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Impact of Flood Risks on Service Disruptions of Critical Infrastructures by the Example of the Euskirchen County, Germany

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ABSTRACT

The increasing severity of flood events poses growing risks to critical infrastructures (CI), with failures often triggering cascading effects across sectors. Despite this, flood risk management (FRM) frequently overlooks service disruptions of CI and systemic interdependencies between infrastructure sectors because of its place-based approach. This study addresses this gap by developing and applying an integrated methodological framework that combines GIS-based flood risk analysis and qualitative criticality assessment. Focusing on Euskirchen County, Germany, the study analyses the exposure, vulnerability, and criticality of CI—specifically in the energy, (tele)communications, emergency service, and transport sectors—under extreme flood scenarios. Expert interviews and workshops informed the identification of cascading failure chains and potential intervention points. Findings reveal significant systemic risks, particularly stemming from power outages, and highlight key interdependencies between infrastructure sectors. The results provide actionable insights for spatial planners and emergency managers, including recommendations for strategic CI siting and contingency planning. By integrating scientific rigor with practical relevance, the study contributes to the advancement of risk-based spatial planning and supports the development of resilient infrastructure systems in the face of increasing flood risks.

1 | Introduction

The increasing frequency and intensity of flood events driven by climate change and land-use change pose significant challenges to many regions worldwide. Beyond direct physical damages, floods disrupt critical infrastructures (CI), such as energy grids, water supply systems, transport networks, and healthcare facilities (Pescaroli and Alexander 2016). These infrastructures are essential for public safety and economic stability (Arrighi et al. 2021; Serre and Heinzlef 2018) and the provision of services of general interest in central places (Greiving et al. 2025). When they fail, cascading effects can amplify impacts, affecting regions far beyond the initially flooded areas (Pescaroli and Alexander 2016). To address these systemic risks, comprehensive risk and criticality analyses become essential, particularly within the context of spatial planning, which is tasked with developing tailored adaptation and mitigation measures.

Since disaster exposure and vulnerability are mostly determined by land use, spatial planning represents a fundamental tool for disaster risk reduction (Greiving et al. 2006; Burby 1998). Traditionally, planning approaches in the context of flood risk management (FRM) including the European Union's *Flood Risk Management Directive* (2007/60/EC) are place-based and therefore focus on hazard and exposure mapping while overlooking the cascading failure chains that may result from CI facility disruptions, potentially affecting areas not directly exposed to flooding (Greiving et al. 2025; Kruse et al. 2021). This gap becomes evident during extreme events, such as the devastating floods in Western Europe in July 2021 (Wolf et al. 2024). The

Euskirchen County, located in Western Germany, experienced severe disruptions of critical services, highlighting the urgent need for an integrated approach that combines risk and criticality analyses.

International frameworks, such as the *Sendai Framework for Disaster Risk Reduction* (UNDRR 2015) and the *EU Flood Risk Management Directive* (2007/60/EC), emphasize risk-based planning approaches in FRM that advocate for integrating socio-economic vulnerabilities and CI protection into risk assessments. Despite these advancements, implementation across countries varies significantly. Germany has advanced in flood hazard mapping and water management, yet the systematic integration of risk-based approaches into spatial planning remains incomplete (Greiving et al. 2023). The recently introduced *Federal Spatial Plan for Flood Protection* (*Bundesraumordnungsplan Hochwasserschutz*, BRPH) marks a significant step toward risk-based planning in Germany (BMI 2021), but still lacks standardized and practical methodologies for assessing CI and their cascading failure chains. This methodological gap limits the ability of planners and decision-makers to identify intervention points and develop and prioritize protective measures effectively.

The scientific literature mirrors this fragmentation. Robust frameworks exist for probabilistic flood risk assessment (hazard, exposure, vulnerability), whereas a separate body of research addresses CI criticality and cascading failures through network flow or system-of-systems approaches (Hall et al. 2016; Schotten et al. 2024). However, studies that combine both analytical perspectives into one coherent framework remain rare in the FRM and planning contexts. Existing integrated approaches are typically limited to sectoral or modeling applications, with little uptake in practice.

This study seeks to bridge this gap by developing and applying an integrated assessment framework that merges spatially grounded risk analysis with a systematic criticality analysis focusing on interdependencies between CI sectors. By linking these two strands of research, the paper introduces a novel perspective into spatial planning practice: A method that identifies high-risk infrastructure nodes and potential cascading failure chains. This methodological integration aims to provide both scientific insights and practical recommendations for FRM and spatial planning. This study focuses on Euskirchen County as a case study to explore how such an integrated approach can be implemented. The following research questions guide the investigation:

1. How can risk and criticality analyses be merged into a comprehensive assessment framework for spatial planning and emergency response while meeting both scientific and practical criteria?
2. What cascading failure chains can be identified when CI fail during and after flood events, and what sector-specific patterns characterize their propagation and interdependencies?
3. What key intervention points can be identified to mitigate cascading effects caused by flood events?

By answering these questions, the study aims to contribute an innovative methodological approach that integrates two previously fragmented strands of research. It thereby advances both the scientific discourse on CI-focused FRM and the development of resilient FRM practices that protect CI and reduce cascading effects during future flood events.

2 | State of Art

A comprehensive approach to FRM requires both a clear conceptual understanding and robust methodological frameworks for flood risk and cascading effects. Our paper focuses on FRM practices in Germany, making it essential to discuss the regulatory framework as well.

2.1 | Fundamentals of Flood Risk Management in Germany

Germany's approach to FRM has undergone significant transformation, driven by international frameworks such as the *Sendai Framework for Disaster Risk Reduction* (UNDRR 2015) and the *EU Flood Risk Management Directive* (2007/60/EC). These frameworks emphasize risk-based, adaptive planning strategies that integrate hazard, exposure, and vulnerability considerations. In alignment with these principles, Germany introduced the BRPH in 2021 (BMI 2021), the first uniform regulatory framework within spatial planning in all federal states for fluvial, pluvial, and coastal FRM—legally anchored in Art. 17 § 2 of the Federal Regional Planning Act (Raumordnungsgesetz).

The BRPH's Objective I.1.1 requires flood risk assessments to inform spatial planning decisions, moving beyond conventional demarcation of flood-prone areas based solely on flood hazard zones (Art. 76 of the Federal Water Act (Wasserhaushaltsgesetz, WHG)) or risk areas (Art. 78b WHG). Instead, it incorporates flood hazard parameters such as water depth and flow velocity, already included in hazard maps under Art. 74 § 2 WHG, but previously unused for spatial planning.

Moreover, the BRPH introduced two innovations for German spatial planning:

- Sensitivity: This factor reflects the vulnerability of specific land uses, not just their location within designated flood zones.
- Protection worthiness: This principle introduced normative judgments regarding differentiated protection goals for distinct land uses, with emphasis on (1) infrastructures that cause major accident hazards if hit by an extreme event, (2) sensitive infrastructures, (3) built heritage, and (4) CI that are particularly worthwhile to protect.

Flood risk assessments thus become an essential basis for spatial planning decisions that move beyond static zoning. In practice, this shifts the focus from the mere presence of assets within flood areas to an analysis of relative risk differences inside these zones. Such differentiation enables prioritization and the design of tailor-made protection measures, particularly for CI.

The BRPH inspired Germany's *Strategy for Strengthening Resilience to Disasters* (BMI 2022), which advocates for a risk-based planning approach as introduced by the BRPH and rolls out this approach to all kinds of threats. This strategy emphasizes sensitivity assessments of protected goods, enabling planners to design more resilient spatial structures. By integrating hazard, exposure, and vulnerability data into land use planning, the BRPH marked a paradigm shift toward holistic FRM, successfully tested in German land use planning by Greiving et al. (2023).

2.2 | Conceptual Foundations of Flood Risk to Critical Infrastructure and Systemic Criticality

Flood risk and systemic criticality are key concepts in FRM, particularly when assessing the vulnerabilities of CI and CI systems. Researchers and practitioners widely discuss both terms in international research and policy frameworks, yet their definitions and applications vary across disciplines. Internationally, flood risk is commonly understood as the interaction between hazard, exposure, and vulnerability (UNDRR 2019). According to UNDRR (2019), risk emerges when a natural or technological hazard coincides both spatially and temporally with vulnerability. In this study, we follow the probabilistic understanding of risk, as commonly applied in FRM and referenced in the *EU Flood Risk Management Directive* and the WHG, rather than the systemic interpretation that is often employed in science. This study therefore adopts this spatial understanding of risk, defining risk as occurring only when a natural event—specifically, flooding and heavy rainfall—interacts with vulnerable elements or human use of space, particularly CI. Thus, both the flood hazard and the associated vulnerability determine the risk of a damaging flood event (see also BBK 2025).

CI comprises systems or assets essential for societal functioning, particularly during extreme weather events (Serre and Heinzlef 2018). Disruptions in these systems can threaten security, economy, safety, and public health (Serre and Heinzlef 2018) and question the accessibility of services of general interest (Greiving et al. 2025). This study considers critical systems such as energy, IT, and (tele)communication, emergency and rescue services, civil protection, and transport and traffic. Criticality refers to the significance of a process to the consequences that impairment or failure of that process would have on the functionality of CI (BBK 2025).

Beyond individual CI, systemic criticality highlights interdependencies that increase cascading effects and amplify the impact of extreme weather events (see e.g., Arvidsson and Johansson 2024; Fekete 2020; Pescaroli and Alexander 2016; Hall et al. 2016). Schmitt (2021) defines systemic cascade potential as the possibility of cascading effects being passed on and an estimation of their potential intensity. She operationalizes it as the product of subsystem relevance and dependencies (Schmitt 2021). The present study builds on this understanding by focusing specifically on functional "systemic" cascading effects, where disruptions in one sector lead to failures in others due to operational dependencies, rather than purely spatially driven cascades (Kruse et al. 2021; Schmitt 2021). This distinction is critical for identifying intervention points that can mitigate cascading failures and enhance overall resilience.

2.3 | Overview of Methodological Approaches for Assessing Flood Risk and Criticality

Similar to the conceptual understandings, methodological approaches for risk and criticality analyses are highly diverse. In the context of flood risk assessments, Li et al. (2023) distinguish five main categories shown in Table 1:

Together, these five approaches encompass statistical, computational, mathematical, and empirical methodologies (Diaconu et al. 2021). Advances in remote sensing, GIS, modeling, and machine learning have improved precision and integration, particularly through hybrid algorithm (Diaconu et al. 2021). However, practical limitations remain. Many methods lack validation in real-world scenarios, and implementation is often constrained by data, infrastructure, or financial resources (Diaconu et al. 2021; Schotten et al. 2024).

Although these FRM methodologies largely focus on hazards, exposure, and vulnerability, a different set of approaches is applied to evaluate criticality and cascading effects, particularly within interdependent infrastructure systems. As Arvidsson et al. (2023) highlight, three broad methodological approaches dominate (see Table 2):

A fundamental challenge in CI analysis across all methodological approaches is data scarcity (De Bruijn et al. 2016; Schotten et al. 2024). CI data is often sensitive due to security and competitive interests, limiting the comprehensiveness (De Bruijn et al. 2016). This is particularly problematic for empirical studies relying on observed data and for simulation-based approaches requiring detailed input parameters. Assumptions are therefore common throughout modeling cycles, reducing output precision and sometimes undermining practical usability (Schotten et al. 2024).

Although risk and criticality analyses typically follow separate tracks, emerging studies attempt to integrate spatially explicit flood risk assessments with systemic criticality analysis. One example is the Area-Based Cascading Effects Method (AB-CEM) proposed by Arvidsson et al. (2023). AB-CEM overlays GIS-derived hazard and exposure data with expert-elicited interdependency mappings, enabling spatial identification of CI nodes both vulnerable to flooding and central to cascading failures. Another significant example appears in the CIRCLE toolbox developed by Deltares (2025), which facilitates hybrid integration between open-source geospatial data, models of CI interdependencies, and expert contributions to visualize potential domino effects among CI installations even in data-scarce environments. Puntub and Greiving (2022) applied a different approach using the health sector as a case study, integrating information on network components and infrastructure functionality as vulnerability indicators within their composite indicator-based scenario assessment. Although mostly used in pilot studies, these approaches mark progress toward the integration of place-based and systemic layers that can support spatial prioritization of interventions.

TABLE 1 | Overview of main categories of methodological approaches to flood risk assessments.

Methodological approaches	Description
Historical disaster mathematical statistics	The historical disaster statistics method evaluates past events to predict future flood frequency, depth, and losses (Li et al. 2023). Although it is straightforward and reflects real-world conditions, its reliance on historical data reduces validity under changing climatic conditions and restricts applicability to small-scale areas (Li et al. 2023; van Steenbergen et al. 2012).
Multi-criteria index systems	Multi-criteria index systems remain among the most widely used approaches, integrating indicators such as slope, land use, precipitation, and population density (Lyu et al. 2018; Kabenge et al. 2017; Fedeski and Gwilliam 2007). Their flexibility and intuitive visualization are clear strengths, though indicator selection and weighting often rely on expert judgment, introducing subjectivity (Li et al. 2023). The integration of GIS technology has further improved mapping and zoning applications.
Remote sensing and GIS coupling	Remote sensing and GIS coupling integrates satellite-derived flood data into spatial models (Li et al. 2023), allowing the prediction of flood intensity, risk distribution, and temporal flood patterns (Al-Omari et al. 2024; Haq et al. 2012; Chubey and Hathout 2004). The method is particularly useful for large-scale disasters but less effective for small floods due to spatial and temporal resolution constraints (Li et al. 2023). Future developments emphasize multi-source data fusion to improve prediction accuracy.
Scenario simulation evaluation	Scenario simulation methods employ hydrological and hydrodynamic models to generate high-resolution spatial assessments of flood risk (Li et al. 2023) and support disaster prevention and flood risk transfer. Coupled modeling techniques have increased accuracy (Lin et al. 2020; Wu et al. 2017; Bisht et al. 2016). However, they are highly data- and resource-intensive, limiting their applicability to large or data-scarce areas (Li et al. 2023).
Machine learning methods	Machine learning approaches provide flexible, data-driven predictions and have demonstrated strong mapping accuracy (Li et al. 2023). Reliability improves when integrated with more traditional methods, such as analytic hierarchy processes and neural networks (Pham et al. 2021; Khosravi et al. 2019; Wang et al. 2015). Their effectiveness, however, depends strongly on data quality and completeness (Li et al. 2023).

Note: Authors' table based on Li et al. (2023).

These examples are still scarce and often limited to single-sector or prototypes, particularly outside GIS-based spatial planning practice. They underline a significant methodological gap: very few frameworks fully combine place-based flood risk analysis with systemic CI criticality modeling in a transferable, planner-friendly format. Our study addresses this gap by providing an integrated risk-criticality assessment approach using the example of Euskirchen County.

3 | Case Study Setting

The study focuses primarily on Euskirchen County but also includes the neighboring counties of Aachen, Düren, and Rhein-Erft (see Figure 1). Euskirchen County is located in the southwest of North Rhine-Westphalia (NRW), Germany. Covering 1249 km^2, it comprises 11 municipalities with approximately 197,000 inhabitants, resulting in a population density of 158 inhabitants/km^2 or 1144 inhabitants/km^2 in settlement and transport areas (IT.NRW 2024a). The population is unevenly distributed, with Euskirchen (59,772 inhabitants) as the largest and Dahlem (4400 inhabitants) as the smallest municipality (IT.NRW 2024b, 2024c). Recent population trends have been stagnant to slightly increasing.

The county's northeast consists mainly of flatlands used for agriculture, whereas the south features the Northern Eifel region with extensive forests and the Ahr Mountains. The Euskirchen County is intersected by numerous rivers and streams, including the Erft, Ahr, Kyll, and Urft. In addition to these watercourses, the county contains artificial still waters and reservoirs, such as Urft, Olef, Steinbach, Eicherscheid, and Madbach (see Figure 1).

In July 2021, Euskirchen County was severely affected by extreme flooding. On July 14, the local weather station in Kall-Sistig recorded 88.5 L/m^2 of rainfall in 6 h and 165.7 L/m^2 in 48 h (DWD 2021). The Erft catchment received twice the monthly average rainfall within 3 days (DWD 2021). Saturated soils, heavy rainfall, and the region's topography contributed to severe flooding, exceeding designated flood zones. The disaster claimed 26 lives and caused widespread damage to private, public, and commercial buildings, as well as critical and sensitive infrastructure, including nursing homes, electricity supply networks,

TABLE 2 | Overview of main categories of methodological approaches to criticality analysis.

Methodological approaches	Description
Expert-based models	Expert-based approach gather knowledge through expert interviews, workshops, or surveys to assess interdependencies between CIs and cascading potential (see e.g., De Bruijn et al. 2016; Moon et al. 2015). To mitigate subjectivity, uncertainty is often addressed through interval estimates or consulting multiple independent experts (Arvidsson et al. 2023).
Empirical methods	Empirical approaches instead examine past disasters to derive lessons from observed cascade chains (see e.g., Johansson et al. 2015; McDaniels et al. 2007; Zimmerman and Restrepo 2006). These are constrained by incomplete or inconsistent datasets, confidentially issues, and a reliance on past conditions, which risks underestimating future systemic vulnerabilities (McDaniels et al. 2007; Yusta et al. 2011).
Simulation-based methods	Simulation-based approaches provide the most systematic means of exploring CI interdependencies. They model CI structures by integrating empirical and expert-based data to identify cascading effects and intervention points (see e.g., Mühlhofer et al. 2023; Arrighi et al. 2021; Guimarães et al. 2021). Within this tradition, CI network flow modeling has proven valuable for examining service disruptions, resource allocation, and the propagation of failures across networks (Schotten et al. 2024). Closely related are system-of-systems modeling approaches (Hall 2020; Hall et al. 2016). By representing interdependent infrastructures as interconnected systems, system-of-systems frameworks allow the exploration of cascading pathways and intervention points. The limitations of these approaches include the requirement for extensive datasets and a thorough understanding of modeling techniques.

Note: Authors' table based on Arvidsson et al. (2023).

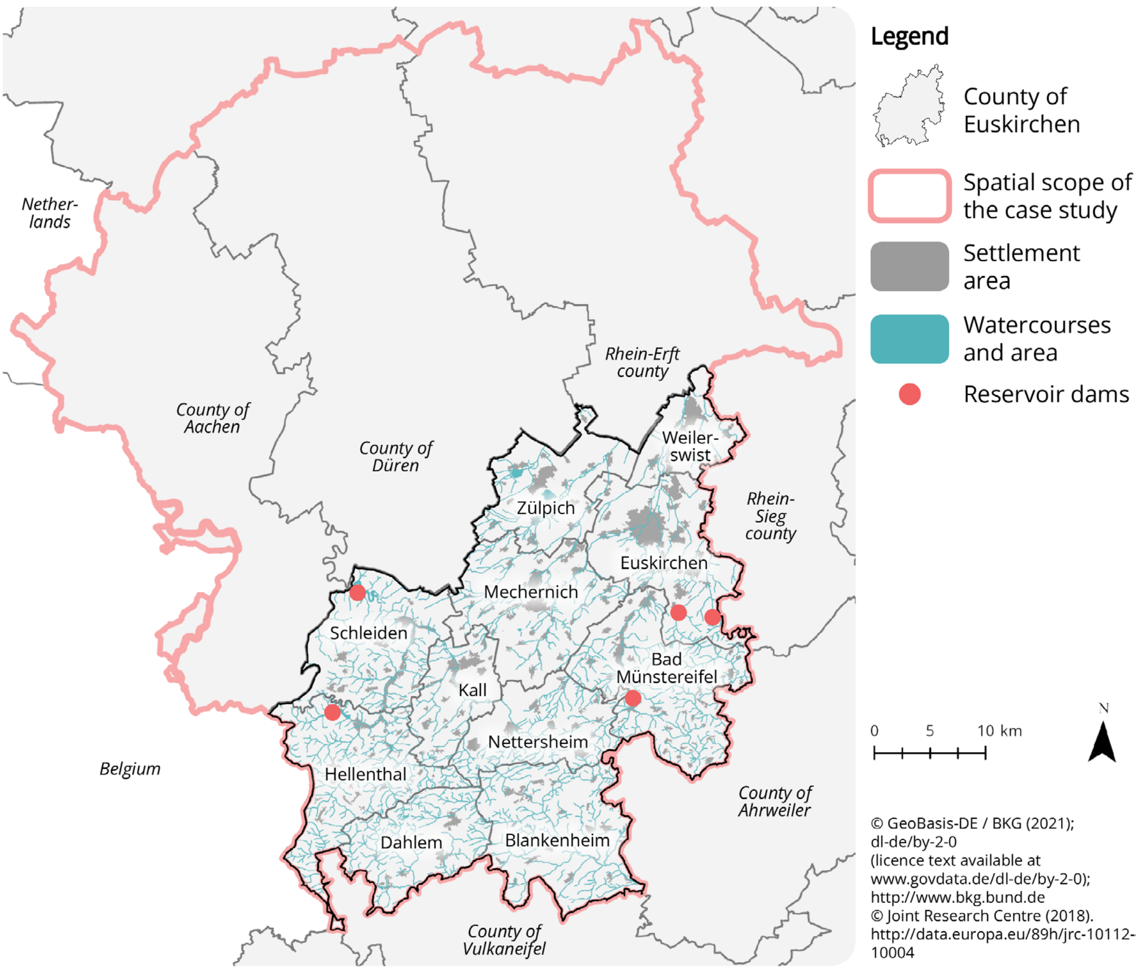

FIGURE 1 | Location of the Euskirchen County. Authors' illustration.

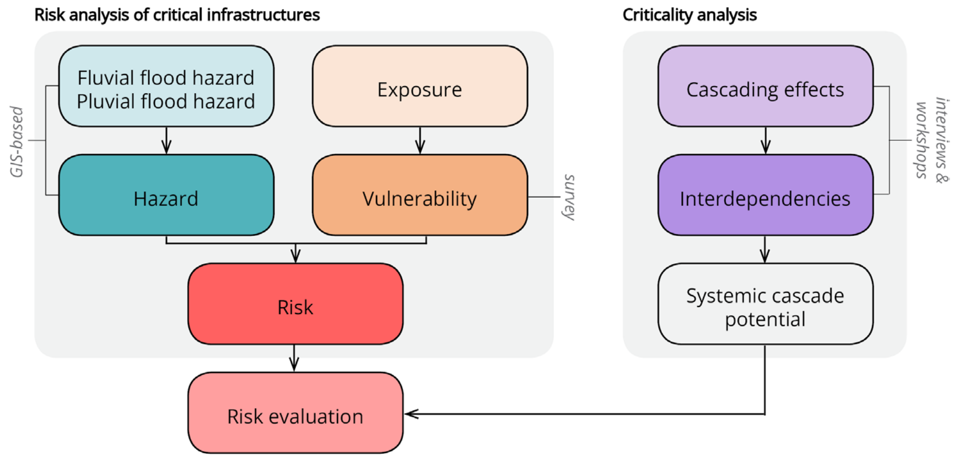

FIGURE 2 | Methodological approach. Authors' illustration.

(tele)communication infrastructure, and drinking water supply systems.

Large parts of the county experienced cascading infrastructure failures. Electricity and communication networks were widely disrupted, leaving whole municipalities without power, internet, and mobile service. Road infrastructure was heavily damaged, with 43 county roads and multiple bridges destroyed or rendered impassable; rail services were severely affected, with more than 80 km of track damaged, some of which remain partially or completely unusable (Uerlichs et al. 2021; DWD 2021). Entire villages and public institutions, including Euskirchen's correctional facility, were evacuated due to the threatened collapse of the Steinbach reservoir dam (Uerlichs et al. 2021). Public institutions, including police stations, fire stations, schools, and childcare facilities, were destroyed or temporarily unusable. Waste management and environmental services faced the removal of more than 90,000 tons of debris and damaged material. In addition, many sports and leisure facilities, as well as local businesses and industries, suffered long-term operational disruptions, with overall infrastructure damages in Euskirchen County estimated at around one billion euros (Schneider 2022). The scale of destruction highlighted the need for a holistic and risk-based planning approach that considers critical and sensitive infrastructures.

4 | Material and Methods

This study combines two analytical components: (1) a risk analysis; and (2) a criticality analysis (see Figure 2). Both components focus on the CI sectors identified as most critical for Germany and particularly sensitive to disruptions from extreme weather events (Schmitt 2021), and which, as prerequisite infrastructures, are central to diverse interdependencies with other infrastructures:

- Energy (i.e., electricity and gas),
- IT & (tele)communications,
- Emergency and rescue services & civil protection, and
- Transport & mobility.

We regularly validated both analytical components with practitioners as part of a co-production process.

4.1 | Risk Analysis

The risk analysis combines two place-based components: a hazard and a vulnerability assessment. We derived the overall risk by combining hazard data with vulnerability information determined through an exposure analysis of public and private point-based and linear CI. We describe both components below.

4.1.1 | Hazard Component

We investigated the hazard component through a structured, data-driven, and GIS-based approach. The data we used is listed in Table 3. We assessed the hazard component (i.e., fluvial and pluvial flooding) using fluvial flood hazard maps and pluvial flood hazard maps of Euskirchen County, as no integrated models combining both hazards are available. For both hazards, we adopted a scenario that reflects the 2021 flood event:

- Pluvial flooding: The N2021 scenario, representing the precipitation intensity of the 2021 flood disaster.
- Fluvial flooding: The $HQ_{extreme}$ scenario, depicting a 1000-year flood event.

For point-based CI (e.g., buildings and facilities, $n = 1474$), we applied a buffer zone of 2 m around each point to assess potential exposure, considering objects affected if inundated above 0.05 m. Although DWA (2016) suggests a 1 m buffer, we used 2 m because the 1 m spatial resolution of the grid and irregular building shapes require a wider buffer to include all adjacent grid cells, including edges. For the maximum inundation depths and flow velocities, we calculated minimum, maximum, and average values. For the 1205 km road and railway network of the Euskirchen County, we identified segments inundated by at least 25 cm, a threshold for impassability. We initially analyzed power grids as well but excluded them as experts involved in the co-production process assessed them as sufficiently redundant.

TABLE 3 | Overview of data. Authors' table.

Data	Publisher	Content	Data format	Year
Pluvial Flooding Map Euskirchen County Scenario N2021	Euskirchen County	Inundation depth (m), flow velocity (m/s), flow direction (°)	Raster (1×1 meter resolution)	2023
Substations and Grid Stations	Electricity supply company	Location of stations	Excel table (Gauss-Krüger coordinates)	2023
Medium Voltage	Local energy provider	Location of stations	Polygons	2023
Gas	Local energy provider	Location of pressure regulating facilities	Polygons	2023
AESTE Road Section	State road authority	Classification and location of roads (A, B, K, L)	Polyline	2023
Geo Rail Network	Railway company	Location of railway network	Polyline	2019
Administrative Boundaries North Rhine-Westphalia	Geobasis NRW	Administrative boundaries of the federal state, counties, county-free cities, and municipalities	Polygons	2023
OSM Buildings Cologne Administrative Region	OpenStreetMap/Geofabrik	Buildings in the Cologne Administrative Region	Polygons	2023
$HQ_{extreme}$ Flood Boundaries	State Agency for Nature, Environment and Consumer Protection NRW	Spatial extent of the $HQ_{extreme}$ scenario for NRW	Polygons	2023

4.1.2 | Vulnerability Component

We assessed vulnerability through a survey with CI operators of sites identified as at risk. We based the survey's guiding questions on the *Municipal Pluvial Flood Risk Management Guide* from LUBW (2016), covering building specifications, usage, and users (see Table 4).

4.1.3 | Risk Assessment

We compiled the flood risk for the individual CI sites in risk profiles based on the template by LUBW (2016). These profiles include a pluvial flood hazard map (scale 1:400) with classified maximum water depths, maximum flow velocities, and flow directions. To improve readability at this scale, we smoothed the spatial resolution of the raster values for flow velocity to 5 m. The risk profiles also indicate whether a facility is affected by the $HQ_{extreme}$ flood hazard maps and integrate the vulnerability assessment of CI sites. In the end, a descriptive risk assessment summarizes all relevant information based on a risk matrix (see Table 5), which differentiates based on risk type.

4.2 | Criticality Analysis

The criticality analysis is based on a common, cross-sectoral and operator-independent scenario: The 2021 flood disaster, which resulted in specific disruptions within the assessed CI sectors. Unlike traditional, place-based risk assessment, the criticality analysis focuses on the systemic effects of service disruptions within the service areas of the various CI operators in the sectors listed in Table 6. These areas are neither limited to the areas being prone to floods nor to the boundaries of Euskirchen County. We analyzed cascading effects and interdependencies between different infrastructure systems using a qualitative approach based on guided expert interviews with employees of public administrations ($n=4$) and a half-day workshop with CI operators and representatives from disaster management authorities. By adopting a qualitative and empirical approach and focusing on the four top-ranked sectors, this study departs from Schmitt's original operationalization concept of systemic cascade potential. Instead, the approach is grounded in the analysis of observed cascading effects and interdependencies in the aftermath of the 2021 flood.

The interviews examined affected CI, cascading effects, interdependencies, civil protection responses, required tools, and post-event changes. We transcribed the interviews and analyzed them using a content-structuring qualitative content analysis according to Kuckartz and Rädiker (2023). In the analysis, we used the following categories and a temporal dimension to structure the data (see Table 6):

The workshop discussions revolved around three key guiding questions to co-produce cascade diagrams:

1. What happened? What restrictions and/or failures occurred within your CI sector due to the 2021 flood disaster?

TABLE 4 | Overview of guiding questions for vulnerability assessment.

No.	Guiding questions
1	Is the building located on a slope, in a depression, or near a body of water?
2	Is the degree of surface sealing on the property and in the surrounding area high (> 50%)?
3	Do flow paths lead towards the building?
4	Can the emergency drainage of the roof be overloaded?
5	Are basement rooms (underground level) and at-risk rooms on the ground floor present (below backwater level)?
6	Do the basement and underground floors have openings leading outside?
7	Are there lowered or recessed entrances (ground floor)?
8	Are higher floors available as emergency refuge levels?
9	Are people present on the ground floor or in the basement, and if so, how many?
10	Are there valuable assets on the ground floor or in the basement? If so, which ones?
11	Are heating, electrical, or IT installations located on the ground floor or in the basement?
12	If so, are they essential for public services?
13	Are there any known protective measures in or around the building (e.g., mobile flood protection, backflow prevention, evacuation plans, retention areas, etc.)?

Note: Authors' table based on LUBW (2016).

TABLE 5 | Risk matrix.

Type of risk	Summary description of the risk
Risk to people in the building	
Risk to high-value assets (equipment)	
Risk to the building (structure, possibly also buoyancy)	
Risk due to functional failure (e.g., utilities such as electricity, gas, water)	
Risk originating from the building (e.g., water-hazardous substances)	
Risk due to restricted accessibility	

Note: Authors' table.

2. What were the consequences? What were the impacts of these restrictions and/or functional losses within your CI sector?
3. To what extent did interdependencies become evident? Were there (mutual) effects and/or dependencies on other CI sectors?

Following the workshop, participants were given time to review, refine, and validate the cascade diagrams.

In the last step of the criticality analysis, we systematically examined the cascade diagrams to identify systemic cascade potential. Given the qualitative approach, we approximate the concept of systemic cascade potential by assuming that the potential increases with the number and branching of subsequent cascading effects, as well as the duration required for functional recovery. The final step integrates all relevant information from risk analysis and criticality analysis into an overall risk evaluation (see Figure 2).

To identify key intervention points, we combined insights from the cascade diagrams with findings from the preceding risk analysis, which provides essential information on the exposure and vulnerability of CI assets under the applied flood scenario. This spatial perspective supported the identification of key intervention points by contextualizing cascade nodes in terms of their spatial risk for concurrent failures. We analyzed the cascade diagrams using two analytical criteria rather than quantitative thresholds: (i) the position of nodes within the cascade chains, focusing on failures that occur early or branch into multiple subsequent effects (including across dependent sectors), and (ii) the observed duration of recovery processes associated with specific infrastructure failures. This heuristic approach reflects the empirical nature of the underlying data and the heterogeneity of cascading processes observed during the 2021 flood. The analysis primarily examines key intervention points at which planning authorities can act preventively or create redundancy. In addition, we identified selected intervention points where effective mitigation or redundancy depends on CI operators. Together, these nodes represent leverage points where early preventive action can interrupt multiple downstream cascades and where targeted protection can reduce prolonged systemic failures.

The findings are transferable to other triggering events and risk scenarios. The analysis of systemic criticality was based on a common, cross-sectoral and operator-independent scenario—the 2021 flood disaster—which was then examined in terms of its specific impacts on the CI sectors under consideration.

5 | Empirical Results

This chapter presents the results of the developed multi-method framework, differentiated into the findings of the risk analysis and the criticality analysis.

5.1 | Risk Analysis

The conducted risk analysis reveals a high risk for many of the examined point and linear CI. If the scenarios underlying the analysis were to occur, road sections totaling 590.10 km in the

Euskirchen County would be affected by water depths exceeding 0.25 m (approx. 50% of the road sections examined), rendering them likely impassable (see Figure 3). Regarding railway sections, the risk analysis indicates that all examined railway segments would be affected. Moreover, in the electricity and gas sector, a significant proportion of electricity stations and gas stations are at risk in case of the underlying scenarios (the exact number cannot be published due to data protection constraints). Moreover, other CI would also be at risk. Figure 4 illustrates the hazard map of a hospital, which is presented here as a representative example to protect the sensitive location data of electricity and gas stations.

5.2 | Systematic Cascade Potentials and Interdependencies in CI Sectors

Figure 5 provides an overview of the recovery trajectories across selected CI sectors in the Euskirchen County following the July 2021 flood disaster. The timeline illustrates the temporal

TABLE 6 | Categories of qualitative content analysis. Authors' table.

Hazard and risk aspects	Sectors	Measures and strategies	Society and governance
• Exposure • CASCade effects	• Impacts on CI facilities • Electricity • Gas • Transport & mobility • IT & (tele) communications • Emergency and rescue service & civil protection • Healthcare & sensitive infrastructure	• Measures and interventions	• Civil society • Civil protection • Administration • Risk dialogue • Resilience

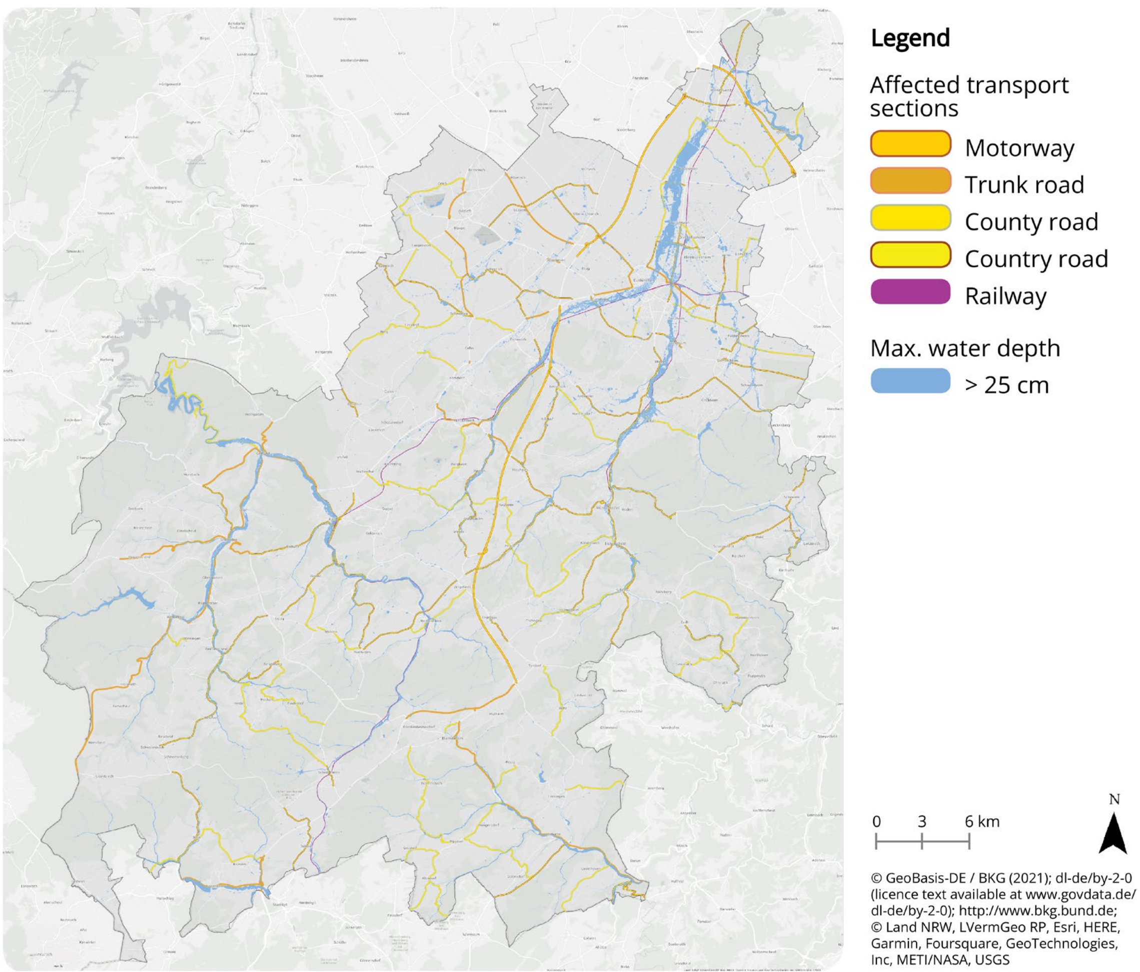

FIGURE 3 | Affected transport sections. Authors' illustration.

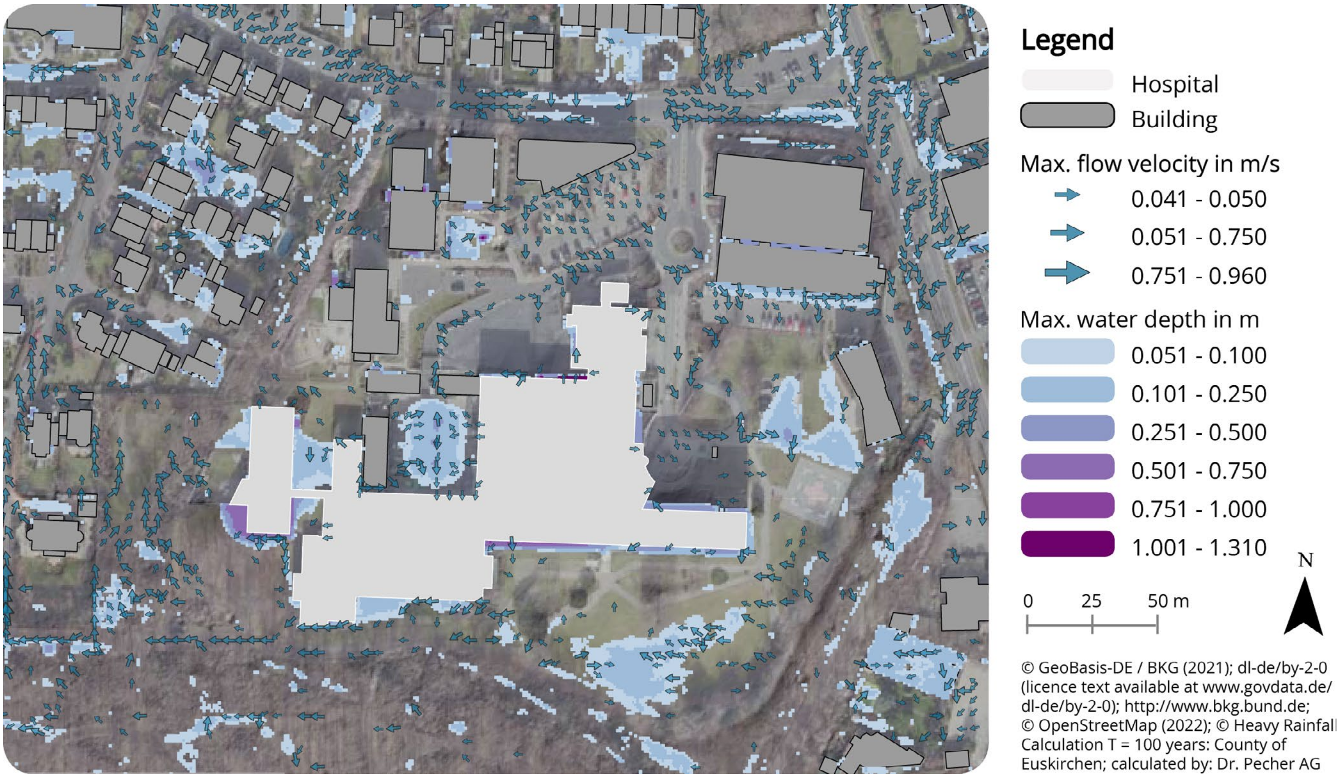

FIGURE 4 | Exemplary hazard map of a hospital. Authors' illustration.

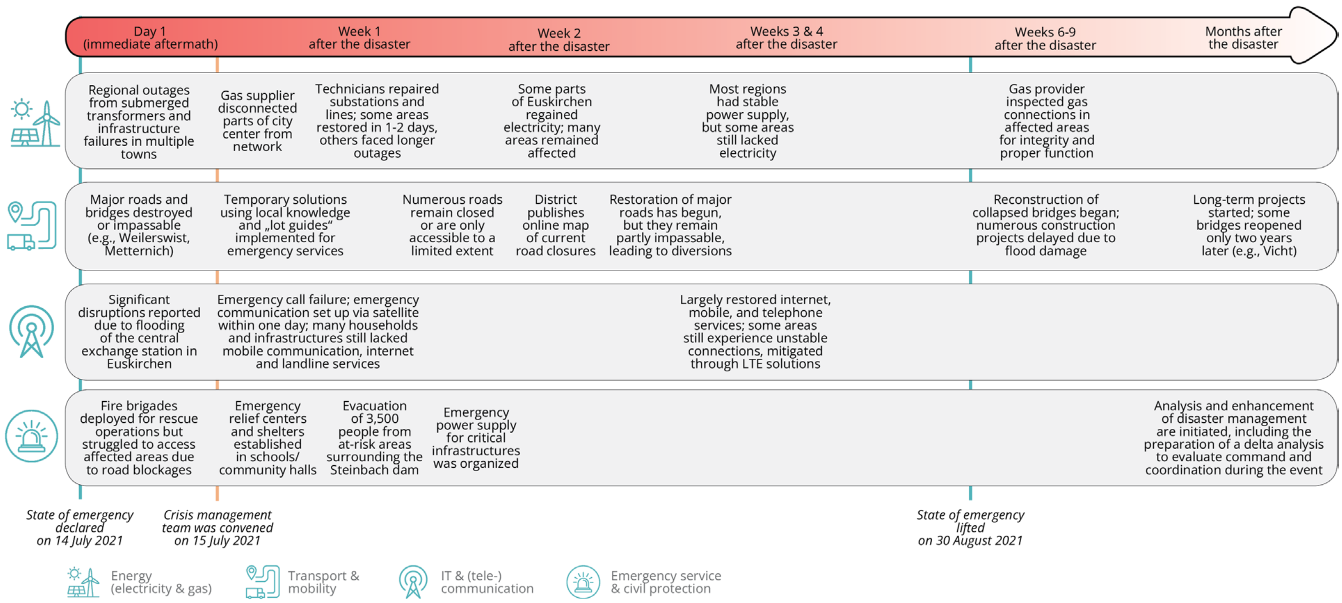

FIGURE 5 | Timeline of recovery. Authors' illustration based on interviews and Uerlichs et al. (2021).

dimension of outages and recovery. It illustrates how recovery unfolded at varying speeds across sectors, ranging from the short-term restoration of emergency communication to the long-term reconstruction of bridges and transportation infrastructure (see Figure 5). This temporal perspective provides an important reference for interpreting the cascade diagrams (see Figures 6–9) and complements the subsequent findings on systemic cascade potentials and interdependencies.

The cascade diagrams reveal substantial differences in the number, length, and branching of cascade chains across the CI sectors. The power sector exhibits significant systemic cascade potential (see Figure 6). Outages originating from substations and network facilities generate multiple, largely independent cascade chains that branch early and propagate across nearly all other sectors. These chains are long and densely interconnected, extending from household-level outages to disruptions

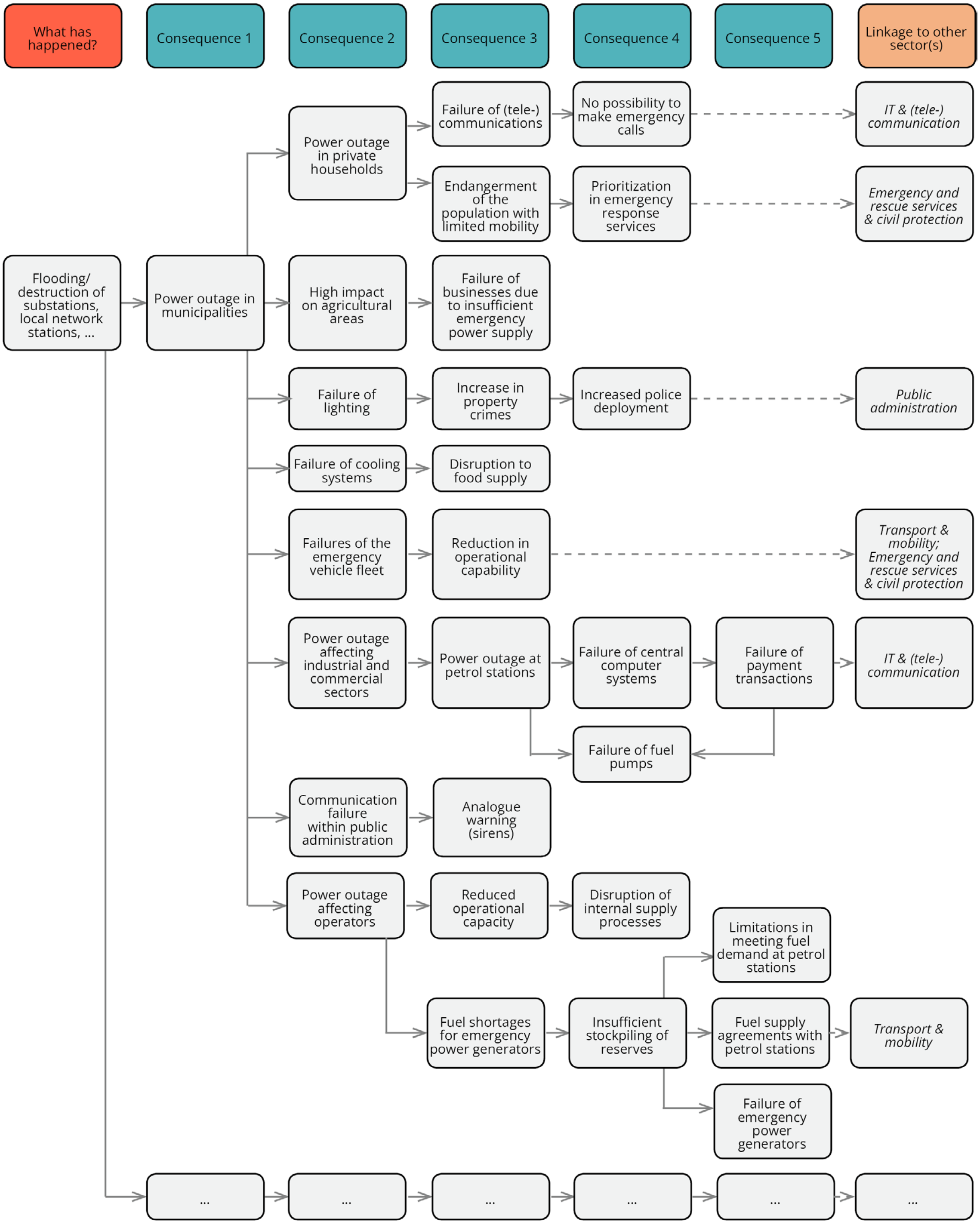

FIGURE 6 | Exemplary extract of a cascade effect chain of the energy sector (electricity). Authors' illustration.

in (tele)communication, fuel supply, cash withdrawals, water supply, and emergency services. The large number of branching points and cross-links illustrates the centrality of electricity as a prerequisite for the functioning of diverse infrastructures and whose failure rapidly amplifies systemic impacts.

The IT & (tele)communications sector also demonstrates extensive cascade potentials, but cascade patterns differ in structure (see Figure 7). Compared to the power sector, this sector shows fewer dominant physical initiating nodes, while functional disruptions due to dependence on energy supply are highly significant; it also exhibits a higher diversity of parallel cascade chains. These chains are typically shorter but partly highly branched. Disruptions of landline, mobile, internet, and radio services repeatedly propagate into emergency and rescue services, public administration, and the wider population. These disruptions hamper internal and external communication for both crisis management agencies and IT & (tele)communications providers, making public communication and information dissemination difficult or even impossible.

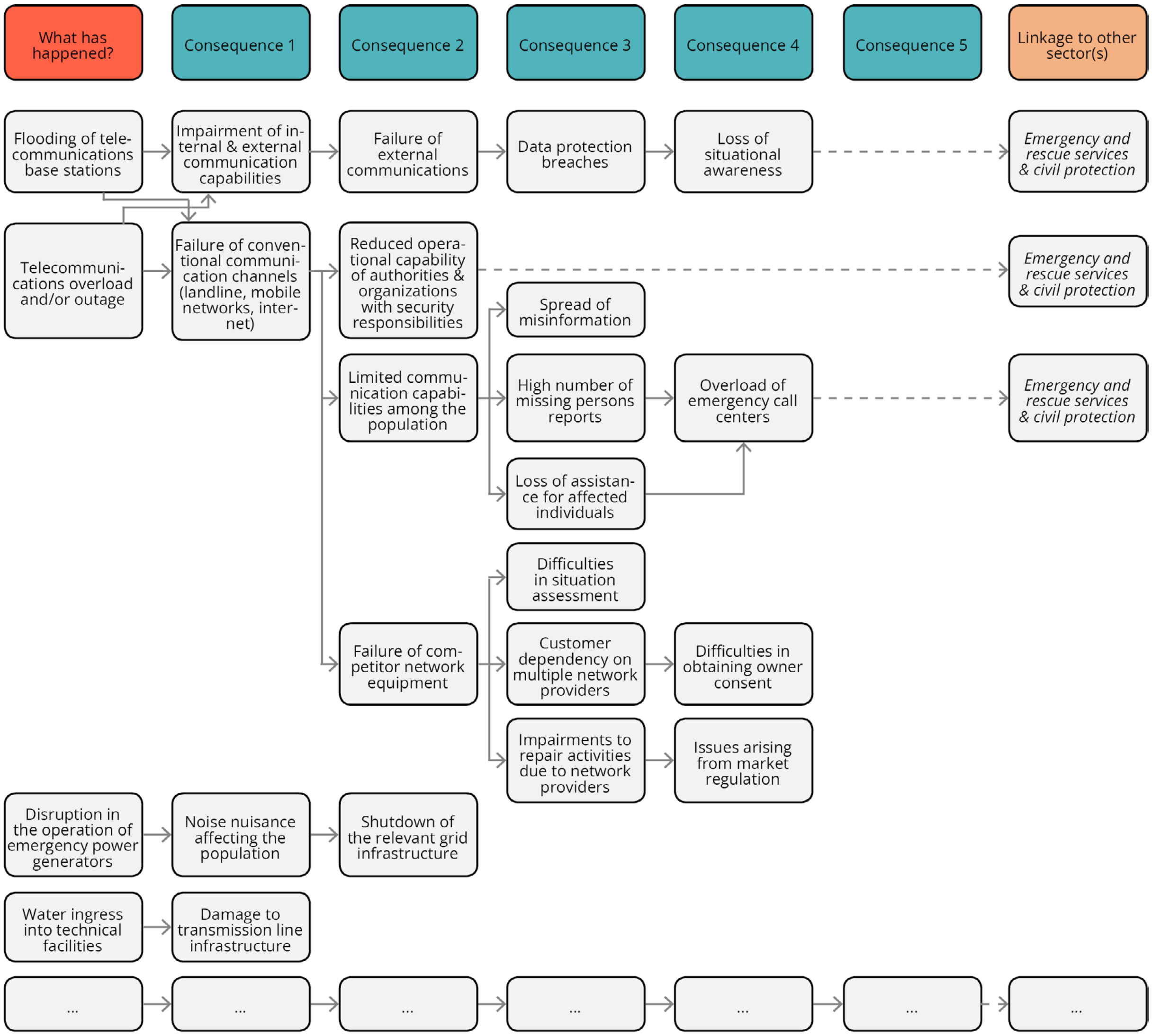

FIGURE 7 | Exemplary extract of a cascade effect chain of the IT and (tele)communications sector. Authors' illustration.

The emergency and rescue services & civil protection sector exhibits fewer and less ramified cascade chains overall (see Figure 8). Though, this sector shows high dependencies on all three other sectors examined. Failures caused by energy outages, impaired communications, inaccessible transport routes, and personnel and equipment shortages directly constrain crisis response capacity, leaving little buffering potential. These challenges resulted in coordination difficulties and even misdirected emergency responses. Additionally, some emergency personnel were personally affected by the disaster, limiting their ability to respond effectively. Although the number of branching pathways is smaller, their impact is immediate and systemically relevant.

In the transport and mobility sector, cascade chains are long-lasting, driven by severe physical damage (see Figures 5 and 9). The diagram reveals a comparatively high number of neuralgic initial points and illustrates multiple consequences arising from destroyed roads, railway lines, bridges, and depots, leading to constrained evacuation routing, overburdening of remaining intact roads and evacuation routes, delayed emergency operations, and disrupted supply chain disruptions. Additionally, many emergency vehicles suffered severe damage, reducing the number of available response units and necessitating urgent replacements.

5.3 | Intervention Points to Mitigate Cascading Effects

Based on the cascade diagrams and informed by the results of the spatial risk analysis, power supply, (tele)communications, and transport networks emerge as crucial leverage points with strong multiplier effects across other infrastructures. These sectors exhibit failure modes that are highly exposed and vulnerable to extreme flooding, occupy central positions in early cascade branching, and—particularly in the case of the transport sector—are characterized by long recovery horizons, making them particularly relevant for preventive intervention and redundancy planning.

In the power sector, ensuring continuity is vital. Beyond technical backup systems such as emergency generators for users, CI operators can enhance the physical resilience of their facilities that were

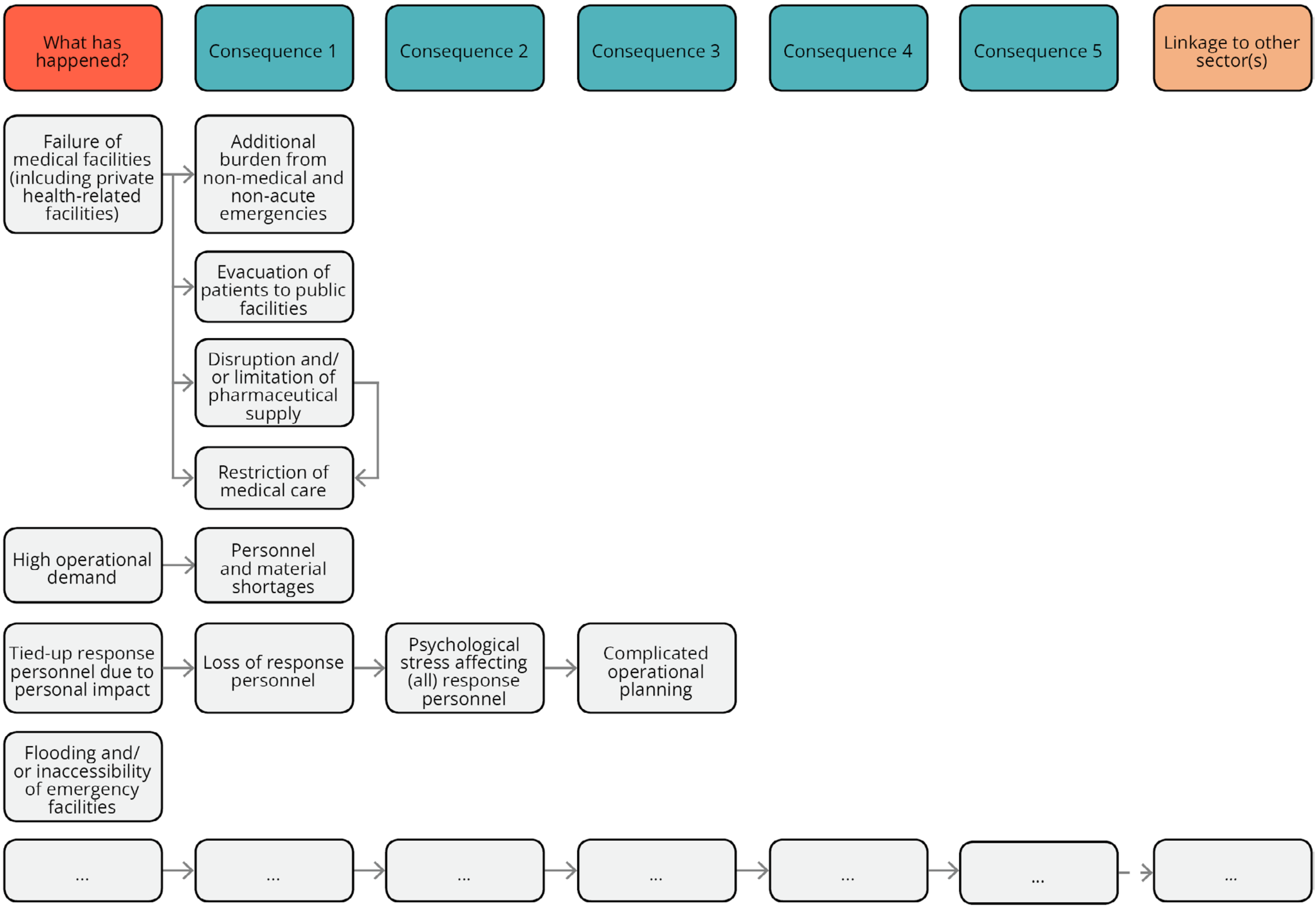

FIGURE 8 | Exemplary extract of a cascade effect chain of the emergency and rescue services & civil protection sector. Authors' illustration.

identified as exposed and vulnerable in the risk analysis. From a spatial and sectoral planning perspective, systemic risks can be mitigated through decentralized renewable energy sources, microgrids, and exclusion zones for substations and transformer stations in flood-prone areas. Such measures directly address early cascade triggers and create redundancy, thereby stabilizing electricity supply and preventing cascading effects in IT & (tele)communications, water supply, healthcare, and financial services.

The IT and (tele)communications sector represents another important leverage point but is structurally dependent on electricity supply. Cascade diagrams show that functional breakdowns in this sector occur early and propagate rapidly into emergency response, crisis communication, population alerting systems, and public administration. In the event of power failures, resilience can be enhanced through analogue fallback infrastructures (e.g., radio) or satellite technology, which introduce functional redundancy and reduce reliance on single points of failure.

The transport and mobility sector functions as a backbone for emergency logistics and evacuation operations and is characterized by particularly long restoration periods. Flood damage to bridges and roads triggered long-lasting access constraints and secondary failures across multiple sectors. Therefore, interventions should prioritize forward-looking planning, for example redundant routing capacities, flood-adapted design standards for critical junctions and bridges, and safeguarding of resilient evacuation corridors. By securing transport networks in this manner, emergency services can maintain their functionality alongside healthcare supply chains and fuel provision.

Emergency and rescue services are highly dependent on transport networks, energy, and telecommunications. Strengthening these prerequisite infrastructures already mitigates many cascading effects. However, interventions such as strategically siting operational centers, logistics hubs, and shelters outside hazard-prone zones, combined with distributed facilities across municipalities, can further reduce risk and the likelihood of simultaneous failures and support rapid mobilization under extreme conditions.

6 | Discussion

Effective FRM for CI requires identifying risks and recognizing their amplifying effects on other critical systems. The results of this study demonstrate that cascading effects are not random side effects, but show specific patterns shaped by functional dependencies, spatial exposure, and recovery dynamics. This evidence is essential for implementing sustainable adaptation and mitigation measures that enhance the resilience of CI. To achieve this, integrating risk and criticality analyses provides a robust methodology. This ensures that planners and emergency

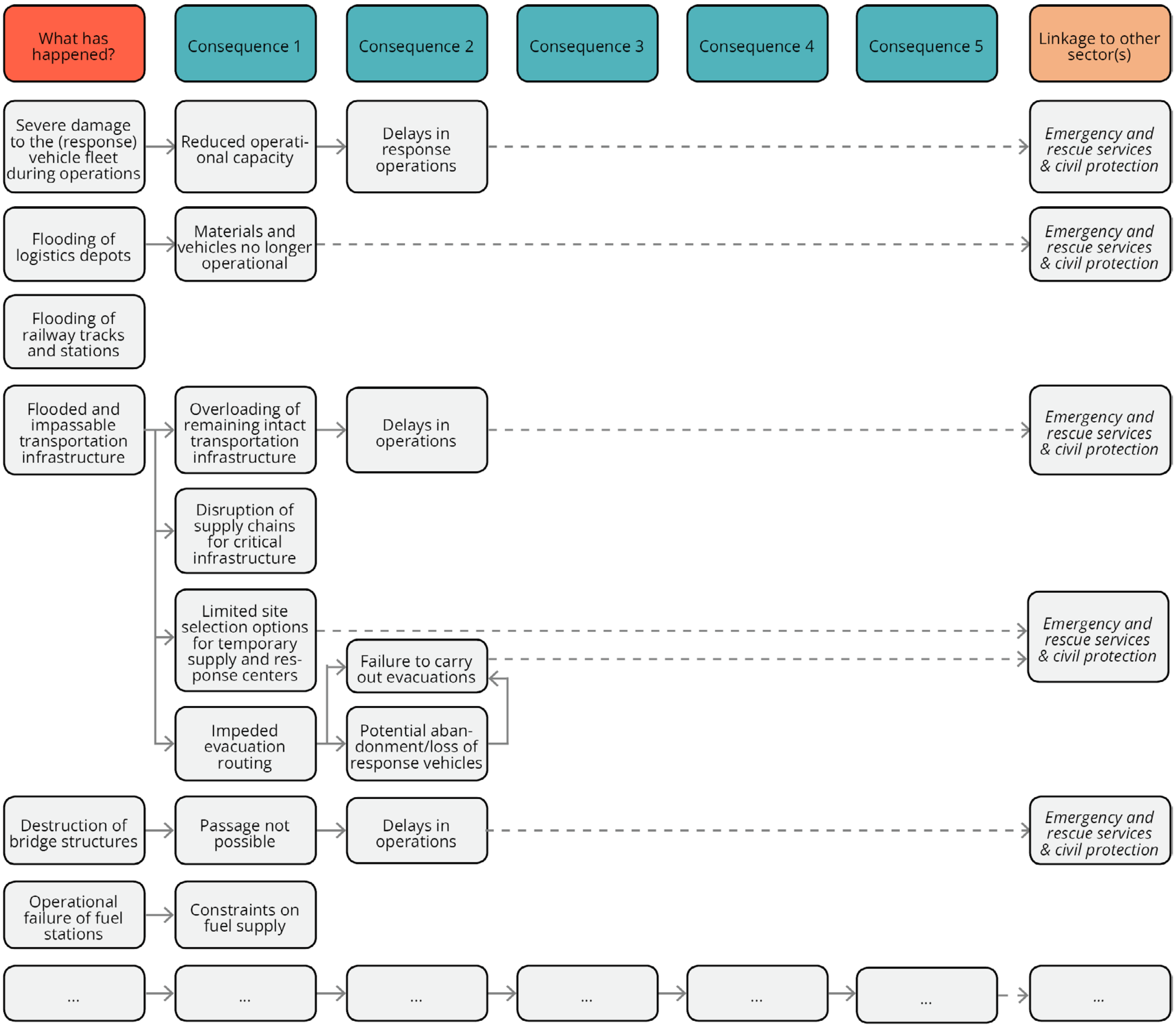

FIGURE 9 | Exemplary extract of a cascade effect chain of the transport and mobility sector. Authors' illustration.

managers have a reliable and practical information base for decision-making. In the following, we discuss our methodological approach, the applicability of our results, and their contribution to the resilience of CI.

6.1 | Methodological Reflection

This study introduces a novel methodological approach that combines GIS-based risk analysis, criteria-based vulnerability assessment, and expert-driven empirical analysis of cascading effects from CI failures. Many existing flood risk analyses rely on GIS-based hazard mapping combined with vulnerability indicators (see e.g., Koks et al. 2015). However, growing research on integrated approaches such as the AB-CEM by Arvidsson et al. (2023) remain scarce, often limited to prototype applications or single-sector case studies. There is still a lack of a comprehensive, planner-friendly approach in FRM and planning practice. The contribution of this study lies less in introducing entirely new analytical techniques than in demonstrating how established methods can be systematically combined to reveal otherwise overlooked systemic risk patterns. Our methodological approach provides a more comprehensive risk assessment that aligns with contemporary research and policy documents advocating for systemic perspectives in disaster risk management (see e.g., Mitra and Shaw 2023; BMI 2022; BMI 2021).

This study presents a practice-oriented combination of methods specifically designed for direct application in risk-based spatial planning. The integration of quantitative and qualitative methods ensures a robust assessment, aligning with the increasing demand for multi-method approaches in resilience research (see e.g., Martinez et al. 2018; Linkov et al. 2013). Despite these strengths, we acknowledge certain limitations. Since the risk analysis relies on the 2021 flood event, identifying specific spatial cascading effects proved challenging. The scale and magnitude of the event led to a widespread collapse and simultaneous failures of essential services, making it difficult to isolate individual cascading effects and reconstruct linear cause-effect relationships. Furthermore, detailed information on the duration, intensity, and spatial extent of specific functional disruptions was not consistently available. Consequently, further interdisciplinary research is required to consolidate fragmented knowledge that may be available. Furthermore, limited data availability hampers the accuracy of results, as incomplete datasets and discrepancies between modeled scenarios and real-world conditions affect reliability. Changes in the surroundings of CI can significantly alter on-site conditions, potentially rendering the model inaccurate. Therefore, careful consideration of these dynamic factors is essential when interpreting the results.

6.2 | Practical Relevance and Applicability

One of the key strengths of this study is its applicability to spatial planning and FRM. The results demonstrate how combining spatial risk with cascade structures enables a shift from generalized protection goals to analytically grounded prioritization and more targeted and effective intervention strategies. It offers practical recommendations for mitigating these risks through adaptive planning strategies. The study highlights that safeguarding prerequisite infrastructures (most notably electricity supply, telecommunications, and transport networks) yields disproportionate benefits by stabilizing dependent CI as well as services of general interests and social systems in general (e.g., social infrastructures of the healthcare and government sectors, food supply; see e.g., Little and Wallace 2020; Wallace et al. 2019; Greiving et al. 2025). They rely on the continuous functioning of these backbone infrastructures, including necessary workforce availability and accessibility, and are particularly vulnerable under just-in-time supply conditions. Safeguarding CI by avoiding placements in high-risk areas is a core principle in resilience planning (see e.g., Greiving et al. 2025). Where relocation is not feasible, the results support targeted reinforcement measures to enhance physical resilience with a priority on those network elements whose disruption has the most significant cascading effects. The GIS-supported analyses and qualitative expert assessments provide decision-makers with accessible, evidence-based tools for risk-based planning, in line with the BRPH and Germany's *Strategy for Strengthening Resilience to Disasters*. They enable both policymakers and CI operators to implement context-specific, strategic adjustments.

Additionally, the transdisciplinary approach fosters collaboration between academia and practitioners, ensuring that the generated knowledge is actionable. By engaging experts from emergency management, CI operators, and local authorities, the study co-produces knowledge that is both scientifically grounded and practically relevant (see e.g., Djenontin and Meadow 2018; Tengö et al. 2014). The cascading diagrams further support intersystem communication by making interdependencies and relational dynamics between CI sectors more transparent. This increased visibility enables stakeholders to anticipate potential effects more effectively and address them across various systems. However, challenges in knowledge exchange must be considered. The sensitivity of CI-related data requires strict non-disclosure agreements, limiting the degree to which findings can be openly shared. Given that CI is frequently targeted in attacks, safeguarding such information is crucial to prevent unintended security issues (see also Arvidsson et al. 2023; Fekete 2020; Schotten et al. 2024).

Another limitation lies in the complexity and resource-intensiveness of the risk assessment. The comprehensive approach presented in this study requires significant data collection, expert involvement, and technical expertise. Given the currently limited resources in the planning sector, many municipalities and regions may struggle to conduct such an extensive assessment, as Diaconu et al. (2021) already pointed out. Consequently, risk and criticality assessments may often be performed at a reduced level of detail, which can potentially limit their effectiveness in capturing systemic risks. Furthermore, risk assessments cannot remain static. As settlement activities and climate change introduce dynamic variables, regular updates of risk assessments are essential to ensure their continued relevance. The mandatory risk assessments at the level of CI operators (Art. 12 CER Directive, EC 2022) are to be carried out at least every 4 years. Establishing institutionalized processes for periodic reassessments and integrating risk-based planning into standard procedures can help address this challenge in the long term. Furthermore, future research should integrate probabilistic modeling to enhance predictive accuracy.

6.3 | Contribution to Resilience Research

This study advances risk assessment by incorporating a systemic resilience perspective that goes beyond the scope of the *Council Directive on the Resilience of Critical Entities* (CER Directive EU/2022/2557). Although the directive mandates risk assessments at the level of member states (Art. 5) and individual critical entities (Art. 12), it overlooks a territorial dimension below the national level that considers the interdependencies between different critical entities from a local to regional perspective.

Although conventional place-based flood risk assessments focus on direct impacts, this approach emphasizes interdependencies and cascading effects, aligning with the shift towards integrated risk governance (see e.g., Greiving et al. 2023; Kruse et al. 2021). By explicitly considering systemic vulnerabilities and failure propagation, the study supports the transition from reactive to proactive resilience planning. That also requires a new way to delineate the area of investigation. It must not be limited to a river basin, but incorporate all service areas of potentially affected CI to address cascading effects properly.

Furthermore, this research underscores the importance of integrating spatial planning, FRM, and systemic risk assessment to enhance infrastructure and urban resilience. The findings contribute to the broader discourse on sustainable urban and regional development by enabling concrete recommendations for resilient infrastructure design. The study also highlights the need for future research to explore dynamic resilience indicators and adaptive planning frameworks that can accommodate evolving risk landscapes.

7 | Conclusions and Outlook

This study demonstrates the necessity of an integrated, systemic approach to flood risk assessment that properly considers service disruptions of CI. The empirical findings reveal substantial risks to both point and linear infrastructure in Euskirchen County, with particularly severe impacts anticipated in the transport, energy, and telecommunications sectors. The potential for cascading effects across interdependent systems such as power outages disrupting emergency services, communications, and fuel supplies highlights the urgency of moving beyond sector-specific risk analyses.

Methodologically, the study presents a novel approach by combining GIS-based risk mapping, criteria-based vulnerability assessments, and expert-based evaluations of cascading effects. This multi-method framework addresses a common shortcoming in existing flood risk analyses in the planning context: The neglect of systemic interdependencies. Although limitations remain—particularly regarding data availability, modeling constraints, and the confidentiality of CI data—the approach enhances both scientific rigor and practical relevance. Future research should focus on refining methodologies to enhance their feasibility for widespread application and ensuring that risk assessments remain adaptable to changing environmental and societal conditions.

In terms of applicability, the study provides valuable insights for spatial planning and disaster risk management. The methodology supports the identification of high-risk CI and enables strategic planning interventions, including location-based risk avoidance and targeted reinforcement. The use of cascading diagrams further contributes to the visualization of interdependencies, enabling more informed decision-making by planners, emergency responders, and CI operators.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Research data are not shared.

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