

Impact of large-scale pluvial flooding on an interdependent electricity and road network: do we need to adapt?

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Abstract

Critical infrastructure (CI) systems of interdependent networks rely on each other to function as intended, both during regular operation, and during emergency recovery. Extreme weather events such as pluvial flooding may damage and disrupt CI systems, including electrical substations and road networks, leading to power outages and disrupted traffic routes. Climate change increases the likelihood of large-scale pluvial flood events. However, there is limited understanding of how pluvial flooding of such scale may lead to electricity outages, and therefore of how to adapt to this threat. In this paper, we investigate the potential for adaptation and disaster risk reduction measures through a case study in the province of South-Holland in the Netherlands. The case considers the consequences of an extreme rainfall event, leading to consecutive days of large-scale pluvial flooding on the electricity and road networks. We additionally model how road disruptions pose accessibility constraints that are also relevant for the recovery process of the electrical distribution network. In our evaluation of adaptation options, we consider the interconnectedness of these two networks and dynamic recovery over time. The adaptation options that may reduce risk and improve resilience work in very different ways, making it difficult to choose between investing in polder pumping capacity to drain water more quickly, protecting electrical substations, or ensuring specific routes remain transitable to reach disrupted substations for repairs. The heavily urbanized, below-sea level, polder situation (with many roads on top of canal embankments) comes with some unique challenges, such as: will faster pumping of the polders exceed the discharge capacity of the canals, leading to even more road closures? We use different impact metrics (population affected, service disruption, and repair costs among others) to evaluate the effectiveness of various operational and structural measures. We aim to answer: do we need to adapt?

Keywords: infrastructure adaptation; risk reduction; pluvial flooding; electricity distribution; road accessibility

Introduction

In July 2021, a large-scale precipitation event caused flooding and widespread destruction of critical infrastructure (CI) in Germany, Belgium, and the Netherlands (Koks et al., 2022). This raised the question: if a similar event happens elsewhere, what would be the consequences? Is it necessary to adapt, and if so, how?

Based on this event, this case study investigates what would have happened to the electricity network in the Dutch province of “South Holland”, if the 2021 rainfall had occurred here. Most of the province consists of low-lying land which is strongly urbanized with cities like Rotterdam, The Hague, and Delft surrounded by intensive greenhouse horticulture and dairy farming. The province is largely composed of polders, areas of reclaimed land that are constantly drained with pumps into a system of interconnected canals. The drainage capacity is therefore not only constrained by the capacity of pumps but also by the discharge capacity of the canals (van Ginkel et al., 2023).

Here we explore how this rainfall would disrupt society with an interconnected road and electricity model and use it to evaluate different adaptation options and recovery strategies. We incorporate uncertainty by considering different fragility curves for the substations and repair crews that are in different locations of the study area when the flood occurs.

Method and Data

A time-explicit disruption and recovery model of the electricity and road networks is used to explore the consequences of pluvial flooding and the benefits of climate adaptation. In our approach, we overlay a synthetically generated timeseries of flood maps with electricity and road assets. Through this overlay, we first determine the damage to electrical substations using a depth-damage curve. Following, we estimate the time required to restore operations (Movahednia et al., 2022). This allows us to identify the potentially disrupted substations. At each timestep, the (flooded) road network is analysed to determine whether disrupted substations can be reached to be repaired; when the substation is reachable and there are repair crews available, they are assigned a repair task, remaining unavailable until the substation is fully repaired and returned to operation.

The flood maps are high-resolution, daily inundation depth maps produced by simulating a large-scale precipitation event of 200 mm in 48 hours under initially wet soil conditions, considering the capacity of the drainage and pumping systems (De Bruijn et al., 2022). The electricity substations considered are the medium-low and low voltage substations of the local operator (Stedin, 2024), while the road network is retrieved from OpenStreetMap (OpenStreetMap contributors, 2025).

The outputs of the model are evaluated through different impact and resilience metrics (Argyroudis et al., 2020) – the number of days substations remain flooded, population affected, total hours of service disruption, economic losses caused by lack of electricity, total repair cost, and repair effort hours. The effect of different adaptation options and response strategies on these metrics is assessed to determine which options should be pursued. The structural options considered are increasing drainage capacity in an area, elevating substations, and guaranteeing certain roads remain transitable, while operational measures focus on the order in which repairs are prioritised.

Results

Our results indicate that a large-scale precipitation event of these characteristics would cause flooding in several electricity substations. In the case of medium-low voltage stations, 198 are flooded above a depth of 0.2 m, representing 3.4% of the substations in the area. In the case of low voltage stations, 142 are flooded, 2.8% of all stations. On average, assets remain flooded for 3.3 days, however, some remain flooded for up to 5 days (Figure 1).

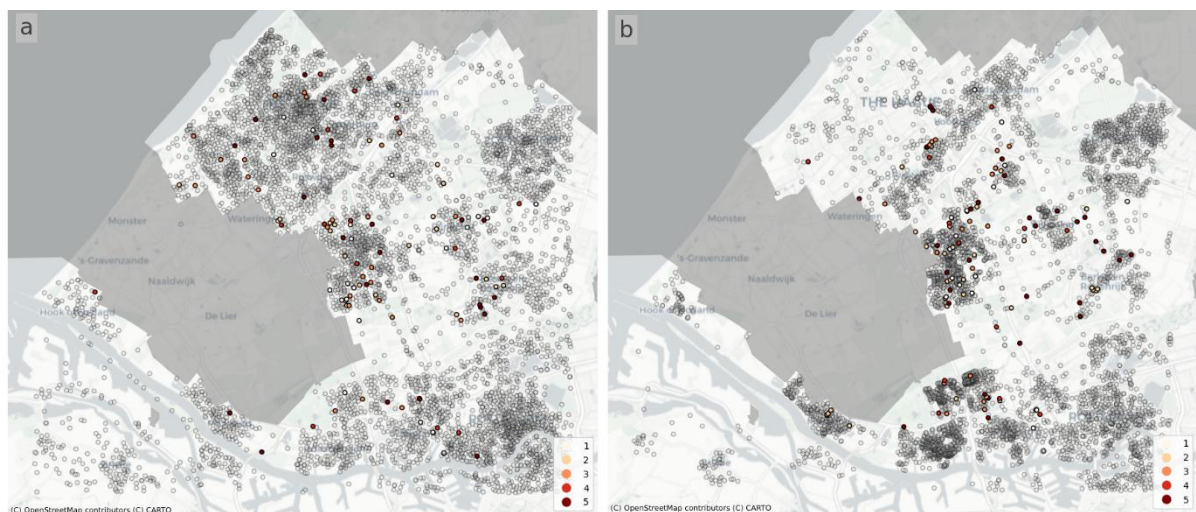


Figure 1. Flood duration (in days) for electricity substations in South Holland, the Netherlands. (a) Medium-low voltage substations; (b) low voltage substations. Zones outside the study area are greyed out.

The depth to which substations are submerged is generally low; during peak flooding (day 2, hours 48-71), the median flood depth is 0.36 m. This is not much higher than the assumed damage threshold of 0.2 m, under which no damage is considered. Given the relatively low flood depth, repairs can be quickly carried out when the flood recedes and the substation becomes reachable, making it possible to finish all repairs ~60 hours after the flood has fully receded, with most repairs finishing within 24 hours after the flood recedes (Figure 2).

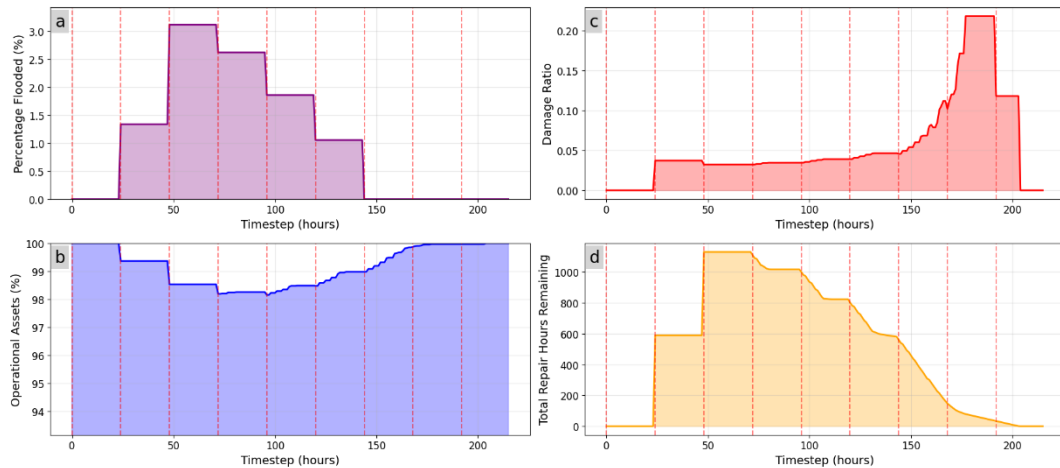


Figure 2. Damage and recovery process for electricity substations. (a) Percentage of assets flooded above 0.2 m; (b) percentage of assets that are operational; (c) average damage ratio across all damaged substations; (d) total backlog of repair hours across all substations.

During the flood, approximately 100 segments of the road network get isolated: completely disconnected from the rest of the road network (Figure 3). Since electrical substations located within these “islands” are impossible to reach, they are often among the last to be repaired.

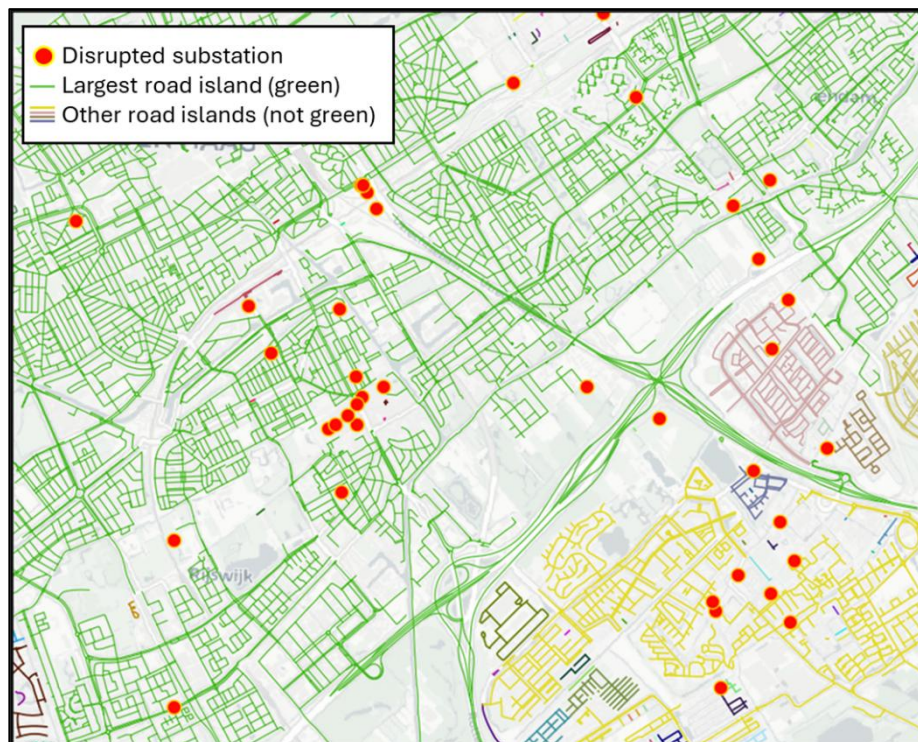


Figure 3. Disrupted substations in the southeastern area of The Hague and isolated sections of the road network (islands) in different colours; the largest connected component is coloured green. Transit between sections of the road network of different colours is not possible due to flooding.

The chosen recovery and adaptation strategies play an important role in the impact observed. For example, prioritising substations with low damage allows them to return to operation more quickly, leading to the lowest total substation outage time; however, these stations may only service a small number of people or areas with low economic productivity, so this is not necessarily the lowest impact in terms of societal disruption.

Regarding adaptation options, since the flooding for most stations is quite shallow, reducing the amount of water present (by increasing pumping) or elevating the threshold from which damage begins by 10 cm greatly reduces the number of stations affected (Table 1), making these attractive general and targeted adaptation options, respectively. Since the drainage system may be too full during extreme precipitation events to receive additional pumped water (van Ginkel et al., 2023), elevating the substations is the more feasible alternative.

Table 1. Percentage of substations affected when different flood thresholds are considered.

Flooding threshold [m]	Medium-low voltage stations affected [%]	Low voltage stations affected [%]
0.1	5.2%	4.8%
0.2	3.4%	2.8%
0.3	2.3%	1.9%

Key Insights and Conclusion

Our study reveals that localised disruptions to power supply would be expected; while the severity of the damage to substations is relatively low, the outage duration in some areas is much longer than the required repair time due to persistent flooding and limited access. This indicates it is especially important to adapt in areas that become inaccessible during flooding.

Furthermore, we learn that prioritising based on criticality (number of people affected) and multiple impact metrics is a way to inform both recovery and long-term adaptation planning, and that considerations should be made for equitable adaptation, repair, and restoration of service. Otherwise, when considering economic losses due to service disruption, high monetary value areas may be prioritized over housing areas with low economic productivity. Further research should fully incorporate equity considerations into adaptation and recovery planning.

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