Critical Infrastructure failure escalates the macroeconomic impacts of disasters

Surender Raj Vanniya Perumal[1], Elco E. Koks[1], Marleen de Ruiter[1] and Mark Thissen[2,3]

1 Institute for Environmental Studies (IVM), Vrije Universiteit Amsterdam, Amsterdam, The Netherlands;
2 Spatial Economics, Vrije Universiteit Amsterdam, The Netherlands;
3 Netherlands Environmental Assessment Agency (PBL), The Hague, The Netherlands.

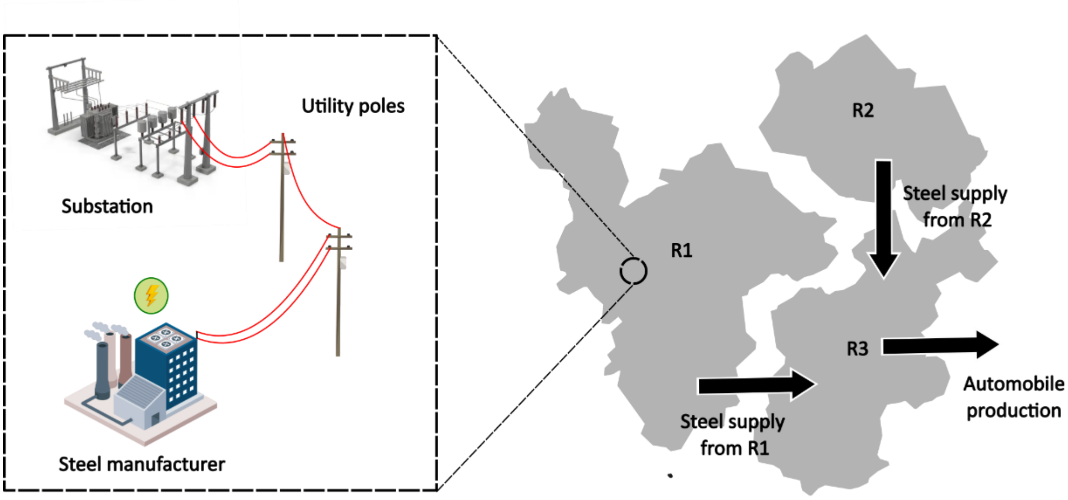
Abstract

Critical infrastructures (CIs), such as power systems, are vulnerable to disaster-induced disruptions, often resulting in industrial shutdowns and production losses. These disruptions cascade through interregional supply chains, amplifying the economic consequences. Conventional macroeconomic disaster impact assessments often overlook production downtimes caused by CI failures and fail to account for the spatial interdependencies between CIs and different sectors of the economy. This study presents a spatially explicit methodology to quantify the macroeconomic impacts of CI failures, demonstrated using power disruptions induced by flood events. Our analysis shows that CI failures can amplify macroeconomic impacts by 30% to 360%, depending on the degree of interregional substitution (i.e., economic resilience) available and the robustness of CI assets. Our results underscore the importance of incorporating CI disruptions into macroeconomic risk assessments Additionally, the findings suggest that CI adaptation decisions solely based on maximum damage assessments may be ineffective. A more systemic approach that targets the adaptation of CI assets serving crucial and less redundant economic sectors proves to be more efficient. Furthermore, the proposed approach provides a basis for transitioning from traditional damage-based adaptation decisions to a more holistic, system-level framework for climate adaptation of CIs.

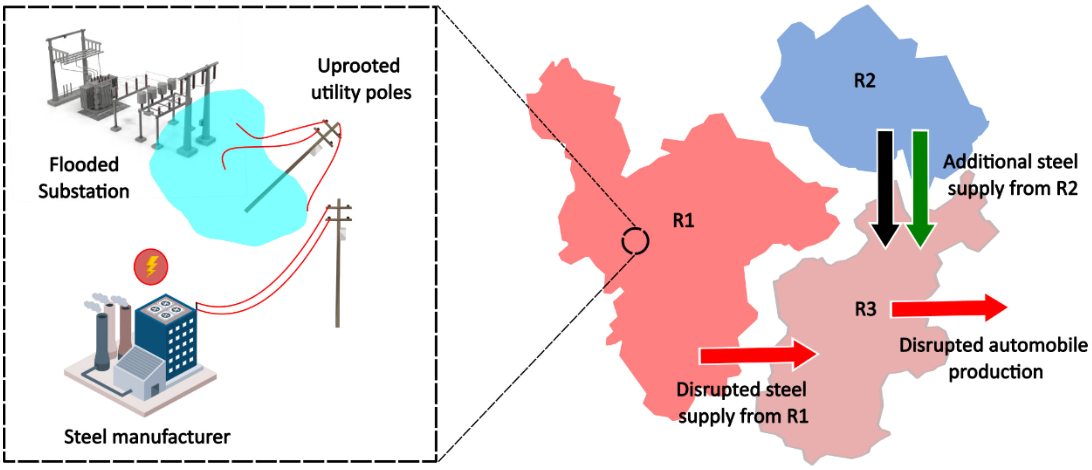
Keywords:disasters, critical infrastructure, power outage, climate adaptation, input – output analysis

Introduction

Recent substation failure events at Heathrow Airport (NESO, 2025) and the Europoort area of Rotterdam (Meijer et al., 2024) led to widespread disruptions in passenger transit and refinery operations, respectively, underscoring strong dependencies between CI services and the socio-economic functioning. The likelihood of CI failures increases during natural hazard events, where multiple critical assets may be damaged simultaneously (Guikema et al., 2010; Li et al., 2022). The consequences of such failures extend beyond physical damages, as the lack of CI services will force the downtime of its dependent industries resulting in production losses. The affected industries are an integral part of supply chains, resulting in broader multi-regional macroeconomic impacts (see Figure 1). In this study, we develop a modelling framework to estimate the macroeconomic impacts of disasters, explicitly incorporating disruptions resulting from CI failures. The framework is applied to a case study in Zuid-Holland—the region with the highest economic output in the Netherlands, subjected to hypothetical flood scenarios and associated power disruptions. By comparing macroeconomic impacts with and without CI failures, we highlight the significance of accounting for CI disruptions. Subsequently, this framework is used to identify CI prioritization strategies for adaptation, differing with conventional damage-based approaches e.g., Chang & Hossain (2024) ; Karagiannakis et al. (2025) . This study offers an early contribution toward incorporating system-level economic impacts into the decision-making process for CI adaptation planning.



(a) Pre disaster scenario



(b) Post disaster scenario

Figure 1. An example to illustrate the macroeconomic consequences of CI failure. The black, red, and green arrows indicate business-as-usual, reduced, and increased trade flows, respectively.

Methods

Figure 1a illustrates a representative pre-disaster scenario highlighting the role of CI services in enabling the normal functioning of supply chains. Figure 1b presents the multi-regional macroeconomic consequences of CI failure following a flood event. Assume a flood event occurs in the region R1. The substation is flooded, and the utility poles are uprooted. Subsequently, the steel manufacturer is forced to shut down the plant due to a power shortage. Knowing this and to satisfy the market demand for steel, the steel manufacturer of R2 extends its steel production to a certain extent and supplies it to R3. Despite this compensatory adjustment, region R3 still receives less steel relative to the business-as-usual scenario, leading to a reduction in automobile production. This sequential failure propagation is taken into account in this study.

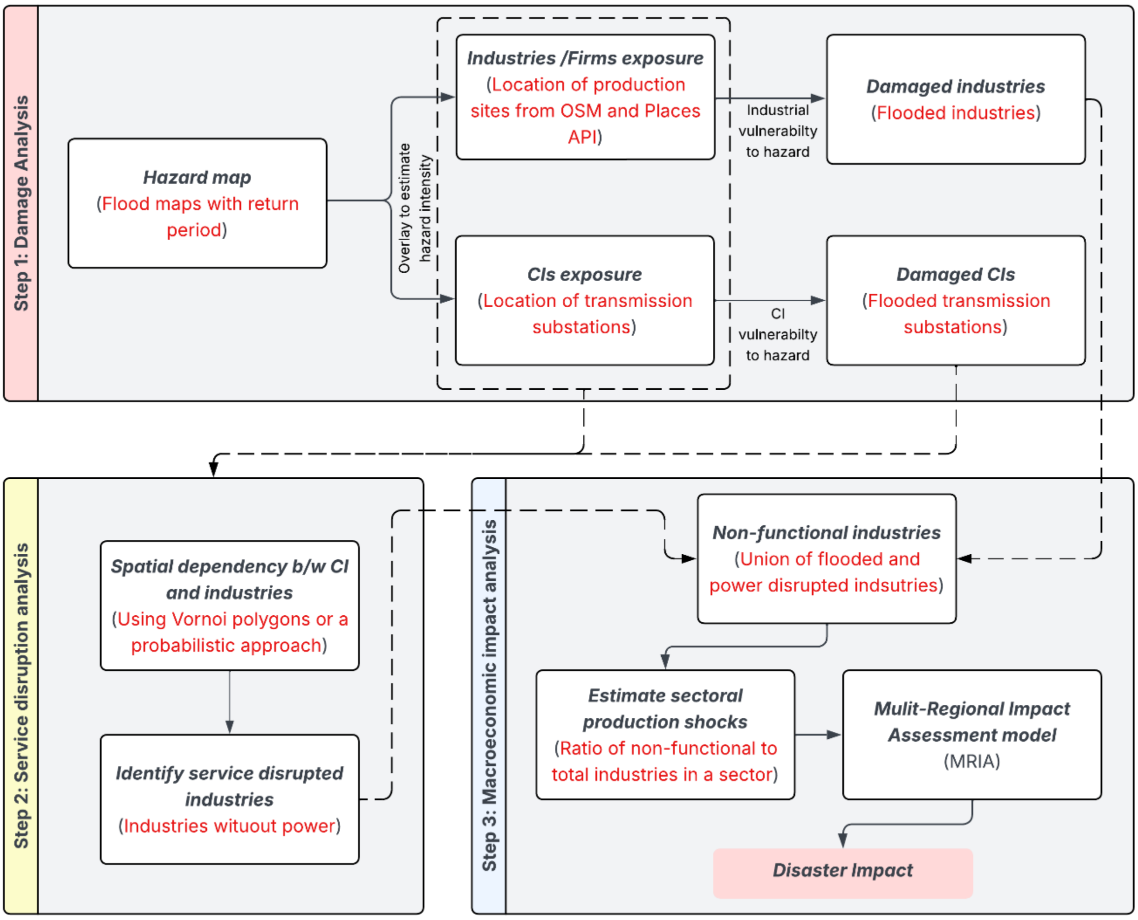


Figure 2. Flowchart outlining the steps involved in estimating the macroeconomic impacts of disasters, with consideration of service disruptions from critical infrastructures. Steps shown in bold represent a generic methodology applicable across various CIs and hazards, while the red text in parentheses highlights the specific steps to the case study presented.

Figure 2 outlines the sequential steps of the proposed framework for estimating the macroeconomic impacts of disasters, explicitly accounting for service disruptions resulting from CI failures. The first step involves identifying the damaged CI and industrial assets. Subsequently, the industries experiencing service disruptions from CI failure is also identified. This combined information is then fed into a multi-regional impact assessment model MRIA (Koks & Thissen (2016) and Raj et al. (2025)) to estimate the multi-regional macroeconomic impacts.

Results

Critical infrastructure failure and its macroeconomic impact during disasters

The exceedance probability (EP) curves associated with the sectoral production shocks—(a) incorporating power service disruptions and (b) excluding power service disruptions are presented in Figure 3a. The Expected Annual Impact (EAI), computed as the area under the EP curve in accordance with Equation 5, is estimated at €3.53 million for case (a) and €2.38 million for case (b), indicating that 32.4 % of EAI is attributable to power service disruption. Fig 3b presents the results of sensitivity analysis of varying economic and CI resilience parameters.

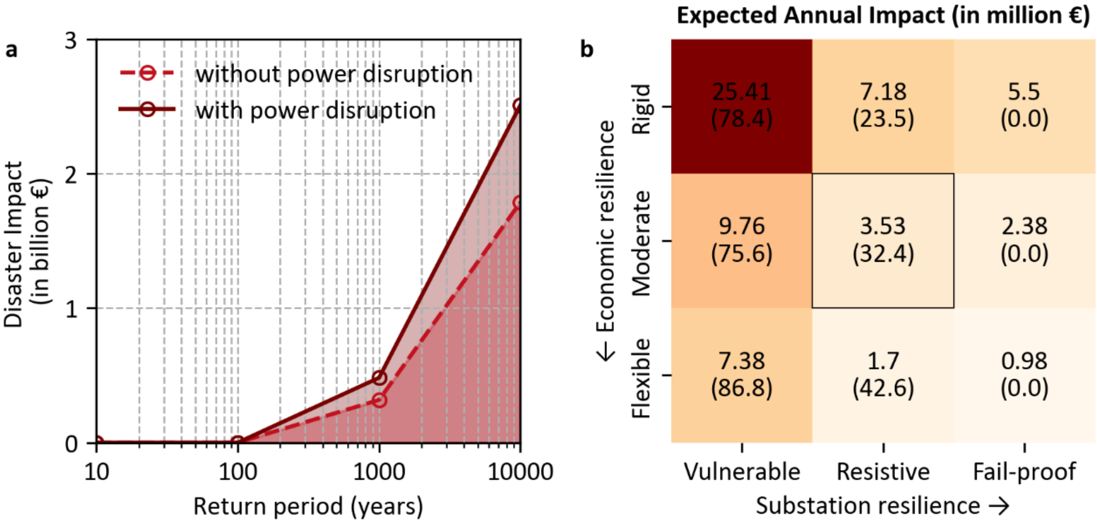


Figure 3. (a) Exceedance Probability (EP) curves depicting macroeconomic impacts with and without the inclusion of power service disruptions. (b) Expected Annual Impact (EAI) estimates under varying economic system configurations (rigid, moderate, and flexible) and substation resilience levels (vulnerable, resistive, and fail-proof). Values in parentheses indicate the power disruption attribution ratio (in %) (i.e., the relative contribution of power disruptions to overall economic impact). Boxed values correspond to the baseline scenario, in which substations remain operational up to a flood depth of 1 meter, with a 1% production extension and 25% trade flexibility.

Critical infrastructure adaptation - a macroeconomic perspective on impact reduction and prioritization

Infrastructure operators face financial constraints for adaptation, making it essential to prioritize investments based on substation criticality. An effective prioritization strategy should aim to maximize impact reduction with minimal investment. In this study, we examine the effectiveness of three different prioritisation strategies. The first strategy ranks substations according to inundation depth under a 10,000-year return period event, with higher inundation depths indicating greater criticality. The second strategy prioritizes substations based on the total area of industrial sites they serve across all sectors. The third strategy ranks substations based on the area of industrial areas they serve associated with the Oil and Petrochemicals (C19) and Chemicals (C20) sectors only. These sectors are considered critical due to their substantial contribution to economic output and, additionally in the case of C19, the absence of spatial substitution possibilities from other regions in the Netherlands (Raj et al., 2025). Fig 5 presents the results of the analysis.

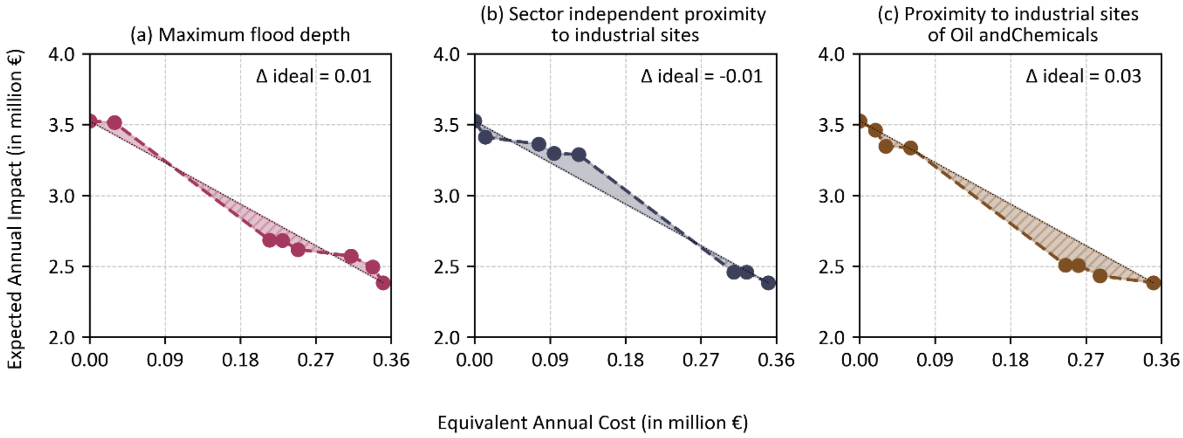


Figure 4. Expected Annual Impact (EAI) and Equivalent Annual Cost (EAC) of investment under sequential adaptation of substations following three prioritization schemes: a) maximum flood depth b) proximity to industrial sites (sector independent), and c) proximity to industrial sites of Oil and Petrochemicals (C19) and Chemicals (C20) sector

To evaluate the performance of the prioritization strategies, we introduce a hypothetical ideal reference line representing a linear proportional relationship between annual investment and expected reduction in economic impacts, as shown in Figure 5. Deviations below this line (hatched area) indicate favourable outcomes—i.e., greater impact reduction achieved with lower investment and vice versa. For each of the three prioritization schemes, substations are sequentially adapted cumulatively, and the corresponding EAI and EAC are plotted. The net area between the ideal line and the observed performance curve, $\Delta ideal$ (expressed in sq.

million Euros) is used as a metric to compare the effectiveness of strategies. Among the schemes considered, prioritising substations that serves higher areas of C19 and C20 sectors yields favourable outcomes with $\Delta ideal = 0.03$. This is followed by prioritization based on maximum flood depth (Δideal = 0.01), and lastly, prioritization based on area of industrial sites served irrespective of the sector (Δideal = -0.01). Although strategies that prioritize hazard intensities may be effective in mitigating physical damage, they do not necessarily perform better when the goal is to reduce macroeconomic impacts (as measured by EAI in this case).

References

Chang, C. M., & Hossain, A. (2024). A Climate Adaptation Asset Risk Management Approach for Resilient Roadway Infrastructure. *Infrastructures*, *9*(12), 226. https://doi.org/10.3390/infrastructures9120226

Guikema, S. D., Quiring, S. M., & Han, S.-R. (2010). Prestorm Estimation of Hurricane Damage to Electric Power Distribution Systems: Prestorm Estimation of Hurricane Damage. *Risk Analysis*, *30*(12), 1744–1752. https://doi.org/10.1111/j.1539-6924.2010.01510.x

Karagiannakis, G., Panteli, M., & Argyroudis, S. (2025). Fragility Modeling of Power Grid Infrastructure for Addressing Climate Change Risks and Adaptation. *WIREs Climate Change*, *16*(1), e930. https://doi.org/10.1002/wcc.930

Kelly, S. (2015). Estimating economic loss from cascading infrastructure failure: A perspective on modelling interdependency. *Infrastructure Complexity*, *2*(1). https://doi.org/10.1186/s40551-015-0010-y

Koks, E. E., & Thissen, M. (2016). A Multiregional Impact Assessment Model for disaster analysis. *Economic Systems Research*, *28*(4), 429–449. https://doi.org/10.1080/09535314.2016.1232701

Li, W., Martinez Cesena, E. A., Cunningham, L. S., Panteli, M., Schultz, D. M., Mander, S., Kim Gan, C., & Mancarella, P. (2022). Assessing Power System Resilience to Floods: A Geo-Referenced Statistical Model for Substation Inundation Failures. *2022 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, 1–5. https://doi.org/10.1109/ISGT-Europe54678.2022.9960296

Meijer, B., Bousso, R., & Ghaddar, A. (2024, March 9). Power failure hits 11,000 homes and businesses in Europoort area. *Reuters*. https://www.reuters.com/business/energy/power-outage-rotterdam-port-area-resolved-electricity-grid-operator-says-2024-09-03/

NESO. (2025). *North Hyde Review Final Report*.

Raj, S. V., Thissen, M., de Ruiter, M., & Koks, E. (2025). *Assessing the Macroeconomic Impacts of Disasters: An Updated Multi-Regional Impact Assessment (MRIA) model* [Dataset]. https://zenodo.org/records/15119803

Stamou, A., Mitsopoulos, G., & Koutroulis, A. (2024). Proposed Methodology for Climate Change Adaptation of Water Infrastructures in the Mediterranean Region. *Environmental Processes*, *11*(1), 12. https://doi.org/10.1007/s40710-024-00691-w