)	≥ 10 cm snow in 24 h and wind gusts ≥ 17 m/s and temperature < 0°C	
Freezing rain	5 mm / 24 h	25 mm / 24 h
Wildfire	Fire Weather Index > 20	Fire Weather Index > 45

The interviews also showed that operators of land-based transport infrastructure are most concerned about heavy rainfall, snow and snowstorms and freezing precipitation, with special attention paid to the impacts of coastal floods and river floods.

In addition, projections of the current spatial distribution of hazard probability and the expected changes according to various climate scenarios have been developed. Regional climate projections for the 21st century indicate that a number of changes are to be expected across Europe (Groenemeijer et al. 2016). In terms of extremes, extreme precipitation, of both short (3 hours) and medium (24 hours) time ranges are forecast to increase across most of Europe. The numbers of sub-daily, high-intensity events are predicted to increase at a higher rate than the number of long-duration events characterised by high accumulated rain amounts.

River floods will become more likely over large areas, unless mitigation efforts are taken. Germany, Hungary, Poland and France are expected to have the largest absolute increases in flood-prone areas. Conditions supportive of severe thunderstorms with large hail, tornadoes and severe wind gusts will become more likely, particularly in South-Central Europe. Lightning will become more common, in particular across northern and central Europe. Longer dry spells will cause conditions supportive of forest fires and wildfires to become much more frequent across Europe, in particular in the south. Generally speaking, heavy snowfall, blizzards, freezing rain and snow load should become less likely across South and Central Europe, but more likely in northern Europe. A widespread increase of coastal flood risk is projected, primarily due to rising sea levels. Areas with a particularly high risk are the French coasts, the central and southern UK, Germany, Italy (Adriatic), northern Poland, and the Danube delta. In these locations, improvements in flood defences are needed. In that regard, the Netherlands are comparatively well-prepared. The hazard probability data produced in the RAIN project is published and can be downloaded in Hazard Probability (2016).

Climate change mitigation (i.e. reduction of greenhouse gas emissions) will help to reduce the trends mentioned above; however for coastal floods the effect is rather small, as the much of the future sea level rise takes place in response to temperature changes that are already occurring.

3. Resilience of Critical Infrastructure

When the system is exposed to any disruption, a resilient system should minimize the consequences, maintaining the adequate level of performance according to the current situation (Nogal and O'Connor, 2017).

A very challenging aspect of the CI resilience is the understanding of the human actors, such as users, operators and managers, and how they interact with the built environment. They are a key component when dealing with the transport systems' resilience, as they represent the main capability of the system. Given the relevance of the human actors, Nogal et al. (2016b, 2017) explicitly consider them when assessing the resilience of the transportation networks impacted by EWE.

The resilience of the European transport system to EWE can be enhanced by analyzing the level of preparedness and identifying the vulnerabilities of the existing infrastructure networks. With this aim, a dedicated application to measure vulnerability and resilience from a user perspective within an Objective Ranking Tool (ORT) tool has been developed. This ORT-application is a dedicated online web tool for self-evaluation by local authorities and infrastructure owners and users at different levels and their stakeholders. Within this application it is possible for them to assess their performance and preparedness to different types of EWE. This assessment expresses elements of vulnerability as such but also allows the identification of the quality of preparation in terms of resilience. 50 criteria by a Delphi-panel (expert judgment panels) were developed for vulnerability and resilience based on state-of-the-art literature review. Table 2 shows some of the selected elements classified according to the social, economic, infrastructural and institutional dimensions.

Table 2. Example of selected variables classified according to the dimension to the evaluation of the vulnerability and the resilience.

Dimension	**Vulnerability**	**Resilience**
Social	Number of vehicles per 1000 inhabitants	Soft mitigation strategies in place
	Population density	Implementation of targeted risk communication tools
	Incidence of centres and settlements	Level of risk awareness among the population
		Capacity of local CSOs to mobilise population
Economic	Per capita income (average income)	Existence of specific funds allocated for mitigation & post emergency recovery by Regional/national authorities
	Employment rate	Capacity to access existing exogenous resources
	Incidence of employed in the industrial sector	Existence of PPPs for economic sustainability of mitigation/prevention strategies
	Number of active enterprises per 1,000 inhabitants	Planning of ad hoc mitigation activities
Infrastructural	Schools (primary and secondary education) per 10 km2	Planning of ad hoc mitigation activities
	Density of building (n. of houses per Km2)	Identification of infrastructural assets needing upgrading as means of mitigation/prevention
Institutional	Municipal spending capacity	Policy making capacity to upgrade identified infrastructural assets
	Funds allocated for major hydrogeological emergencies (2009-2012) - in EUR	Existence of civic engagement mechanism in local governance settings
		Implementation of updated Emergency plans
		Existence of participated bodies for risk management (i.e. involving all stakeholders)

The CI operators, having seen a clear picture of their strengths and weaknesses in the face of extreme weather, can act to improve their resilience. The (self)-assessment tool is based on the principles of the Delphi-panel, Analytic Hierarchy Process and Similarity Judgment. The principles behind the similarity judgment methodology are used to prioritize or compare objects. Through the use of Delphi-panels and the use of Analytic

Hierarchy Processing, a reliable identification of characteristics is possible and proper weight percentages to these characteristics can be provided. See *www.psjadvies.nl* for further details.

Within this application some fictive municipalities were scored during two real-life interviews with responsible officers in The Netherlands and Italy.

The application showed the level of preparation compared to an ideal situation and provided insight into those criteria that will give the highest contribution in improvements. The main conclusions derived from the application of the ORT Tool with stakeholders are the following; (i) the degree of vulnerability (shaped by context factors that are by their nature more 'static') of a region or municipality to extreme weather events is the least likely to be reduced by targeted actions in the short term. Resilience (as the capacity of a community to face a stress, and rooted in its organisational capacity and flexibility to change) however is something that can be influenced by stakeholders in a shorter-term timeframe. (ii) For stakeholders on regional level it will be possible to compare the outcome between, e.g., municipalities, so decisions can be made for those geographical areas where the greatest improvements should and can be made; (iii) Stakeholder involvement is needed from the beginning of projects on vulnerability/resilience assessment, as their perception shapes also the way in which the community is going to organise itself to face external stress.

The analyses can be executed in a limited time-frame so results can be gathered on short notice.

4. Decision-making under EWE scenarios

The information presented previously converges into a risk-based decision-making framework for single events and cascading effects of single or multiple hazard events, aimed at helping the decision –making process of infrastructure managers and policy makers. Due to the high impact low probability nature of the cascading effect hazards, they have started to be recognized not only by risk and safety practitioners but also in technical standards and legislation concerned with the control of major accident hazards (Council Directive 2012/18/EU).

The proposed framework, as elaborated by Van Gelder et al. (2016), presents two phases, the inference phase, in which the probabilities of the possible outcomes are quantified as a function of the actions that a risk manager might be contemplating to take and then, in the decision phase, the action that promises to minimize the pertinent risks identified. The risk-based decision making support tool uses the laws of probability theory (i.e., the product and sum rules) for its inference phase and the insights from decision theory for its decision phase. It considers an alternative criterion of choice which takes into account not only the most likely scenario (i.e., expectation value), but also the worst- and best-case scenarios (i.e., lower and upper bounds). A neo-Bernoullian decision theory that adopts Bernoulli's original utility function, on the strength of a consistency derivation, but which takes its cue from the Allais paradoxes of behavioural economics, as it recognizes the fact that the most likely trajectory (i.e., the expectation value) is not the only information upon which we typically base our decisions; since worst- and best-case scenarios (i.e., the lower and upper bounds of our outcome probability distributions) are expected to intrude themselves upon our decision making as well (Van Erp, Linger, and Van Gelder, 2016a, 2016b).

Regarding the introduction of the cascading events into the general framework, a methodology is developed by which system state probabilities may be estimated for systems that are subjected to cascading effect hazards. This methodology, which may be used, for example, to model potential cascades of landslides where the triggering event is a landslide most upstream, makes use of the so-called Probability Sort algorithm in order to estimate Markov Chains for what otherwise would have been intractable (in)homogeneous transition matrices (see Van Erp et al., 2017).

The proposed approach is implemented and validated by means of two case studies of different geographical scales, namely, the 2003 flash flood in the Northeast Italy and the flooding of 2005 at the Gulf of Finland. In this paper only the first is explained, but the interested reader is referred to the RAIN website for further information.

The case of the 2003 flash flood in Malborghetto – Valbruna in North Italy was caused by an extreme storm resulting in catastrophic flooding at drainage areas up to 80–90 km2, with a dominance of debris floods at basin scale up to some tens of km2. The flash flood led to the death of two people, 600 residents were evacuated, and caused damages for almost 1 billion Euro (Borga et al., 2007), as a consequence of the failure of critical infrastructure such as the railway and road networks connecting Northeast Italy and Central Europe. More precisely, the Italian motorway Autostrada A23 part of the European route E55, the national road SS13, which is one of the most important of the Italian state roads, and the Pontebbana railway line from Udine to Tarvisio and the Austrian border, go throughout this arc-shaped mountainous area of the eastern Alps (see Fig. 3). Due to the complex orography, 29 bridges and 10 tunnels have been identified within the transport system of the studied area.

The hazard assessment considers not only the probabilities of occurrence of the extreme weather event, but also the probabilities that this event triggers other hazards. In the Italian case, for instance, the assessment considers the interaction of the extreme rainfall with the triggering and intensity of floods and landslides. This interaction is modelled using risk maps (see Fig. 4), local rainfall-landslide probability curves and the output of a rainfall-river flood model. The hazard interactions in the multi hazard scenarios to be studied are identified; as were the network interaction needed to be accounted for in the multi-mode analysis.

The chains of probability from triggering event to infrastructure failure and the resulting consequences are modelled using a Bayesian probabilistic model. Figure 5 shows the development of a Bayesian Network (BN) for the Italian case study. These BN models the risk to bridges along the two critical roadways from floodwaters triggered by extreme rainfall calculating the consequence that the case study area cannot be traversed. The risk to bridges due to the flooding is calculated using a rating system in which the infrastructure components are scored against the hazard type. The BNs for the complete case study analysis are completed by including other critical infrastructure elements in the region and the remaining hazards. After modelling the multi-hazard, multi-modal infrastructure network interaction, mitigation measures are introduced into the model. As a final output, a ranking of the mitigation actions, for given budgetary constraints, that minimize the societal, security and economic risks are provided in the decision phase, helping the decision-making process.

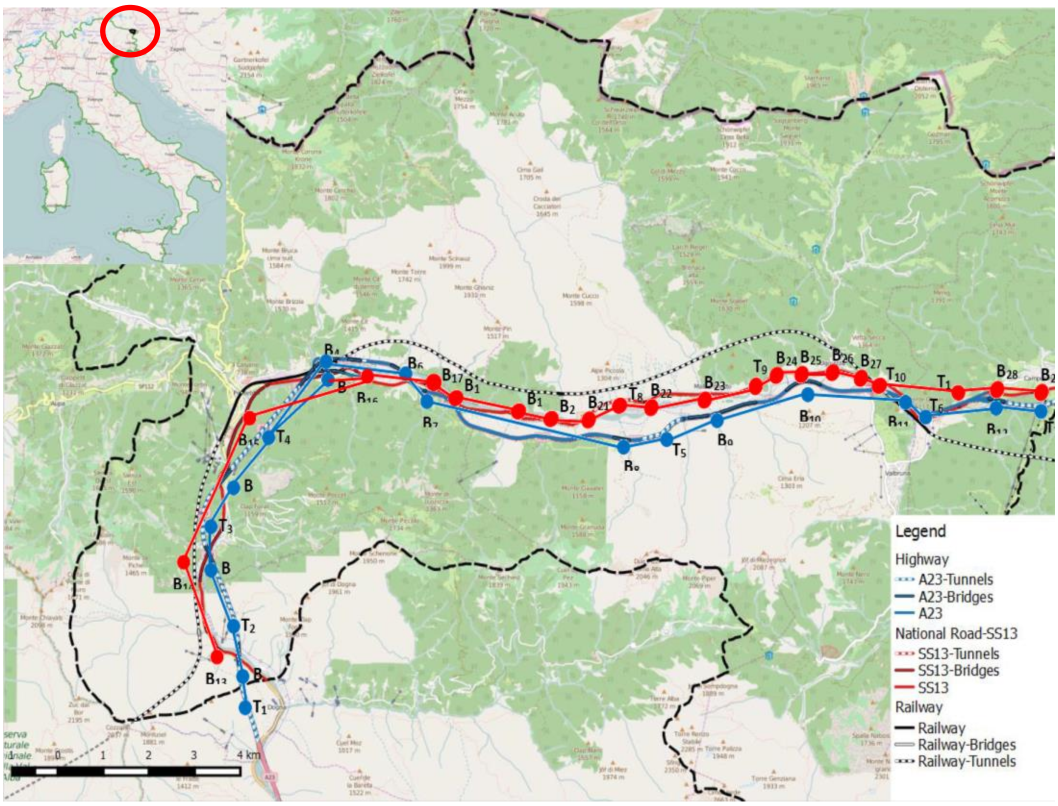

Fig. 3 Land-based infrastructure in the area of Malborghetto – Valbruna in North Italy, indicating the bridges (B) and the tunnels (T) presented in the motorway A23, the national road SS13 and the Pontebbana railway line

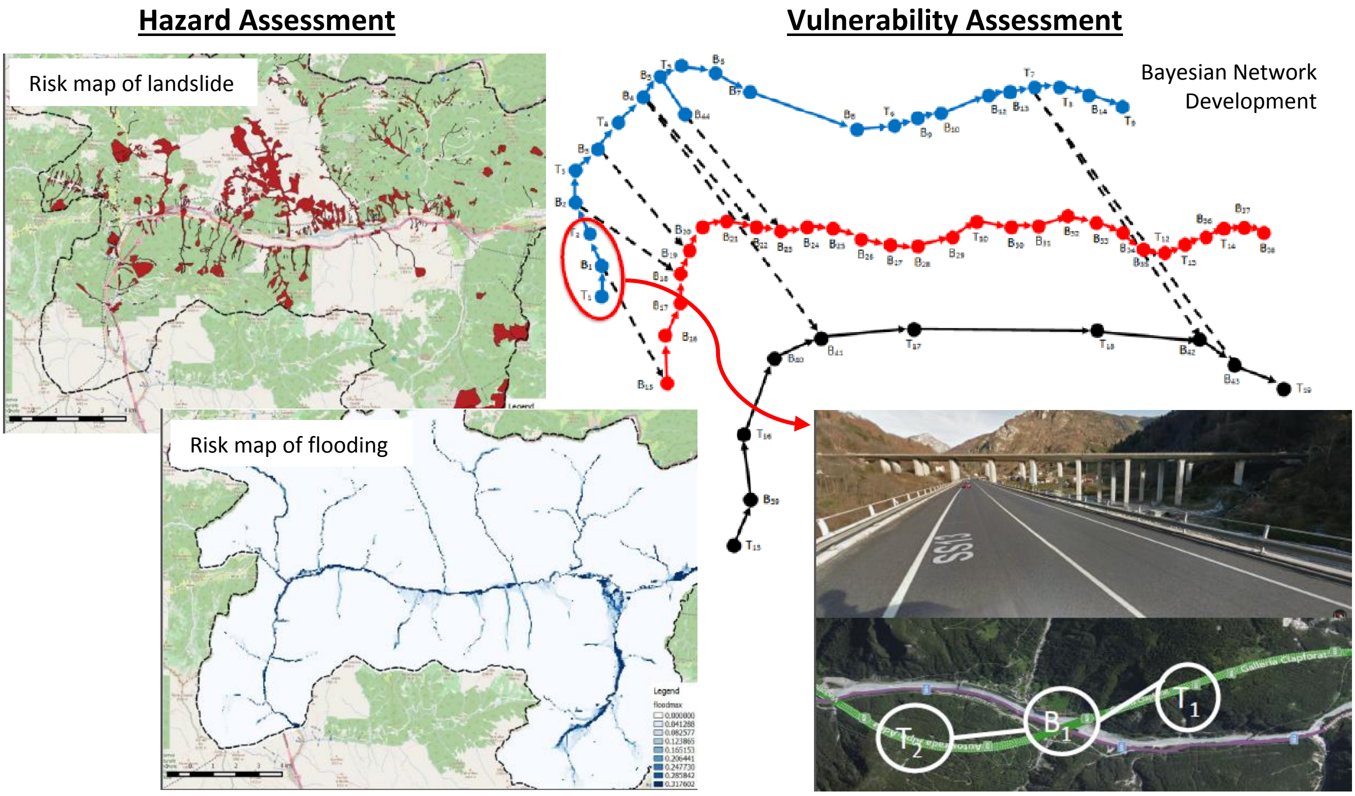

Fig. 4 Hazard assessment based on risk maps and vulnerability assessment of the elements identified in the transport network in the area of Malborghetto – Valbruna.

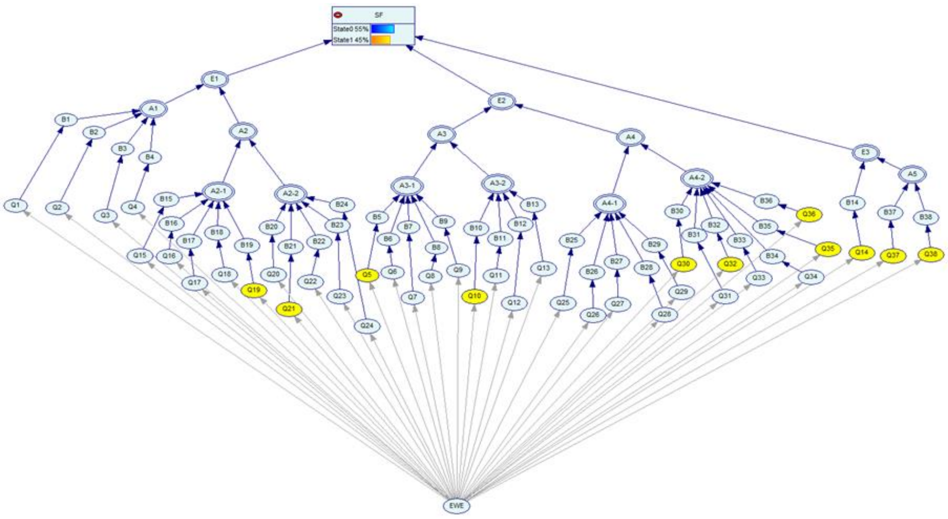

Fig. 5 Bayesian Network to model the Bridges on a Road Transport Network. The model calculates the risk to connectivity due to flooding triggered by extreme rainfall.

5. Measures to improve transport systems' resilience

The RAIN project considers mitigation strategies with a focus on measures that can be adopted to improve the resilience of the existing transport infrastructure. These measures include physical adaptations and changes to management strategies to increase the level of redundancy and prevent cascading effects.

Various mitigation measures are in place, which are heavily based on weather (or climate) forecasts. The mitigation measures are typically aimed at temporally increasing resilience. In fact, some CI operators include climate changes into their long-term planning by having established platforms of cooperation with climate scientists. The quality of forecasts and early warning systems is fairly high on timescales between a half day and three days in advance, for many hydro-meteorological hazards. Nevertheless, forecasts for hazards that are complex and local or rare, but potentially have a high-impact had a lower availability and/or quality. This is true for coastal floods, forest fires and thunderstorm-related hazards (flash floods, tornadoes, severe wind gusts). In that regard, efforts to monitor these hazards on a European scale are recommended.

Although more and more early warnings tailored to stakeholders are being prepared, the adoption of probabilistic forecasts by CI stakeholders is slow. Some CI operators use public warnings. These warnings are issued according to warning thresholds that vary among countries.

Major failure of elements of infrastructure as a result of weather impacts is increasing. The report "Impacts of Europe's changing climate – 2008 indicator-based assessment" (JCR, 2008), identifies the need to limit deterioration effects from adverse weather conditions (e.g. prolonged precipitation, heat stress, freeze-thaw cycle) and damaging consequences in case of extreme events (i.e. storms and floods) as a key factor influencing construction designs.

Since elements of transport infrastructure represent significant assets, and portions of the network are very old, e.g. parts of the European rail network are more than 150 years old, a focus is given to increasing the resilience of existing infrastructure. Whilst a range of effective methods of increasing resilience is available to infrastructure managers, the choice of which solution to adopt will depend primarily on available budget and the risk rating for the element. For that reason, within the RAIN project a ranking system, based on the technical impact matrix approach was developed to assess the impact of various remediation options considering the efficacy of the methods under the following headings; (i) technical effectiveness, (ii) cost, (iii) human and financial loss and (iv) environmental impact. It is concluded that direct methods are preferable, e.g. rock protection, rather than indirect approaches, e.g. reducing the impact of flooding on bridge scour by introducing a regional flood protection system.

6. Conclusions

Increasing data availability, and supporting efforts to monitor, forecast and study hazards on a European level will likely help to increase resilience to extreme weather impacts on critical infrastructure and society as a whole. Such actions are important regardless of climate change, but the fact that a majority of the hydro-meteorological hazards is expected to become more frequent until the year 2100 stresses this importance.

The ORT-application on vulnerability and resilience to extreme weather events might be seen as a practical, easy to use, assessment for any local authority, infrastructure owner or user. Within the tool, it is possible to compare the outcomes of different local assessments and to decide on a regional level where to improve preparation or where investments will have the best improvements in terms of preparedness. The analyses can be executed within a limited time frame.

The case studies analysed, which consider the probabilities of EWE, the status-quo of the land-based transport networks and their interdependencies, the societal vulnerability and the potential mitigation measures, demonstrate to infrastructure owners the benefits of RAIN risk-based decision-making framework to address European policies in the areas of safety and security, inter-modality and emergency response planning.

The results of the RAIN project will help stakeholders to focus on institutional, economic, social and infrastructural aspects that could be improved so to enhance the resilience of the transport systems.

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