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Uncertainty as part of multi-hazard resilience and adaptation planning for road infrastructure

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Quantifying natural hazard impacts on critical infrastructure networks inherently involves uncertainties which makes decision-making complex. Here, we present an approach on how to account for uncertainties in the resilience assessment and in adaptation planning. These uncertainties stem from the hazard, exposure, vulnerability, and end-user data, as well as economic valuation. The consequences of natural hazards on critical infrastructure networks such as road transport networks has been proven to be evident, illustrated by recent flooding events in Western Europe. Due to climate change, many of these hazards may intensify and occur more frequently. Over the past years this has invoked progress in research that has led to an increased understanding of the effects of natural hazards on infrastructure networks. Currently, most analyses focus on the estimation of exposure, vulnerability, and the estimation of (annual expected) damages to the infrastructure assets and socio-economic losses for the users. This is subsequently used to identify hotspots for potential measures. The next step is to include adaptation in maintenance and construction planning. However, this step is often not linked to the assessment preceding the hotspot selection and because uncertainties in the assessment are not quantified, this results in decision making under (very deep) uncertainty. Here, we show the results for the Dutch highway network where we used the RA2CE - Resilience Assessment and Adaptation for Critical infrastructurE - platform, which makes use of hazard maps, user defined vulnerability curves and traffic information to produce resilience and risk maps for the infrastructure networks (resulting annual expected damages for the road operator and socio-economic losses for the road user), but also offers the possibility to perform cost-benefit analyses for proposed adaptation measures. Based on the cost-effectiveness analysis of potential measures, economically viable intervention strategies can be defined, including spatially explicit cost-benefit ratios to demonstrate economic performance of the different strategies. However, cost-benefit assessments should acknowledge the uncertain future related to climate change and socio-economic developments. Therefore, we progress the current state of the art by adding an uncertainty analysis, which takes into account all identified uncertainties in the model chain. This is based on Monte Carlo analyses providing insight in the sensitivity to all uncertainties in the process stemming from hazard, exposure, vulnerability and traffic data, as well as from the changes to the future related to climate change and socio-economic developments. The results provide an increased insight in the robustness of the strategies, instead of only one (best guess)

prediction. It further allows the user and decision-maker not only to look at the expected change, but also at the high-impact, low-likelihood events. Based on validation with decision-makers future research has been identified to include black swans (unknown-unknown events) in decision-making, but also progressing on the user level, by for example including equity.