Technical University of Munich

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Impact of Cross-Border Critical Infrastructure Interdependencies on National Analysis of Network Vulnerability to Cascading Effects

A Case Study of Flood Risks within the Euregio Meuse-Rhine

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Acknowledgements

I would like to express my gratitude to Prof. Dr. **Svetlana A. Ikonnikova** and Prof. Dr. **Walter T. de Vries** for the academic supervision, providing an interdisciplinary framework that allowed my research to bridge two distinct scientific fields, one in economics of energy markets and closely related sectors of critical infrastructures, the other in land management and the impact of natural hazards and floods on modern society.

Deep and sincere thanks go to my project supervisors, **Ingo Schönwandt** (*DLR*) and **Kymo Slager** (*Deltares*). I am grateful for their unwavering support, continuous mentorship and the constructive guidance in the completion of my academic's journey ultimate achievement. Their insights into the realm of critical infrastructures and theory of flood risk assessment, together with their commitment to this dual-company partnership, constitute the true foundation of my work.

I would also like to thank the external academic experts, Dr. **Roman Schotten** and Prof. Dr. **Daniel Bachmann** for their valuable support, sharing their profound knowledge on the assessment of resilience of critical infrastructures and the analysis of cascading effects in thereof networks. My thanks extend to the professional experts Dipl.-Wirt.Ing. **Johannes Wilde**, **Giulia Stroink**, **Sven Robertz**, **Sophie Verstraelen**, Dr. **Benni Thiebes**, and **Michel Carlier** who generously offered their time to provide factual insights into sectors of critical infrastructures in cross-boundary settings.

A special thank is due to the administrative and technical staff behind regional and national institutions, from online geoportals to municipalities and service providers, for their responsiveness in providing contacts of relevant experts or organisations, direct downloadable flood geospatial datasets, and helpful assistance regarding QGIS integration.

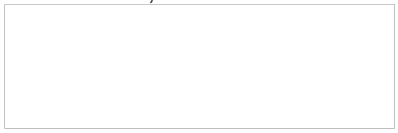
Finally, I thank my family and friends for their unwavering encouragement during this academic work.

Declaration of Authorship

The Master's Thesis is submitted in partial fulfilment of the requirements for the degree *Master of Science in Management and Technology*.

I assure the single-handed composition of this Master's Thesis only supported by declared resources.

Munich, 02.03.2026 Arthur Debelle



Abstract

As social, economic and climatic dynamic environments continue to develop in 2026, nations' intricate networks of critical infrastructures are under increased threat of natural hazards and therefrom induced cascading disruptions. On this topic, scientific literature and national risk assessments often overlooked the cross-border capabilities of failures spreading across networks, in contrast to flood risk experts unanimously certifying: "Natural hazards do not obey to political borders".

In this context, the thesis investigates how legal, functional and spatial discrepancies between the Netherlands and Germany, specifically between the Euregio Meuse-Rhine cities of Maastricht and Aachen, influence the analytical frameworks assessing the national vulnerabilities of critical infrastructure systems to cascading effects induced by flood scenarios. Through both qualitative reviews of legal acts and online documentation, and quantitative network assessments using expert technical testimonies and geospatial modelling, it is demonstrated how the exclusion of cross-border interdependencies adversely impact national vulnerability assessments of critical infrastructures networks to cascading effects.

The results reveal a crucial lack of granularity in present regulatory frameworks, creating a definition gap affecting the accuracy of empirical cross-border and cross-sectoral networks comparisons. In the Euregio Meuse-Rhine case study, open-source geospatial data demonstrates the necessity to transboundary interactions in the modelling of critical infrastructure networks and assessment of flood risks. In conjunction with the observation that cross-border institutional cohesion is principally occurring at regional levels, it can be reasonably inferred that this necessity is amplified in studies on national network interdependencies. Collectively, the findings underscore the necessity to consider extraterritorial influences on domestic vulnerability, an incentive for national and intergovernmental institutions to standardise critical infrastructures legal frameworks and functional protection strategies.

Keywords: Critical infrastructures, Cascading effects, disruptions, Transboundary, cross-border, Flood risk management.

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List of abbreviations

- CE(s) = Critical Entity(-ies)
- CI(s) = Critical Infrastructure(-s)
- Comm. = Commercial
- EC = European Commission
- ES = Essential Services(-s)
- EU = European Union
- GIS = Geographic Information System(ss)
- Gov. = Government(-al)
- LIM = Limburg (region in the Netherlands)
- MS = Member State(-s)
- NRW = Nordrhein-Westfalen (region/land in Germany)
- NATO = North Atlantic Treaty Organization
- R&D = Research & Development

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1. Introduction

In modern geopolitical and climate contexts, infrastructure critical to human well-being, sustenance and security are under widespread, diverse and frequent threats. Due to climate change, intensified and more frequent natural hazards represent a growing threat to nations' critical infrastructures and their network interdependencies (Leal Filho et al., 2024), resulting in aggravated economic and societal consequences. Damages to such infrastructures may prompt cascading failures in the global system, interrupting energy and water supply chains, as well as healthcare and emergency services. Consequently, nations are compelled to coordinate for prompt recovery interventions and service restorations.

As networks of CIs span across countries, and because natural hazards affects regions regardless of the boarders, a global systemic understanding is required. Because networks of critical infrastructures are complex and cover wide geographical areas, at times crossing borders, nations may not always anticipate all adverse outcomes of natural hazards, particularly when not directly affected by them. With international partnerships and agreements, particularly in the European Union, most networks of critical infrastructures have connections spanning across national borders. Similarly, natural hazards affecting critical infrastructures do not obey to geographical delimitations either. This sparks a need for an adequate assessment of the global network, and a systemic analysis of intricate relations at its core. Failing to do so may precipitate unforeseen and detrimental outcomes to several countries and their respective populations.

In such scenarios, a disruption in a critical infrastructure induced by natural-hazards may cascade through the networks and country borders, occasionally onto a point of interest far off the initial failure's origin. This thesis investigates how disruptions caused by inundations may cascade from one critical infrastructure (CI) onto another, at times in a disparate system. The focus is set on cascading failures from and between energy and water supply networks to emergency services, and how the latters' facilities are thereby affected. Such events sometimes affect and propagate inside an entire network, spreading across regions of one or several nations. In these regards, CIs in the Dutch-German border region are assessed, evaluating interdependencies both between distinct infrastructure networks and countries. CIs national definitions, locations and characteristics are necessary to determine if connections and synergies within the networks exist, consecutively allowing to examine the latter's vulnerability towards failures and propagating disruptions. Therefrom, insights are drawn for policy-makers and relevant experts.

Data on critical infrastructures and floods is collected through a two-methods research design, allowing to combine quantitative and qualitative data for a better modelling of the region's CI landscape. In a qualitative approach, existing legal regulations and governance structures are examined to determine intangible synergies or flaws between networks of CIs (see Section 3. and Appendix A.). In a quantitative approach, data is retrieved to build a geospatial GIS model, using insights from interviews with experts to integrate interdependent relations within the CI networks. After multiple spatial analyses, a synthesis provides an overview of the region's status quo, as well as a discussion about what truly impacts cascading effects vulnerability assessments network in terms of flood risk. Along the spatial analysis, visual figures enable stakeholders to appraise specific CIs networks and existing interactions with others in times of natural hazards. In turn, this enables to comprehend what transnational relations exist, and how these may mitigate or precipitate adverse effects of climate events and cascading effects.

1.1. Motivation

At times, a single failure in a critical facility may already affect, on its own, thousands of inhabitants in its vicinity. A lack of electricity or water supply can affect populations health, healthcare and emergency response services, and ultimately, countries' economies. When cascading onto other facility networks or nations, such disruptions can rapidly aggravate the service level of multiple energy, water and healthcare infrastructures. Additionally, when such sectors witness failures causing discontinued services, they may also represent a threat to the global economy or security of a nation. The present section provide motivation behind the selected region and CI sectors.

The Euregio Meuse-Rhine & the 2021 floods

The studied area is chosen for its unique geographic, demographic and hydraulic features. In the southern part of the region, the Belgian Ardennes and the German Eifel, the land use principally consists of forest and wildlands. Towards the north, more cities appear and the region comprises more agricultural areas, with higher permeability and water retaining capabilities. The two major cities of Maastricht and Aachen offer large urban areas, and are mainly separated by cultivated fields (cf. section 4.1.1). Nonetheless, both have significant differences: Maastricht is crossed by a river, unlike Aachen, and the Dutch city has half as many inhabitants (125,913 in 2024 (StatLine CBS, 2025)) as Aachen (252,769 in 2023 (Wegweiser Kommune, 2025))). Given these geographic and demographic features, different land and CI management directives are required.

Just as any natural hazard, floods do not obey to geographical borders. Even smaller instances affecting local areas may sometimes induce disruptions on broad regions. Given the area of expertise of the thesis partner the research institute *Deltares*, the focus on natural hazards is set on floods. Additionally, the region's hydrogeology, water dynamics and history to floods further demonstrate its relevance. With the July 2021 large precipitations that occurred in the region, the area represented a good candidate for the JCAR-ATRACE teams and its extended transnational water systems stress investigations. For similar reasons, the scope of this thesis concentrates on the mentioned rectangular area. Moreover, the presence of main European nations and major cities both inside and in proximity of the area adduce economic facets. Together with various land uses, these provide a strong rationale for the study.

Economy

Critical infrastructures –power grids, water networks and healthcare systems amongst others– constitute the foundation of modern society and are essential to its current functioning. Their networks get increasingly and severely disrupted by ever aggravated floods induced by climate change and growing urbanisation, as seen in the July 2021 Western European floods or the intense rainfalls initiated by the storm "Anett" in central Europe in September 2024. Damaged infrastructure not only include critical facilities, but also essential transportation arteries (railways, roads and bridges) and utility networks (water, electricity and waste management), vital for CIs operations. Insurance association estimate the financial burden to €180 mil. in the South Netherlands (Verbond van Verzkeraars, 2022) with casualties approaching 220, and € 8.2 bil. in all of Germany (Gesamtverband der Versicherer, 2022).

To mitigate such effects and losses, authorities and population must conduct research to better anticipate and forecast failures, to then undertake (critical) infrastructures improvement projects. Accordingly, a better comprehension of their country's CIs networks is imperative. This necessitates a full grasp of what (inter-)national dependencies a network of CIs possesses, how resilient it is to floodings scenarios and

other natural hazards, and what cascading effects a single disruption may possibly induce onto the broader system.

Berlin & Portugal

In early 2025, the German capital of Berlin experienced an important localised electricity outage, that highlighted the vulnerability of old and aging urban infrastructure for the distribution of this energy source. Due to politically motivated sabotages on a cable bridge in the Steglitz-Zehlendorf district, 45,000 household and 2,000 business were left without electricity for a period of 5 days (Parker, 2026). This grid failure highlighted the security gap of German critical infrastructure and the KRITIS-Gesetz (Tagesspiel, 2026).

Later that year, a greater electricity blackout happened also in Europe, this time affecting larger geographical areas and causing electricity disruptions in two neighbouring countries: Portugal and Spain. Due to an initial power surge in the Iberian Peninsula's grid, a series of overvoltage fluctuations cascaded onto the network, causing outages for almost an entire day in the two countries, and briefly affecting southwestern France. This cascading effect, considered as one of Europe most severe for the past 20 years, also highlighted the vulnerability of networks to dominos failures and the criticality of incorporating such scenarios in various risk assessments frameworks (Comerford & Hedgecoe, 2025).

National and Global Security

Political and environmental conflicts give to national governments an incentive to care for their inhabitants' security and thereby strength of own, and others', networks of critical infrastructures. In an era when climate change jeopardises civilisations across multiple dimensions, discerning such dangerous repercussions and mechanisms becomes essential for authorities and decision-makers to build a safe, disaster-resilient environment for their population.

Amidst international geopolitical conflicts observed around the world, the NATO state members jointly agreed during their summit of June 25th, 2025 (The Hague, Netherlands) to commit 5% of their respective GDPs towards defence and security matters (NATO, 2025). Specifically, 1.5% thereof have been promised to be invested in critical infrastructures and networks protection, with primary objective the development of enhance systemic resilience. Accordingly, understanding CIs networks, their cross-border dependencies and possible weaknesses facilitates CI protection measures and enables more effective fundings allocation.

1.2. Natural Hazard, Geographical and CI Scope

The following scopes define the main thesis aspects and confine the study's boundaries.

The study concentrates on disruptions induced by fluvial and pluvial floods caused by climate change and heavy rainfalls, and occurring to critical infrastructures located in flood-prone areas. The study focuses exclusively on direct-impact floods, therefore intentionally excluding localised minor floods induced by infrastructure failure (e.g. dam or sluice breaks, levee or dike collapses), as these are assumed unlikely in the studied area.

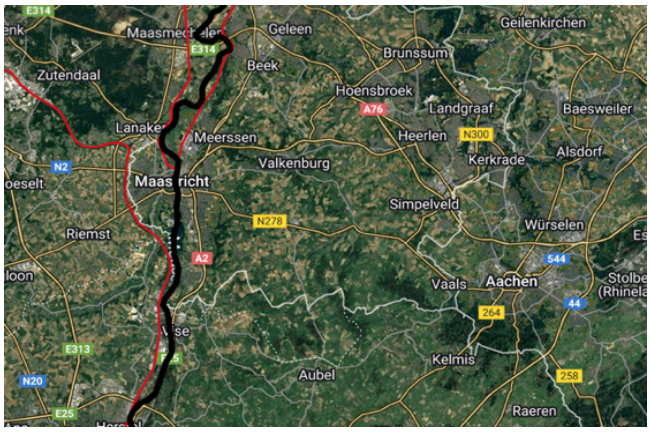


Figure 1.1: Studied Region / Canvas
(Debelle, 2026)

Considering the present study is conducted in partnership with the *German Aerospace Center (DLR)* and the Dutch applied research institute *Deltares*, a geographical region encompassing both institutes' nation is favoured. The present project sets focus on floodings occurring in the geographical area around and between the cities of Maastricht (NL) and Aachen (D) (see Figure 1.1). The region encompasses a major river from the area, the Maas, together with some adjacent canals, reservoirs, lakes and ponds. Further details are provided in section 4.1.1.

Amongst many, the EU-NATO task force on the resilience of critical infrastructure defines the energy sector as most essential in the contemporary era (2023), and is therefore deemed as pressing relevance for the thesis scope. Given the core domain and expertise area of Deltares, the water management sector is the second type of critical infrastructure considered in the thesis study. Finally, as regional studies indicate that infrastructure of the healthcare sector was the most exposed to floods during the 2021 natural hazard (Nick & Sandholz, 2022), the healthcare and emergency response sectors are included at last. Often highly ranked in significance to security and network vulnerability, further sectors cannot be integrated due to the temporal constraint of the present work.

1.3. Research Question

In light of the foregoing, the present study sets as research question:

> *"How do cross-border interdependencies between networks of energy, water and healthcare critical infrastructures impact the analysis of national vulnerability to cascading effects?"*

To answer it, several supporting sub-questions guide the present paper, focusing on the specific case study of flood risks in a representative sample of the Euregio Meuse-Rhine:

SQ1: What divergences exist between Dutch and German national definitions and legal frameworks, potentially influencing the nations' respective structural governance of critical infrastructures and thereof networks?

SQ2: What underlying, conceivably miscomprehended, undocumented or indirect interdependencies exist between the energy, water and healthcare CI sectors, specifically between the Netherlands and Germany?

SQ3: How are the existing networks of critical infrastructure in the Euregio sample geographically distributed, connected and exposed to flood events, and what national asymmetries exist?

SQ4: How can identified legal, functional and spatial discrepancies collectively influence the analysis of national network vulnerability to cascading effects?

1.4. Paper & Research Structure

The present paper is structure as follows: Ch. 2 first provides a concise review of the literature addressing transboundary cascading effects in CI networks. Then, legal and regulatory frameworks existing in the European Union, the Netherlands and Germany are studied, and insights into governmental and commercial CI responsibilities are presented. Thereafter, the methodology for data collection, processing and analysis is described in Ch. 3. From the collected (geospatial) data retrieved online, and using expert testimonies regarding the targeted sectors, results are provided on a macro, meso and micro level in Ch. 4. At last, Ch. 5 summarises the study's findings, highlighting key limitations and recommendations for future research.

Figure 1.2 below provides an overview of the research steps undertaking in the present master's thesis.

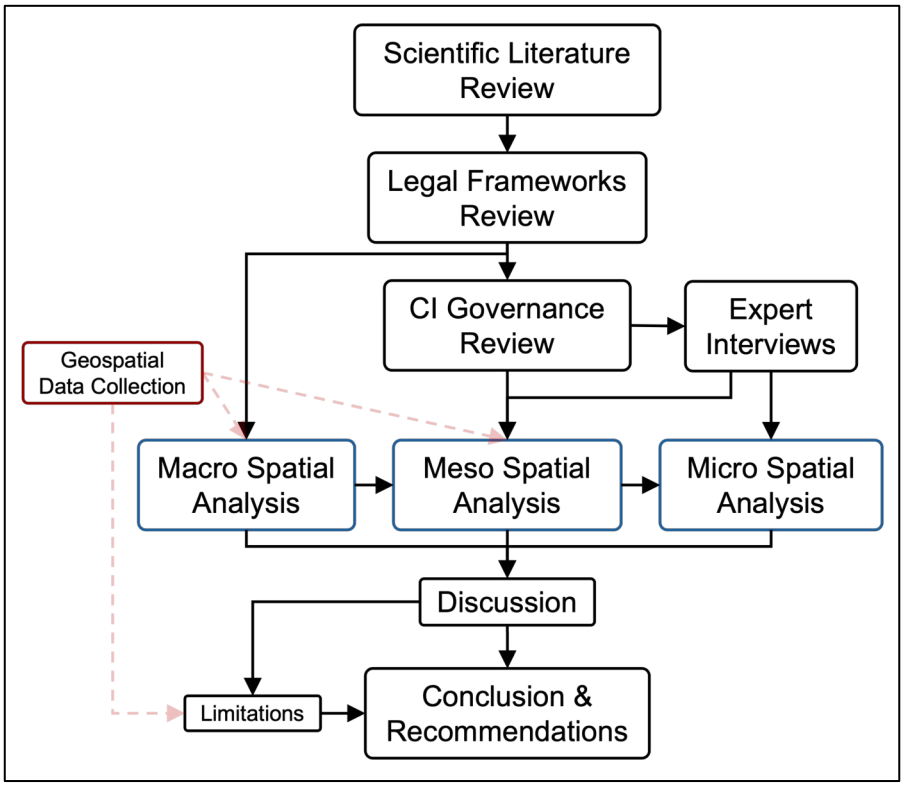


Figure 1.2: Flow Chart of Thesis Research Steps (Debelle, 2026)

1.5. Term Definitions

Given the multidisciplinary nature of critical infrastructures, divergent definitions persist across sectors, research and (inter)national jurisdictions. To ensure terminological precision and avoid ambiguity, Table 0.1 in Appendix A consolidates synonymous terms and definitions of central concepts utilised throughout the present study: Cross-border, Healthcare, Network(s) and Cascading effects. The national and European definitions of critical infrastructures, necessary for the research sub-question (SQ1), are profoundly examined in sections 2.2 and 2.3.

2. State of the Art: Science, Law and Governance

The present chapter establishes the theoretical and regulatory foundations of this research, providing a comprehensive 'State of the Art' review of scientific, legal and governance literature on critical infrastructures. In particular for the former scientific review, the focus is set on research involving cross-border characteristics and cascading effects. For the latter legal and governance review, if the Netherlands and Germany do not share equal attention, interests and stakes into their CIs, a threat may arise from mismatching goals for CI resilience. If discrepancies exist in legal considerations, a disruption in one country's network and its potential cascading effects in the neighbouring country may not always be considered or foreseen, given the countries' disparities in definitions.

To investigate the complexities of transboundary networks of CIs, the chapter addresses distinct but interrelated domains. In section 2.1, a scientific literature review is conducted. Thereafter, section 2.2 and 2.3 respectively review how intergovernmental organisations and national institutions define CIs and address the therefrom arising legal challenges. By cross-examining the respective legal frameworks of the previously addressed entities, section 2.4 provides a synthetic understanding of both the national and international legal and strategic configurations. Last, section 2.5 establishes a comprehensive overview of governmental and commercial responsibilities with regards to the administration, management and command of CIs and thereof networks.

2.1. Scientific Literature Review

This section provides a synthesis of the existing research body regarding cascading disruptions in networks of critical infrastructures, particularly in transboundary regions where national borders impose legal and economic constraints onto governmental institutions and service providers of CIs. By evaluating the current state of research, this review establishes the theoretical framework necessary to assess and evaluate the impact of cross-border dependencies on the vulnerability of the Euregio's critical infrastructure networks to cascading effects.

In section 2.1.1, research is reviewed on cascading effects in heterogeneous networks of critical infrastructures, followed by a review of the literature capturing the same effects on multi-national regions in section 2.1.2. Last, section 2.1.3 briefly indicates the present research's contribution.

2.1.1. Heterogeneous Networks of Critical Infrastructures

A considerable threat to cross-sectoral networks of infrastructures is the likelihood of a single disruption spreading on other facilities or networks, in turn susceptible to reach further, possibly even more critical nodes of a system. Such consequences are discussed by recent research, providing spatially explicit models and framework to understand systems comportments with regards to cascading effects, allowing to better predict basic services' vital availability and performances. To this end, an extended comprehension of all networks, existing interdependencies and potential points of synergies for resilience is needed. Schotten and Bachmann (2023) address the connection between floodings and CI network management with a case study in Ghana, demonstrating the feasibility of integrating critical infrastructure issues and challenges in flood risk management models. Nonetheless, the authors do not consider a geographical region spreading across political borders, where different legal regulations, fundings frameworks and political environments apply. As the latters significantly influence the state, condition and performance of critical infrastructures and their relative networks, their integration in the said models becomes essential as well. While Borghetti and Marchionni (2022 & 2023) provide analytical and assessment models for studying cross-

border CI resilience, their works predominantly set focus on transportation infrastructures. As stated earlier, other types of infrastructures are deemed more critical in current times, particularly with a cross-sectoral focus.

On another note, literature suggests that a gap exists between the scientific approaches and methods employed to assess cascading effects of disruptions, and the wider network vulnerability required by practitioners to implement national resiliency strategies. In a Swedish case study of 2023, Barquet et al. (2023) show that although frameworks and methodologies do exist to assess impacts of multiple hazards, these often reveal to be too intricate for local authorities to utilise. Because the literature offers elaborated models for the complex systems of CIs, a profound necessity for technical skills, processing time and data collection appears. This observed lack of shared understanding and the existence of conceptual ambiguities at the national level of a single European country highlights the significant challenge of managing such issue across multiple nations. Additionally, this further underscores the pressing imperative for clear and consistent definitions of critical infrastructures and cascading effects.

Wang et al. (2018) address the effects of cascading effects on the Chinese road-railway coupled network, showing how these are influenced by different types of attacks (random, malicious, shell-based and local, or orientated and local) in different type of cascading effect scenarios (non-, inner-system or inter-system cascading). Although their work underscores the uncertainty of outcomes of cascading effects, and thereby the relevance of practical research on the topic, the geographical area examined in this paper presents merits and but also limitations. On the one hand, the immense scale of China's land area, covering 9,4 mil. km^2 (Food and Agriculture Organization, 2023) – second to 4^{th} largest country on earth, depending on sources and excluding Antarctica (Britannica, 2026)–, is characterised by its geographic heterogeneity in climates, landscapes, demographics, urban and rural settings. This offers a compelling region for investigating cascading effects in complex systems of critical infrastructures. Conversely, the PRC's State Council unveiled in 2021 the country's "Regulations on the Security and Protection of Critical Information Infrastructure" (Huld, 2021), suggesting the government is the nation's sole CIs decision-maker, as in most countries. Henceforth, the study by Wang et al. lacks an analysis of essential legal or economic constraints that do not exist by nature between Chinese provinces, with regards to the management of critical infrastructures.

2.1.2. Spatially Transnational CI Regions

Local and sometimes minor disruptions to one critical infrastructure may occasionally have aggravated consequences on another, dependent CI network or thereof facilities. At times, repercussions disseminate into a neighbouring nation, or cause in turn more severe failures and damages. Since floods do not obey to human set geographical boundaries, and with their increasing magnitude and frequency over the years (Fang et al., 2024), such international impacts require crucial attention and infrastructures urgent adjustments.

In this matter, Mühlhofer et al. (2023) emphasise their work on largescale risks applied to a vast geographic scope, whilst also addressing human-centric impacts. On the other hand, Scheiner et al. (2025) focus principally on a method requiring less input data to determine dependencies of a network in contexts of largescale disaster scenarios. Nevertheless, both papers validate their models on restricted geographical levels: a territory encompassing three contiguous US states (Alabama, Florida and Georgia) for the former, and an urban setting in the city of Cologne for the latter. Besides, the latters sets a general focus on broader types of natural hazards or disaster scenarios, including amongst others: storms, earthquakes, wildfire and heatwaves.

In the European Commission Joint Research Centre's technical report of 2023, the authors provide a profound and precise overview of the European political and research landscape in terms of "Cross-border impacts on Networks due to natural hazards" (Menoni et al. 2023). First, and despite limitations in available sources, the paper exhibits numerous severe cross-border incidents caused by natural hazards, between 2002 and 2021 and affecting two or more countries. This highlights how a natural hazard, whether itself directly or through cascading effects, may have devastating consequences on transboundary regions. Subsequently, the paper explains that such cross-border impacts on essential services are mainly due to interdependencies of the infrastructure networks, where the consequences of an incident may cascade or escalate onto broader networks, sectors and regions. The network's systemic vulnerability is herewith a key concept to understand cascading effects of natural hazards. The study then offers deep insights into available conceptual frameworks and methodologies for risk and resilience assessment, and good practices for cross-border cooperation. Here, examples show how collaboration between nations have already proven their utility:

- An action plan between the USA and Canda for coordinated efforts in the protection of critical infrastructures, which aimed at sharing information and jointly implement risk management solution, and later expanded onto other nations like the UK, Australia, New Zealand or Europe;
- An agreement of collaboration on civil defence as well as emergencies and crisis management between Nordic countries, where experts highlight each nation's high dependency to "international flows of critical goods, products and services", meaning none is self-sufficient and a disrupted supply chain may become critical to any sector or country;
- Countless multi-lateral cooperations of border police and civil protection, in the European Union amongst others, helping nations to tackle terrorism and illegal migration issues, in border areas but also nation-wide;
- The Euregio Meuse-Rhine Incident Control and Crisis Management (EMRIC) interservice collaboration, where services for public safety such as fire services and emergency medical care jointly operate for quick assistance regardless of the incident location, sharing resources, capacities and knowledge;
- The Swiss-Italian coordination on joint interventions in their mountainous border region, in events of natural disasters or transportation systems.

All abovementioned examples highlight the existence of numerous incidents affecting neighbouring or partnering countries, while also underscoring the presence of projects and frameworks to alleviate the consequences of such crises. In addition, recent crises from wildfires in southern countries of the European Union have accentuated the broad international capacity to collectively respond to such threats (Tidey, 2025).

2.1.3. Contribution

The study conducted in this master's thesis emphasises the importance of assembling and integrating global, cross-border understandings of networks of critical infrastructures, in order to accurately assess their vulnerability to cascading effects. In turn, this helps national governments and international organisation to better forecast unexpected consequences of natural hazards, and build a resilient future for their populations.

2.2. Legal Framework: Intergovernmental Organisations (EU, NATO)

After reviewing the existing literature with regards to cascading effects on cross-border networks of CIs, a deeper look into the national legal definitions of critical infrastructures is required. Since variations may exist between geographical areas, nations may not all have the same legal, financial and economical approaches in terms of protecting their CI networks. Furthermore, the studied countries are part of greater intergovernmental organisations such as the European Union (EU) or the North Atlantic Treaty Organization (NATO), which may advise or dictate what approaches to take in the national economic and defence action plans.

Below, the legal frameworks concerning critical infrastructures governance is first provided from intergovernmental organisations standpoints, as national security of European countries and NATO member states is particularly influenced by the institutions of the European Commission and the NATO.

2.2.1. European Union (EU)

The European Union and the European Commission play a central role in the establishment of new laws and regulations to the benefit of its member states, their economy, their security and their population's well-being. With regards to the resilience and security of their critical infrastructures, the EU published two important directives on the 14th of December 2022: the *Critical Entities Resilience* Directive (CER) and the 2nd version of the *Network and Information Systems* Directive (NIS2). These directives directly aim at strengthening the resilience and cybersecurity of entities operating essential European services. These updated and improved directives, created to repeal older versions (respectively 14 and 6 years old for the CER and NIS2 directives) appear just months after the Russian invasion of Ukraine in late February 2022. This compelling evidence of a direct link suggests already an awareness of European states towards a growing instability of the geopolitical environment. Considering the incoming pressure from the American government on NATO Allies to increase expenditures on defence and CI resilience, as established in the NATO Summit in The Hague on the 25th of June 2025 (NATO, 2025a; 2025b).

CER Directive

On the one hand, the CER directive targets operators of critical infrastructures, to ensure their preparedness to prevent, resist to and recover from disruptive events to their facilities. To this end, the European Commission (EC) makes a clear distinction compared to the 2008/114/EC Council Directive, which it is thereby repealing (since October 2024): *critical infrastructures* and *critical entities* are to be defined and identified separately.

In the 2008/114/EC directive, a CI is defined as "an asset, system or part thereof located in Member States (MS) which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact in a MS as a result of the failure to maintain those functions". This definition is today replaced by the CER directive updated version:

> *A **critical entity** (CE) is a provider of one or more essential services, operating critical infrastructures in the territory of a MS and to which an incident would have "significant disruptive effects" on the provision of one or more essential services, by the entity itself or from another entity dependent on these very essential services. From this definition, two important terms arise:*

> *an **essential service*** (ES)*, defined by the EC as "a service which is crucial for the maintenance of vital societal functions, economic activities, public health and safety, or the environment";*
>
> *a **critical infrastructure**, defined by the EC as "an asset, a facility, equipment, a network or a system, or a part of an asset, [...], which is necessary for the provision of an essential service".*

According to Pursiainen and Kytömaa (2023), the concept replacement of Critical Infrastructure to Critical Entity is to shift the focus from the CI sectors (e.g. "Energy") to the CI operators (e.g. "energy company" or "power plant"). This puts an incentive to carried out required analysis and action plans both deeper in and beyond the systems and networks.

To determine the significance of a disruptive effect, MS must consider all criteria of the directive's 7th article. These are:

1) the numbers of users relying on the Essential Service provided by the CE;
2) the extent to which other sectors are impacted or dependent on the ES;
3) the potential impact, in terms of degree and duration, on economic and societal activities, the environment, and the public's safety, security and health;
4) the CE's market share in the ES;
5) the geographic area potentially affected, including cross-border impact, considering the vulnerability of isolated areas;
6) the importance of the entity with regards to a sufficient provision level of the ES, considering alternative means of provision.

Once all CEs, ES and CIs identified by the Member States, it shall communicate about them to the European Commission. The CER directive pushes MS to identify their CEs and subsequent resilience strategies, for the sectors and subsectors it mentions, by the 17th of July 2026 at latest. The MS should therefore carry out prior to this a risk assessment to support the determination of CEs, which must then be repeated at most every four subsequent years. Equally so, a CE has nine months after being notified of its criticality to carry itself a risk assessment, whenever necessary thereafter and at least every four years. All MS must have had adopted, published and applied the measures required to comply with the directive by the 17th of October 2024 at latest.

The CER directive also enforces other duties on the MS and CEs regarding the identification of criticalities and notification of incidents, the reporting of legal adoptions or updates, or the establishment of responsibilities regarding the resilience of CEs and provision of ES. Lastly, the EC considers a CE to be of "particular European significance" if it provides an ES to six or more MS.

A MS may adopt provisions achieving higher resilience of CEs, provided they are consistent with the CER's minimum provisions. All MS must outlay their strategies to enhance CEs resilience, including at least the following eight elements:

1. Objectives to enhance the overall resilience of CEs, including cross-border and cross-sectoral (inter-)dependencies;
2. A framework to achieve these objectives;
3. A description of thereof necessary measures, including risk assessment;
4. A description of the process defining CEs;
5. A description of the process in charge of supporting the CEs with regards to the CER, including public and private sectors and entities);
6. A list of stakeholders involved in implementing the strategy;
7. A policy framework between the authorities of the MS and those of the EU, to share information on (non-)cybersecurity risks, threats and incidents;
8. A description of measure already in place for the risk assessment and resilience measures.

NIS2 Directive

On the other hand, the NIS2 directive focuses on public and private entities operating for the provision of ES, seeking to strengthening the cybersecurity across the EU by imposing strict risk management, reporting and information sharing requirements. Accordingly, MS must adopt national cybersecurity strategies and designate crisis management authorities. The directive focuses on equal resilience topics of similar CIs as the CER directive, with extra sectors such as the waste management, manufacturing and production and distribution of chemicals, digital providers of online marketplaces and social networking platforms, or research organisations.

Although intimately related to the CER directive and the EU's intentions to move towards highly resilient CIs, the NIS2 directive primarily focuses on information systems, electronic communication, digital data and network cybersecurity, and is therefore not further developed here. Because of its relevance to the topic of CI resilience and cascading disruptions, many nations such as the Netherlands and Germany do nonetheless also consider this directive when implementing the CER directive in their national legislations.

CIs Included

At last, the CER directive provides the MS a list of sectors, subsectors and categories of CEs to be considered in the national regulations. An overview of these may be found in Annex of the directive itself, for instance in Annex I and II of the NIS2 directive. These sectors (and subsectors) are:

- Energy (Electricity, District heating and cooling, Oil, Gas, Hydrogen);
- Transport (Air, Rail, Water, Road, Public transport);
- Water (Drinking water, Waste water);
- Banking; Health; Digital infrastructure; Public administration; Space and Production, processing and distribution of food.

Relevant subsectors to the present study are further described below.

Sectors	General Overview
Energy	**Electricity**: - Electricity undertakings as per Art.2.57 of the Dir. 2019/944, carrying out at least one of the functions of generating, transmitting, distributing, aggregating, responding to demand, storing, supplying or purchasing electricity, and responsible for commercial, technical or maintenance tasks of these functions - Distribution and transmission system operators as per Art.2 point 29 and 35 of the Dir. 2019/944 - Producers as per Art.2.38 of the Dir. 2019/944 - Nominated electricity market operators as per Art.2.8 of Reg. 2019/943 - Market participants as per Art.2.25 of the Reg. 2019/943
	District heating and cooling: - Operators as per Art.2.19 of Dir. 2018/2001
	Oil: - Operators of oil transmission pipelines, of production, refining and treatment facilities, storage and transmission - Central stockholding entities as per Art.2.f of Dir. 2009/119
	Gas: - Natural gas undertakings as per Art.2.1. of the Dir. 2009/73, carrying out at least one of the functions of producing, transmitting,

	distributing, supplying, purchasing or storing natural gas, including LNG, and responsible of commercial, technical or maintenance tasks of these functions. - Supply undertakings as per Art.2.8. of Dir. 2009/73 - Distribution, transmission, storage and LNG system operators as per Art.2 point 6, 4, 10 and 12 of the Dir. 2009/73 - Operators of natural gas refining and treatment facilities
	Hydrogen: - Operators of hydrogen production, storage and transmission
Water	**Drinking water**: - Suppliers and distributors of water intended for human consumption as per Art.2.1a. of Dir. 2020/2184, excluding distributors of which it is not an essential part of their activity
	Wastewater: - Undertakings collecting, treating or disposing of urban, domestic or industrial waste water as per Art.2. point 1 to 3 of Dir. 91/271, excluding undertakings of which it is not an essential part of their activity
Health & Emergency	- **Healthcare providers** as per Art.3.g of the Dir. 2011/24 → Dir. 2023/2450: provision of healthcare services - EU reference **laboratories** as per Art.15. of Reg. 2022/2371 → Dir. 2023/2450: analysis and R&D - Entities carrying out R&D activities of medicinal** products as per Art.1.2 of Dir. 2001/83 - Entities manufacturing basic **pharmaceutical products** and preparations as per Sec.C.21 of NACE Rev. 2 - Entities manufacturing **medical devices** considered as critical during public health emergencies as per Art.2. of Reg. 2022/123 - Entities holding a distribution authorisation (of medicinal products, substance(s) for treating or preventing disease in human beings) as per Art.79. of Dir. 2001/83

Table 2.1: European Commission – Overview of Relevant (sub)Sectors (Debelle, 2026)

** "*Medicinal*" refers specifically to substances or products used to prevent or treat disease in human beings, or restore, correct or modify a physiological function (Medicines and Healthcare Products Regulatory Agency, 2013) (Committee on Public Health (SANT), 2025). "*Medical*" usually refers to products being devices helpful in the provision of healthcare services.

Comments

Generally, the European Union and the European Commission have few powers to enforce the directive onto its MS and their national regulations. Whether the CEs as defined by the EU and those considered by the Netherlands and Germany are comparable will be further discussed in section 2.4.2 and 2.4.3, after the nations' respective implementation of the directive. Notwithstanding, another intergovernmental organisation possess quite some indirect enforcement powers, notably on economic, financial and defence aspects of CIs' resilience. Recently, NATO summits and Allies discussions, particularly influenced by its principal member the United States of America, have led other states to increase their GDP's share of expenditures towards their defence budget and the resilience of their CIs (NATO, 2025).

2.2.2. North Atlantic Treaty Organization (NATO)

Since both nations of the Netherlands and Germany are Allies of the NATO, and because recent geopolitical events have had an influence on budgets and incentives for the resilience of CIs, this intergovernmental organisation is also relevant to the study of CI definition. The NATO defines resilience as the "individual and collective capacity to prepare for, resist, respond to and quickly recover from shocks and disruptions, and to ensure the continuity of the Alliance's activities". It hereby considers civil preparedness as key pillar of resilience and enabler of joint defence of the allies. According to the NATO, civil preparedness refers to the continuity of government activities, essential services and support to military operations, during emergencies. Article 3 of the North Atlantic Treaty lays fundamental principles to this preparedness and states the following:

> *"[...] the Parties, separately and jointly, by means of continuous and effective self-help and mutual aid, will maintain and develop their individual and collective capacity to resist armed attack."*

Though with initial intention oriented towards military and defence purposes, this article indirectly dictates the resilience of CIs against natural disasters, failures, armed attack or a mix of these as well (NATO, 2024). This therefore puts a responsibility onto Allies to manage their national resilience in all kinds of disruptive events, on their CIs but not only. To this end, the Allies agreed to seven requirements for national resilience, to which Allies may estimate their (civil) preparedness (7 baseline requirements, BLRs) (bold elements are of particular interest to the present study):

a) Continuity of critical government services;
b) Resilient energy supplies;
c) Ability to deal with uncontrolled movement of people;
d) Resilient food and water resources;
e) Ability to deal with mass casualties and disruptive health crises;
f) Resilient civil communication systems;
g) Resilient transport systems.

Besides, the NATO provides the following definition for CIs (NATO Energy Security Centre of Excellence, 2025):

> *"Critical infrastructures refer to the physical and cyber-based systems vital for the basic functioning of the economy and security of states"*

In cooperation with the European Union, the NATO launched a Task Force on the Resilience of Critical Infrastructures in March 2023. This task force was initiated with main objectives to identify and map actual security challenges to CIs across EU MS and NATO Allies, providing a cooperation incentive between the EU and the NATO for the protection of CIs and the enhancement of their resilience. The task force published a final assessment report in June 2023, focusing on the sector of energy, transport, digital infrastructure and space, and coming to the conclusion that the sectors are particularly vulnerable due to interdependencies between nations and sectors, the presence of hybrid threats (both physical and cyber), and the cross-border nature of many CIs.

2.3. Legal Framework: National Institutions (NL, DE)

Below, the legal frameworks concerning critical infrastructures is now addressed from the view of the respective national entities and states, being the Kingdom of the Netherlands and the Federal Republic of Germany.

2.3.1. Netherlands

The Dutch governmental institutions refer to critical infrastructures as "Vitale Infrastructuur" (EN: vital infrastructure). The Netherlands' public administration is divided into four jurisdictional levels: the central government, the 12 provinces (of which the *Limburg* province is one), the municipalities and the 21 water authorities (called "waterschap", "heemraad" or "hoogheemraad") (Ministry of the Interior and Kingdom Relations, n.d.). This last level underscores the country's awareness with regards to water management and flood risks, as a quarter of the country lies below the sea level, and more than half of it is susceptible to witness floodings (Dutch Water Authorities, n.d.). The Rijkswaterstaat ("water state of the realm") is the executive agency of the Ministry of Infrastructure and Water Management (Ministerie van Infrastructuur en Waterstaat – I&W), and closely collaborates with the local water boards in terms of regional and national protection against floods, droughts, extreme precipitation and generally water-related natural hazards (Rijkswaterstaat Ministerie van Infrastructuur en Waterstaat, n.d.).

The NCTV, "Nationaal Coördinator Terrorismebestrijding en Veiligheid" (EN: National Coordinator for Security and Counterterrorism) is part of the country's Ministry for Justice and Security (JenV), and is a central actor in the protection of national interests, caring amongst other for the country's CIs by identifying disruptive threats and strengthening both their local and global resilience. Together with other governmental partners such as the AIVD, "Algemene Inlichtingen- en Veiligheidsdienst" (EN: General Intelligence and Security Service) or National Cyber Security Centre (NCSC), the agency also drafts policies and develops resilience tools for the protection of Dutch CIs. Additionally, the will of the government to strengthen its nation's CIs resilience is endorsed and validated by Dutch employer organisations and business federations such as the VNO-NCW or the MKB-Nederland (Gielens, 2025). Both emphasise the urgent need for increased resilience, government support for businesses and policies, and clear incentives and communications about Dutch defence needs.

Definition

The Netherlands, through the JenV, define critical infrastructures as "*Products, services and the underlying processes which, if they fail, can cause large-scale societal disruptions*", according to the Dutch security council "Veiligheidsberaad" and its 2015 Guideline document on the roles and responsibilities on Dutch territories in events of threats to or disruptions in vital services (Littooij & van Eck, 2015).

As per the Netherlands Institute for Public Safety (NIPV), the Dutch public research institute tied to all safety regions, the central government as well as partner crisis management institutions, outlines the term of vital infrastructure as

> *"Processes, products, or services such as access to drinking water, electricity, internet, and payment transactions that are essential for the daily lives of most people in the Netherlands".*

On the governmental side, the Tweede Kamer der Staten-Generaal (EN: the lower house of the Dutch parliament) describes –in its draft bill of the 5th of June 2025– a CE and a CI just as they are defined in the EU's CER directive. Other aspects, such as the "significance of a disruptive effect" and its 6 criteria (see Ch.4 Art.6.2), are also fully drawn and directly translated from the CER directive.

These are then also divided into two categories, depending on the severity of consequences a disruption to such CIs may have. Though deeper criteria for the attribution of these categories seem to not be publicly available, the "Thematic report on threats to vital infrastructure" from the Dutch *National Security Analyst Network* (ANV) appears to indicate that the scale of cascading effects in both affected area surface and duration are benchmarks to the allocation of categories. Additionally, it provides a first

overview of vital processes and their respective category, sector and responsible ministry (Analistennetwerk Nationale Veiligheid, 2022). Published in July 2022, the report is redacted on behalf of the JenV by the NCTV, the AIVD, the Military Intelligence and Security Service (MIVD), and the National Institute for Public Health and the Environment (RIVM) amongst others. Altogether, the reports identify and assess threats to the Kingdom of the Netherlands, through risk analyses. Separately, the NCTV affirms that the decision-making of category allocation is based on economic, physical, societal and potentially cascading consequences of a failing process (NCTV, n.d.-a).

It is pertinent to highlight that the NCTV, and many ministries, legally referred to vital infrastructures (CIs) as vital providers, in policies existing prior to the CER directive. In the Wwke Act transposing this EU directive, Dutch institutions and governmental bodies therefrom adopt the same term and refer to it as Critical Entities (NCTV, n.d.-b).

Acts

The ministry of Justice and Security submitted on June 4th (resp. June 2nd), 2025, the *Critical Entities Resilience Act* (Wwke – Wet weerbaarheid kritieke entiteiten) resp. the *Cybersecurity Act* (Cbw – Cyberbeveiligingswet), with primary objective to transpose and implement the European CER resp. NIS2 directive into the Dutch legislation (Tweede Kamer der Staten-Generaal, 2025a; 2025b). According to the Tweede Kamer der Staten-Generaal (House of Representatives of the Netherlands), both acts are not yet signed into law and are currently at the parliamentary proposal stages. On June 18th, the National Inspectorate for Digital Infrastructure, part of the Ministry of Economic Affairs (EZ), asserted that the government wishes both acts to enter into force in the second quarter of 2026 at the latest (Rijksinspectie Digitale Infrastructuur, 2025; NCTV, n.d.-d).

The Wwke and the Cbw are currently still draft bills (“voorstel van wet”) under parliamentary preparatory processes since early June 2025, and are accompanied amongst others by an explanatory memorandum (“memorie van toelichting”), which provides explanation onto why the law is proposed and needed, what is the correct interpretation of the articles and how it should be adopted with regards to other, existing Dutch regulations. Updates from the Tweede Kamer are provided on a regular basis, with documents such as the Council of State’s advice, the government’s response to Parliament, decision notes, or draft implementing decrees.

The Wwke mandates entities critical to the functioning of the Dutch society, amongst others, to systematically catalogue and map risks that may possibly affect them. To support businesses and organisations in these regards and in identifying the climatic threats to their facility, the I&W ministry for example therefore commissioned the independent research institute of *Deltares* based in Delft, to develop and provide a guideline (Deltares, 2025; Ministerie van Infrastructuur en Waterstaat, 2025).

CIs Included

Overall, the NCTV and relevant ministries consider the following sectors as vital to the provision of essential services: Energy, Transport, Banking, Financial Market Infrastructure, Healthcare, Drinking Water, Wastewater, Digital Infrastructure, Government, Aerospace, and Food Production, Processing, and Distribution (NCTV, n.d.-c). With regards to the present study, a summary table with insights into the relevant sectors’ subdivisions is provided below. It must be underlined that the NCTV classifies them as critical process (i.e. services) and not CEs or CIs per se.

While most of the subsectors provided in the table below originate directly from the Wwke or the Cbw, being a relatively direct transpositions from the European directive, some subsectors are drawn from official governmental websites or articles. Sometimes published before the two draft acts, they do describe the status quo from still applicable

laws (as the draft acts are not yet signed into law), and mention other relevant facilities not mentioned in the Wwke or Cbw. The Netherlands' only act about CIs before the Wwke is the Wbni, implementing the first NIS directive in 2016 and not providing enough details on the current legal landscape / environment around CIs.

Sectors	General Overview
Energy	**Electricity**: - Transportation, distribution and production of electricity, onshore and offshore, national and regional - Storage, production and processing of nuclear materials **District heating and cooling**: as defined by the CER-directive **Oil**: - Storage, transport, refining, and processing of crude oil and petroleum products - Large-scale production, processing and storage of petrochemicals **Gas**: - Transportation, distribution, production, regasification of gas, onshore and offshore, national and regional
Water	**Drinking water**: - Supply and distribution **Wastewater***: - Collection, discharge and treatment of domestic and industrial wastewater **Water infrastructure**: - Water quantity control, water management, flood defences, vessel traffic service
Health & Emergency	- **Healthcare providers*** as per the CER Directive - **Laboratories** as per the CER Directive - **R&D entities** as per the CER Directive - **Manufacturers** of **pharmaceutical products** or **medical devices** as per the CER Directive - Entities holding a distribution authorisation as per the CER Directive - Communication with and between emergency services through the 112 number and C2000 communication network - Police deployment and military deployment N.B.: the Cbw law proposal indicates that, contrary to all the abovementioned CIs, the manufacturing and distribution of pharmaceutical products are of lower importance and significance (they are considered "important" rather than "essential", which is higher in significance).

Table 2.2: Netherlands – Overview of Relevant (sub)Sectors (Debelle, 2026; Data: Appendix C Section 1)

* The Wwke indicates that wastewater and healthcare infrastructures are not yet part of any legislations regarding the reporting duty, duty of care, or of risk assessment of physical security and threats. Once signed into law, the Wwke will change this.

2.3.2. Germany

In the German governmental institutions, critical infrastructures are referred to as “Kritische Infrastrukturen”, often shortened to KRITIS. The Federal Republic of Germany is constitutionally established as a democratic, federal parliamentary republic operating through a decentralised system, distributing legislative and administrative responsibilities between the federal government (Bund) and the 16 sub-national administrative states (Bundesländer, of which the *NRW – Nordrhein-Westfalen* is one) (BMI, 2026). Both the federal state and the constituent states all possess their own constitutions, parliaments, administrative structure, responsibilities and therefore their own powers. The Länder have the right to legislate in all areas which are not bestowed to the federal level in the German constitution (the Grundgesetz – GG, Basic Law) (Bundesverfassungs-gericht, n.d.). The Bund is in charge of foreign policies, defence topics, railways, telecommunications, and the federal police (Bundespolizei) (Landesbildungs-server Baden-Württemberg, n.d.; Bundeszentrale für politische Bildung, 2014; Bundesministerium der Justiz und für Verbraucherschutz, 2023). On the other hand, Länder are responsible for education, the state police (Landespolizei), the administration of justice, cultural affairs and state roads and hospitals.

The management and protection of CIs is a shared competences between the federal government and the federal states, as the sectors and domains studied in the present paper overlap in many ways (BMI, n.d.-a; BMI, n.d.-d; BSI, n.d.-c). Principally, the German federal authorities are responsible for setting the national objectives, procedures and strategies for the protection and resilience of their CIs, and cooperate locally with federal states when necessary for crisis management (BBK, n.d.-f; BSI, n.d.-b). The resulting federal laws and regulations, in hierarchy above the state laws (Grundgesetz für die Bundesrepublik Deutschland [Basic Law], 1949, Art. 31), then serve as guidance to the states for the management of CIs, though the core responsibility of resilience mostly resides within the operator of a CI itself (BSI, n.d.-e). Three ministries / offices are predominantly involved in projects for the protection of German CIs:

Abbre-viation	German name	English name	Responsibilities
BBK	Bundesamt für Bevölkerungsschutz und Katastrophenhilfe	Federal Office of Civil Protection and Disaster Assistance	Civil protection through protective structures, disaster relief, health and cultural heritage protection, ...
BMI	Bundesministerium des Innern	Federal Ministry of the Interior	Modernisation of the state and its administration, civil protection and security, promotion of social cohesion and constitution through integration and information technology
BSI	Bundesamt für Sicherheit in der Informationstechnik	Federal Office for Information Security	Prevention, detection and response in the information security sector, for the government, industry and the society

Table 2.3: Ministries and Responsibilities (Debelle, 2026; Data: Appendix C Section 2)

Definition

The BMI and other federal ministries define critical infrastructures as

> "*organisations and facilities of vital importance to the state, whose failure or impairment would result in sustained supply shortages, significant disruptions to public safety, or other dramatic consequences*",

according to the BMI's "Draft of the Cybersecurity Strategy for Germany 2021", or the BBK's, BMI's and BSI's homepage on critical infrastructures (KRITIS) (BBK, n.d.-b; BMI, n.d.-e; BSI, n.d.-e).

From a statutory perspective with juridical terms, CIs are legally defined in the BSIG (BSI-Gesetz, BSI's Act, § 2 Subs.10) (still applicable) (BMI, 2024) as:

> "*Facilities, installations or parts thereof which are*
>
> *1. part of the sectors of energy, information technology and telecommunications, transport and traffic, health, water, food, finance and insurance, and municipal waste disposal and*
>
> *2. of high importance for the functioning of society because their failure or impairment would lead to significant supply shortages or threats to public safety*."

The threshold to which a supply is considered short or a failure considered threatening is defined by the BSI and all pertinent ministries relevant to the CI sectors (BSI, 2024-b; Bundesministerium der Justiz und für Verbraucherschutz, 2026; Bundesministerium der Justiz und für Verbraucherschutz, n.d., para.1). The BSI's definition in the BSIG is further specified in 2015 through the BSI-KritisV (BSI-Kritisverordnung, BSI's CI ordinance), which provides clear definitions of and criteria for thresholds and facilities of concerned CIs operators (OpenKRITIS, 2025b; Bundesministerium der Justiz und für Verbraucherschutz, n.d.). It is worth noting that the German scientific community, such as the research institute Fraunhofer, seem to agree to the governmental definitions of CIs (Fraunhofer, n.d.).

Acts

The BSIG act serves as legal basis for CI and their operators in Germany, and has been undergoing several amendments throughout the years, with current drafts for the transposition and implementation of the EU's CER and NIS2 directives: the CI Protection Act or KRITIS umbrella law ("*KRITIS-Dachgesetz*" – KRITIS-DachG) for the CER directive and the NIS2 Implementation Act ("*NIS2-Umsetzungsgesetz*") for the NIS2 directive (OpenKRITIS, 2025a; 2025b). These drafts represent new laws, not amendments to previous act.

The KRITIS umbrella law draft has been adopted by the German federal cabinet on the 10th of September 2025 (Die Bundesregierung, 2025; BMI, n.d.-e). This law provides for example new threshold and minimum requirements for the protection of CIs. An institution or a facility is considered as essential supplier of services if it provides such to more than 500,000 people (BMI, 2025a; 2025b, Art.5.2). This threshold is provided as generic statistical example (BMI, 2025b, p.52-53, "Zu Absatz 2"), and is then used in formulas present in Annexes of the BSI-KritisV to determine threshold individually for each type of facility of a specific critical sector (for example in Anhang [Annex] 1 of BSI-KritisV from the Bundesministerium der Justiz und für Verbraucherschutz (n.d.)).

The NIS2 Implementation Act has been adopted likewise on the 30th of July, 2025 (BMI, 2024). For example, this new act rises security obligations for 30,000 business in Germany and obligates them to provide proves of compliance on a 3-year basis (OpenKRITIS, 2025e).

The BSI is responsible for the national implementation of the NIS2 and CER directive (BSI, n.d.-f). The next steps in these legal implementations are a review from the 16

federal state (Länder), three further readings by the parliament (Bundestag), an approval from the federal council (Bundesrat), and countersignatures from the federal minister who initially submitted the draft as well as from the German chancellor and president (BSI, n.d.-a; BMI, n.d.-f). The law then enters into force once published in the federal law gazette ("*Bundesgesetzblatt*"). The prime source of explanations to legal subjects around these matters is the OpenKRITIS Plattform and its webpages on the NIS2-Umsetzung and KRITIS-Dachgesetz (OpenKRITIS, 2025a; 2025c).

CIs Included

According to the Art. 4 of the KRITIS-Dachgesetz, critical sectors are those providing a critical service to the general public in terms of: Energy, Transport and traffic, Finance, Social security benefits and basic income support for job seekers, Healthcare, Water, Food, Information technology and telecommunications, Space and Municipal waste disposal. Further details into each sector are provided in the BSI-KritisV, as well as in older acts still applicable by the time of the present study, and are summarised below for the sectors relevant to the present paper.

Sectors	General Overview
Energy	**Electricity**: - Electricity and power supply for the general public, by means of generation, trading, transmission and distribution **Oil**: - Fuel and heating oil supply for the general public, by means of crude oil production, product manufacturing, mineral oil trading, oil transport and storage, and fuel and heating oil distribution **Gas**: - Gas supply for the general public, by means of production, trading, transport and distribution **District heating**: - district heating supply to the general public, by means of generation, control, monitoring and distribution N.B.: For detailed insights into the literal facilities involved in this sector, together with lists of criteria and thresholds to select them, the BSI-KritisV provides an extensive document and table in Annex 1 of the same document
Water	**Drinking water**: - Drinking water supply to the general public, by means of extraction, treatment, distribution, control and monitoring **Wastewater**: - Wastewater disposal from the general public, by means of urban drainage, treatment, discharge into water bodies, control and monitoring **Water infrastructure**: no mention N.B.: For detailed insights into [...], in Annex 2 [...]
Health & Emergency	- **Inpatient medical care** (hospitals) and emergency response team - **Pharmacies** - Supply of immediately life-sustaining consumable **medical products**, by means of **manufacturing** and distribution, donation control centres (blood and plasma), operating and storage space, pharmacies

- **Supply of prescription drugs**, blood and plasma concentrates for use in/on the human body, by means of manufacturing and distribution - Laboratory and thereof information network N.B.: For detailed insights into [...], in Annex 5 [...]

Table 2.4: Germany – Overview of Relevant (sub)Sectors (Debelle, 2026; Data: Appendix C Section 3)

2.4. Comparative Analysis of Regulatory Frameworks and Implementation

Building on the legal frameworks covering the sectors of critical infrastructures in the studied countries seen in the previous section, the present section provides a comparative analysis of how the European Union's, the Dutch and the German CI resilience mandates are transposed into their laws, and translated into practice. This section aims at providing a comprehensive understanding of potential functional alignments or disparities between the three polities, beginning with the consideration and integration of cross-border and cascading events in local laws. A series of comparative evaluations then enable the identification of key similarities and distinctive features between the EU, the Netherlands and Germany, allowing to draw implications for the present study.

The following insights are drawn on the basis of publicly available information and documentation. Confidential sources may deeper address the presented topics, or consider more factors than accessible to the general public via articles, reports or legal acts.

2.4.1. Integration of Cross-Border and Cascading Effects Dimensions in National Initiatives

Cross-Border Dimensions

The CER directive highlights several aspects key to the relevance of the present study. First, it underscore the necessity for MS to include cross-border relations and activities in their risk assessment and strategies. This is consistent with the European Union and its general goal of cooperation between its MS, regardless of the activity. That aspect is also presented by the assessment report of the EU-NATO Task Force. The Netherlands have published, in July 2025, an extended report on the threat landscape to CIs in the same year, and include threats from major geopolitical conflicts such as the Russia-Ukraine war, from cyberattacks and espionage from nations as China, but also from neighbouring countries such as sabotage acts in Germany (NCTV, 2025). Regarding Germany, no publicly accessible risk assessment report are available by the time of this research.

Cascading Disruptions Dimensions

Additionally, the CER directive and the EU-NATO assessment report (in-)directly mention the importance of considering cascading effects, as both state that MS / Allies and CEs must consider, in their risk assessment, dependent nations/CEs and related operators responsible of the provision of other dependent ES. In the current state of literature and available online information, the Netherlands and Germany do not exhibit evidence of acknowledging the existence of such effects in national legislation or considering it in assessment undertakings.

2.4.2. Comparative Assessment of CIs Definitions

After providing exact and granular definitions of critical infrastructures and thereof subsectors for the European Union and both countries in sections 2.2 and 2.3, a comparison is crucial to gain a broader and macro overview of commonalities (C) and differences (D) in the institutional definitions. Despite the CER-Directive setting a common baseline, the national specificities for what counts as critical subsector or infrastructure often differ from the European institutions' standpoint and, unequivocally, from neighbouring countries.

Table 2.5 provides clear and concise comparisons of these definitions, showing exactly where the local governmental agencies have agreed or differed from the European CER foundations. This analysis later serves to understand where transboundary consensus or friction may exist within the networks of CIs, as well as within strategic collaboration opportunities between nations.

CI Sector	EU	Netherlands	Germany
Energy (C)	The EU, the Netherlands and Germany all agree that entities involved in the most common activities of the provision of following resources are critical entities: electricity, oil, gas.		
Energy (D)	District heating and cooling is part of the critical sector, is the CER directive and the Wwke.		District heating is part of the critical sector, but only in the BSIG-V, not the KRITIS-DachG.
Water (D)	The EU, in any of its two directives, does not consider as CI any water work or infrastructure that does not directly serve the provision of drinking water, the treatment of wastewater, or the sector of water transportation.	The Netherlands declare, in distinct articles from its two draft bills, that water works and infrastructure for water management or flood defence purposes are of high priority when considering critical entities (NCTV, 2018).	Germany, in any of its two draft bills and just as the EU, does not consider as CI any water work or infrastructure that.
Water (C)	For all, the provision of drinking water, treatment of wastewater and overall the management of and activities involved in these are considered as critical infrastructures.		
Health & Emergency (C/D)	All agree that the provision of primary and essential healthcare services is critical, such as the activities the following entities / facilities engage in: hospitals, general practitioners, pharmacies, pharmaceutical manufacturers and laboratories. Nonetheless, differences exist between their definition of healthcare provision.		
	For the EU, healthcare providers assess, maintain or restore a patient's state of health, including the prescription, dispensation and	For the Netherlands (Wet kwalieit, klachten en geschillen zorg), healthcare providers engage in all activities of long-term care (Wlz-zorg,	For Germany, the KRITIS-Dachgesetz provides only general information on the healthcare sector, not naming any kind of entity or facility. The BSIG-V act

	provision of medical products (Art.3.g of DIR 2011/24/EU) → long-term care is not a critical service (KRITIS-DachG. p.49 para.2).	admitted to a healthcare institution) or short-term care (Zvw-zorg, visit to general practitioner or hospital) (Sociale Verzekeringbank).	mentions “inpatient medical care”, further developed in annex as hospitals only.
Health (C&D)	In the EU and both countries, a significant ambiguity persists concerning its subsectors. Though all agree on the aforementioned, little to no article of any directive or act mentions emergency response services not located within hospitals, nor firefighter stations, police stations or the military compounds / troop headquarters (for emergencies and rescue purposes). The Netherlands briefly mention the “deployment of police and military forces”, without further explanations.		
Health (D)	The EU and the Netherlands provide an extended list for types of medicinal products part of the subsector distributing them: human blood and blood products, animal or vegetable or chemical products, vaccines or serums, ... (see Art.1.3 of Dir.2001/83)		Germany specifically considers blood and plasma on a separate level (BSIG-V), and never mentions other medicinal products.
Other	Further commonalities and differences exists for the sectors not addressed in the present study.		

Table 2.5: Comparison on CIs definitions (Debelle, 2026)

2.4.3. Comparative Assessment of Institutional Approaches and Governances

Beyond the static comparison of sector-specific legislation and associated provisions from the national bodies to transpose the European CER-directive, it is equally significant to evaluate the institutional conduct and responsiveness of the EU and both member states. This includes an assessment of their approach toward the formulation, implementation and enforcement of these legal frameworks and subsequent evaluation or collaboration projects.

Table 2.6 compares these approaches from an EU, Dutch and German standpoint, with topics of comparison inspired from the readings of legal documentations, newspapers and assessment reports of various bodies.

Topic	EU	Netherlands	Germany
Risk awareness	The European Union and both countries entirely acknowledge all categories of threats: - Natural hazards: storms, rainfalls & floodings, droughts, earthquake, pandemics - Anthropogenic hazards: accidents & system failures, sabotage and cyber-attacks, terrorism, war (European Commission, 2026; NCTV, 2025; BBK, n.d.-c)		
Implementing the directives	/	Both countries have announced, via a national minister to their respective governments and parliaments, the intent to fully transpose and implement the CER and NIS2 directives*. Both their draft acts transpose the CER and NIS2 directive	

		nearly as is, without altering much any article or definition. Previous and presently enforced acts exhibit significant differences.	
Level of detail	The EU provides descriptions of the overall sectors considered as critical, as well as the affected subsectors of each (CER) and the type of underlying facility and operators (DIR2023/2450).	The Netherlands provide descriptions of the overall sectors considered as critical, but do not go deeper than the subsectors of each.	In the KRITIS-DachG., Germany provides less explanations and details as the CER directive, but the BSIG-V provided it already, with even more precise selection criteria for each of the categories (sector, subsector and facility/operator).
Thresholds and criteria for CI/CE selection	The EU and the Netherlands do not provide measurable criteria or thresholds for the identification and selection of CIs, just brought requirements.		Germany provides measurable thresholds to identify and select its CIs.
Identification of its CIs	The EU has not undertaken any project to identify all CIs of its member states.	The Netherlands have not undertaken extensive projects to identify their CIs.	Germany has identified a substantial quantity of CEs, but does not publicly provide further details on their characteristics.
Conducting risk assessments	The EU will not conduct any risk assessments (RA) for its MS.	The Netherlands have published a threat landscape report in 2025, possible after the CER directive.	Germany has not yet undertaken / published its RA.
Significance of disruption	The EU delegates the responsibility of significance determination to its MS.	An infrastructure is either essential (category A), important (category B) or not a CI.	An infrastructure is either a CI or not, depending on if it exceeds the threshold as per BSIG-V.
Necessity for cooperation	The EU highlights the need for cooperation between its members. states in the CER and NIS2 directives.	Although neither of the countries have published a risk assessment of their CIs and therefore possible threats from neighbouring countries, both are aware of the necessity for cooperation, acknowledge the EU's incentive for cooperation (KRITIS-Dachgesetz Art.3.8), and already carry out a variety of projects in these regards, or in regards of existing threats: - JCAR-ATRACE & EMRIC - BBK and BSI projects, NCTV	

Table 2.6: Comparison on the institutional approaches (Debelle, 2026)

* In theory and by announcing their intentions, both countries should have similar if not identical views on their CIs, as they aspire to transpose and implement the European directives as they are.

2.4.4. Synthesis and Practical Implications of Comparative Findings

Synthesis

Overall, the European Union, the Netherlands and Germany all consider the identical primary sectors as critical entities and facilities. In contrast, upon examination of their subsector's definitions, both minor and significant similarities and discrepancies are discernible. While all are closely aligned on the energy sector, the Netherlands considers more facilities into its water sector than do the EU and Germany. To this nation, any water infrastructure, including for water management and flood defences, is deemed as critical, and not just those of drinking water and wastewater. Regarding the healthcare sector, Germany does not seem to consider medicinal products other than blood and plasma, as part of critical medical products (e.g.: vaccines). Last, although all consider quite the same entities for the healthcare sector, none truly include emergency response services and thereof teams such as firefighter, rescuers, or law enforcement operators such as the police.

About the implementation of the CER directive, although Germany seems to provide less information in its draft bill than do the Netherlands, it has provided detailed and measurable criteria for the selection of entities and operators in its BSIG-V act already, and governmental institution and ministries (BBK, BMI, ...) provide further explanation in website articles. Publicly, it also seems to have already identified most if not all of these facilities, whereas the Netherlands have not. On the contrary, the Netherlands have published a risk assessment in 2025, which appears to be in accordance with the EU's incentive from the CER directive, and offers a clear view on the threat landscape to CIs of the country.

Implications of Discrepancies

The aforementioned commonalities and differences in national definitions of critical infrastructure may influence the assessment of geospatial data and the integration of interdependencies within the countries' networks, as studied in Chapter 4. As the availability of primary legal sources and literature data may be limited to publicly disclosable acts only, the below mentioned implications may be altered if confidential sources are available to integration.

On the one hand, the energy CIs are uniformly and almost identically defined. This simultaneously permits an empirical comparison of the countries' energy networks, and the integration of interdependencies drawn from other sources, as the physical asset are considered identically on both sides of the border.

On the other hand, regarding the water CIs, similar assessment will only be possible for the networks of drinking water and waste water. As Germany places a significantly reduced emphasis on water infrastructure existing independently of the former two subsectors –put simply, water infrastructure for flood defence purposes–, physical assets in German territories might undergo fewer protective measures against damages and failures, from which a flood could cause greater damages, particularly downstream and therefore in Dutch territories.

Lastly, in the event of natural hazard events, the lack of common and precise definition of infrastructure and entities relevant to the provision of healthcare could severely impact potential cross-border cooperations. As hospital facilities vary in parameters such as size and patients capacity, diversity of services, location or workforce availability, not sharing common grounds for the application of protective or resilience measures may impede

opportunities for cross-border dispatching of patients or alleviating over capacitated hospitals. In addition, the lack of framework around fire departments may particularly affect the capacity of local municipalities to conduct transboundary rescue missions if not clearly defined by legal, financial and criticality measures.

2.5. CIs Responsibilities

The following section provides a comprehensive overview of the institutions and partners responsible for each subsector. These are analysed across both studied countries, distinguishing between governmental entities and commercial actors, and presented under hierarchy diagrams.

All hierarchical diagrams in the current section 2.5 delineate the organisational and administrative structures of the CI sectors investigated in the present study, and are derived from a systematic review of legal documentation from national and regional governmental documentation, as well as of official corporate media channels and online communication of the identified entities. Within the Energy sector, while “district heating and cooling” is categorised as a distinct subsector following the national directives on the resilience of CIs, it must be noted that it only represents a significantly small share of the energy market in both the Netherlands and Germany, respectively 4 and 14% (Interreg North-West Europea HeatNet NEW, n.d.; Epp, 2024). Additionally, the providers of this niche often hold overlapping operations with the other Energy sub-markets of electricity and gas. On another note, the “Health services” sector is here defined as an aggregation of all subsectors found relevant in sections 2.3.1 and 2.3.2, i.e.: hospitals and clinics, manufacturing facilities of pharmaceutical products and medical technology devices, laboratories and research facilities, police and fire stations, as well as crisis management entities in charge of emergency responses.

For the purpose of this study, bodies involved in the provision and distribution of blood and plasma are integrated in the subsector of “Hospitals and clinics”, while other medicinal products manufacturers are grouped under “Products (pharma + medical technology)”. Regarding commercial responsibilities, the diagrams prioritise central organisations that manage either the country’s subsector in national matters, or onto the regional level of the studied areas (LIM / NRW). This selective approach is adopted to preserve an analytical clarity of the diagrams, and ensure the visual coherence for the mapping of the subsectors, keeping only large actors relevant to the study. This simplification is further required as smaller infrastructures are frequently commanded at a decentralised municipal level, with small governing bodies falling outside of the macro-level scope of this assessment.

2.5.1. Governmental responsibilities

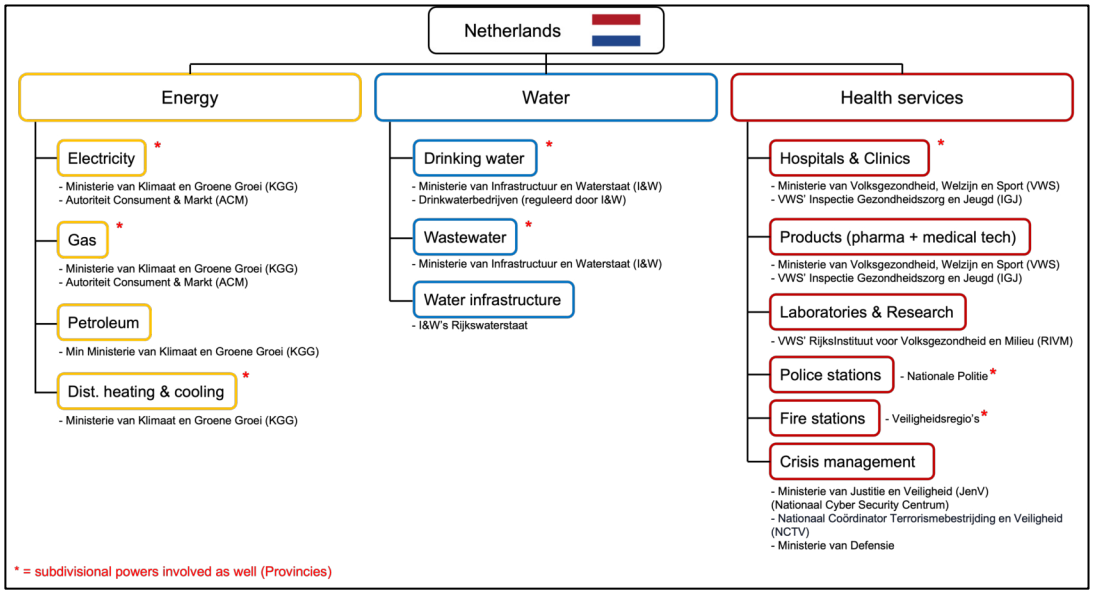


Figure 2.1: Governmental Responsibilities in the Netherlands (Debelle, 2026)

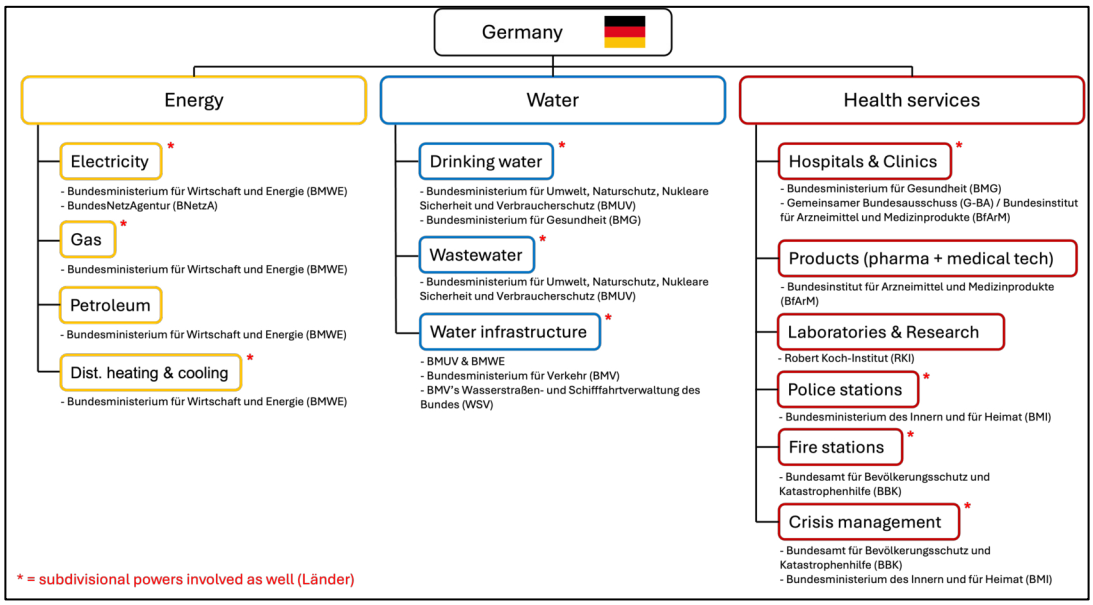


Figure 2.2: Governmental Responsibilities in Germany (Debelle, 2026)

As illustrated in Figure 2.1 and Figure 2.2, the primary responsibility for energy and water affairs is respectively consolidated within a single ministry of each country. Due to the formation of new governments since the publication of relevant papers, the CER-directive and thereof national transposition projects from the respective countries, some ministries may possess different designations according to the publishing date of the consulted documentation.

- For the Energy sector, it is the Dutch Ministry of Climate Policy and Green Growth (KGG), formerly part of the Ministry of Economic Affairs and Climate Policy (EZK) until June 2024 (van Gastel, 2024), and the German Federal Ministry for Economic Affairs and Energy (BMWE), also named the Federal Ministry of Economic Affairs and Climate Action from December 2021 to May 2025 (Bundeskanzler, 2021; Federal Ministry for Economic Affairs and Energy, 2025).

– For the Water sector, the Dutch Ministry of Infrastructure and Water Management is in charge, which is also responsible for affairs in maritime, aviation and road mobility, as well as environment and sustainable economy topics. The German counterpart is the Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety (BMUKN), also named the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection until May 2025 (Deutscher Bundestag , 2025)

Having these two ministries respectively overseeing such wide ranges of critical infrastructure sectors suggests a clear and unified criticality definition in both countries. For current and future resilience projects undertaken by the governmental institutions of the Netherlands and Germany, this could mean that a global comprehension of the national energy and water infrastructures and thereof interdependencies is acquired, therefore enabling better cooperation amongst stakeholders prior to —or at times of— crises, perhaps even with the neighbouring countries.

On the contrary, most subsectors of health and emergency response services do not share a common overarching governmental entity. While all subsectors fall under institutions with national missions and mandates, this administrative divergence could indicate a health sector uniquely vulnerable to coordination bottlenecks and information silos during crisis scenarios. Here, the existence of entities such as the German Committee for Disaster Reduction (*DKKV – Deutsches Komitee Katastrophen-vorsorge*) may reveal evidence that governmental institutions alone do not automatically or sufficiently coordinate on disaster preparedness and CI protection topics. The global heterogeneity observation in the Health sector demonstrated above would be consistent and aligned with the finding of the overall conclusion of section 2.4**Error! Reference source not found.**, indicating that the Health sector is not sufficiently mastered and/or defined by relevant authorities.

2.5.2. Commercial responsibilities

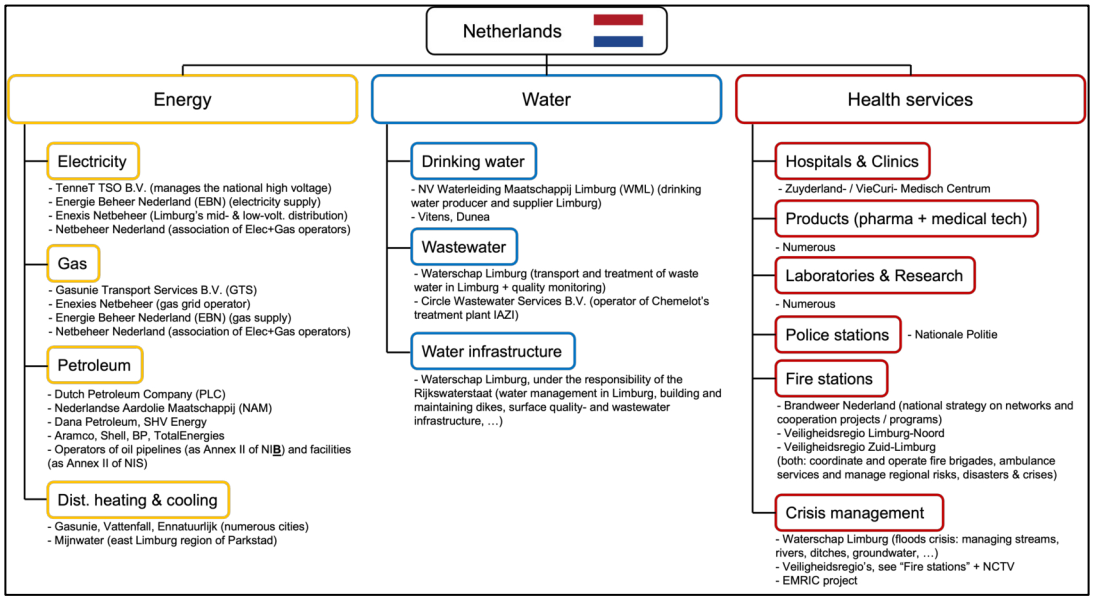


Figure 2.3: Commercial Responsibilities in the Netherlands (Debelle, 2026)

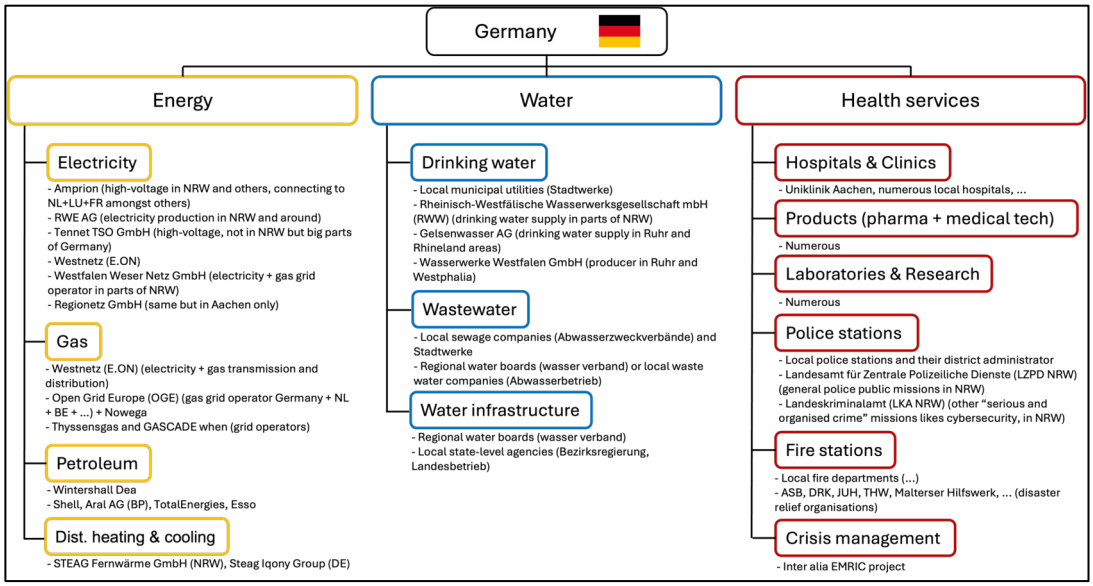


Figure 2.4: Commercial Responsibilities in Germany (Debelle, 2026)

Several conclusions may be drawn from Figure 2.3 and Figure 2.4, as the graphs visually demonstrate a gap in the governance of critical infrastructures, again between the Energy and Water sector on the one hand, and the Health sector on the other.

In Energy, the subsectors are vastly characterised by oligopolies, with few large companies managing vast portions of the network, at times onto other subsectors (e.g. *Gasunie* or *Enexis Netbeheer* in the Netherlands, or *Westnetz E.ON* in Germany), if not onto other countries (like *Tennet TSO* having grounds and activities in both countries, just as *Shell*, *TotalEnergies*, or *BP* and its subsidiary *Aral AG*). In the German subsector of gas for example, the company *Wintershall Dea* has initiated collaboration projects in late 2023, partnering with *Open Grid Europe GmbH* and the Belgian oil and gas operator *Fluxys* (Wintershall Dea, 2023) to open a gas corridor between the two countries.

In Water, the subsectors and thereof networks are mostly managed by region-wide companies (Vewin, n.d.), as also indicated in their name, all being public and mostly owned by governmental bodies. Here again, the local water boards and agencies in both countries mostly possess double roles in leading both wastewater facilities and water infrastructures, with drinking water facilities being always closely related to wastewater ones.

On the contrary, infrastructure in the Health subsectors are overseen by multiple entities: Despite most hospitals being part of wider group organisations like the *Dutch Association of Hospitals* (NVZ – Nederlandse Vereniging van Ziekenhuizen) (NVZ, n.d.) or the Germn Hospital Federation (DKG – Deutsche Krankenhausgesellschaft) (DKG, n.d.), and although the allocation of patients is Europe-wide manage by services like behind the emergency phone number 112 (or EMRIC in the Euregio), the responsible national partners for the management of hospitals are often alone and local. Similarly for fire departments and crisis management teams, cross-regional organisations have to be created to enable better cooperation and communication between the actors of the subsector (German and Dutch fire brigade associations, German Red Cross, Dutch safety regions, ...). Even in such scenarios, the Limburg region for example counts already two separate Safety Regions (Veiliheidsregio's), independently in charge of the presence of fire stations and establishment of disaster and crisis management agreements (Rijksoverheid, 2019). This suggests again a fragmented management of resources, within regional borders already. Lastly, countless distinct institutions govern infrastructures and facilities from the pharmaceutical and technical medical products subsector, and equally from the research facilities and laboratories subsector.

The sectoral consolidated market supervision in the Energy and Health sectors would enable a transparent and direct collaboration between the providers and the local authorities, representing an indispensable attribute when natural hazards threaten public safety and economic stability. In contrast, the fragmented aspect of most Health subsectors could indicate complex and hindered communication paths at times of flood crisis, having dozens of independent actors to coordinate with in order to secure the global sector and its numerous intrinsic supply chains and information flows. Authorities must rely on initiatives like the EMRIC project to ensure both local and cross-border efficient cooperation amongst all actors involved in emergency response services.

Simultaneously, the disconnection between health service providers of an individual subsector may prove higher autonomy levels in case of local disruptions, impeding serious consequences onto the broader network. For example, a cyberattack targeting a single local hospital will most likely only affect the facility itself, allowing authorities to dispatch patients to neighbouring clinics if required. Conversely, if a service provider from the energy or water is witnessing hack assaults onto its IT infrastructure, the global management of locations under its responsibility is jeopardised.

Lastly, the Energy sector on its own is primarily comprised of global (semi-)private organisations, whereas the Water and Health sectors largely possess public-service oriented companies, at times NGO alike. This difference may suggest that CI resilience strategies must account for corporate interests in the Energy sector, whereas essential human needs such as access to drinking water, sanitation and healthcare services is a matter of public mandate, therefore presumably not ruled nor commanded by business decisions. In light of the investigation for (geo)spatial data from providers' online sources and contact persons, as well as the information search along sector experts, this aspect will perhaps explain why Energy technical data was generally harder to obtain during the present study than within the Water and Health sector.

3. Methodology

The purpose of the present chapter is to delineate the methodological framework employed to assess the vulnerability of critical infrastructures against flood risks in the Euregio Meuse-Rhine. By integrating the qualitative legal and governance analysis from section 2.2 to 2.5 with quantitative geospatial data and modelling, the study adopts a mixed-method approach linking administrative particularities with physical features. Given the restricted public access to geospatial information for the latter, geographical assumptions and ambiguous network features are backed by qualitative evidence and figures from interviews conducted with experts relevant to the study and the CI sectors, providing insights into intricate peculiarities and vulnerabilities remaining undocumented online. By following this procedure, the study seeks to ensure an empirical fidelity and provide an accurate representation of the Euregio's current regulatory and geographical CI realities.

The chapter is organised into five main sections. First, the global research design is outlined in section 3.1, clarifying the choices and reasons behind the multi-method approach. Section 3.2 details the diverse data acquisition strategies, both for legal and geographical matters. Thereafter, technical workflows utilised to harmonise data and conduct GIS integrations are explained in section 3.4. The following section 3.5 describes the analytical methods employed and reasonings adopted to interpret the processed data. Finally, section 3.6 concludes with a discussion on the methodological limitations, particularly the challenges of data availability and heterogeneity, and cross-border inconsistencies.

3.1. Research Design and Framework

In the present section, the two-method approach for the study is substantiated. Given irregularities in national legal definitions of CIs, and inconsistent availability of geospatial data from both governmental and commercial entities, information from all sources must be combined and blended to allow a uniform interpretation and processing of data.

3.1.1. Methodological Rationale: Top-down and Bottom-up Integration

Below, the matrix-like Table 3.1 illustrates the mixed-methods of this study, showing how the qualitative and quantitative research aspects compare themselves on legal and regulatory evidence against geographical and geospatial data. The two far right columns indicate how these aspects impact key scales of the research: the level of detail, granularity and resolution available in the different sources on the one side, the relevance to the broader scope of the research on the other. The wider and darker the side of a triangle is, the more the research stream entails a high granularity of data, respectively a high relevance to the global comprehension of the cross-border properties.

Regulatory data entail law articles and legal documentation, mostly referring to the CER-directive and the transposition acts of the respective countries. Spatial data refers to any kind of geographical network details or GIS information, mostly referring to governmental and commercial reports, experts inputs, and data obtain from online geoportal or geo databases such as OSM.

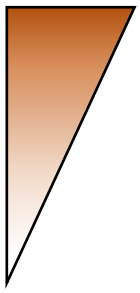
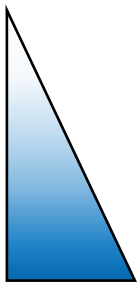
Approach	Regulatory Data	Spatial Data	Relevance to Comprehens.[1]	Data Granularity
Qualitative	- Study of legal regulations - Study of partnerships	- Official gov. or comm. body's websites - Experts' insights on partnerships		
Quantitative	- Legal numerical thresholds	- GIS mapping and modelling - Experts' insights on data		

Table 3.1: Two-Method Approach Overview (Debelle, 2026)

From a top-down perspective, the qualitative approach is essential to grasp national, international and transboundary characteristics of the regions' and countries' networks of critical infrastructures. To understand how cross-border cooperation projects and partnerships affect the management and resilience of CIs, legal frameworks and official declarations provide essential and fundamental insights into the broad functioning of national and cross-border CI governance. At his level, the minor data granularity is not impeding, as one tries to apprehend what general, transboundary legal dissimilarities and geographical connections exist with regards to the respective national networks of CI.

From a bottom-up perspective, the quantitative approach is crucial to obtain a detailed and empirical view of the networks, by acquiring geospatial information about critical infrastructure. This enables to locate CIs at risk of flood-induced disruptions, potential aggregates of CI nodes or synergies between sectors, as well as to identify CIs nodes central to the global networks (e.g. directly linked to many others, or providing their services to a significant share of inhabitants, lower levels own sector, or other sectors entirely). At this level, the lack of data relevance to the broad, international and cross-border stakes is not relevant, as one tries to map and model the real networks into a GIS software, allowing to extract quantitative results and draw local conclusions.

When combined, both approaches simultaneously allow the identification of prominent critical infrastructures and intrinsic characteristics of their networks and governance. Thereby, the study of resilience to floods is enabled both for single groups of infrastructures and for the transboundary networks. For instance, the qualitative approach will later reveal that the intake ill or injured patients is managed and operated irrespective of necessary border crossings. On the other hand, the quantitative approach will whether given the area, the patient dispatching to the closest care infrastructure necessitates a border crossing or not.

Practically, the quantitative method allows to model the current networks with the greatest possible accuracy, using geodata and GIS tools to build a static geospatial proxy. Complementary, the qualitative framework contextualises the former with macro dimensions sometimes unavailable in or irrelevant to geodata.

3.1.2. Quantitative Vulnerability and Criticality Assessment

To quantitively determine the vulnerability of a CI type, its network or it sector, a QGIS spatial model is built, offering visual insights onto the landscape of critical infrastructures in a rectangle area of the Euregio Meuse-Rhine.

[1] Relevance to the comprehension of the research's broad, transboundary scope of systems of (networks of) CIs.

A single CI node is considered as vulnerable to a disruption if it is located in an area prone to floods (cf. ** in section 3.2.2), and on some occasion, if its direct access road or surroundings are flooded as well. A network of identical CI nodes is considered as vulnerable or prone to cascading failures if it demonstrated higher levels of interconnectivity, or if it crosses-border, implying that new and unexpected failures may occur. The cross-border vulnerability is further addressed with online data from service providers and through field experts testimonies. In few parts, emphasises are put on the vulnerability of a network due to other parameters such as its system's structure, governance or budget. A network of networks, or a multisectoral network, is considered vulnerable to cascading effects if critical and important vulnerable nodes are closely connected to others. The criticality and importance of a node is determined by the amount of inhabitants it serves and the amount of cross-sectoral connections it has to other major facilities (i.e. key role in the supply of their services in theirs or neighbouring regions).

3.2. Data Sources and Collection

This section outlines the collection processes and data sources utilised throughout this study. First, the reasoning behind the selection of source is provided, detailing the accuracy of the provided data and assumptions taken to consider the data relevant to the study. Second, the data collection process is described.

3.2.1. Regulatory Data

Data Accuracy and Assumptions

Due to the inherently righteous and legitimate nature of legal documentation and regulatory acts, always redacted by national governmental institutions or regional bodies and provided by their official online resources, it is considered that CER Directive (CER), the Wet weerbaarheid kritieke entiteiten act (Wwke) and the KRITIS-Dachgesetz (KRITIS-D) advance authentic and correct information of the legal status quo. Therefore, besides annexes, linked acts and documents directly mentioned in them, few other legal sources are sought (e.g. no policy maker or legal stakeholders are interviewed for this study). Despite the CER dating from December 2022, it is in force since January 2023, and the Wwke and the KRITIS-D (and associated acts) are freshly published by the time of the present study finalisation (February 2026), if not still only available as drafts or yet under parliamentary discussion. Therefore, these are regarded as temporally accurate enough to be considered for the study.

Nonetheless, given the consistent judicial lexicon of these sources, and a significant amount of documentations not being redacted in English but in Dutch or German, websites from governmental agencies, academic institutions and newspapers which provide general CI information and summaries written with comprehensive vocabularies are also consulted and trusted. Additionally, using browser plug-ins, the translation of such websites to the English language is often simpler. Besides, for PDFs of legal and regulatory acts, translation tools and AIs are assumed accurate enough to convey trustworthy and comprehensive English interpretations.

Data Sources & Collection

Table 0.2 in Appendix D Section 1 provides an overview of the principal online resources, i.e. websites, utilised for the present study's chapter 2.2. Legal Framework. Note that the URL-website links on top of the displayed texts are for mere indication only. Thereof webpages regarding any critical infrastructures topic may have been consulted as well. For a detailed list of sources used or cited in this paper, please refer to the Bibliography.

The collection of legal data is done as follows: articles are either saved locally as PDF files, or URL-links are saved in a MS Excel document, categorising them under different topics.

3.2.2. GIS Data (OSM & Primary Geoportals)

Data Accuracy and Assumptions

For Geographic Information System (GIS) data, the mapping database OpenStreetMap (OSM) is used as primary source. The database is maintained worldwide by a community of scholars and academics, personnel from public agencies and private companies, and geographics enthusiasts. Since its creation, the mapping database is widely accepted by and used across the literature and research community. Despite being a product of volunteering publics, OSM has demonstrated sufficient levels of accuracy in urban and rural settings, particularly in European contexts (Sun et al., 2026). This is notably due to the large amount of contributors and participating members, as Helbich et al. (2010) have demonstrated for instance in Germany. Mondzech and Sester (2011) also show that the OSM data on the London and broader English road network is on average within 6 metres of Great Britain's mapping agency of *Ordnance Survey*. By assuming such accuracy is observed in the Euregio's area of the OSM database, and considering that even a 10 or 20m accuracy would be sufficient for the present study's purposes, it is chosen as primary source for GIS data (Bartzokas-Tsiompras, 2022).

Additionally, papers addressing cascading disruptions in networks of CIs, for flood risk analyses purposes, have equally used OSM data in the past. This is for example the situation in Schneider et al.'s paper on a case study on Cologne, Germany, and Schotten and Bachmann's paper on a case study in Accra, Ghana. The authors of both papers further corroborated the relevance of using OSM for this study during personal exchanges, stating the database's consistency and availability to be most adequate for the scope and timeframe of the present work.

As will be seen in sections 3.6, the data rarely includes broader information on the connections and dependencies found within the various (transboundary) networks of CIs. Moreover, the availability, accuracy and temporal validity of OSM geodata regarding floods is less common. Accordingly, the GIS data sets obtained from the OSM database is complemented by data from:

- Geoportals and geodata services (WMS, WFS) made publicly available by national and regional agencies in the Netherlands, Germany and Belgium[2], or by databases from European Institutions;
- Downloadable files obtain from personnel of geoportals, as well as from colleagues of the partnering companies DLR and Deltares.

Because cross-border aspects are rarely found in any of the above, online sources of commercially involved entities are consulted and interviews with experts of relevant CI sectors are conducted, in order to discover or discern interdependencies between the national networks (cf. section 3.2.3).

Ultimately, regarding GIS data on land use and population densities, official and publicly available data from the *European Space Agency* (*ESA*) –respectively from the *United Nations Office for the Coordination of Humanitarian Affairs* (*OCHA*)– is collected and trusted, given both agencies' global mandates and established credibility.

[2] Given that the rectangular area around the Maastricht – Aachen region overlaps with Belgian territories, and that the former city is geographically very close to them too, Belgium data sets are also sought.

Data Sources

The sources for GIS data are available for consultation in Table 0.3 of Appendix D Section 2. Note that some GIS data sources may also have been used as flood data sources, and vice versa. Additionally, GIS data for a comprehensive view of the land uses in the region is collected from the *ESA*'s WorldCover project. GIS data about population densities in the region is collected from the UN OCHA's HDX – Humanitarian Data Exchange platform.

Data Collection

For the collection of GIS data, regardless of the source, a file manager and the software QGIS (version 3.42.1) are employed. Data originating from a downloadable file found on a geoportal or online source is stored and arrange in a locally based folder. Data originating from WMS or WFS services[3], as well as from OpenStreetMap, is first retrieved using the QGIS software's data source manager and QuickOSM plug-in, then stored locally in the same folder. The folder is thus constituted from RAW data, yet to be cleaned and processed (cf. section 3.4). Table 0.4 in Appendix E Section 1 provides an overview of the data categories, the spatial data models and geometries sought, and under which file formats these are stored.

Data Selection Criteria

Because the data collected is often spreading over an entire region or country, a QGIS vector layer is created, designating a single rectangle comprising the city of Maastricht and Aachen, and a reasonable perimeter of 15km and 13km around them (voluntary larger around Maastricht to include more of Belgian territory, thereby increasing potential cross-border network connections). This rectangle is further below referred to as the canvas, canvas rectangle or canvas layer. The coordinates of this rectangle, as well as the perimeters around the cities, are shown in Figure 3.1 (white = UTM coordinates, blue = geographic coordinates in WGS 84).

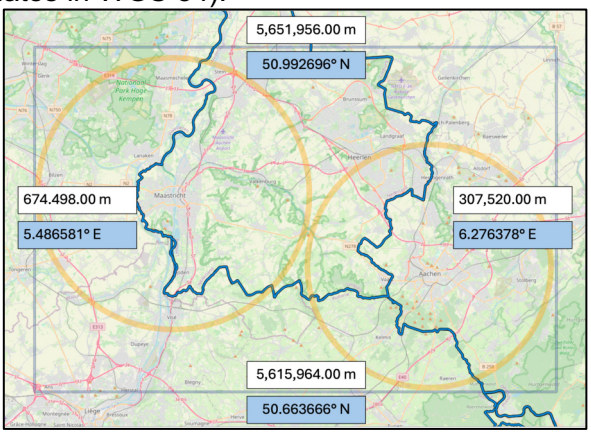


Figure 3.1: Extent of the canvas QGIS vector layer (Debelle, 2026)

Table 0.5 in Appendix E Section 2 provides an overview of the data categories, the spatial data models and geometries sought, and under which file formats these are stored. Evidently, the principal criterion for data is to contain information geographically within the canvas.

[3] WMS, WFS, WCS or WMTS services are protocols allowing data queries which deliver mapping geodata from remote servers.

3.2.3. Expert Elicitation and Commercial Data

Data Accuracy and Assumptions

In alignment with the expert selection criteria (cf. below), the insights, testimonies and affirmations provided by the interviewees during online meetings or via email exchanges are treated as credible and empirically accurate for the purpose of this study.

Expert Selection Criteria

To identify relevant intervenors, organisations and institutions with a direct implication into the management or governance of multiple critical infrastructures are contacted. These are all governmental, private and public entities within the sectors of energy, water, healthcare and emergency response services active in any of the regions overlapping with the canvas extent. Entities in charge of a single or few critical infrastructures are disregarded. Most contacted organisations are listed in the hierarchy diagrams of section 2.5. Few more are received by collaborators of municipalities and other institutions.

Reach-out and Interviews Protocols

Stake holding entities falling under the abovementioned selection criteria were reached out by mail and phone, over contact details found on their respective official websites. For all initial communications, regardless of the medium, the following outreach protocol applied:

- Project introduction: The topic of the study is briefly presented, mentioning the partnering organisations of *DLR* and *Deltares*;
- Inquiry: By describing the challenge faced and what insights would help the research, a formal request for information / an appropriate contact person is put forward;
- Engagement proposal: The availability for a short 20min interview (or a brief email exchange) is offered, involving four targeted questions;
- Closing: A statement of gratitude to the interlocutor and an offer to share further study details upon request are presented.

Entities from French or German speaking regions are directly approached in their language, while entities from Dutch or Flemish speaking regions are approached in English. The same applies for the following vocal / textual exchanges.

For the interviews, the following 4 questions are asked. Q1 and Q2 serve to put the interviewee's role into context for the study, not omitting their preferences for attribution and confidentiality. Q3 represents the core of the experts intervention, providing insights into the broader picture of networks of CIs, not going into details of a specific location. Q4 then helps to understand how much legal and regulatory topics potentially influence their employer's mandates. The same questions were provided per mail, if contact persons were not available for online meetings. The questions are available in Appendix P.

Data Sources & Collection

Table 3.2 presents a brief overview of experts that agreed to an interview, via online call or email exchange, and answering the questions. The table does not include other responses from contacted agencies, which provided contact details of relevant experts but could not directly answer the questions. The complete table and summaries of the interview may be found in Appendix Q.

Organisation (Country)	***Expert(s)***	***Current Role(s)***
Uniklinik Aachen (DE)	Johannes Wilde	- Head of the plant fire brigade of the Aachen University Hospital - Lecturer at Technical School of Cologne
EMRIC (BE, NL, DE)	Giulia Stroink	Programme manager at EMRIC, coordinating the collaboration between partnering institutions
Waterschap Limburg (NL)	Sven Robertz	- Project manager of the Euregio Meuse-Rhine Interreg Flood Wisdom project - Employee at Waterschap LIM.
	Sophie Verstraelen	Advisor in international relations and coordinator at Waterschap LIM., specifically for collaboration with German partners and in water quality topics
Noodplanning Crisisbeheer Limburg (BE)	Michel Carlier	Director of the emergency planning and crisis management dept. at the Governor of Limburg (BE)

Table 3.2: Experts Agreeing to an Interview (Debelle, 2026)

If carried via online call or meeting, all comments from experts were manually redacted in a MS Word document, in bullet points.

3.3. Data and Tools Specification

This section serves non-specialist readers to obtain a foundational understanding of geospatial principles and data structures utilised throughout the study, as the methodology outlined in the present chapter relies on specific GIS techniques requiring clarifications. Key data models and tools are defined such as GIS layers of physical assets and environmental hazards, possible alterations of these using QGIS tools, an overview of their existing file types, the logic and utility of Voronoi polygons, and finally the necessity of a common and standardised Coordinate Reference System (CRS).

Data Models: Geometries, Data Structures and File Types

Amongst others, the QGIS software allows to retrieve geospatial data from local or cloud servers, clean and rework layers of data, and provides analytical tools to be applied on the resulting output data to derive and extract geographic and flood-related managerial insights from raw data sets. In QGIS, a layer is the fundamental building block which organises and maps geospatial data. In a GIS environment, layers are either represented by *vector* or *raster* data models. A layer may be enabled and disabled, depending on the user's need.

A *vector layer* typically represents:

- Points (physical assets like electrical transformers or healthcare facilities);
- Lines (from water networks, streams and rivers, or shape of dikes);
- Polygons (surface area of power plants or hospital complexes).

such layer usually comprises multiple *elements*, typically each representing a single point, line or polygon. Each *element* of such layer is visible in an *attribute table* as a single row, where columns or *fields* indicate specific attributes (property, feature or characteristics) commonly shared amongst all elements (e.g. name, type or size of facility). In the present study, *vector layers* will principally represent locations of critical infrastructures.

On the other hand, a *raster layer* consists of a continuous grid of cells of varying pixel size, where each specific cell contains a unique colour and/or value representing a geographic variable (e.g. depth of flood, population density per square kilometre). In the present study, *raster layers* will principally represent floods. Naturally, two base layers are included in the QGIS project, consisting of a regular OSM map (showing borders and city names, and road networks or infrastructure as different colours and shapes), and a satellite imagery layer (showing mere satellite picture without any additional information). Both layers comprise up-to-date data from 2025.

For the QGIS project, *vector layers* are only saved and used under ESRI Shape files (.shp) or GeoPackage (.gpkg), and *raster layers* only as GeoTIFF (.tif).

Geometric Helpers: Buffers, Centroids, Voronoi polygons

For the cleaning, processing and analysis of geodata, the QGIS software provides a myriad of tools to work with data. Three of them provide a type of geometric helper frequently used in throughout the project, being:

- A buffer around a polygon allows to extend the polygon by a certain distance, usually perpendicular to its edge, for instance widening the polygon vector of a river bed by 20 metres to check what physical assets falls within a 20 metres distance from the river).
- A centroid from a line or polygon provides the mathematical centre of the shape, being the arithmetic mean position of all points constituting the line or polygon. Simply put, it is the centre of a line or shape.
- Voronoi polygons are polygons mapped around their respective source points, indicating to every possible geographical location of the area which source point is the closest to the location. For instance, if a location $\mathrm{loc\_1}$ is within the Voronoi polygon $\mathrm{hospital\_5}$, then $\mathrm{loc\_1}$ is closer to $\mathrm{hospital\_5}$ than all other hospitals of the region.

Coordinate Reference System

A Coordinate Reference System (CRS) is a geographical mapping framework used to place physical locations with three-dimensional coordinates onto a two-dimensional representation of earth's curved surface, given the arising complexities from flattening a 3D ellipsoidal shape into a flat 2D map.

For the purpose of this study, the EPSG:3857 (WGS 84 / Pseudo-Mercator) coordinate system is kept to maintain a global compatibility across all layers, given it is the default web mercator used by many maps and geospatial data providers, notably Google Maps and OpenStreetMap (EPSG.IO, n.d.). This also applies for the present project, as most data sets retrieved from online sourced are projected in this very CRS.

3.4. Data Processing and GIS Integration

While OpenStreetMap and online geoportals provide extended resources and geospatial information, the data acquired requires cleaning and processing before being usable for analysis. Additionally, given the frequently missing functional links (edges or connectors between nodes of CIs), these are derived through a triangulation of technical data (geospatial point locations) and data obtained during official website screenings and experts interviews (i.e. insights in network connections).

3.4.1. Data Cleaning and Harmonisation

Cleaning

Both in the file manager of the local machine (using folders), as well as in QGIS in the layer panel (using groups), flood and CIs geospatial data is renamed and organised as follows:

- Each raw file (layer) is renamed, using the prefix:
  - OSM_Key_Value for any data originating from OSM, which comprises data for all regions already, as explained in Table 0.5;
  - BE_ / WAL_ / VLA_ if the data originates from a national or regional (Wallonie, Vlaanderen) Belgian geoportal;
  - NL_ / LIM_ if the data originates from a Dutch or Limburg geoportal;
  - DE_ / NRW_ if the data originates from a German or NRW geoportal.
- As OSM layers are already limited to the canvas, all other layers from geoportals are clipped to the canvas layer, i.e. CI locations or flood areas outside of the canvas are deleted[4]. Using the QGIS Clip tool (for CI vector layers) and Clip raster by extent tool (for flood raster layers), new output layers are created, hence not altering the initial raw input files.
- The newly clipped layers (and thereof saved files) are placed in groups (folders) of their respective and corresponding category, i.e. Energy CI, Health CI, Water CI, or Floods.

Harmonisation of CI Data

Because an OSM query for a single combination of a key and a value may simultaneously provide a layer of pts, lines and polygons for a CI, three layers often coexist for one specific CI. For instance, the QuickOSM query with key: amenity and value: hospital will provide a layer of pts (locations), a layer of lines (contours) and a layer of polygons (surface areas) for single hospitals or hospital complexes.

Due to the crowd sourced property of OSM data, not all physically existing CI assets are mapped identically in OSM, meaning some may only be mapped as locations, others as contours, and others as surfaces. To this end, for each type of CI –single combination of a key and a value–, the data is harmonised into a single point layer as follows:

1. Using the Centroids tool, the regular line (RL) and polygon (RP) layers of a CI type (e.g. hospitals) are respectively transformed into point layers, where each point element is the centroid of a line (a CI's contour) or polygon (a CI's surface) element from the two RL and RP source layers.
2. Using the Select Within Distance tool, line centroids and polygon centroids falling within a 100m distance from the initial point layer are selected. The selection is inverted and deleted, thereby keeping only elements falling within 100m in the two centroid layers. Beyond 100m, it is assumed that any new point element is a separate and distinct CI entity.
3. By manually skimming through all of the remaining centroids, the following decision process follows:
   a. If the 2025 Google satellite imagery does not show signs of the said CI to be located there, all points elements from the regular point (RPt) layer, the line centroid (LC) layer or the polygon centroid (PC) layer are deleted.

[4] As WMS/WFS are not editable, local duplicates of the layers are created (cf. Flood Data)

b. If otherwise, a single point element from all three RPt, LC and PC layers is kept per CI type[5], given the layers possesses at least one element in the area. Generally, the most visually geometrically centred element is kept (all other points are deleted from their respective RPt, LC or PC layer).

4. Using the Merge vector layers tool, the three RP, LC and PC layers are merged into one uniform point layer, which is renamed with the suffix "_ALL". In this layer, no physically existing CI is represented twice, with duplicate elements.

Flood Data Aggregation and Harmonisation

As up-to-date flood data is obtained from multiple online data bases and geoportals, several layers, some as vectors and others as rasters, contain overlapping data. Additionally, some flood data represent likely flooded areas due to increased river levels (i.e. fluvial floods), while others represent likely flooded areas from locations witnessing stagnant water levels due to rain falls (i.e. pluvial floods). Naturally, these flooded areas also overlap at times, and for the purpose of the present study, the origin of flood is regarded as irrelevant.

Besides, some data sets refer to flooding likelihood scenarios (i.e. 'low', 'medium' or 'high' likelihood) instead of a precise period of return i, and not all retrieved data includes information on the floods' depth. To this end, the harmonisation process below takes place. Note to the reader: In a flood raster layer, the visual opacity of a single pixel (from white to black or dark-blue) represents a specific numerical value tied to the precise water depth metric in the location of the pixel.

0. Since raster layers from WMS/WFS databases are not editable as is, they are locally duplicated and saved using the Convert map to raster tool. To this end, all other layers of the QGIS project are deactivated, and the tool then renders a replicate image of the visually remaining pixels. The tool allows to limit the rendering to the extent of a layer, which is here always the canvas layer. The 'Map units per pixel' parameter, allowing to choose the output raster layer's resolution, is set to the lowest possible value that does not produce an error code within QGIS, being 2 pixels. All other parameters of the tools are kept as set to default by QGIS.

1. As flood depths are disregarded due to inconsistent availability, and to ease calculations and processing times in later stages, raster layers are transformed to polygons using the tool Polygonize (Raster to Vector) tool. This tool transforms every raster pixel into a single large vector polygon, even if pixels are not adjacent.

2. For rigorousness purposes, the output layer is transformed to obtain a single polygon element per group of adjacent pixels. This is done using the Multipart to singleparts tool.

3. For each country (Belgium, Netherlands, Germany), flood vector layers are selected and merged as follows. All layers containing the terms[6] (unchanged from their original source layer and thereof raw file):

    a. HQ10, HQ25, HQ50, (HQ)high, (HQ)frequent, T10;

[5] Collections of buildings employed for the provision of a single service (care, electricity supply, water waste treatment, ...) are considered as a single individual CI point, as long as the collection is not cut by a road (e.g. several hospital buildings not separated by a road). On the other hand, single elements not consisting of buildings, such as storage tanks or electricity transformers, are always counting as individual CI point.

[6] As well as the Dutch, French or German translations of the English terms

b. HQ100, (HQ)regular, T100;
c. HQ500, HQ1000, (HQ)low, (HQ)extreme, T1000;

and sharing the same country are respectively selected, merged into a single vector layer, which is then renamed with the prefix of the country (BE_, NL_ or DE_) and the suffix HQ10_ALL, HQ100_ALL or HQ1000_ALL.

3.4.2. Voronoi Polygons

To identify from which specific CI another individual CI or a share of inhabitants is serviced, the rule is chosen to associate the physically closest CI. Geometrically, this is performed by associating to each point layer of a CI type a corresponding layer of Voronoi polygons. However, as online screening and experts insights are required to determine if cross-border service perimeters exists, Voronoi polygons are created twice, pending on the former findings. The polygons layers are therefore generated once by disregarding national borders (border-blind), once by stopping at them (border-restricted). The former, labelled with the suffix 'international', are generated in a single step, using the Voronoi polygon tool. The latter, labelled with the suffix 'national', are generated using a QGIS algorithm –named Models and built using the QGIS Model Designer–, which functions as shown in Figure 3.2:

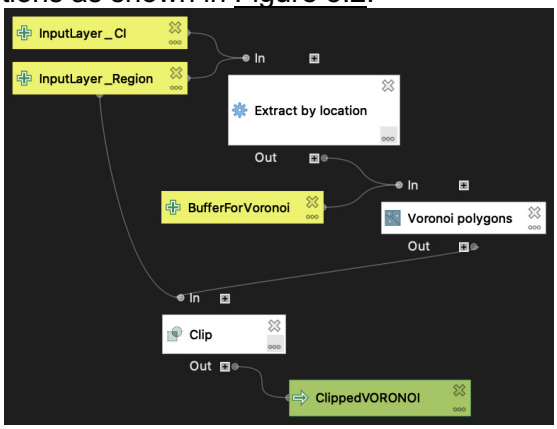


Figure 3.2: QGIS Model "VoronoiClippedToRegions" (Debelle, 2026)

0. The following inputs are provided (yellow boxes): The CI point layer to generate Voronoi polygons from, the border polygon layer for an individual country, and the buffer percentage*.
1. CIs only falling within the input country are extracted using the Extract by location tool.
2. The output layer of 1. is used to generate the Voronoi polygons using the Voronoi polygons tool.
3. The output layer is clipped to the very same border input layer, using the Clip tool.
4. The model in Figure 3.2 is used three times for all three countries, and the three separate output layers are then manually merged together.

* Given the functioning of all abovementioned tools, buffers are sometimes required to ensure that the layers of Voronoi polygons cover the full canvas. These buffers were intuitively selected from 100% to 500%, until the layer visually covered the canvas entirely. As these then often cover areas beyond the canvas, the ultimate outputs are always clipped backed to the canvas before being locally saved.

After creating the respective Voronoi polygons for all point layer of CIs, the tool Zonal statistics allows to extract the amount of inhabitants located within each polygon, using the global raster layer of population density. This creates a new identical layer, with an extra column (field) "Pop_sum". This field is associated to the respective elements of the initial layer using the "Open field calculator" and the input function:

attribute(get_feature('Zonal Stat OUTPUT', 'polygon_id', "polygon_id"), 'Pop_sum')

To associate a point layer of a CI (e.g. hospitals) to another, nearest point layer from a CI it is dependent from (e.g. closest power station), the tools Join Attributes by Location allows to add a column (field) of closest features, using the above created corresponding Voronoi polygon layer (e.g. power station Voronoi polygons). To then visually connected dependent CIs for a visual analysis, the tool Hub lines creates the connectors through a line vector layer.

3.4.3. Data Triangulation

To ensure an accurate representation of CIs locations, the OSM data is triangulated with other data sources. Using insights from experts, the selection of the type of Voronoi polygon layer to be used ('international' or 'national') is made for analyses outlined in chapter 4.

Using point data from geoportals and online data bases, the completeness of OSM point layers is verified. When data is simultaneously available from such sources for all three countries or all four regions[7], it is merged for all areas and manually verified by visually comparing each of its point elements (hereafter referred to as 'X_CI') with those of the corresponding OSM CI point layer ('OSM_CI'). , as follows:

0. A new empty vector layer is created;
1. If both the 'OSM_CI' and 'X_CI' layer contain an element to represent a same single CI (visible on satellite imagery[8]), then the 'X_CI' point element is considered more accurate and is appended to the empty layer;
2. If one of the layers does not contain an element to represent a CI (visible on satellite imagery), then the other's point element is appended to the empty layer;
3. The filled-in resulting layer is named and saved appropriately.

Based on the rationale outlined in section 3.6, the triangulation will prove to be feasibly applicable only for the CI type 'Hospitals'. Given the lighter work this rationale involves, and because the canvas possesses less than 100 hospitals and clinics in total, every point element is manually inspected, using satellite imagery and online Google searches and official healthcare institutions' websites to determine the size of a healthcare complex. The size are categories as follows in the study:

- Hospitals (H): Large healthcare facilities, often comprising several buildings and providing 24/7 primary, secondary and emergency care services, with accommodation for patients and license practitioners across a broad spectrum of medical disciplines;
- Care Centres (CC): Medium-sized healthcare facilities, comprising a single building or small scaled complex, with limited accommodation possibilities and lower diversity in medical disciplines of practitioners, yet able to care for patients at times of emergency response to natural hazards;

[7] The decision to not triangulate if a country's or region's non-OSM data is missing is justified by the desire to keep each OSM point layer equally accurate across all its –canvas wide– elements.

[8] Evidently, the canvas map is only visually analysed around point elements of the said layer, at a zoom level where infrastructure is recognisable. The canvas map is not visually scanned at such zoom level in its entirety.

- Emergency Services (ES): single, distinct facilities possessing few beds to locally care for emergencies, often at night or in remote areas.

Following the same rationale, the attribute standardisation presented below is only made for layer originating from OSM or from data triangulation.

3.4.4. Attribute Standardisation

For reasons detailed in section 3.6, only OSM and triangulated layers are considered for the data processing step hereby presented. As these layers possess numerous fields (attributes) not always commonly share between them, an attribute standardisation is required. To do so, the following steps are taken for all OSM and triangulated layers:

0. All layers are merged into a single layer named 'CIs_ALL_OSM-only', adding a field 'Type' represented by the name of the original layer, in order to quickly retrieved the origin of an element, i.e. also the type of CI it is;
1. All attributes are deleted, keeping only the following original and commonly shared attributes[9]: fid, full_id, osm_id, osm_type, layer, path;
2. A 'MasterID' attribute is added, constituted of the letter 'E' for energy, 'H' for heath or 'W' for water, indicating what CI sector the element belongs to, and followed by the row number the element is at (the elements are sorted by CI sector, and the row number count for this attribute is set back to 1 when a new sector starts);
3. Using the Select by Location tool with the parameter "are within" and by comparing to the polygon layer of all countries and regions, the attributes 'Country' and 'Region' are added and filled for all elements (BE, NL or DE for countries, VLA, WAL, LIM or NRW for regions);
4. Similarly, the attributes 'Flooded_HQ10', 'Flooded_HQ100' and 'Flooded_HQ1000' are added, filled with a "Yes" string using the tool Selection by Location with the parameter "are within" and by comparing to the three merged polygon layers of flood 'COUNTRY_HQYYYY_ALL';
5. Similarly, by creating a 10 metres buffer polygon layer for each merged flood layer, the attributes 'Flooded_HQ10_buff10', 'Flooded_HQ100_buff10' and 'Flooded_HQ1000_buff10' are added*;

* For the present study, it is considered and assumed that point elements of a critical infrastructures are affected by floods in a near distance of their vicinity, for several reasons:

- The point location of a CI consists of a single set of coordinates, for buildings often at the centre of their surface, which therefore does not integrate the fact that a part of the building's surface may be under water. Considering that building vary in sizes and that not all CIs are represented by buildings (electric transformers, pipeline valves), the distance of 10m is chosen.
- In some case, the entire CI is safe from a flood, but either fully surrounded by a flood, or its only access road is flooded (required for maintenance purposes, or the supply of goods or patients). Here, the assumptions is taken that a 10m distance suffices to consider the CI as also affected.

Additionally, given the absence of flood depth information from some sources, making the harmonised flood layer excluding this data, CIs are considered affected and potentially disrupted by a flood as soon as their coordinates are located in an area prone to be submerged, regardless of the water depth in these coordinates, or of a CI asset's height and physical structure (i.e. besides electrical power towers carrying high-voltage lines, any other CI is considered as prone to a disruption if it is located in a flood of any depth).

[9] Being 'NULL' if an element originates from a triangulation of a non-OSM source.

3.4.5. Miscellaneous: Power-Towers and Potential Electricity Hubs

As the OSM retrieved data includes power-towers, these elements' attributes regarding floods (within or within a 10m buffer) are set back to 'NULL'. Additionally, this OSM data is not only available as points, but also as lines connecting all the towers together ("connectors" layer).

Because electricity is one of the most critical resources to a hospital, and as power towers convey high-voltage electricity over long distance and to key power hubs, nodes of the power towers network are visually identified and evaluated, as their failure would affect wider portions of the global network than small random parts of the electricity grid would. For this purpose, a new vector layer 'ElectricityHubs' is created, with manually added points where electric hubs are assumed present, where several lines of power-towers lead to the location. Hubs are also appended to the layer where an agglomeration of electricity CI nodes (regardless of the CI type) exists. Each point is visually analysed and given a value for the attributes presented in Table 3.3:

Attribute	Description	Values
'id'	An ID for QGIS purposes	String of any length
'Name'	The name of the location as displayed on the Google Maps base raster layer, preceded by the country abbreviations	BE_, NL_ or DE_
'MasterID'	An ID for analyses purposes, composed of the id and the name, separated by a "_"	String of any length
'Size'	The visually estimated size of the hub's infrastructure	S, M or L
'RoadAccess'	A literal description of how the facility is accessible by road, analysed visually using the flood layers	String of any length
'Comment'	A literal comment describing how the facility seems to be flooded, how it seems to be connected to the electricity grid or other CIs, and what urban settings are surrounding it	String of any length
'Cr.Bo.Imp'	A value attributed to the hub, estimating the possibility of having a cross-border impact (should transboundary connections exist within the electricity CI sector): -1= unlikely 0 = possible 1 = likely	-1, 0, 1
'ImpactSev'	A value attributed to the hub, estimating the severity of the impact it would have in the area and on neighbouring countries, considering the latter 3 attributes. -1= none 0 = mild 1 = severe	-1, 0, 1
'FloodDeg'	A value attributed to the hub, estimating the degree to which the facility is flooded and impacted by the flood, from a mere visual analysis only. -1= not flooded 0 = partially flooded, but accessible by road for maintenance purposes 1 = totally flooded, at least not accessible by road for maintenance purposes	-1, 0, 1

Table 3.3: Attributes for the layer 'ElectricityHubs' (Debelle, 2026)

As this connectors layer was not available for any other type of CI, this hub task could not be attempted for the networks of gas or drinking water, or of the treatment of wastewater, or for any care chain of patients between hospitals and clinical facilities.

3.5. Quantitative and Qualitative Analysis

By mixing quantitative and qualitative outputs from various findings, further clarifications are provided in the present subsection. By employing the MS Excel software facilitates further quantitative analysis, notably synthesising some output results from the QGIS model (3.5.1). Last, several qualitative assessment criteria are specified, providing empirical comparison benchmarks for the vulnerability and criticality of a CI (3.5.2).

3.5.1. Quantitative Synthesis

For statistical and visualisation purposes, the MS Excel software facilitates the construction of graphs and charts, used in Ch. 4 to provide the reader with accessible visual syntheses and illustrative materials, enabling a clear overview of the current network in the Euregio area, and comprehensive insights into the findings. To this end, the attribute table of a layer merging all CIs is exported as CSV file and reworked in the MS Excel software. From there, averages and totals are easier to calculate and present, transforming the mapping data from QGIS into statistical data through spreadsheet and graphs.

3.5.2. Vulnerability and Criticality Assessment

For the qualitative and quantitative analysis of the QGIS model presented in Ch. 4, the assessment of a critical infrastructure's vulnerability is based on criteria developed from an assessment of the existing body of knowledge presented in Ch. 2, as well as empirical findings discussed throughout this research. Moreover, certain methodological assumptions are adopted to ensure a consistency throughout the assessment, particularly when empirical data remains fragmented on unavailable. For instance, all critical infrastructures located within a flooded area, or at a 10 metres distance from it, are considered as vulnerable to a disruption of their services, and therefore more critical than others. This methodological choice is necessitated by the heterogeneity of flood datasets, with some lacking consistent numerical flood depth data. Consequently, a rigorous assessment would require a three-dimensional analysis of the terrain for all CIs nodes where depth information is absent.

Further generic criteria for criticality evaluation are the amount of inhabitants considered as served by the CI (i.e. closest CI rule, cf. 3.4.2 Voronoi polygons), the spatial proximity to a national border and spatial density of other CIs in the location's periphery (both identified through visually examination), and the degree of dependency and connectivity to other CIs.

Last, based on the interviews led with experts and the consultation of online source from commercial service providers, the general findings indicate that

- Energy: The energy sector generally does not cross borders, except for high-voltage lines north of canvas spatial extent, and gas pipelines south of the canvas spatial extent.
- Health: As confirmed by online sources and experts, agreements for cross-border cooperation between healthcare and emergency response services exist, both for daily incidents and operations, as well as during natural hazard crises. Although expert testimonies indicate that cross-border "EMRIC packages" (assistance protocols) were not activated during the 2021 flood events, this is

accredited to the saturation and overwhelming duties of national emergency response teams, rather than a lack of transboundary systemic cooperation frameworks. Additionally, 705 cross-border interventions were recorded in 2024, 638 thereof from ambulances only (EMRIC, 2024). Consequently, the infrastructure networks of healthcare and emergency response services, excluding pharmacies whose supply chains fall outside the research scope, are presumed transboundary in the QGIS model. This encompasses hospitals, care centres, police station and fire departments.

- Water: While natural water bodies and systems are inherently transboundary, the drinking- and wastewater networks are generally constrained by national borders. Despite the existence of rare small municipalities being located in two countries and traversed by a national border (e.g. Vaals / Vaalserquartier), such towns – and thereof potentially connected water networks– are considered negligible for the purpose of this study and the analysis of cascading effects.

3.6. Methodological Limitations

While the assembled legal and geospatial data used for the QGIS model provide a solid basis for the analysis of cross-border dependencies and network vulnerabilities, several methodological limitations must be acknowledged.

Primarily, these shortcomings and thereof constraints arise from irregular geospatial data completeness and availability (3.6.1). Simultaneously, the computational resources of local hardware restrain the processing demand required for accurate processing and transformation of geospatial data, notably floods (3.6.2). Ultimately, due to the prescribed timeframe of this research, the focus is set on a static spatial analysis of criticality, serving as precursor for intensive dynamic simulations (3.6.3).

3.6.1. Data Heterogeneity and Completeness

Critical Infrastructure Data Limitations

The following CI-related data constraints are identified as central factors linked to the completeness and availability of data, influencing the research and the accuracy of the spatial model:

- Data Heterogeneity: Geospatial data from local, regional and national geoportals shows substantial heterogeneity, lacking in consistency within and across subsectors of critical infrastructures. While the Netherlands provide significantly extended information on drinking and wastewater networks, and flood-defensive infrastructure, Germany's available data often relates more to renewable energies and electricity. Notwithstanding the European INSPIRE Directive and its associated open-source data platform, pushing nations to openly share standardised spatial data (European Commission, n.d.), the INSPIRE data repositories do not deliver harmonised and consistent data across critical infrastructure type. This limitation is observed across the three countries of the research, and persists across broader areas of the European Union and its member states. Besides geospatial data on the subsector "hospitals" – which was harmonised and triangulated with OSM data as indicated in section 3.4.3 –, no other data set could be retrieved consistently for all three nations, or even aligned between the primary Dutch and German study areas. Consequently, analyses in Ch. 4 exclude geospatial data retrieved from geoportals, as these do not allow a uniform comparison across regions and countries. An overview of these data set is available in Appendix G.

- Data Availability: In addition to the irregular availability across and within open geoportals and public data platforms, the data's accessibility is fundamentally restricted, limited by confidentiality protocols and national security and defence matters. These are inherent to the sensitive nature critical infrastructures. Research therefore often relies on OSM, as seen in section 3.2.2, or necessitates interactions with commercial bodies and governmental agencies to request more data, if publicly obtainable.
- Data Accessibility and Online Sources Availability: While navigating though regional and national online geoportals, some webpages (resp. geospatial files) prove to be inaccessible (resp. corrupted). Similar behaviour also occur by retrieving data from WMS / WFS data bases. In certain instances, accessibility issues are resolved following outreaches with administrators, or after passage of time. Beyond this, as national CI topics, directives, studies and projects are under ongoing development and represent nascent concerns in political agendas, datasets –and regulatory frameworks– continuously emerge throughout the drafting process of the present study. Given this dynamic nature of availability and the limited completion time of the present study, recursive consultation of data sets and geoportals is unfeasible.
- Data Completeness: Despite OSM being generally trusted for geospatial studies not requiring sub-metre close accuracy, its nature as crowd- and open-source platform cannot guarantee the completeness and uniformity of a dataset for a specific infrastructure subsector in a given studied geographical area.
- Complexity of CIs and Interdependent Networks: Geospatial data alone is not sufficient enough to comprehend perplex dependencies without networks and systems of CIs. An empirical analysis and a robust model necessitate deep insights into both granular and global connections within and between networks, which often remain unclear, overlooked or confidential from governmental sources (through public geoportals). To address this, a study requires supplemental information for the mapping of CIs, usually through expert interviews and commercial screenings, introduction additional analytically and temporally demanding constraints. Furthermore, when such research extension is not feasible or restricted in time, logical proxies are required to replace the lack of verified network topologies and characteristics. Such were used in the present study, where any modelled CI connections is always considered as "from the closest node" rule (cf. 3.4.2 Voronoi polygons).
- Time Consuming Data Exploration: The requirement to consult multiple regional geoportals introduces longer exploration times of geospatial data, further complicated by unknown abbreviations and different languages employed which browser plug-ins may not always interpret or translate. Moreover, navigating distinct geoportal forces additional temporal investments, particularly when no global, national data repository exists.

3.6.2. Flood Data Limitations

The following flood-related data constraints are observed and experienced during the study, compromising the spatial fidelity of areal flood data and forcing a computational burden through extensive data processing.

- Unstandardised Flood Periods of Return: As European standardisation frameworks only require member states to study floods and provide data for low, medium and high probability of likelihood, no common numerical value of flood periods of return exist. Consequently, one nation's high likelihood flood of HQ10 may not be empirically compared with another's nation high likelihood flood of

HQ50. As the three studied nations all agree to a return period of 100 years for a medium likelihood, this data aggregation is selected for analysis in Ch. 4.

- Data Quality Loss: Due to the inherent specificities of WMS and WFS databases, raster data from such sources is not directly modifiable within QGIS. As flood data from such sources is often provided for entire regions if not nations, cropping it down to the studied canvas area is a necessity to lower computational resource utilisation when working with it. As this is not possible, a visual rendering copy of the WMS/WFS raster layer must be created using the QGIS tool Convert map to raster. By disabling all other layers, the tool simply takes the RGB (Red, Green, Blue) data of the remaining flood raster layer and outputs it as new layer. As a consequence, all possible flood depth data is lost. Concurrently, the tool requires the user to choose a rendering quality ("Map units per pixel"), indicating how many initial map units should one pixel of the output raster have. Due to local hardware limitations, this parameter could not be reduced below 2 map units per pixel, to prevent software failure during rendering processes. In such cases, the tool takes 2 map units of the initial raster layer and make an average of colour to then create a single pixel in the output raster layer. Evidently, data loss occurs.
- Time Consuming Geoportals Interaction: To avoid the former limitation, maintenance staff of public geoportals is contacted to request downloadable files[10], leading to additional administrative work. Moreover, geoportal websites are at times outdated, yielding error codes, or providing corrupted downloadable files.
- Slow Flood-Data Reworking: Given the datasets sizes and the restrained local hardware capacities, common QGIS data processes such as rastering pixels to polygons[11], dissolving polygons or creating peripheral polygon buffers required extended temporal calculations.

3.6.3. Time Frame

Sectoral and Regional Exclusion

For motives presented in Ch. 1, the study concentrates exclusively on the sector of Energy, Healthcare and Emergency responses, and Water. Because of the temporal boundaries of the present research, essential sectors are excluded despite the existent of significant dependencies between them and the selected sectors.

While the initial research design aimed at a comprehensive analysis of the South Dutch-German border region, the canvas extends over Belgian territories, due to the perimeters defined around the cities of Maastricht and Aachen. In this context, to due temporal boundaries and to ensure a rigorous legal analysis of the cities' nations, the inclusion of Belgium in the analysis of regulatory frameworks is omitted, particularly due to the extended data acquisition time constraints thereby involved, not to mention the complications put forward by the administrative fragmentation of the Walloon and Flemish region. Nonetheless, to simplify the mapping within a rectangular canvas, Belgian territories and thereof (geospatial) data –OSM, geoportals, experts and other sources– are still included.

[10] Technical staff of the Walloon geoportal and from Waterschap Limburg provided direct support to the present research, supplying downloadable data extracts.

[11] For faster and easier analyses of flood data and flooded CIs, polygon layers required less computational efforts than raster layers.

Dynamic Simulation

The complexity of critical infrastructures interdependencies suggests a dynamic simulation approach, capturing temporal cascading failure and evolving flood levels over time. For instance, hospitals possess emergency generators, able to supply clinical facilities with electricity for up to 72 hours (Wilde, 2025). Considering such realities significantly changes the modelling and analysis approaches developed in the current study. Due to temporal constraints, limited data availability and several other aforementioned limitations, such dynamic modelling revealed itself beyond a feasible research scope.

4. Results

In the present chapter, retrieved and built spatial maps are analysed, integrating previous findings from legal, functional and expert aspects. From section 4.1 to 4.2 and 4.3, spatial assessment are conducted respectively from a macro (preliminary global insights), meso (detailed insights within the Euregio Meuse-Rhine) and a micro (profound analysis of network interaction in border-blind vs border-restricted context) perspective. Section 4.4 then provides a synthesis of previous sections, and a result discussion is offered in section 4.5.

4.1. Contextual Analysis and National Baseline

To comprehend and interpret the analyses from the later sections, insights into the Euregio's land-use, water features and socio economic profile (4.1.1), as well as the national macro interactions (4.1.2) within each sectors, help to assess the human and functional impact of failing critical infrastructures. By supplementing technical flood and geospatial data with synoptic and commonly used metrics, the comparison between both allows concrete reflections and apprehensible conclusions.

4.1.1. Land Use, Water Features and Socio-Economic Profile

Land Use

In Figure 4.1, land-use patterns are presented for the studied canvas region, retrieved from the ESA WorldCover 2021 initiative.

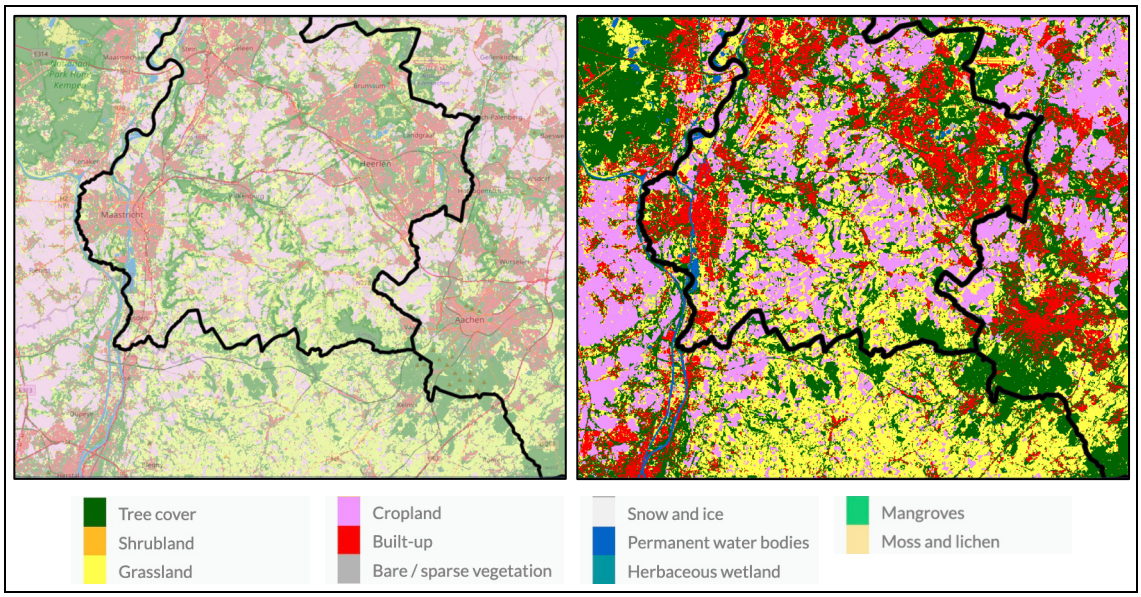


Figure 4.1: Land-Cover and -Use in the Canvas
[30% and 100% opacity] (Debelle, 2026; Data: Zanaga et al., 2022)

The canvas' regional landscape is characterised by a significant degree of fragmentation, with distinct features and dominating land uses:

- The canvas is traversed by a southwest-northeast area of crop lands (pink), interspersed with built-up areas –cities and towns– (red);
- This cutting area separates a forest in the northwest of the canva and the Hoge Kempen national park (green), from other forested regions in the southeast, such as the Dutch Geul Valley, the Belgian Ardennes and German Eifel (yellow and green).

- Distinct major populated areas and cities are visibly built-up (red), namely Liège in South-West, Maastricht in the West of Limburg, Geleen-Sittard in the North, Heerlen in the East of Limburg, and Aachen in the South-East of the canvas.

Due to human construction using materials like concrete and asphalt, built-up areas are more prone to impermeability behaviours, often in favour of worsened flood events.

Rivers, Waterways and Basins

In Figure 4.2, major rivers (wide blue lines), waterways (thin blue lines) and waterbodies (red areas) are displayed for the studied area, providing a hint into areas possibly affected by floods, or on the location of flood defence infrastructures.

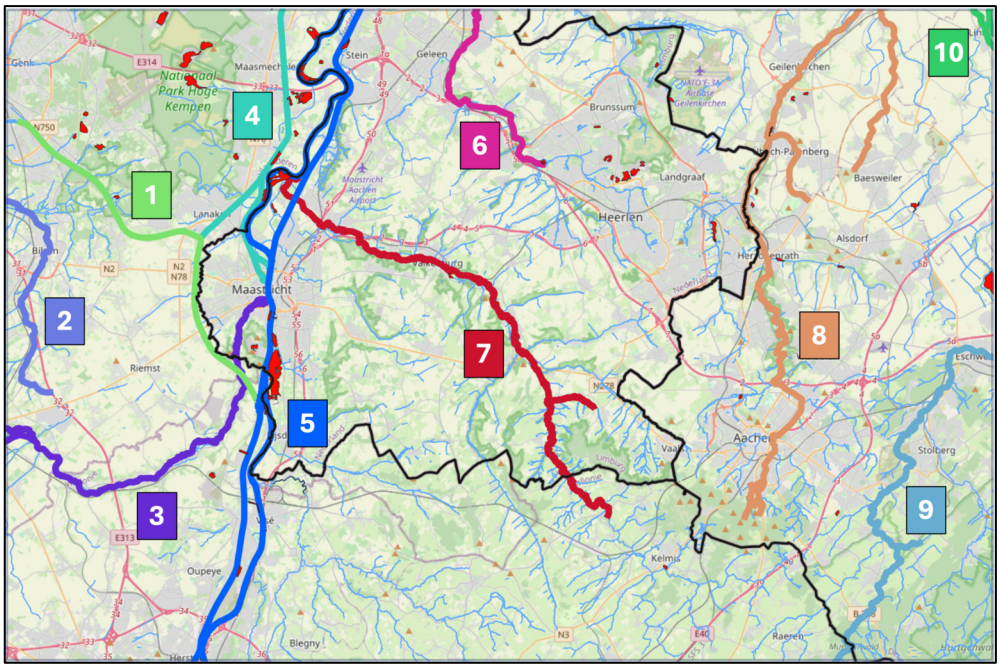


Figure 4.2: Major Rivers, Water-Ways and -Bodies in the Canvas (Debelle, 2026)

Table 0.7 in Appendix H describes the major rivers and waterways. Below are few important comments about the river landscape of the canvas:

- The Meuse (5) is named as such in French, “Maas” in Dutch;
- The Roer (10) is named as such in Dutch, “Rur” in German, “Rour” in French;
- Except the Demer (2) river, all other water ways either cross borders or follow the alignment of borders, as some even delineate these. This reality aligns with insights from interview and partnering experts, whom all emphasised the inherent truth that “rivers do not adhere nor obey to national borders”;
- Small waterways (thin light blue lines) and waterbodies (red polygons) are not described with further details, serving only as indicator of natural water features to be acknowledged in upcoming analyses.

Population & Demographics

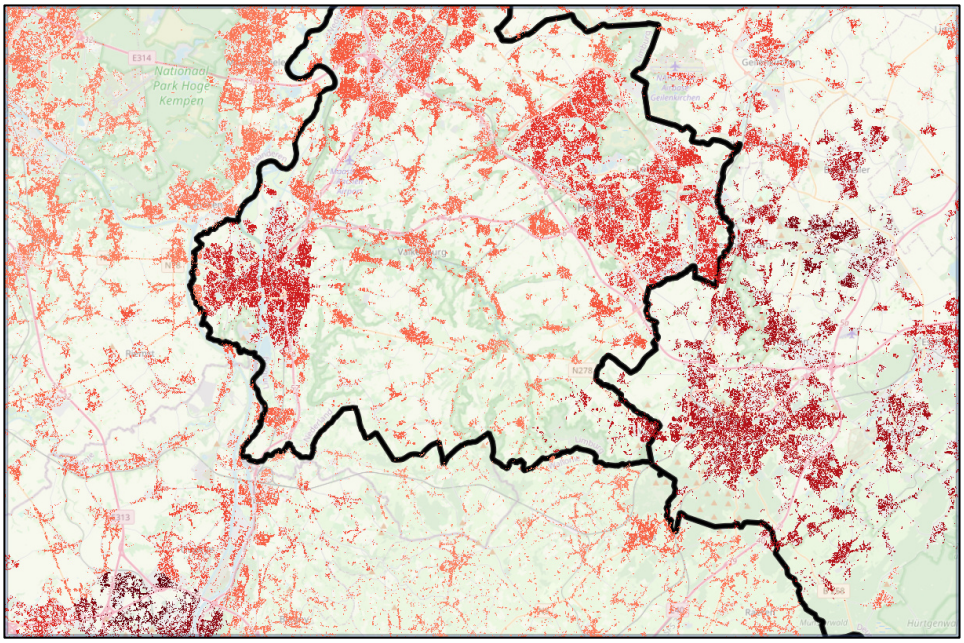


Figure 4.3: Population Density Map of the Canvas
(Debelle, 2026; Data: HDX, 2021)

Similar to the land use map, the population density map equally outlines and highlights major urban areas and populated cities. As shown in 1.2, Maastricht and Aachen respectively have a population of 125,913 and 252,769 in the middle of the 2020s. The city of Liège, partially included in the canvas, has a population of 197,323 in the same period (IWEPS, 2025).

Floods & Inundations

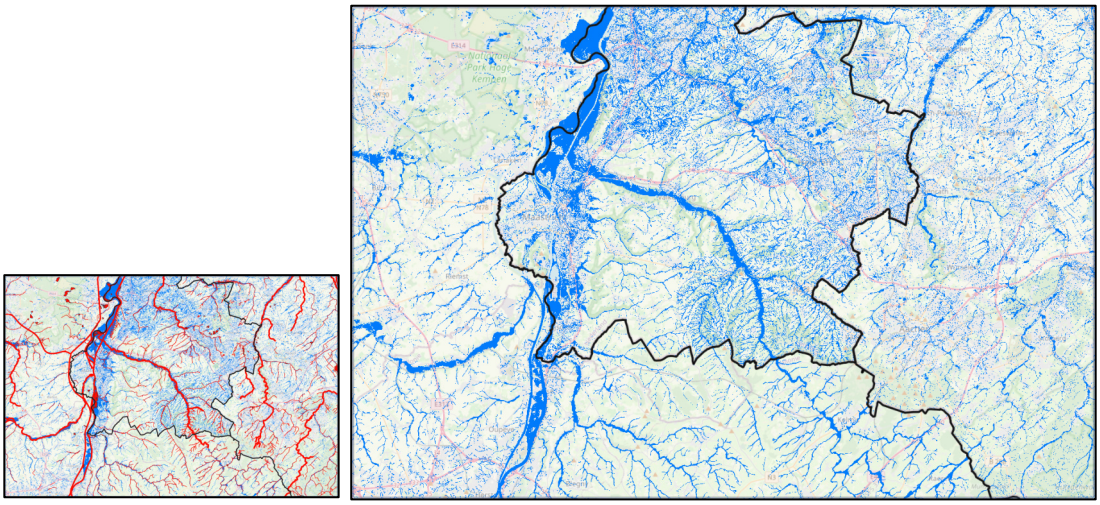


Figure 4.4: HQ100 Flood Map of the Canvas (red = rivers)
(Debelle, 2026; Data: cf. 4.2.2 Data Sources)

As observable in Figure 4.4, most populated regions of the canvas witness flood levels in an HQ100 scenario, or at least within a short perimeter of urban area. Artificial canals do not exhibit river overflows, given their construction properties. Nonetheless, the Meuse and its Juliana Canal demonstrate significant overflows in the region, particularly within the Dutch borders and after meeting their tributary “Kleine Geul”, equally indicating flood overflows. The city of Maastricht seems particularly affected by the floods, potentially creating more affected inhabitants than elsewhere.

Belgium and Germany reveal less flooded areas, with principally the end of the Demer (BE), the Jeker (BE), and the second half of the Wurm (DE) suggesting potential overflows. Impacts could be lesser, given the waterways crossing low populated areas compared to the Meuse and Maastricht.

4.1.2. Sectoral Dependencies

Electricity Network(s)

As visible in Figure 4.5, TenneT's complex high-voltage electricity grid covers the entire country of the Netherlands, connecting it to Germany in the northern most part of their shared border. This network crosses border towards other service providers, twice towards Belgium, three times towards Germany. The uncropped map, available in Appendix I, shows the German part of the TenneT network spanning across the country on a North-Northwest (NNW) to South-Southeast (SSE) axis, from Bremen over Hanover, Kassel, Nuremberg, ending in the region of Bavaria and the city of Munich, and connecting to Czech and Austrian grids.

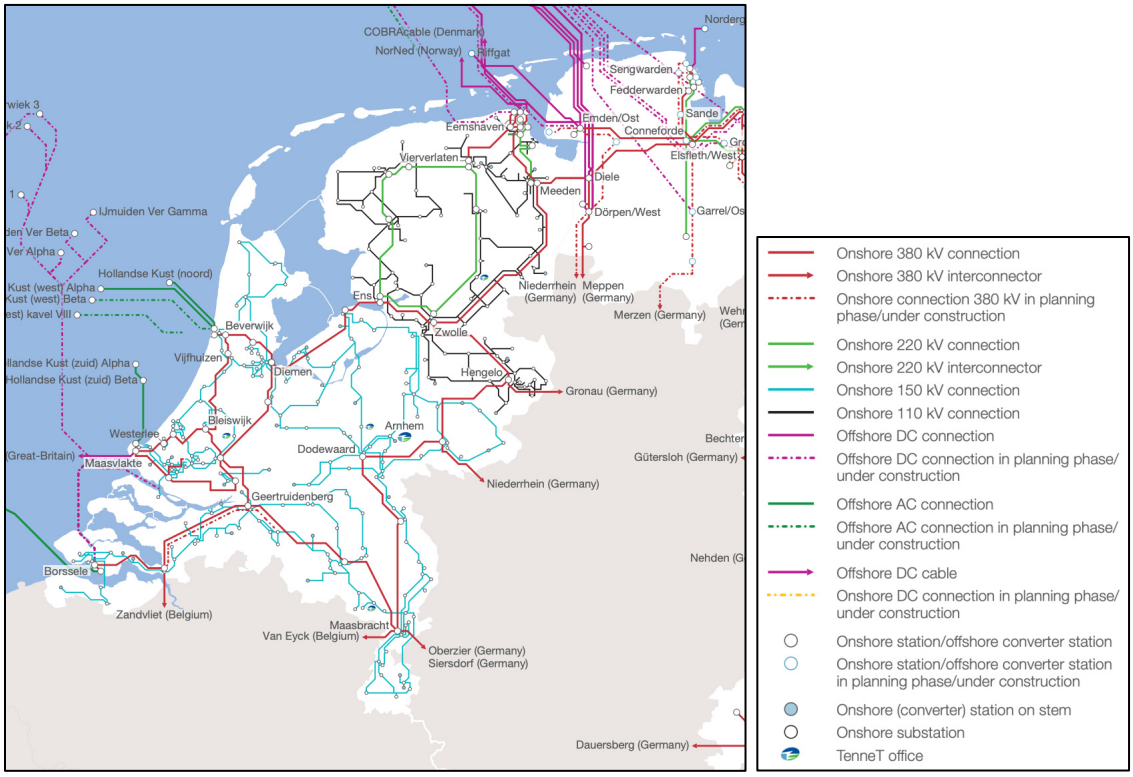


Figure 4.5: Tennet TSO's On- & Offshore Electricity Grid Map (TenneT, 2026)

Despite the visible redundancy in high-voltage lines, cross border connections mostly consist of single edges, making a single infrastructure disruption conceivably cascade onto other nodes of the network. While both countries' offshore activities could theoretically suffice for the individual national electricity demands, the only cross border connection of Meeden-Diele, exclusively managed by Tennet TSO on both sides, represents a unique case where two probable and opposite scenarios may occur:

A. The unique management facilitates rapid service restoration after a disruption, whereas a cross-border connection with neighbouring service providers could require more time and effort;

B. The unique management of both large networks facilitates the propagation of a failure far from the Meeden-Diele connection, whereas a connection with a partnering service provider could rapidly stop it due to different governance, management or safety systems.

As seen in the figure, the Dutch high-voltage network does cross borders in the Limburg region, in an area near but outside of this study's canvas. The TenneT TSO company, contacted via email and by phone, stated that no granular network map could be provided. Therefore, low-voltage grids and thereof possible transboundary connection cannot be addressed or studied in this paper (TenneT Holding, 2025;2026).

Likewise, the Belgian electricity provider Elia Group displayed in Figure 4.6 provides a comprehensive overview of the Belgian network and its cross-border connections, also confirming the absence of transboundary edges within the present study's canvas area and highlighting the Maasbracht town's double outward connections. Although a cross-border edge within this canvas exist (purple line), linking the Belgian Lixhe Alegro electric substation to the German Oberzier electric substation, this connection is underground and therefore assumed as not affected by floods. The uncropped map, available in Appendix K, shows the Belgian networks in its entirety, allowing similar transboundary conclusions similar conclusions to be drawn as for the TenneT network, but here with the additional countries of France and Luxembourg.

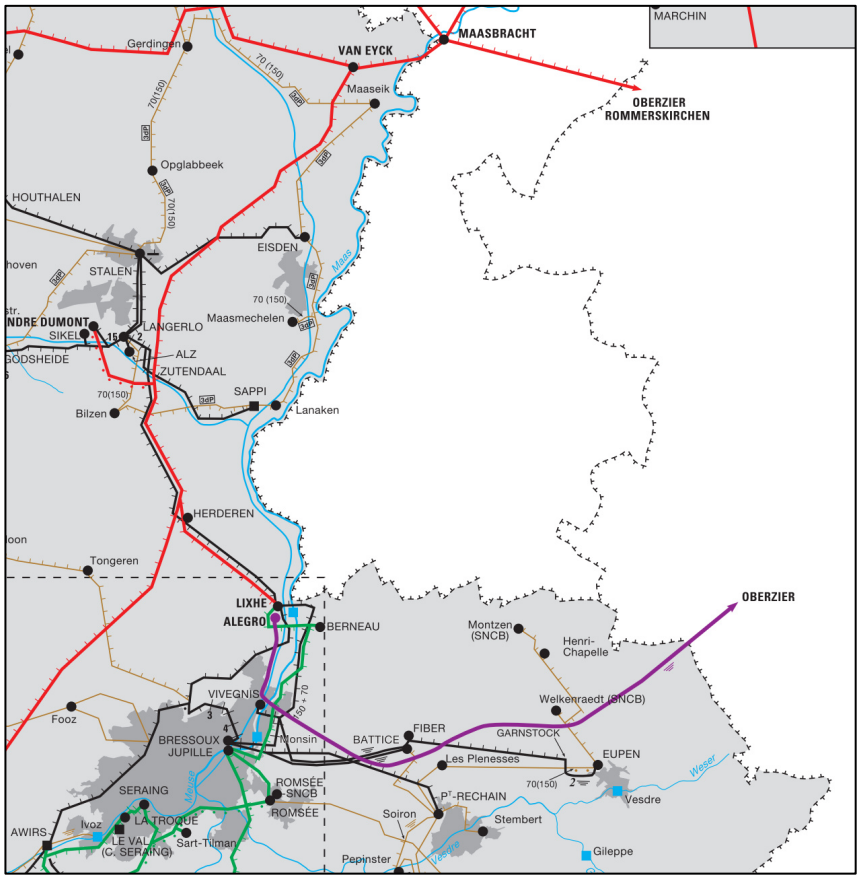


Figure 4.6: Elia Group's Belgian Electricity Grid Map (Elia Group, 2023)

In the absence of granular data on low-voltage electricity grids crossing borders in the region, given the high-voltage maps considered above did not exhibit cross border connections in the study's canvas, and given that suppliers' grid maps suggest at net responsibility boundary at national borders, the CI network of electricity is treated as a discontinuous and non-transboundary system in the QGIS spatial modelling of this research. Public institutions and commercial entities of the sector were contacted for requests of interview and detailed geospatial data, but the neither could be provided for confidentiality reasons.

Gas Network(s)

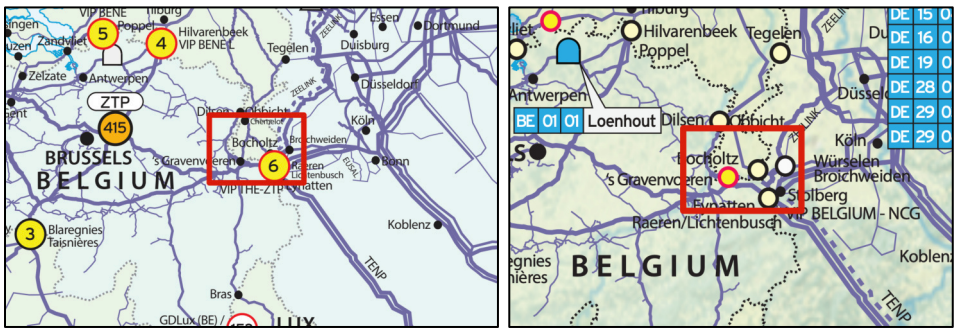


Figure 4.7: GIE System Capacity (left) & Storage Operators Grid Maps (right) (GIE & ENTSOG, 2024)

Gas Industrie Europe (GIE), an association representing the interest of European gas infrastructure operators, and ENTSOG, the European Network Transmission System Operators for Gas (GIE, 2025), provide several maps that indicate possible gas grid overlappings with the research's canvas area, placing special indicators for cross-border interconnection points, as apparent in Figure 4.7. At the cross-border point n°6, transmission capacities agreements exist between the Belgian operator Fluxys and the German GASCADE, Open Grid Europe and Thyssengas partners (ENTSOG & GIE, 2024).

The cooperation between gas operators all over Europe may again demonstrate the dichotomous effects of a single and global management system of a singular gas market, comparable to TenneT for the Dutch-German electricity grid. This effect may reveal itself either helpful or detrimental to the resilience of the transboundary interconnected network. As the geospatial data behind these maps could not be retrieved from online sources nor provided by contacted operators, further granular investigations remain methodologically infeasible.

Nonetheless, GIE is constituted of 72 member operators across 25 European countries, and take part in transmission, storage and regasification activities of most commonly supplied gases such as natural gas, liquified natural gas (LNG) and hydrogen (GIE, n.d.). Therefore, the gas grid maps remain an important asset and baseline for the study of transnational cascading disruptions on the large scaled network of primary gas pipelines. Uncropped maps are available to the read under the web source in Appendix J.

Due to a lack of granular data of the gas distribution networks to cities and industries, and because large-scale transboundary connections presented above cannot be precisely located with geospatial data, the CI network of gas is treated as a discontinuous and non-transboundary system in the QGIS spatial modelling of this research. This assumption is further supported by the sector's management system, which is closely tied to that of the electricity grids, as energy service providers often operate both (cf. 2.5.2).

Water Network(s)

While the drinking and wastewater networks in the regions involved in the study's canvas area are somewhat present and documented –in OpenStreetMap data bases–, a significant data shortcoming exists regarding both granular and macro information from commercial entities responsible of these networks. Despite extensive research and contact outreaches, no grid maps or geospatial data could be retrieved for drinking and wastewater pipeline networks within the Euregio Meuse-Rhine or any of the three studied countries. Although point data sets exist for water quality measuring locations, these are considered irrelevant for the supply of drinking water and collection of wastewaters from inhabitants or healthcare facilities.

Through an interview conducted with experts from the Waterschap Limburg (WL), the Dutch organisation in charge of the Limburg region's wastewater collection and generally its water / flood defence infrastructure, several key factors and insights are acquired.

First, inter-agency communication and information exchanges exist and take place, both with WL's counterparts within and across borders (other Dutch 'Waterschapen' and German 'Wasserverbände'), as well as with partnering organisations from Dutch and German governmental bodies (municipalities, provinces, regions or the Rijkswaterstaat). Given the size difference between the Netherlands and Germany, the WL communicates significantly more with German regional entities (Länder) than with national and federal bodies of Germany. Naturally, communication and information exchange channels also exist with Belgium, again less with national entities. Presumably given the Netherlands' awareness of water levels and floods management, experts added that Dutch federal ministries such as the Rijkswaterstaat have at times shown greater involvement with the Waterschap Limburg and or concerns over the Euregio Meuse-Rhine than Belgian and German ministries. In these countries, the topic is more often addressed regionally than nationally.

Secondly, the Waterschap Limburg and its partners closely collaborate on projects such as the Flood Wisdom – Interreg Meuse-Rhine. From the desire to improve weather and water data collection in Belgium, Limburg and North Rhine-Westphalia, the project seeks to understand water flows and nature to better predict and mitigate floods risks in the future (Interreg Meuse-Rhine, n.d.). Funded at 50% by the EU, the WL and its partners currently conduct research on water behaviours to create digital GIS twins for flood modelling purposes. They also undertake local construction projects to install measuring devices across borders. Notwithstanding, greater international water and flood defence systems are still conceptual projects under development. Additionally, the Waterschap Limburg aerial responsibility is strictly limited to the Limburg province, as is for any water company in the Euregio Meuse-Rhine. To this end, the CI sector of drinking water, wastewater and general water infrastructures is considered as a discontinuous and non-transboundary system in the QGIS spatial modelling of this research.

Healthcare & Emergency Response Services Networks

Dependencies in and interactions within the Healthcare and Emergency Response CI sectors are provided by experts testimonies. The overall conclusion drawn for cross-border activities in the present sectors is that dispatched ambulances from hospitals and fire or rescue engines from fire stations may intervene in mission in neighbouring countries, without prior authority consultation, as collaboration frameworks exist. Therefore, all healthcare and emergency response geospatial data presented in section 4.2 is considered constituting transboundary networks. An exception remains to pharmacies, for which no specific expert insights were collected, and are therefore not considered as forming transboundary networks.

Synthesis of the interviewees' testimonies are available in Appendix Q, and further insights drawn from experts are presented and utilised in subsequent sections.

4.2. Model Description and Preliminary Regional Insights

The present section transitions from a macroscopic appraisal of critical infrastructure networks, addressed in section 4.1, to a mesoscopic examination of the retrieved geospatial data and thereof constructed QGIS model, analysing the region's current configuration in terms of possible vulnerable CI facilities in HQ100 flood scenarios. By layering the CIs point data sets above flood rasters, a preliminary study of flood-exposure levels is established within the canvas extent. This step enables the identification of

potential trigger points or areas for disruptions cascading through networks and sectors. The energy, health and water sectors are individually examined in section 4.2.1 to 4.2.3.

Due to inherent inconsistency within some OSM data sets, three criteria are used to maintain only geographically comparable layers and to simplify the examination of the QGIS model. Following the criteria of data availability (at least one node per country), data homogeneity (nodes equally spread across the QGIS canvas) and of CI level of cross-border influence (degree to which a CI type may significantly ease the cascading of a failure across borders), some OSM layers are omitted in the following subsections. The extended selection process of retained and disregarded layers may be found in Appendix O.

4.2.1. Energy Infrastructure Synthesis

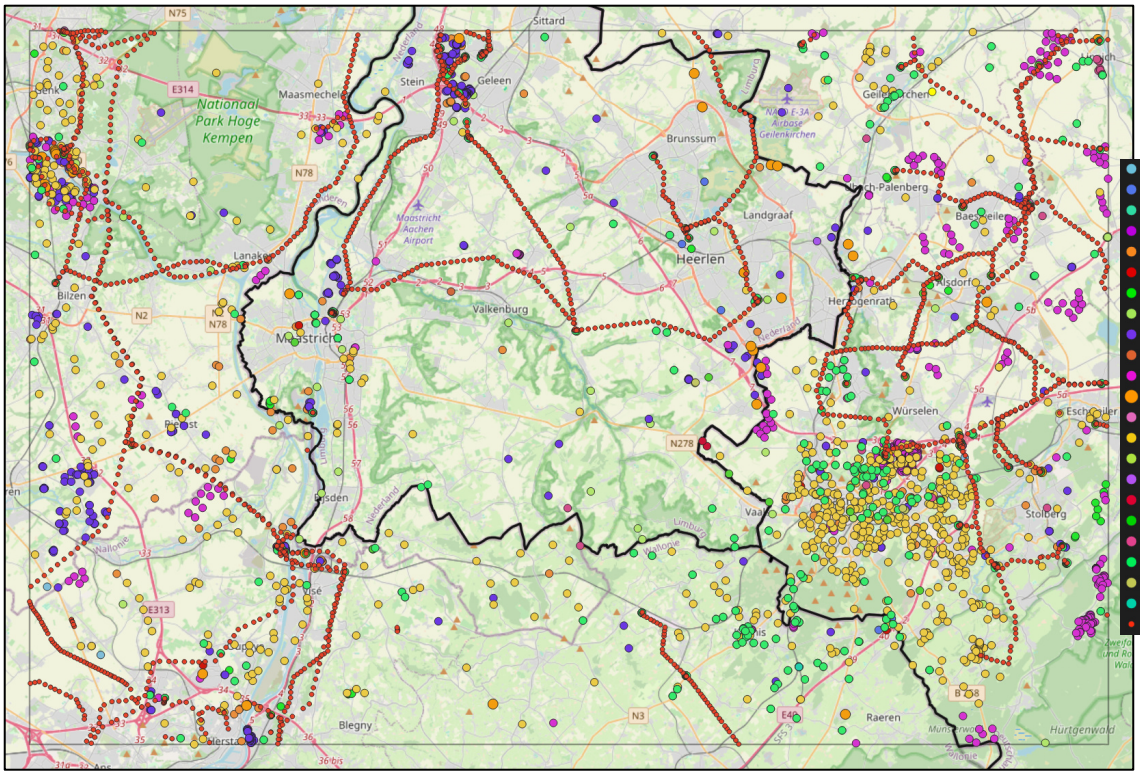
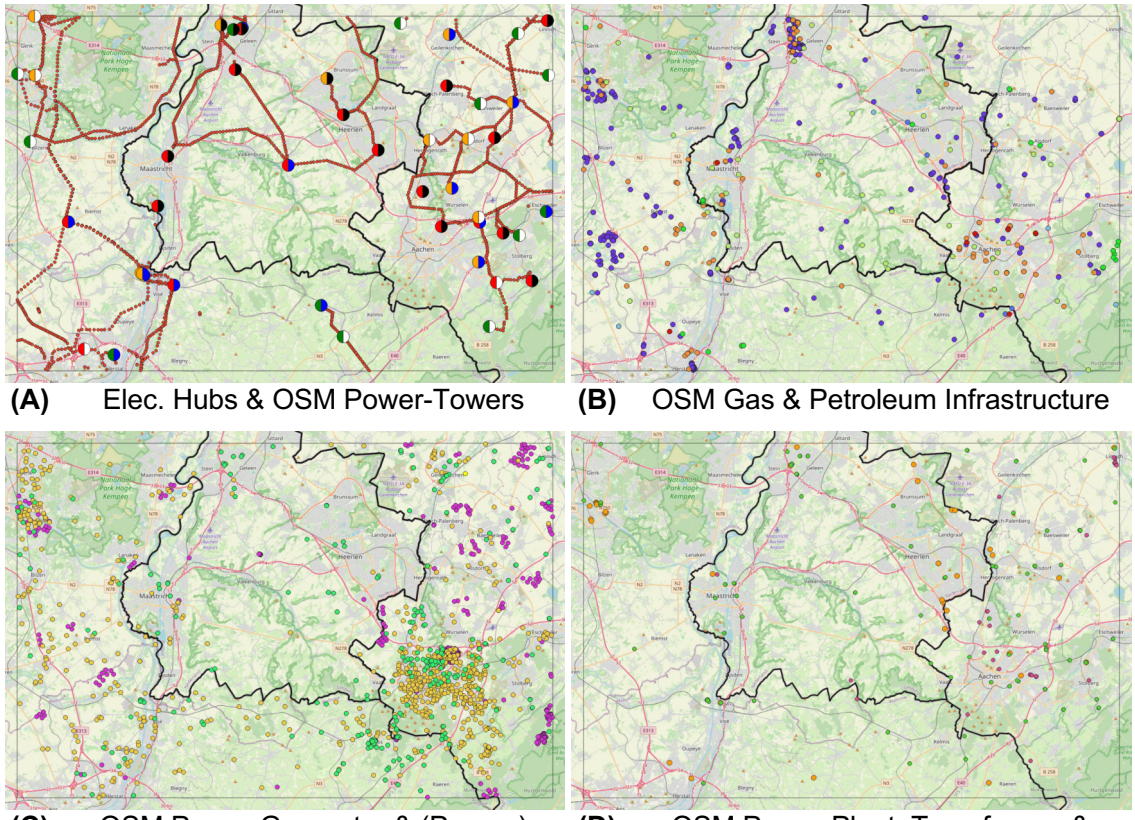


Figure 4.8: Energy Point Layers from OSM Data (Debelle, 2026)

Figure 4.8 shows the 23 retrieved OSM data sets for the canvas extent of the present study. At initial observation, a clear visual correlation appears between urban density and concentration of energy infrastructure assets. Such agglomeration of critical energy infrastructures and clusters underscores how topologies of networks are highly contingent to urban-rural settings, which thus influence the probability and behaviour of a cascading disruption. The studied canvas area encompasses a diverse spectrum of settings: urban-rural between Maastricht (NL) and the Flemish Limburg region (BE), urban-urban between Aachen (DE) and Heerlen (NL), and rural-rural between the Geul (NL) and Ardennes (BE) national parks. While this trait may provide a representative sample of a border region or of the Euregio Meuse-Rhine, subsequent map assessments demonstrate further realities influencing network analyses, essential to integrate in failure propagation research.

Given the many overlapping point elements and information density, insights are derived by deconstructing the map into legible data layers, as displayed in Figure 4.9 below, with:

- Map **(A)** displaying the high-voltage electricity grid;
- Map **(B)** displaying all gas- or petroleum related layers (i.e. industrial gas, industrial oil, man-made chimney, man-made gasometer, man-made mineshaft, man-made monitoring station, man-made storage tank);
- Map **(C)** displaying the remaining electricity layers with many point elements;
- Map **(D)** displaying the remaining electricity layers with few point elements;
- The remaining layers are not addressed here, as all of their point elements are physically nested within compounds of electricity hubs, which are acutely studied in section 4.3.1 (line bay, line busbar, power-compensator, power-portal, power-switch, power-switchgear, power-terminal).



(A) Elec. Hubs & OSM Power-Towers

(B) OSM Gas & Petroleum Infrastructure

(C) OSM Power-Generator & (Power-) Substations

(D) OSM Power-Plant, Transformer & Street-Cabinet

Figure 4.9: Deconstructed Maps of Energy Data Sets (Debelle, 2026)

- Network Redundancy:

  At first visual inspection of map **(A)**, the German and possibly Belgian transmission grids suggest higher degrees of redundancy compared to the Dutch network. While this possibly enhances the electricity provision robustness by enabling alternative supply paths during local failures, the increased connectivity may also facilitate propagation of disruptions across the broader CI network. It should be noted that this observation is made for the studied canvas extent overlapping with the respective regions, and may not hold true in other parts of the Dutch-German, Dutch-Belgian or Belgian-German border.

- Industrial Clusters in Gas and Petroleum Industry:

  Map **(B)** allows the identification of gas and petroleum nodes clusters, indicating industrial sites or parks of these industries. The point agglomerations from the

man-made storage tanks (purple) and chimneys (orange) layers represent, amongst other, the:

- Petroleum Port of Wandre (northeast of Liège);
- Imerys industrial zone (across the southwest Dutch border corner);
- Tongeren-Oost industrial zone (mid-way between Liège and Genk);
- Logistics Valley Flanders –Port of Limburg– (south of Genk);
- Beatrixhaven (northern Maastricht port);
- Chemelot industrial district (northwest of Geleen).

To the exception of Tongeren-Oost industrial zone, all other parks are close and connected to a major waterway. Specifically, the two Dutch industrial parks are significantly impacted by HQ100 floods, such as the Chemelot industrial district in Figure 4.10.

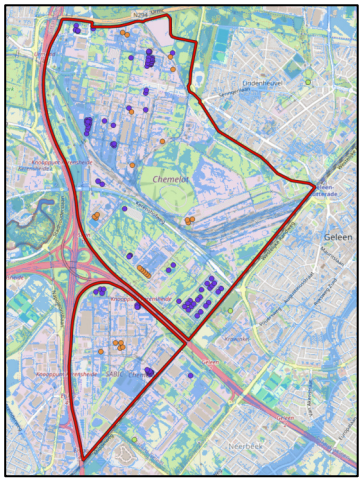


Figure 4.10: Chemelot Site with Gas and Petroleum Infrastructure Flooded (Debelle, 2026)

Such sites, possessing connections to rail network, waterways and high-voltage infrastructures, are particular crossing points of natural hazard disruptions, bridging from one CI network to another. On an independent note, 103 of the 686 gas and petroleum nodes (15.0%) are flooded in HQ100 scenarios.

– Dissimilar Data Availability or Energy Systems:

As visible on map **(C)**, the city of Aachen appears to possess a specifically higher amount of (power) substations (yellow and green) than other cities. This may either be explained by a higher crowd-source participation in the public OSM data base, or by a different organisation of the electricity provision system in Germany or the NRW than in the neighbouring countries and regions. This highlights the methodological limitations of transboundary cascading effects research, as retrieving exclusively geospatial data and only building a QGIS model does not suffice to analyse a disruption spreading onto or between networks. Dissimilarities in CI systems' structures and data availability must be examined and integrated to ensure the comparability of data and regions. Studies comprising cross-border characteristics and assessments may not simply consider the studied area as single, equally mapped and structured region, but must also account for non-CI information such as legal, technical, topological and political differences in the management and governance of critical infrastructures.

– Remaining Insights:

Map **(D)** provides few additional and general insights from the retrieved geospatial data. First, the power-transformer and street-cabinets are again principally presenting data in German territories, substantiating the crowd-source or disparate electricity system conclusions from map **(C)**. Second, the layer power-plant layer principally contains solar-power generating facilities, which may appear counter-intuitive. This accentuates the complexity of cross-sectoral cascading failure studies, requiring knowledge in multiple CI domains and infrastructure systems to recognise that wind turbines are also key assets of an electricity network. Given their height, the collection of the latter's geospatial data is omitted in the present study. Lastly, the power-plant layer may also not be most up to date, as some solar parks visible on latest satellite data are not necessarily contained in the layer.

4.2.2. Healthcare and Emergency Response Infrastructure Synthesis

The following Figure 4.11 displays deconstructed maps of the OSM-retrieved data sets relating to facilities of healthcare or emergency response services. Following the narrative of visual observations, a series of statistical metrics are detailed.

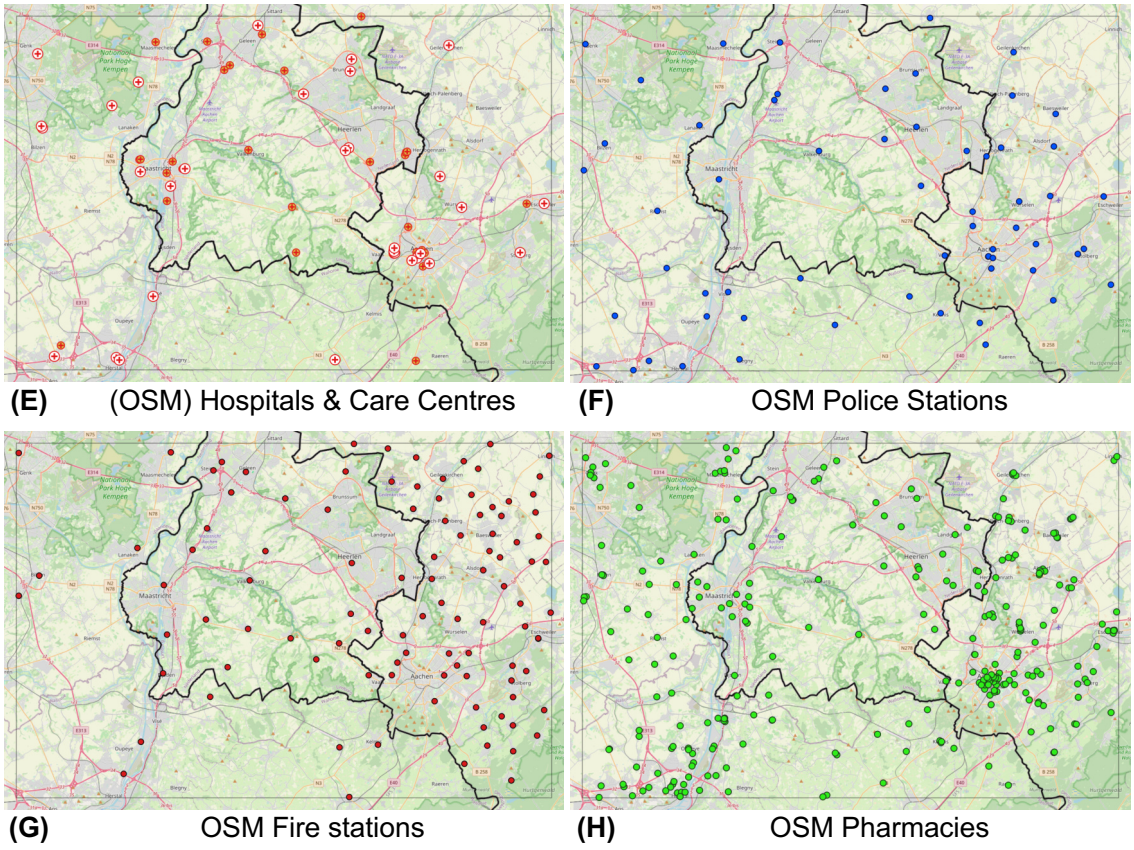


Figure 4.11: Deconstructed Maps of Healthcare and Emergency Response Data Sets (Debelle, 2026)

Hospitals & Care Centres

In map **(A)**, hospital facilities (red cross on white background) exhibit a relative uniform and homogeneous distribution across the studied canvas, with larger urban areas often possessing three to five hospitals. It should be noted that hospitals with physically distinct buildings are not considered as single but as multiple nodes, as medical campuses usually comprise large areas rarely entirely flooded, some buildings being safe. On the contrary, care centres (red cross on orange background; cf. definition in section 3.4.3) are more prevalent in the Dutch Limburg region. A thorough review of the healthcare service infrastructures and their vulnerability to cascading disruptions is following in section 4.3.2.

Police Stations & Pharmacies

Police station and pharmacies visible in maps **(F)** and **(H)** follow similar trends as energy infrastructures, being typically more densely present in areas than rural areas. From a visual scrutiny, the Belgian rural region is showing a greater concentration of these facilities than Dutch and German rural region. On the contrary, the large city of Aachen appears to possess more facilities per habitants than Maastricht or northern Liège. These observations suggest possible dissimilarities in national or regional public policies regarding the availability levels of police and pharmacy services. In flood risk assessment and cascading effects research, the two networks may be regarded as of

lower vulnerability and lesser criticality to other CI sectors, given their extensive geographic presence. Additionally, in the present study, the police and pharmacy CIs are considered as not interconnected within their subsector (layer), and cannot directly initiate a cascading failure onto the energy, healthcare or water sector. Moreover, it is assumed that the dispatching of police units or selling of pharmaceutical products is possible even if a facility lacks the supply of electricity, gas (petrol) or drinking water due to a failing nearby energy or water CI. Accordingly, their influence on the provision of healthcare services is neglected.

Nonetheless, experts have emphasised the importance of IT infrastructures and communication channels prior to and at times of natural hazards, from which police stations (and fire stations) heavily rely on for incident alarms and emergency call-outs. Evidently, the two types of CIs also greatly depend on the network of roads. These sectors both fall outside the scope of the present study, and are discussed in section 5.2.

Fire Stations

Regarding the fire stations, a clear density disparity appears on map **(G)**. From Belgium to the Netherlands and Germany, the following figures provide ground insights about the status quo of emergency response teams' availability in the countries' studied area (considering their service area, i.e. Voronoi polygon, crosses borders):

Country	Total (/)	Density (per 100km^2)	Mean Catchment (inhab. / fire station)	Mean Fire Stations (per 100,000 inhab.)
Belgium	11	1.3	30,910	3.2
Netherlands	25	4.1	21,530	4.6
Germany	68	11.7	8,352	12.0

Table 4.1: Fire Stations Figures for the Canvas (Debelle, 2026)

Data from Table 4.1 indicates that the NRW region maintains superior per capita service levels than its neighbouring regions, with Belgium provinces possessing particularly few fire stations per inhabitants. The former could be a sign of a robust German emergency network, as more units are available for dispatching in case of emergency response or natural hazards. Notwithstanding, further fire department facility characteristics may influence the quality and supply levels of emergency response services: size of the station (in workforce) and labour skills, possessed equipment (in category and amount of vehicles and gadgets), resources for self-sufficiency in cut-off scenarios (food, clean water and medical supplies stored on site), influence of floods on the facility (access roads, functional equipment), etc. More logically, it can be concluded that German fire department networks are far more decentralised than Dutch and Belgian ones, possessing grouped subdivisions and consolidated stations with conceivably greater workforce capacities and equipment availability.

Flood Insights

Table 4.2 below provides base statistical numbers on the amount of flooded health-sector CIs flooded in HQ100 scenarios. Explanations on the methodology used to determine the visual flooding parameter, as well as the full table, are available in Appendix N (the column "Node Flooded CIs" and the rows "Hospital (ES)" and "Pharmacy" are deleted for legibility purposes). Generally, an infrastructure is considered as unable to operate or provide its regular service if visually evaluated as flooded.

Country (CI)	Total	Visually Flooded		CI Density
	#	#	%	(# / 100km^2)
Belgium	**157**	**35**	**22.3%**	
Hospital (H)	10	3	30.0%	0.4
Hospital (CC)	3	0	0.0%	0.2
Fire Station	11	3	27.3%	1.2
Police	24	5	20.8%	12.6
Netherlands	**116**	**75**	**64.7%**	
Hospital (H)	9	7	77.8%	3.0
Hospital (CC)	18	11	61.1%	4.1
Fire Station	25	21	84.0%	1.5
Police	13	7	53.8%	8.4
Germany	**237**	**79**	**33.3%**	
Hospital (H)	14	5	35.7%	1.6
Hospital (CC)	9	4	44.4%	11.7
Fire Station	68	31	45.6%	2.4
Police	23	5	21.7%	21.2
Grand Total	**510**	**189**	**37.1%**	

Table 4.2: Statistical Numbers on Flooded CIs (HQ100) from the Healthcare and Emergency Response Services Sector (Debelle, 2026)

By analysing the direct exposure to HQ100 flood scenarios of health-sector CIs, the data reveals significant vulnerability discrepancies across the national subareas of the Euregio Meuse-Rhine. As the south Dutch Limburg region is mainly urbanised along the Meuse river, critical infrastructure is mostly located there and therefore in flood-risk areas. This fact explains why twice more health CIs are flooded in this part of the Netherlands (64.7%) than in the neighbouring regions. On the core emergency response services specifically, being hospitals (H) and fire stations, the Dutch region systematically possesses on average twice more flooded infrastructure. This underlines the importance of cross-border collaboration agreements, to share the load of patients intake at time of emergencies from natural hazards.

Moreover, the Belgian areas of the canvas consistently possess lower health-CIs densities than Germany, which possibly reveals an underlying structural difference between both nations. This shows that regions of the Euregio Meuse-Rhine do not share equal laws, policies, budgets or governance systems regarding their critical infrastructures and thereof networks.

Together, the numbers indicate greater vulnerabilities on Dutch and Belgian territories (respectively for geographical / natural and for structural reasons), pushing thereof authorities to rely on their German counterparts for CIs of the health sector. This not only highlights the importance of transboundary agreements on collaboration, but also why research omitting cross-border partnerships and events does not permit proper national vulnerability assessments, as external factors may heavily alter technical conclusions.

4.2.3. Water Infrastructure Synthesis

Figure 4.12 shows a map of the retrieved OSM data regarding drinking water, wastewater and flood defence infrastructure.

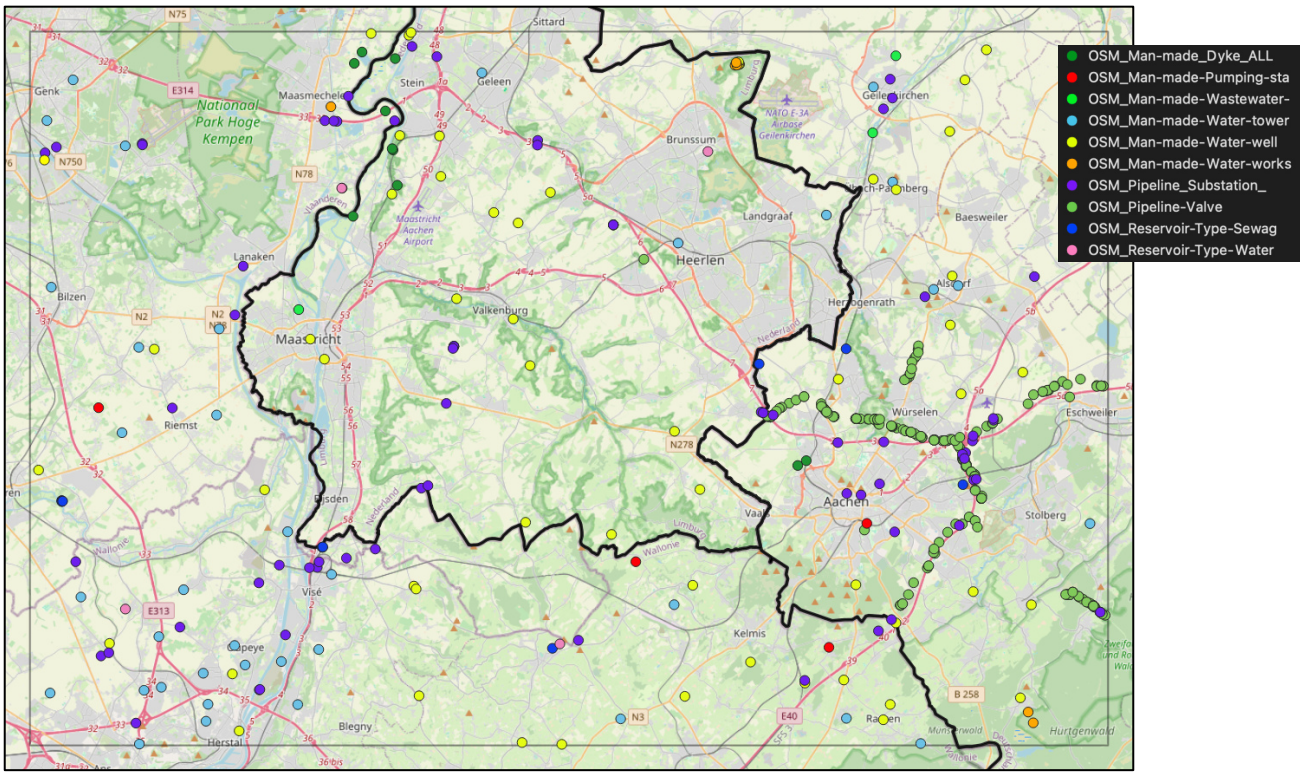


Figure 4.12: Water Point Layers from OSM Data (Debelle, 2026)

The map allows to draw similar insights as the energy sector, with specific OSM layers being either more complete in German territories, or the German authorities having different water grid structures as its neighbouring countries. In both CI sectors, Germany generally stands out with more data point elements. Following brief insights are drawn:

- Reservoir infrastructure (for general [pink] or sewage [dark blue] purposes) are not homogeneously present across the canvas. If accurately mapped and documented, this could possibly indicate a weakness point of the (waste)water networks in the Dutch Limburg, where a flood –and thereby initiated disruption– could start a cascading failure chain;
- Likewise, the water-work (orange), pumping station (red) and dyke (dark green) layers are heterogeneously spread across the canvas, but do not provide specific insights into their subsectors. Dykes are principally observable in the northern end of the Meuse river's bed, precisely at the border of flooding areas in HQ100 scenarios.
- Water wells (yellow) are homogeneously spread on the canvas extent, indicating a natural and decentralised sourcing of drinking water. In the event of flooding, although localised wells may not be serviceable anymore, the aggregate supply of water could remain largely resilient;
- Similar to map **(A)** of Figure 4.9, and if accurately mapped, the pipeline substation network (purple) suggest a higher degree of water grid redundancy in German and Belgian territories than in Dutch regions (the countries respectively possess 25, 31 and 10 substation nodes, or 4.3, 3.7 and 1.7 per 100km^2);
- Some CI elements are principally present in a single country, such as pipeline valves layer (light green) in Germany, or water towers (light blue) in Belgium. If the data is correctly registered in the OSM databases, this could indicate that distinct countries have very different elements in their global CI sectors. Therefore, nations should not just consider their own system structures and criticality definitions when assessing neighbouring countries' resilience to natural

hazards and CI cascading failures. If the data is incorrectly registered, then an identical conclusion as earlier apply;

- Last, the OSM queries provided three wastewater plants (fluorescent green), with none in Belgium. When comparing with a Belgian geoportal-retrieved data set, six wastewater plants are located within the canvas. This underscores the sometimes unreliable data quality of OpenStreetMap.

4.3. Criticality and Vulnerability Assessment

In the present section, the micro assessment of networks vulnerability is conducted. First, the existence of vulnerable electricity hubs is presented in section 4.3.1. Thereafter, each sector's vulnerability is individually assessed with relation to the electricity hubs just elaborated in section 4.3.2. At last, the sectors are again analysed, but with their direct impact on inhabitants and civilisation in section 4.3.3.

Due to inconsistency in data availability and with some assumptions taken, few OSM layers are omitted from the micro vulnerability assessment. In the healthcare sector, only hospitals are assessed, considering that fire departments, police stations and pharmacies may send units or sell products without a supply in electricity. For the electricity sector, the same assumptions permit to disregard dykes, water towers and water wells. Additionally, it is assumed that infrastructure such as sluices and dykes truly critical in their flood defence aspects rely on secondary or emergency sources of energy, or may not require electricity, or may not witness dysfunctions from floods. Pipeline substations are also ruled out as they principally concern private infrastructure disconnected from the public grids. At last, for the energy sector, only the major facilities of power plants, transformers, power generators, substations and monitoring stations are kept, as other layers are deemed too granular even for a micro analysis.

4.3.1. Electricity Hubs and Cross-Sectoral Influences

Due to the absence of a dynamic simulation including temporal events and constraints, the analysis of cascading disruptions is undertaken through a spatial proximity and dependency assessment. To this end, vulnerable 'primary' nodes of collected CI networks –point layers– are identified, where a service disruption of such due to a flood (e.g. electricity hub) would logically imply effects cascading and interrupting services from other, dependent 'secondary' physical assets (e.g. hospitals) or populated areas, within its spatial catchment.

The greater part of the following assessments and analysis is based on the identified 'Electricity Hubs', a point layer of 47 electrical facilities which are visibly central to the high-voltage power grid, and are therefore considered as critical to the supply of electricity (cf. 3.4.5). From all point layers of critical infrastructures, the "Electricity Hub", as well as the "Hospitals" layer, are the only layers manually screened through, element per element, to comprehend their structure, size and CI catchment, and understand their individual geographical situation with regards to the HQ100 flood scenarios.

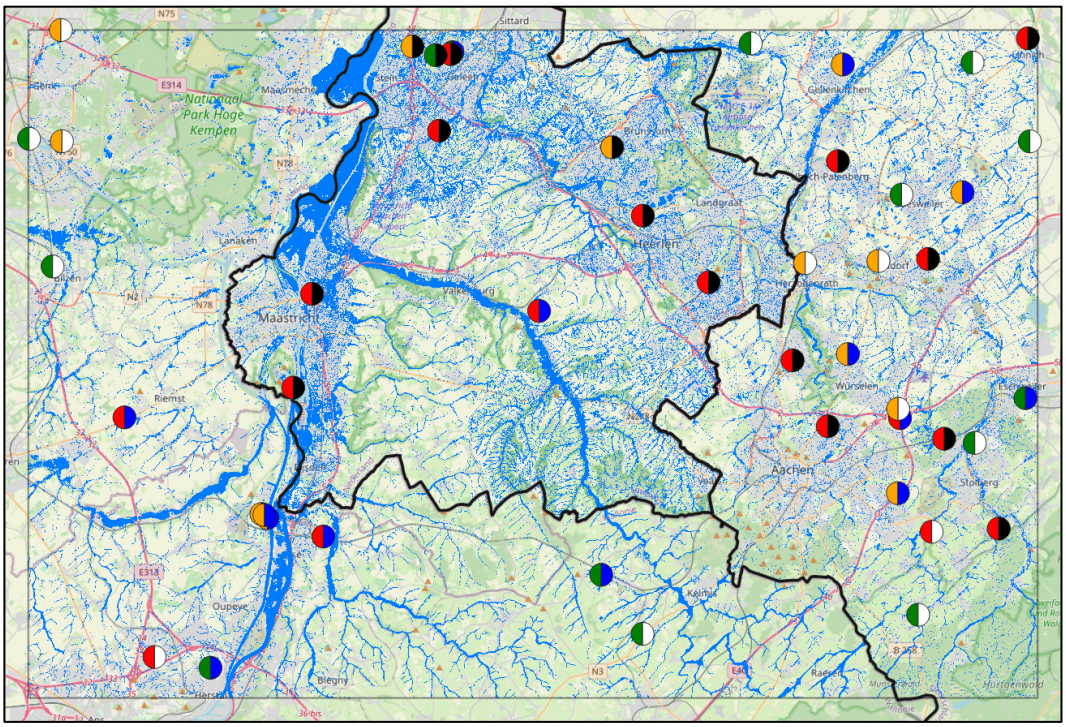


Figure 4.13: Identified Electricity Hubs in the Canvas (Debelle, 2026)

Figure 4.13 shows the layer "ElectricityHubs" with an HQ100 flood scenario raster layer. Nodes are identified with a double-coloured circle:

- The left semi-circle indicates the visually determined severity of impact on other critical infrastructures, in case of disruption (green, orange or red if the element's attribute "ImpactSev" is -1, 0 or 1).
- The right semi-circle indicates the visually determined estimated extent to which the facility is flooded and impacted by the flood (white, blue or black if the element's attribute "FloodDeg" is -1, 0 or 1).

A closer look is provided below in Figure 4.14, showing the Limmel power station (Maastricht, NL) almost fully submerged. Though the flood depth and electrical assets' physical structure does not necessarily imply a disruption of the said asset nor the entire hub, this assumption is still adopted (cf. 3.4.4).

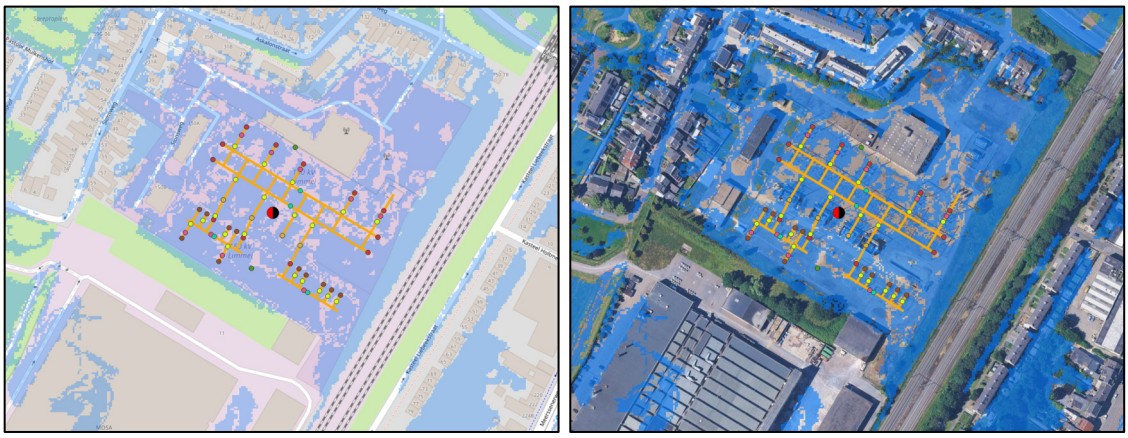


Figure 4.14: Limmel Power Station under HQ100 Floods (Debelle, 2026)

Here, the employed colour theme is logical and intuitive for interpretation. The Limmel power station (North of Maastricht) is located within the boundaries of Limburg's capital city, most likely connecting a large share of the city's population and CIs to the high-voltage power grid. Therefore, a disruption of this node would severely impact a

significant part of the population and CIs, justifying the attribute "ImpactSev" to be set to 1 (red). On another note, having most of its components flooded, and having its access roads widely submerged, the flooding degree is coherently set to 1 (black) as well.

4.3.2. Energy-to-Sector Dependencies

Energy to Healthcare Sector

In Figure 4.15 and Figure 4.16, we select key CI from the health sector, that are within the national border restricted, resp. cross-border unrestricted Voronoi polygons of critical and vulnerable "Electricity Hubs", i.e. with a high severity of impact (1) and a medium to high degree of flooding (0 or 1).

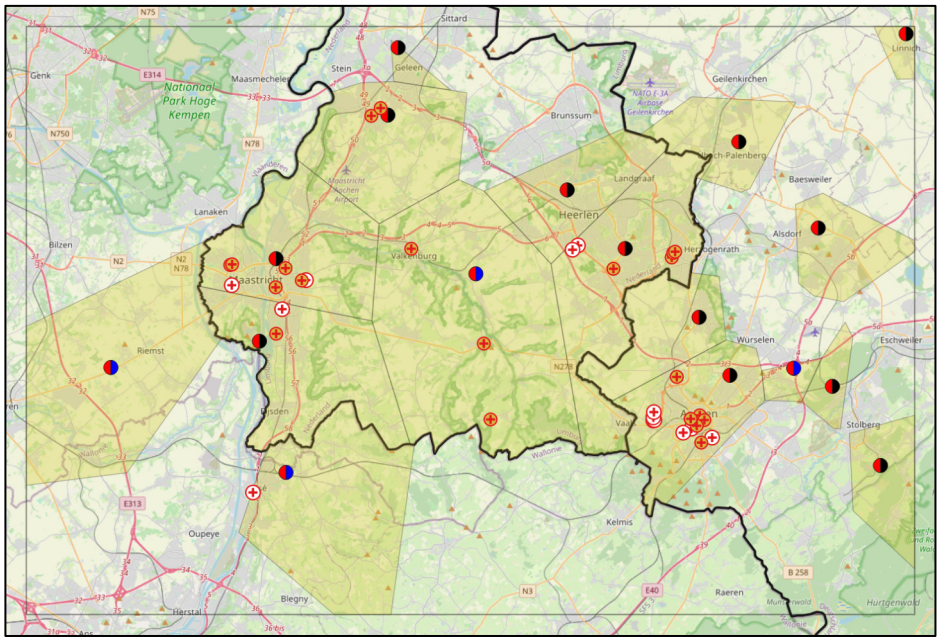


Figure 4.15: Healthcare CIs close to Critical Electricity Hubs (National) (Debelle, 2026)

Affecting the Health sector, three electricity hubs appear of particular criticality for the supply of power to hospitals (white) and care centres (orange). The northern Maastricht hub (Limmel), the northeast Aachen hub (Grüner Weg) and the southeast Heerlen hub (Terwinselen) are supplying a notably high share of hospitals and care centres, key to the area's provision of healthcare services for patients, particularly at times of natural hazards. As developed in section 4.1.2, experts explained how crucial the Uniklinik Aachen is to the region, especially for cross-border provinces and municipalities in Belgium and the Netherlands. If a disruption from the hub or a neighbouring electric CI happened to cascade up onto these hospitals, electricity shortages could apply to a large section of the population, local industry and a multitude of other local CIs.

Arguably in a broader context, the southern Maastricht hub (ENCI) and the northern Liège hub (Rue Longue) are equally threatening the regional supply of healthcare services. The former is perhaps complementary to the Limmel station in the energy, if not a full substitute in case of disruptions. The latter, though only linked to a single hospital, is significantly attached to the power grid (connecting with high-voltage lines the city of Genk and the Belgian Limburg province with Liège and its province) and to the water network (4 pipeline substations in its vicinity) (see sections below). A cascading failure originating from or reaching there could interrupt the supply of electricity to the city of Liège, if not cities of the Limburg province and Flemish region, and discontinue the provision of drinking water for inhabitants of the northern Liège province.

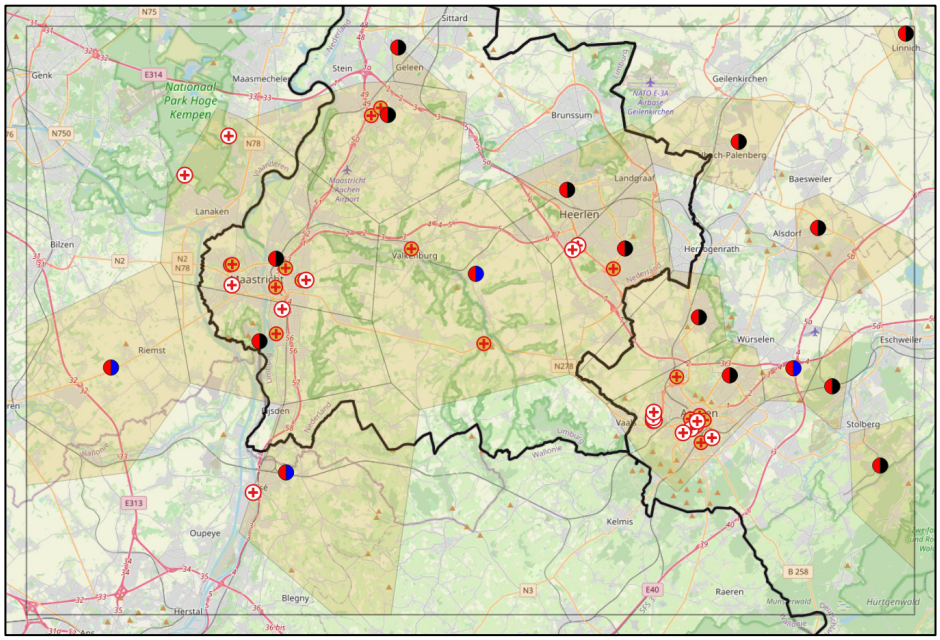


Figure 4.16: Healthcare CIs close to Critical Electricity Hubs (Cross-Border) (Debelle, 2026)

As presented in 4.1.2, large energy providers such as TenneT and Fluxys possess networks of high-voltage lines and main gas pipelines, which do cross borders between Belgium, the Netherlands, and Germany. Because these crossings are outside of the studied area, and to enable the comparison of cascading effects between national and transboundary networks of CIs, a cross-border electricity network is mimicked by analysing the electrical hubs' influence considering their service area is not bound to national borders (i.e. now using the international Voronoi polygons). Figure 4.16 displays this, considering the same critical hubs and their impact on the health sector. This replicates the consideration that governmental agencies and commercial organisation would cooperate to bring the management and governance of local provision of electricity at a central and international level.

When comparing the results from Figure 4.15 with the above figure, minor changes are visible: while the south Limburg central hub (Ransdalerstraat) and the Heerlen hub (Terwinselen) are linked to less care centres, the Maastricht Limmel hub is now connected to two remote and rural Belgian hospitals. While such a small shift might initially be dismissed as insignificant, it must be considered that the canvas' specific geographic features, as well as common urban planning characteristics, may alter this observation. In fact, the cities of Liège, Maastricht, Heerlen and Aachen all are disconnected by rural areas with crop lands, forests and green valleys (Geul Valley, Ardennes and Eifel), as seen in section 4.1.1. Moreover, due to electricity networks' specificities, identified hubs vary in size and location: they are often large and singly present at city outskirts, given the restricted place and higher demands of urban areas, while often more present in small sizes in rural settings. In the QGIS model, all hubs' influence perimeter also span identically in the Voronoi polygons, regardless of their sizes. Consequently, the canvas' specific network may demonstrate less cross-border impacts than other border regions (whether NL-DE or other countries), as large hubs are located closer to cities –meaning further away from other cities of neighbouring countries–, themselves separated by nature reserves, and the model possibly underestimating the hubs physical span of influence.

Energy to Energy Sector

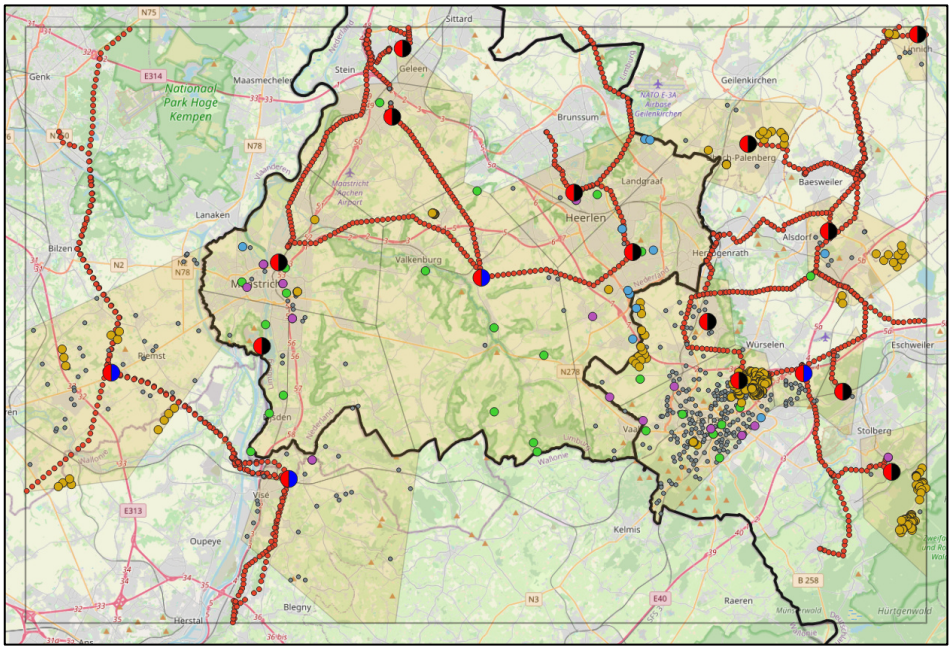


Figure 4.17: Energy CIs close to Critical Electricity Hubs (National) (Debelle, 2026)

Affecting the Energy sector, many hubs are particularly at risk of enabling the propagation of disruptive failures, given their central position on and connection with the high-voltage power grid. In Figure 4.17, power towers with an uninterrupted connection to the affected hubs are displayed (orange), even outside of the Voronoi catchments. As visible, the vulnerable hubs with severe impact scores are connecting wide and distant areas of their respective regions:

- The aforementioned Genk-Liège affected axis;
- The visible Dutch Limburg region having its entire high-voltage grid connected to critical hubs (from, to and between Maastricht, Heerlen and the non-visible part of the region);
- The visible NRW region having all of its core high-voltage axes from Aachen towards neighbouring towns joined by critical electricity hubs, possibly including parts of the major branches leading to the Düsseldorf city and the metropole of Cologne.

To contextualise the magnitude of involved high-voltage infrastructure, 1344 out of 2052 power towers (65.5%) are directly linked to critical electricity stations (hubs).

N.B.: The cross-border high-voltage line, northern of the Dutch Brunssum city, is re-entering the Netherlands few kilometres upwards of the visible canvas, without any German ground connection through a portal or substation. Although a tower could be affected by a natural hazard in the German crossing and allow a failure to cascade onto the Dutch network, the assumption of power towers not being structurally susceptible to floods precludes this possibility.

Besides the impact of high-voltage lines, several other CIs are in proximity of critical hubs and could lead a failure there. In the proximity of southern Dutch and German critical hubs (on the canvas extent), a significant amount of power plants (blue), transformers (purple), power generators (yellow) and substations (grey) are close or coupled to the electric hub stations. Should such CIs be flooded and experience a failure, its possible propagation up until an electric hub could have deleterious consequences on far located areas through the high-voltage lines, as developed earlier. Likewise, whether rural or urban, several monitoring stations (green) are linked to crucial hubs. Although an

interruption monitoring operations due to a flooded facility would not propagate onto the electricity grid, the failure of such CI to track energy distribution or support emergency provision planning could similarly deteriorate the immediate regional response to a natural hazard and thereof emergencies and crises. Out of 44 monitoring stations in the canvas, 27 are connected to critical electricity hubs, from which 7 (25.9%) are located in a HQ100 flooded area. N.B.: the higher density of substations and power generators in the NRW area may be explained by a regional difference in structure and governance of the electricity system, if not by a higher crowd-source participation on the OpenStreetMap data base in this region.

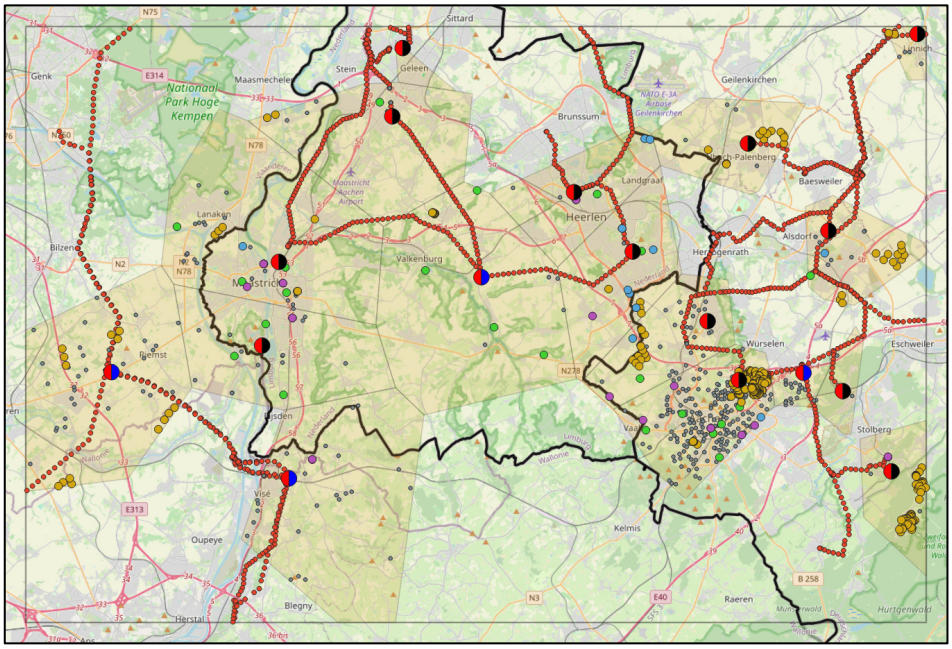


Figure 4.18: Energy CIs close to Critical Electricity Hubs (Cross-Border) (Debelle, 2026)

In an approach analogous to the comparison assessment of the previous Energy to Healthcare Sector section, Figure 4.18 provides an influence map of electricity hubs onto other energy CIs, considering the networks operates irrespective national borders (i.e. using international Voronoi polygons). Here again, the results yield minor changes in the possible impacts of cascading disruptions, yet must again not be neglected given the canvas' geographic specificities, misrepresenting the realm of true repercussions.

Energy to Water Sector

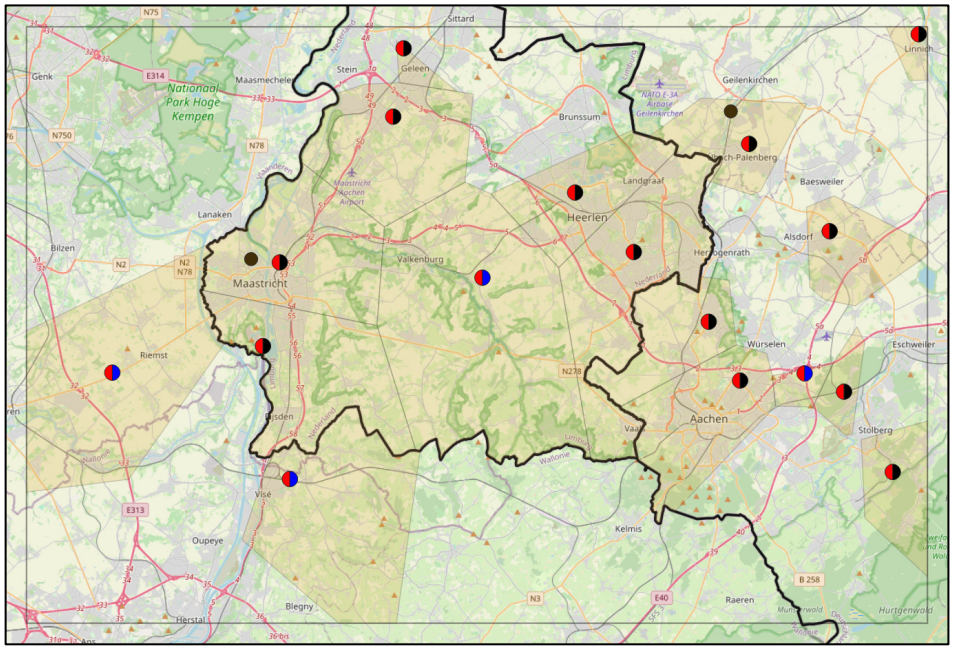


Figure 4.19: Water CIs close to Critical Electricity Hubs (National) (Debelle, 2026)

Figure 4.19 shows the selected water CIs (brown, only wastewater plants) close to critical electricity hubs, considering the border-restricted service areas of hubs. Affecting the Water sector, two distinct hubs seem of particular criticality for cascading disruptions. Considering the network of wastewater collection in the region only possesses the OSM-retrieved wastewater plants, a failure in the northern Liège Maastricht hub (Limmel) or the southern Geilenkirchen hub (Heidberg) cascading up to these plants would singlehandedly disrupt their respective region's –limited by the studied canvas' extent– complete wastewater collection.

Given the limited canvas size, and previous adopted assumptions making the sparsely dense network of wastewater plants the only relevant CI to be discussed, a comparison with the electricity network transcending national borders is dispensable, as the same hubs and wastewater nodes are affected. When including the non-OSM geospatial data on wastewater treatment plants –found only for Belgian territories–, one more plant falls under the electricity provision of a critical hub, the Tongersesteenweg hub western of the Belgian Riemst town.

4.3.3. Population at Risk of Cascading Effects

In analysing the number of inhabitants at risk of cascading effects, both from a healthcare service provision as from an electricity service provision perspective, underlying evidence arises demonstrating the relevance of assessing cross-border CI networks.

Hospitals Perspective

When comparing the share of a regions' population serviced by individual hospitals, considering patients are always brought to the closest hospital, experts insights are corroborated. Furthermore, the importance of considering cross-border topics in the governance and management of healthcare and emergency response services are accentuated.

Table 4.3 shows the amount of inhabitants served by individual hospitals, first in a fictional scenario where patients are dispatched to the closest hospital within same national borders ("Inhab. Nat."), then in the realistic scenario (as asserted by the EMRIC initiative and thereof interviewed experts) where transboundary assignment of patients takes place ("Inhab. Internat."). Additionally, the change in percentage, from national to international, is provided and sorted from largest to smallest.

N.B.: Despite the five distinct buildings of the Uniklinik RWTH Aachen being considered as separate infrastructures in previous assessments (due to their separation by roads and different flood context), the hospital is here regarded as a single entity. The full table may be consulted in Appendix L.

Hospital Institution	Inhab. Nat.	Inhab. Internat.	Change to Internat.
Uniklinik RTWH Aachen (DE)	37,910	70,490	+85.9%
Medisch Centrum Maastricht Annadal (NL)	45,647	64,527	+41.4%
Zorgcentrum Schuttershof (NL)	15,438	20,968	+35.8%
...	...	...	...
Zuyderland Medisch Centrum Nord (NL)	104,367	83,488	-20.0%
Ziekenhuis Oost-Limburg (NL)	23,763	16,778	-29.4%
Zuyderland Medisch Centrum Zuid (NL)	56,773	31,774	-44.0%

Table 4.3: Inhabitants Serviced by Hospitals of the Canvas, in Border-Restricted vs. Border-Blind Contexts (Debelle, 2026)

In international context, as is today, the Uniklinik RWTH Aachen observe an increase of 85.9% of functional reach in comparison to border limited services. This corroborates the assertions of J. Wilde, which even claimed that the hospital's reach expanded further into Belgium, to the city of Liège and beyond. If a facility-wide service failure occurs in such hospitals, significant amounts of patients or inhabitants would have to be transferred or redirected to other hospitals, not necessarily within the same country as the failing hospital. This could lead to patient congestions in facilities not originally designed for large inflows of patients, thereby causing a new service failure (such as a closed patients intake), creating further patients re-dispatchings and therefor a cascading disruption in the healthcare network of a transboundary area. Moreover, in a border-blind example, a failure to the Uniklinik RWTH Aachen could lead Belgian patients to be brought at a Dutch hospital. Existing research addressing cascading effects of healthcare service-disruptions on single-nation territories only, such complex patient exchanges would not occur and, consequently, not be assessed. Likewise, assessing a hospital servicing less patients in international than national contexts would lead to overestimation of its service load and therefore skew the study's results.

While expert testimonies indicate that no cross-border help packages were activated during the 2021 flood events, the help rejections were mainly attributed to workforce scarcity in all three countries, as emergency response teams were simultaneously occupied and engage in their national disaster's consequences. However, in an asymmetric hazard scenario –such as a targeted cyberattack on the critical infrastructure of a single nation–, the resulting cascading effects as present above would be comparable, yet now with emergency response services available to accept help packages inquiries.

Electricity Hubs Perspective

Similarly to the Hospitals, Table 4.4 shows the amount of inhabitants served by individual electricity hubs, first in the actual local scenario where households are dependent on an electricity supply from the closest hub within the same national borders ("Inhab. Nat",

keeping the assumption that all hubs have the same reach), then in the macro-like scenario of cross-border high-voltage networks (i.e. considering bigger networks like of TenneT of Fluxys), where households are dependent from the closest hub regardless of national borders.

N.B.: Despite the three distinct buildings of the Belgian Lixhe electricity hub being considered as separate infrastructures in previous assessments (due to their physical separation), the hub is here regarded as a single entity. The full table may be consulted in Appendix M.

Electricity Hubs	Inhab. Nat.	Inhab. Internat.	Change to Internat.
Chemelot (NL)	15,980	41,092	+157.2%
Herzogenrath (DE)	20,928	44,812	+114.1%
Hombourg (BE)	15,048	30,337	+101.6%
...	...	...	...
Terwinselen (NL)	116,129	71,173	-38.7%
Elia Stalen (BE)	28,957	14,165	-51.1%
Langerlo (BE)	43,926	17,465	-60.2%

Table 4.4: Inhabitants Serviced by Electricity Hubs of the Canvas, in Border-Restricted vs. Border-Blind Contexts (Debelle, 2026)

Here again, similarly to Table 4.3, electricity hubs hold significantly different shares of the canvas' population, with locations such as the Chemelot (NL), Herzogenrath (DE) and Hombourg (BE) hubs exhibiting doubled to tripled demographic catchments if border-blind cascading failures assessments are attempted. This observation is better illustrated in the map comparison provided in Figure 4.20 below.

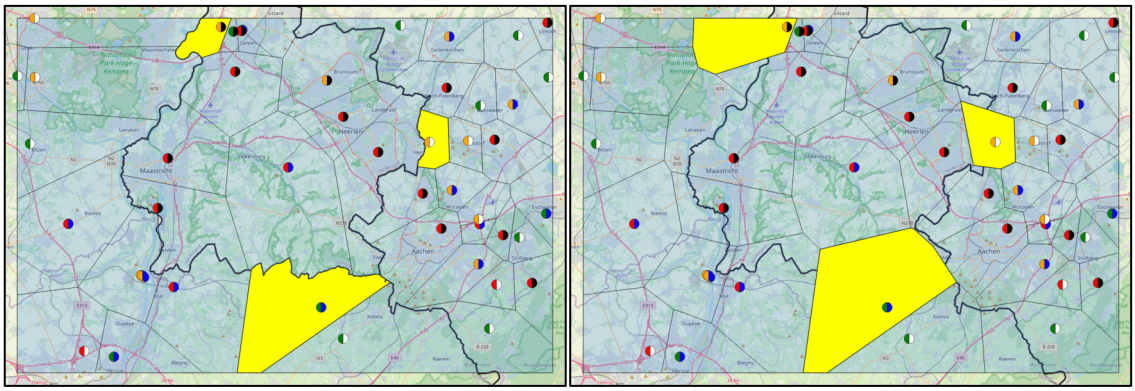


Figure 4.20: Voronoi polygons of Electricity Hubs, in Border-Restricted (Left) vs. Border-Blind (Right) Contexts (Debelle, 2026)

Supplementarily, the maps allows to underscore the significance of considering the land uses and urban / rural settings around a CI, particularly for an electricity hub. In fact, in border-restricted scenarios, the southern –rural and with forests– Belgian hub Voronoi polygon possesses a similar concentration of inhabitants as the northern –urban and built-up– Dutch hub, despite having a significant difference in surface area (the Chemelot hub being 6.6 times smaller). However, in border-blind scenarios, the Belgian hub's population share doubles in size, while the Dutch increases by a factor of 2.5. Conversely, the Belgian surface area increases by a factor of 1.5, while the Dutch one by 3.3. This is better illustrated in Table 4.5 below:

Hubs	Population Size (10^3)			Surface Area (km^2)			Pop. Density ($10^3/km^2$)		
	Nat.	**Int.**	**Δ**	**Nat.**	**Int.**	**Δ**	**Nat.**	**Int.**	**Δ**
BE	15.1	30.3	+100.7%	96.5	139.4	+44.5%	0.16	0.22	+38.9%
NL	16.0	41.1	+156.9%	14.6	47.4	+224.7%	1.10	0.87	-20.9%
Δ	+6.0%	+35.6%	+55.8%	-84.9%	-66.0%	+405.3%	+600.4%	+298.9%	

Table 4.5: Comparison of Population Size, Surface Area and Density, between the electricity hubs of Hombourg (BE) and Chemelot (NL) (Debelle, 2026)

In light of the substantial variations in supplied inhabitants emerging from factor modifications (degree of urbanisation and surface area), accounting these variables becomes imperative for robust analyses of cascading disruptions within networks of critical infrastructures.

Moreover, as electricity and generally energy networks span on entire regions and countries, the simple comparison provided in Table 4.4 does not allow to determine if considering border-restricted scenarios are more or less appropriate than border-blind networks of CIs. Additionally, the reality of electricity supply and thereof systems is likely a mix of both border approaches. Nonetheless, the displayed numbers explain why border crossing ought to be considered for cascading effects assessments, given the close equivalence with the healthcare sector studied above.

4.4. Synthesis of Findings: Impact on Regional Vulnerability

This synthesis is structured in three levels, looking at the Macro Foundation 4.4.1, the Meso Exploration 4.4.2, and in detail at the Micro Consequences 4.4.3.

4.4.1. Macro Foundation

In section 4.1, the nexus between the region's geographical setting and its potential critical infrastructure landscape is set. The canvas region, part of the Euregio Meuse-Rhine, can be understood as a tight landscape of multiple heterogeneity in land uses and population density, as well as in local natural water bodies, water ways and forested parks. Vast built-up areas are mixed with crop areas for agriculture, providing an ideal study area as elucidated in Chapter 1. Likewise, the HQ100 flood scenarios suggest a well-chosen area, with the city of Maastricht visibly more flooded than Liège or Aachen. The city being potentially a central dependent urban hub from its neighbouring countries and region, the Limburg region demonstrate interesting characteristics for the analysis of a cross-border region's vulnerability to transcending cascading CI disruptions.

Simultaneously, general sectoral dependencies are investigated for the researched CI sectors. In the energy sector, data principally suggests that cross-border interactions are characterised by discrete and localised points of interconnection, for major edges of the networks (high-voltage lines and main gas pipelines) and along the entire border between the involved countries. Regarding the water sectors, a notable paradox appears. While rivers, water bodies, weather events and flood hazards are indifferent to national borders, the associated physical assets for drinking water, wastewater and flood defence infrastructure are largely confined to countries' jurisdictions and governance, involving minimal cross-border connectivity, with the exception of information and data exchanges. Last, about the healthcare and emergency response services, experts' testimonies indicate that the sector exhibits a high degree of transboundary integration. Benefits of long-standing and functioning partnerships agreements and collaborative projects such as the EMRIC are twofold: Without constraining procedures and bureaucracy, cross-border ordinary emergency interventions from ambulances and fire

engines are enabled on a daily basis, while collaboration frameworks are established for rapid mutual aid at times of severe and extraordinary crises.

4.4.2. Meso Exploration

By focusing on the retrieved geospatial data, section 4.2 investigates the national distribution of critical infrastructure in the studied region, sector by sector. Commonalities and discrepancies are thereby unveiled, which could not be gained by means of the macro examination of the sectors and territorial specificities.

Considering the intra-sectoral dependencies highlighted in the macro foundation, the geospatial data underpins national differences in all sectors, notably about possible network redundancies, inherent vulnerabilities from network layouts, existing cluster of critical infrastructures or major sectoral assets, and variation in density and accessibility of some sectors' services. Additionally, the geographical settings reveal the Limburg region's heightened vulnerability to floods, and how its critical infrastructures are likely relying on neighbouring counterparts for the provision of their services.

Concurrently, the section underscores limitations in the assessment of network vulnerabilities, due to inconsistency in data availability and quality.

4.4.3. Micro Consequences

Using findings from the previous sections, section 4.3 delivers an inter-sectoral comparison of CI vulnerability to floodings. By identifying electricity hubs susceptible to generate the most critical cascading disruptions, each sector's vulnerability is assessed with regards to these essential nodes of the energy network.

More importantly, section 4.3 investigates the influence of border-restricted versus border-blind networks on their own and others' vulnerability. This shows why cross-border aspects, cooperation frameworks and network interdependencies may affect research on cascading disruptions within critical infrastructure systems. It demonstrates why national authorities should evaluate their domestic networks by also incorporating neighbouring systems, with their strengths and weaknesses, to accurately capture potential cascading risks. In addition, interviewed experts and online documentation underline the importance for authorities to possess solid communication channels at times of crises, and to exchange information on systems, capacities and procedures, beyond providing direct support in the provision of electricity, gas, water or healthcare. In other respects, the findings underscore the necessity of a system of networks approach that transcends national borders, perhaps an incentive for research groups or intergovernmental institutions to expand vulnerability assessment to broader geographic scopes and encompassing further diverse CI sectors.

4.5. Discussion

Building upon the legal and spatial findings of previous sections, the discussion addresses three central and cohesive dimensions: the lack of granularity and presence of a definition gap in section 4.5.1, observable cohesions only across regions, less across nations in section 4.5.2, and possibly hidden influences of CI network redundancies and cross-sectoral dependencies on the assessment of global vulnerability to cascading effects in section 4.5.3.

4.5.1. Lack of Granularity & Definition Gap

The analysis in Chapter 2.2 and the spatial findings developed in previous sections reveal a fundamental inconsistency. While the sectors of energy, water and healthcare demonstrate different levels of physical dependencies and functional vulnerabilities across the Euregio and the broader countries, the national legal frameworks and geoportal information lack of substantive depth. This creates a gap with observable realities from open-source data and experts insights, obstructing the empirical assessment of CI systems' vulnerability to cascading effects.

In the energy sector, the high degree of definition alignment between the Netherlands and Germany provide a baseline for risk assessment, as both nations consider identical subsectors as critical to the global network of infrastructure, as well as to their society. Additionally, high-voltage lines and primary branch of the gas grid being managed and governed by identical commercial entities across borders, the communication with authorities is facilitated, and assessments or protective measures to undertake are easily supported given common partners and shared legal standards. Nonetheless, this reality is primarily applicable for macro levels of the networks. On the one hand, legal frameworks fail to provide granular description of critical facilities, as they mostly describe "critical entity" or generally the provider of a service, keeping the descriptions as subsector-levels only. Thereby, the spatial assessments of physical asset remain methodologically challenging, as retrieved data consists of discrete facilities which cannot automatically be categorised under a single subsector of energy. On the other hand, governmental agencies and commercial entities fail to provide low-voltage or secondary grid spatial data, forcing vulnerability assessments to rely on open-sourced data, which does not provide information on granular network interconnectivity. Therefore, despite the countries sharing grounds on the definitions of energy subsectors, studies of cross-border CI disruptions may only integrate major interdependencies, potentially overlooking the aptitude of smaller network connections to generate broad cascading effects.

The water sector presents a significant discrepancy in protective considerations. The Dutch framework inclusion of flood defence infrastructure –distinct from drinking and waste water–, reflects a greater awareness of that subsector's criticality, which is absent in German documentation. This definition gap implies misaligned priorities in the management of flood defence assets, where events in German territories may affect and cascade onto downstream, Dutch regions and urban areas. While established flood risk assessment models and simulation tools are widely available and include water bodies and events outside of domestic boundaries, their analytical scope is predominantly limited to direct flood-to-infrastructure impacts. This upstream threat, combined with insufficient availability of spatial and connectivity data for flood defence infrastructure, impedes the analysis of cascading disruptions from the water subsector to other energy or healthcare subsectors. Although far from optimal, this flaw highlights the importance of cross-border consideration and communication with neighbouring nations, both prior to and during events of floodings. To this end, regional authorities are already undertaking transboundary projects to understand and anticipate transboundary influences, an approach currently sought by initiatives such as the Flood Wisdom or JCAR ATRACE project. This presents a notable paradox when contrasted with the national levels of the respective countries, consistently omitting transboundary consideration in legal and regulatory topics.

The healthcare sector entails the largest inconsistency between national legal definitions and the current state of cross-border cooperation. Both countries fail to properly delineate their healthcare sector, with insufficient details provided for the subsectors' physical assets. While geospatial information on hospital and pharmacies may be retrieved, a comparison between the nations' subsector is theoretically complex and inconceivable, as criticality parameters are non-existent and vital facilities such as fire departments remain unacknowledged. However, in reality, expert testimonies and the

EMRIC initiative show that transboundary cooperation is an everyday practice, operational for years already. Service providers from healthcare and emergency response entities (hospitals, fire stations) closely collaborate notably thanks EMRIC, with existing intervention frameworks for regular healthcare missions as well as responses to extraordinary natural hazard crises. This gap again exposes the paradox of regional institutions effectively integrating transnational topics, while nation-wide applicable legal frameworks fail to incorporate neighbouring infrastructure parameters.

Taking all sectors into consideration, national sources fail to provide granular information, both on legal definitions of subsectors as on geospatial data for existing physical assets. Despite expert testimonies and open-source data supplying sufficient evidence for criticalities of infrastructures and vulnerabilities of global networks, the absence of granularity hinders accurate cascading effects assessments. On a legal note, the absence of detailed parameters for assessing the criticality does not permit a fair comparison of infrastructure between countries, as physical assets of an identical subsector may not possess an identical prominence. For instance, an electricity hub along a historically overflowing river and supplying ten major hospitals of a region is legally considered as equally critical as another electricity hub, far from dangers of natural hazards and surrounded with enough grid redundancy to less likely provoke a cascading disruption onto the healthcare sector. This may be further compounded by realities such as the Limburg region being significantly dependent on German healthcare facilities, and as demonstrated in this study, does not hold any legal provision for neighbouring interdependencies. Augmented by a lack of geospatial accuracy due to inconsistent official geospatial data (forcing the use of open-source data and formulation of assumptions), the modelling of cross-border and cross-sectoral interactions is rendered significantly less faithful to reality. Consequently, the study of cascading disruptions in critical infrastructure network may fail to identify pivotal network nodes and latent vulnerable connections, at risk of jeopardising the global system of dependent sectors.

Complementary, a paradox subsists between the legal granularity of sub-sectoral divisions within a sector of critical infrastructure, and the existence of granular interconnectivity of a sector across borders. The two aspects present inversely proportional behaviours. While the Netherlands and Germany consider remarkably identical subsectors of energy, the level of granularity diminishes in the water sector with German acts not considering flood defence infrastructure, and both countries then even exclude essential emergency response facilities in the healthcare sector. On the contrary, the healthcare sector, through most of the interviewed experts and available online sources, offered valuable and comprehensible insights into its existing transboundary and tangible connections. For the water sector, fewer insights were provided, principally indicating that cross border flood projects are ongoing topics. At last, for the energy sector, only large connections across border could be identified, notably from high-voltage lines and principal gas pipelines. This paradox underscores the core structure and functioning of modern sectors, where energy demands are primarily of federal matters and managed by oligopolies, while drinking water and flood risks concern mainly regional authorities and commercial partners, and ending with a healthcare sector fully constructed and dictated by regional requirements and geographical constraints, managed by diverse local partners for heterogeneous local populations and communities. This perhaps explains why the evaluation of the energy and water sectors present greater analytical complexities than the healthcare sector.

4.5.2. Functional Cohesion: Interregional, not International

As already hinted in much of section 4.5.1, the integration of neighbouring systems of critical infrastructures is crucial for an appropriate evaluation of both domestically bounded as transboundary regions' vulnerability. Such considerations have only been observed between regional entities, yet are crucial on international levels as well.

On all addressed sectors, regional structures and governance prove their utility. For instance, the 2021 floods demonstrate the existence of a working –yet improvable– system of emergency response. The Euregio's EMRIC cooperation frameworks were put in place and functioning, but inquiries for help packages could just not be accepted given the saturation of local fire departments in domestic emergency responses. Nonetheless, the daily collaboration is fully operational and proves to be efficient for the care of patients. This is enabled thanks to regional partners engaging in multilateral dialogues to plan ahead of crises, to insure availability of services and continuous exchange of information between stakeholders during crises. In the water sector, water board such as the Waterschap Limburg possess dedicated workforce to collaborate with cross-border political and sectoral counterparts. Stakeholders and institutions in this sector are aware of the challenges arising from natural phenomena and water bodies, which do not obey to national borders. Here again, initiatives such as the Interreg Flood Wisdom show the awareness of local authorities on pressing topics around areas and populations at risk of floodings and thereof dangers. While a direct equivalent of interregional cooperation is absent in the energy sector, the observation that regional Dutch networks are all managed by a same entity (TenneT), which also holds responsibilities in greater parts of the German country, indicates again that the cross-region oversight of a CI network is feasible, even from principally commercial context.

When consulting legal and online sources of governmental entities of both countries, the influence and impact of border-crossing effects remains widely underdeveloped. Despite acknowledging existing foreign geopolitical instabilities and climatic threats, hints of international cooperation and inclusion of neighbouring countries are lacking. In the present study, geospatial evidence shows the Euregio Meuse-Rhine's heightened exposure to flood events, with specific localised facilities demonstrating higher vulnerability to cascading consequences from electricity hubs particularly at risks of failure. Blended with mixed densities of CIs and spatial asymmetries of identified CI clusters, and considering heterogeneous distributions of land uses and populations, geographical discrepancies appear between the studied regions. It has been shown how the consolidation of such realities affect cascading effects assessments of geographically small areas, encompassing only small portions of major European nations. Such dynamics are likely to be even more pronounced when considering countries in greater extents, if not in their entirety. As the electricity provider TenneT's off-shore sources of energy theoretically span across Germany to then connected the Austrian grid, major dominos events may originate from countries far further than direct neighbouring nations. Although the present study did not address risk assessment reports of respective nations, legal acts and new laws fail to include such broader context into national definitions, remaining bound to domestic consideration. In the CER Directive, the European Commission briefly mandates Member States to consider cross-sectoral and cross-border impacts when assessing the significance of a disruptive effect. Although the Netherlands and Germany may publish their respective assessment reports shortly after the course of this study, the immediate availability of drafted and signed legal acts implies that lessons and empirical insights from the reports are unlikely integrated in national definitions. Moreover, a significant risk persists for regulatory acts to remain uninfluenced until enough incentives exist to update them.

4.5.3. Infrastructure Redundancy & Cross-Sectoral Dependencies

As the study's scope principally targets cross-border integration in cascading effects assessment, cross-sectoral interdependencies are addressed to a lesser extent. Notwithstanding, conducted geospatial assessments have unveiled potentially critical connections for the cascading of disruptions from one sector to the others. In particular, the city of Aachen presents specifically higher degrees of infrastructure redundancy, principally in the electricity grid and the network of hospitals and fire stations. If preliminary analyses suggested Maastricht and the Dutch Limburg region as more

vulnerable to floods and thereby more likely to generate cascading effects within and across its borders, this unique attribute of the German city warrants a more rigorous investigation. As cross-sectoral interdependencies have not been systematically explored, the intertwined redundancies of critical networks in the city of Aachen could be representative of either weaker or stronger systems of systems. To examine this contingency with greater analytical depth, subsequent studies should include further critical sectors (e.g. transportation, IT & telecommunication, finance and insurance), specifically carrying research on underlying (hybrid) cross-border and cross-sectoral interdependencies. Nonetheless, the robust mapping of intersectoral connections is often constrained by restrictive confidentiality protocols, obstructing the accessibility to granular data. De facto, national datasets are siloed, preventing cross-jurisdictional use and application, even within an integrated political framework such as of the European Union. Generally, the findings suggest that an international system-of-networks approach is essential for domestic vulnerability assessments, providing an incentive for national and intergovernmental institutions to harmonise CIs legal, functional and governance procedures and strategies.

5. Conclusion & Outlook

5.1. Conclusions on Research Findings

The present research and case study analysis demonstrate that while the Netherlands and Germany, both members of the Euregio, share conceptual alignments with regards to the definition of critical infrastructures, significant granular discrepancies in regulatory frameworks, structural connections and spatial flood exposure exist. This creates a complex heterogenous systems of CI networks, where cross-border interdependencies influence the degree of risk and vulnerability affecting specific areas and sectors of a nations critical infrastructure landscape.

In addressing the sub-research question (SQ1) on the national definitions and legal frameworks, the ground baselines reveal that both nations agree on the overarching definition of CIs in the energy sector. However, divergences persist in the water and healthcare sector. Unlike Germany, the Netherlands provide extensive legislative details regarding water infrastructure not related to the provision of drinking water or collection of wastewaters. Rather, the country makes a clear distinction with key water assets built for flood defence purposes or part of waterways infrastructure (otherwise categorised strictly under separate CI sector such as that of transportation). This fact highlights the stronger Dutch focus on flood resilience, not mirrored in German CI definitions and initiatives. Such dissimilarity may provide a first hint towards different levels of vulnerability in the nations' respective networks of critical infrastructure, as the Netherlands may consider more assets relevant to flood disruptions than its neighbour. Moreover, both nations and the EU framework manifest a lack of precision regarding infrastructure assets of the healthcare sector. While hospitals, clinics, pharmacies and manufacturers of pharmaceutical and medical products are included, other facilities required for emergency responses to natural hazards and crises are not considered in the sector's scope. Such infrastructure, critical for the protection and rescue of civilian lives, are notably fire departments, police stations, and crisis centres.

Regarding the second sub-research question (SQ2) on the interpretation of underlying interdependencies between –systems of– critical infrastructure networks, the study finds that the structural governance of the selected sectors remains principally similar across border, both from governmental as from commercial responsibility standpoints. Nonetheless, through testimonies of field experts from the water and healthcare sectors, functional interdependencies, or lack thereof, are unveiled. In the water sectors, a paradox appears between its infrastructure and underlying element: While man-made water infrastructures and their governance are strictly limited by countries' borders, waterways such as rivers and natural hazards such as floodings do not obey to national boundaries. Although existing frameworks for the sharing of weather forecast information and water levels data, authorities and partners are aware of the criticality and significance of collaboration initiatives from the greater international protection of lives and infrastructures against flood. For this purpose, cooperation projects in the Euregio Meuse-Rhine (Flood Wisdom, JCAR ATRACE) are presently ongoing. Therewith, interdependencies are discovered for the energy subsectors of electricity and gas, with online maps retrieved from service providers. These indicate localised yet major border crossing, influencing primary branches of the subsectors' grids.

In the specific case study about a sample of the Euregio Meuse-Rhine, served to answer the sub-research question (SQ3), geospatial analyses employ aforementioned findings, combined with identified spatial asymmetries, to comprehend the global vulnerability of the region's CI networks. Using the distribution of critical infrastructures mapped onto the studied regions, dependencies and connections from previous assessment allow to establish the degree of connectivity (border-restricted or border blind) of sectors and subsectors. This interconnectivity unveils specific individual infrastructure or regional networks particularly vulnerable to floods. For instance, the Dutch Limburg region, and specifically the city of Maastricht, exhibit heightened vulnerability to HQ100 flood

scenarios compared to its neighbours, showcasing the critical dependence of the region's service providers on their German and Belgian counterparts. More broadly, the geospatial analysis provides a clear comprehension on the necessity of integrating cross-border interactions and neighbouring countries' critical facilities in one's assessment of a domestic or international system of networks of critical infrastructures.

In essence, the present study stresses the weakness of restricting the analysis of critical infrastructure networks to only national consideration, whether for cascading effects research purposes or through government vulnerability assessments. By failing to incorporate transboundary divergences in legislations, regulatory frameworks, functional governances or geospatial data, such assessments possess a "blind spot", answering the last sub-research question (SQ4). Neighbouring network strengths and weaknesses such as the reliance on cross-border provision of electricity, gas or healthcare services are external sources of synergies or complications to national systems. When ignoring such factors with significant influence on domestic infrastructures, research groups or national authorities may inaccurately capture true network risks or cascading disruptions.

Building upon the findings of all four sub-research questions, the present study addresses the overarching research question. Notwithstanding the few commonalities between the countries of the case study, discrepancies in legal, functional and geospatial matters and frameworks considerably affect transboundary assessments. Consequently, the omission of cross-border interdependencies within networks of the energy, water and healthcare sectors risks fundamentally skewing and distorting conclusion of national vulnerability assessment regarding cascading disruptions.

In a discussion subsequent to empirical findings, global challenges in vulnerability assessment of cascading effects are underlined. With a general insufficiency of granularity and definition gaps hindering comparative analysis, ground aspects are impeding empirical undertakings to provide insights into the status quo of critical infrastructure systems. Although regional cooperation structures are present in the Euregio Meuse-Rhine and have proven their utility, international consideration are yet to be embodied in national agendas. Crucially, a thorough and comprehensive vulnerability analysis must incorporate both network redundancies and cross-sectoral interdependencies to ensure a robust and systemic risk assessment. This provides an incentive for (inter)national institutions to align and standardise their critical infrastructure frameworks, ensuring a unified approach to CI vulnerability to floods assessments.

5.2. Limitations & Recommendations

Upon the analysis conducted within this thesis, several inherent limitations have impeded and inhibited the work. Although the CER Directive was enacted in 2022, national transpositions remain in nascent and evolving stages. With many national laws acts only recently promulgated and signed, if not still in drafting phases, a notable shortfall of scholarly analysis prevails. Moreover, as geospatial data is largely inconsistent and incomplete among national providers, the mapping of critical infrastructure and modelling of networks is restrained to open-source data. This necessitates supplementary methodological approaches (investigating service providers and interview experts) to discover underlying dependencies and network realities. Lastly, the natural phenomenon of floodings and structural phenomenon of cascading disruptions are inherently complex and possess both a stochastic characters, presenting profound complexities and significant challenges for robust modelling and predictions of systems behaviour. For instance, flood heights vary over time and some emergency responses vehicles possess enough clearance to navigate through water levels too high for conventional cars. Simultaneously, facilities of a same sector, subsector and category rarely share exact same features, therefore not being equally vulnerable to a disruption or likely to generate a cascading effect. Protective building projects against natural hazards may be

undertaken, infrastructures may be at varying stages of lifecycle, and interconnectivity is rarely equal across infrastructures. In view of these complex limitations, and given the temporal constraint of the present study, recommendations are provided for future works.

To conduct robust assessment of vulnerability, study should incorporate all of the critical infrastructure sectors with deeper technical investigations into the subsectors and facility characteristics, not omitting to include cross-sectoral interdependencies. Additionally, a wider geographical area encompassing more than two countries could reveal broader, macro influences not uncovered in the present study, such as the influence of varying heterogeneity degrees in urban-rural, land use, demographic and natural features. In an ideal case, complete, qualitative and current data provided by governmental institutions is accessible or obtainable. Ultimately, future research would benefit from an implementation of a dynamic modelling, to simulate failure propagation over time which allows to consider time-dependent variable such as flood heights or hospital self-sufficiency and autarky with regards to electricity supply. A promising tool could be the ProMaIDes software and QGIS plug-in for flood fisk management, in particular with its CIN – Critical Infrastructure Networks module. The tool is developed by Dr. Roman Schotten and Prof. Dr. Daniel Bachmann and available on https://promaides.h2.de/promaides/.

Bibliography

Al-Mhdawi, M. K. S., O'connor, A., Qazi, A., Rahimian, F., & Dacre, N. (2024). Review of studies on risk factors in critical infrastructure projects from 2011 to 2023. *Smart and Sustainable Built Environment, 14*(2), 342-376. https://doi.org/10.1108/SASBE-09-2023-0285

Analistennetwerk Nationale Veiligheid. (2022, July 31). *Themarapportage bedreiging vitale infrastructuur [Thematic report on threats to vital infrastructure]*. Nationaal Coördinator Terrorismebestrijding en Veiligheid (NCTV) [National Coordinator for Security and Counterterrorism]. https://www.rijksoverheid.nl/documenten/rapporten/2022/07/31/themarapportage-bedreiging-vitale-infrastructuur

Barquet, K., Englund, M, Inga, K., André, K, & Segnestam, L. (2023). Conceptualising multiple hazards and cascading effects on critical infrastructures. *Disasters, 48*(1). https://doi.org/10.1111/disa.12591

Bartzokas-Tsiompras, A. (2022, April 12). Utilizing OpenStreetMap data to measure and compare pedestrian street lengths in 992 cities around the world. *European Journal of Geography, 13*(2), 127-141. https://doi.org/10.48088/ejg.a.bar.13.2.127.138

BBK – Bundesamt für Bevölkerungsschutz und Katastrophenhilfe (2008). Schutz Kritischer Infrastruktur: Risikomanagement im Krankenhaus [Protection of critical infrastructure: risk management in hospitals]. https://www.bbk.bund.de/SharedDocs/Downloads/DE/Mediathek/Publikationen/PiB/PiB-02-risikoman-krankh-kurzfassung.pdf?__blob=publicationFile&v=5

BBK – Bundesamt für Bevölkerungsschutz und Katastrophenhilfe. (n.d.-c). KRITIS-Gefahren. https://www.bbk.bund.de/DE/Themen/Kritische-Infrastrukturen/KRITIS-Gefahrenlagen/kritis-gefahrenlagen_node.html

BBK – Bundesamt für Bevölkerungsschutz und Katastrophenhilfe. (n.d.-e). Sektoren und Branchen KRITIS [Critical Infrastructures Sectors and Branches]. https://www.bbk.bund.de/DE/Themen/Kritische-Infrastrukturen/Sektoren-Branchen/sektoren-branchen_node.html

BBK – Bundesamt für Bevölkerungsschutz und Katastrophenhilfe. (n.d.-d). Kritische Infrastrukturen – Sektoren- und Brancheneinteilung [Critical infrastructures – sector and industry classification]. https://www.bbk.bund.de/SharedDocs/Downloads/DE/KRITIS/kritis-sektoren-brancheneinteilung.pdf?__blob=publicationFile&v=7

BBK – Bundesamt für Bevölkerungsschutz und Katastrophenhilfe. (n.d.-a). *Das BBK stell sich vor* [The BBK introduces itself]. https://www.bbk.bund.de/DE/Das-BBK/Das-BBK-stellt-sich-vor/das-bbk-stellt-sich-vor_node.html

BBK – Bundesamt für Bevölkerungsschutz und Katastrophenhilfe. (n.d.-b). *Kritische Infrastrukturen* [Critical Infrastructures]. https://www.bbk.bund.de/DE/Themen/Kritische-Infrastrukturen/kritische-infrastrukturen_node.html

BBK – Bundesamt für Bevölkerungsschutz und Katastrophenhilfe. (n.d.-f). *Strategien und rechtlicher Rahmen* [Strategies and legal framework]. https://www.bbk.bund.de/DE/Themen/Kritische-Infrastrukturen/Strategien-und-rechtlicher-Rahmen/strategien-und-rechtlicher-rahmen_node.html

BMI – Bundesministerium des Innern. (2024, July 24). *Entwurf eines Gesetzes zur Umsetzung der NIS-2-Richtlinie und zur Regelung wesentlicher Grundzüge des Informations-sicherheits-managements in der Bundesverwaltung* [Draft law for the implementation of the NIS-2 Directive and for the regulation of essential principles of information security management in the federal administration]. https://www.bmi.bund.de/SharedDocs/gesetzgebungsverfahren/DE/CI1/nis2umsucg.html

BMI – Bundesministerium des Innern. (2025a, September 10). *Bundeskabinett beschließt Gesetzentwurf zum KRITIS-Dachgesetz* [Federal Cabinet approves draft law on the KRITIS umbrella law]. https://www.bmi.bund.de/SharedDocs/pressemitteilungen/DE/2025/09/kritis-dg-kabinett.html

BMI – Bundesministerium des Innern. (2025b, September 10). *KRITIS-Dachgesetz: Gesetzentwurf der Bundesregierung* [KRITIS Umbrella-law: Government draft bill]. https://www.bmi.bund.de/SharedDocs/gesetzgebungsverfahren/DE/Downloads/kabinettsfassung/KM4/reg-kritis-dachgesetz.pdf?__blob=publicationFile&v=1

BMI – Bundesministerium des Innern. (2026). *Föderalismus und Kommunalwesen* [Federalism and local government]. https://www.bmi.bund.de/DE/themen/verfassung/staatliche-ordnung/foederalismus-und-kommunalwesen/foederalismus-und-kommunalwesen-artikel.html

BMI – Bundesministerium des Innern. (n.d.-a). *Crisis management*. https://www.bmi.bund.de/EN/topics/civil-protection/crisis-management/crisis-management-node.html

BMI – Bundesministerium des Innern. (n.d.-b). *Das BMI stell sich vor* [The BMI introduces itself]. https://www.bmi.bund.de/DE/ministerium/das-bmi/das-bmi-node.html

BMI – Bundesministerium des Innern. (n.d.-c). *Ministerium* [Ministry]. https://www.bmi.bund.de/DE/ministerium/ministerium-node.html

BMI – Bundesministerium des Innern. (n.d.-d). *Protecting Critical Infrastructure*. https://www.bmi.bund.de/EN/topics/civil-protection/critical-infrastructure-protection/critical-infrastructure-protection-node.html

BMI – Bundesministerium des Innern. (n.d.-e). *Schutz Kritischer Infrastrukturen* [Protection of Critical Infrastructures]. https://www.bmi.bund.de/DE/themen/bevoelkerungsschutz/schutz-kritischer-infrastrukturen/schutz-kritischer-infrastrukturen-node.html

BMI – Bundesministerium des Innern. (n.d.-f). *Weg der Gesetzgebung* [Legislative process]. https://www.bmi.bund.de/DE/themen/verfassung/gesetzgebung/gesetzgebungsverfahren/gesetzgebungsverfahren-node.html

Britannica (2026, January 9). List of the world's largest countries and dependencies by area. https://www.britannica.com/topic/list-of-the-total-areas-of-the-worlds-countries-dependencies-and-territories-2130540

BSI – Bundesamt für Sicherheit in der Informationstechnik. (2024-a). Konkretisierung der Anforderungen an die gemäß § 8a Absatz 1 und Absatz 1a BSIG umzusetzenden Maßnahmen [Specification of the requirements for the measures to be implemented in accordance with Section 8a(1) and (1a) BSIG]. https://www.bsi.bund.de/SharedDocs/Downloads/DE/BSI/KRITIS/Konkretisierung_Anforderungen_Massnahmen_KRITIS.pdf?__blob=publicationFile&v=20

BSI – Bundesamt für Sicherheit in der Informationstechnik. (2024-b). *Rechtsgrundlagen* [Legal basis]. https://www.bsi.bund.de/DE/Themen/Regulierte-Wirtschaft/Kritische-Infrastrukturen/Allgemeine-Infos-zu-KRITIS/Rechtsgrundlagen/rechtsgrundlagen_node.html

BSI – Bundesamt für Sicherheit in der Informationstechnik. (2025, September 30). Historie der Diagramme auf KRITIS in Zahlen [History of the diagrams on KRITIS in figures]. https://www.bsi.bund.de/DE/Themen/Regulierte-Wirtschaft/Kritische-Infrastrukturen/KRITIS-in-Zahlen/Historie/historie_node.html

BSI – Bundesamt für Sicherheit in der Informationstechnik. (2026, January 30). KRITIS in Zahlen [Critical Infrastructures in Numbers]. https://www.bsi.bund.de/DE/Themen/Regulierte-Wirtschaft/Kritische-Infrastrukturen/KRITIS-in-Zahlen/kritis-in-zahlen_node.html

BSI – Bundesamt für Sicherheit in der Informationstechnik. (n.d.-e). *Erklärung der Darstellung "Umsetzungsstand"* [Explanation of the "Implementation status" representation]. https://www.bmi.bund.de/DE/ministerium/gesetzgebungsverfahren/umsetzungsstand/umsetzungsstand-node.html

BSI – Bundesamt für Sicherheit in der Informationstechnik. (n.d.-a). *Kurzprofil des BSI* [Brief profile of the BSI]. https://www.bsi.bund.de/DE/Das-BSI/Auftrag/BSI-Kurzprofil/kurzprofil_node.html

BSI – Bundesamt für Sicherheit in der Informationstechnik. (n.d.-b). *Kritische Infrastrukturen (KRITIS)* [Critical Infrastructures (KRITIS)]. https://www.bsi.bund.de/DE/Themen/Regulierte-Wirtschaft/Kritische-Infrastrukturen/kritis_node.html

BSI – Bundesamt für Sicherheit in der Informationstechnik. (n.d.-c). *Legal basis: IT Security Acts of 2015 and 2021*. https://www.bsi.bund.de/EN/Themen/Regulierte-Wirtschaft/Kritische-Infrastrukturen/Allgemeine-Infos-zu-KRITIS/Rechtsgrundlagen/rechtsgrundlagen_node.html

BSI – Bundesamt für Sicherheit in der Informationstechnik. (n.d.-d). *Organisation UP KRITIS*. https://www.bsi.bund.de/DE/Themen/Regulierte-Wirtschaft/Kritische-Infrastrukturen/UP-KRITIS/Organisation/organisation_node.html

BSI – Bundesamt für Sicherheit in der Informationstechnik. (n.d.-e). *Sektorspezifische Infos für KRITIS-Betreiber* [Sector-specific information for operators of critical infrastructure (KRITIS)]. https://www.bsi.bund.de/DE/Themen/Regulierte-Wirtschaft/Kritische-Infrastrukturen/Sektorspezifische-Infos-fuer-KRITIS-Betreiber/sektorspezifische-infos-fuer-kritis-betreiber_node.html

BSI – Bundesamt für Sicherheit in der Informationstechnik. (n.d.-f). *What are Critical Infrastructures?*. https://www.bsi.bund.de/EN/Themen/Regulierte-Wirtschaft/Kritische-Infrastrukturen/Allgemeine-Infos-zu-KRITIS/allgemeine-infos-zu-kritis_node.html

BSI – Bundesamt für Sicherheit in der Informationstechnik. (n.d.-f). *Zweite EU-Richtlinie zur Netzwerk- und Informationssicherheit (NIS-2-Richtlinie)* [Second EU Directive on Network and Information Security (NIS-2 Directive)]. https://www.bsi.bund.de/DE/Das-BSI/Auftrag/Gesetze-und-Verordnungen/NIS-2-Richtlinie/nis-2-richtlinie_node.html

Bundeskanzler (2021, December 8). Organisationserlass des Bundeskanzlers [Organisational decree of the Chancellor]. https://www.bundesregierung.de/resource/blob/974430/1990040/df69951d83f08c0b7b04cb40210e1221/2021-12-08-organisationserlass-data.pdf

Bundesministerium der Justiz und für Verbraucherschutz. (2016, April 22). *Verordnung zur Bestimmung kritischer Anlagen nach dem BSIGesetz (BSI-Kritisverordnung - BSI-KritisV)* [Regulation on the designation of critical installations according to the BSI Act (BSI Critical Installations Regulation - BSI-KritisV)]. https://www.gesetze-im-internet.de/bsi-kritisv/BJNR095800016.html

Bundesministerium der Justiz und für Verbraucherschutz. (2023, April 10). *Aufgaben von Bund und Ländern* [Tasks of the federal and state governments]. https://www.bmjv.de/DE/rechtsstaat_kompakt/grundgesetz/aufgaben/aufgaben_node.html

Bundesministerium der Justiz und für Verbraucherschutz. (2026, January 11). *Act on the Federal Office for Information Security (BSI Act - BSIG)*. Bundesamt für Justiz. https://www.gesetze-im-internet.de/englisch_bsig/index.html

Bundesministerium der Justiz und für Verbraucherschutz. (n.d.). *Verordnung zur Bestimmung kritischer Anlagen nach dem BSI-Gesetz (BSI-Kritisverordnung - BSI-KritisV)* [Regulation on the Determination of Critical Installations under the BSI Act (BSI Critical Installations Regulation - BSI-KritisV)]. https://www.gesetze-im-internet.de/bsi-kritisv/index.html#BJNR095800016BJNE001102116

Bundesverfassungsgericht. (n.d.). *The Basic Law*. https://www.bundesverfassungsgericht.de/EN/BasicLawLegalBasis/TheBasicLaw/thebasiclaw_node.html

Bundeszentrale für politische Bildung. (2014, May 1). *Wer regelt was bei Bund und Land?* [Who regulates what at the federal and state level?]. https://www.bpb.de/lernen/angebote/wahl-o-mat-im-unterricht/188466/wer-regelt-was-bei-bund-und-land/?p=all

Comerford, R., & Hedgecoe, G. (2025, October 3). Blackout in Spain and Portugal 'first of its kind', report finds. *BBC*. https://www.bbc.com/news/articles/cg7d4vjdlrmo

Committee on Public Health (SANT). (2025). *Medicines and Medical Devices*. Fact Sheets on the European Union. https://www.europarl.europa.eu/factsheets/en/sheet/50/medicines-and-medical-devices

Deltares. (2025, October 17). *Nieuwe handreiking helpt vitale aanbieders klimaatrisico's beter in kaart te brengen* [New guideline helps vital providers better map climate risks]. https://www.deltares.nl/nieuws/nieuwe-handreiking-helpt-vitale-aanbieders-klimaatrisicos-beter-in-kaart-te-brengen

Deutscher Bundestag (2025, June 16). Rechtliche Verfahren unter Beteiligung des BMUV [Legal proceedings involving the BMUV]. https://www.bundestag.de/presse/hib/kurzmeldungen-1089434

Die Bundesregierung. (2025, September 10). *Stärkerer Schutz kritischer Infrastrukturen* [Stronger protection of critical infrastructures]. https://www.bundesregierung.de/breg-de/aktuelles/kabinett-kritis-dachgesetz-2383682?

DKG – Deutsche Krankenhaus Gesellschaft (n.d.). Mission and Objectives. https://www.dkgev.de/englisch/the-german-hospital-federation/mission-and-objectives/

Dutch Water Authorities. (n.d.). *About*. https://dutchwaterauthorities.com/about/

Elia Group (2023). Map of the electricity transmission system 2023. https://www.elia.be/en/infrastructure-and-projects/our-infrastructure

EMRIC (2024). Jahresbericht 2024 [2024 year report]. https://www.emric.info/sites/default/files/2025-05/EMRIC%20Jahresbericht%202024%20DE.pdf

ENTSOG & GIE (2024). System Capacity Map 2024. https://www.entsog.eu/sites/default/files/2024-02/ENTSOG_GIE_SYSCAP_2024_Update%20Feb.pdf

Epp, Ä. (2024, April 28). "District heating has never had such a high significance in Germany". *Solarthermalworld.org*. https://solarthermalworld.org/news/district-heating-has-never-had-such-a-high-significance-in-germany/

EPSG.IO (n.d.). EPSG:3857 – WGS 84 / Pseudo-Mercator -- Spherical Mercator, Google Maps, OpenStreetMap, Bing, ArcGIS, ESRI. https://epsg.io/3857#:~:text=Attributes,UoM:%20m.

EU-NATO Task Force on the Resilience of Critical Infrastructure (2023). *Final Assessment Report*. https://commission.europa.eu/system/files/2023-06/EU-NATO_Final%20Assessment%20Report%20Digital.pdf

European Commission (2026, January 13). Critical infrastructure resilience at EU-level. https://home-affairs.ec.europa.eu/policies/internal-security/counter-terrorism-and-radicalisation/protection/critical-infrastructure-resilience-eu-level_en

European Commission (n.d.). INSPIRE Directive. https://knowledge-base.inspire.ec.europa.eu/legislation/inspire-directive_en

Fang, B., Bevacqua, E., Rakovec, O., & Zscheischler, J. (2024). An increase in the spatial extent of European floods over the last 70 years. *Earth System Science, 28*(16), 3755–3775. https://doi.org/10.5194/hess-28-3755-2024

FAOSTAT – Land Use. Food and Agriculture Organization of the United Nations (n.d.) [Data set]. https://www.fao.org/faostat/en/#data/RL

Federal Ministry for Economic Affairs and Energy (2025). Katherina Reiche Federal Minister for Economic Affairs and Energy. https://www.bundeswirtschaftsministerium.de/Redaktion/EN/Artikel/Curriculum-Vitae/curriculum-vitae-reiche.html

Fischer, S., & Schumann, A. H. (2024). Temporal changes in the frequency of flood types and their impact on flood statistics. *Journal of Hydrology X, 22*. https://doi.org/10.1016/j.hydroa.2024.100171

Frauenhofer. (n.d.). *Schutz Kritischer Infrastrukturen* [Protection of Critical Infrastructures]. https://www.fraunhofer.de/de/forschung/aktuelles-aus-der-forschung/archiv/forschung-fuer-den-schutz-kritischer-infrastrukturen.html

Gesamtverband der Versicherer (2022). *Naturgefahrenreport 2022 – Die Schaden-Chronik der deutschen Versicherer*. https://www.gdv.de/resource/blob/105828/0e3428418c45df91f7ee5f280a5a9bff/download-naturgefahrenreport-2022-data.pdf

GIE – Gas Infrastructure Europe (2025). Members. https://www.gie.eu/wp-content/uploads/filr/9454/GIE_members_Dec_2025.pdf

GIE – Gas Infrastructure Europe (n.d.). Who is GIE?. https://www.gie.eu/press-corner/starter-kit/

Gielens, S. (2025, May 6). *Contribution to the National Security and Resilience Committee debate, May 15, 2025*. VNO-NCW – MKB-Nederland. https://www.vno-ncw.nl/brieven-en-commentaren/inbreng-commissiedebat-nationale-veiligheid-en-weerbaarheid-15-mei-2025

Grundgesetz für die Bundesrepublik Deutschland [Basic Law for the Federal Republic of Germany], Art. 31 (1949). https://www.gesetze-im-internet.de/englisch_gg/index.html

Hagenlocher, M., Okamoto, S., Nagabhatla, N., Diedrich, S., Hassel, J., van der Heijden, S., Kreft, S., De Lombaerde, P., Nick, F., Oakes, R., Rackelmann, F., Rimmert, M., Sandholz, S., Sebesvari, Z., Shen, X., Skripka, T., Stojanovic, T., Szarzynski, J., van de Walle, B., & Werners, S. (2023). Building Climate Resilience: Lessons from the 2021 Floods in Western Europe. *United Nations University*. https://cris.unu.edu/sites/cris.unu.edu/files/CRI_Report.pdf

Helbich, M., Amelunxen, C., Neis, P., & Zipf, A. (2010). A Comparative Study of Proprietary Geodata and Volunteered Geographic Information for Germany. https://gispoint.de/fileadmin/user_upload/paper_gis_open/537521013.pdf

Huld, A. (2021, August 30). *Critical Information Infrastructure in China – New Cybersecurity Regulations*. China Briefing. https://www.china-briefing.com/news/critical-information-infrastructure-chinas-new-regulations/

Interreg Meuse-Rhine (n.d.). A greener, low-carbon Meuse-Rhine region – Flood Wisdom. https://www.interregmeuserhine.eu/en/projects/flood-wisdom/

Interreg North-West Europe HeatNet NWE (n.d.). Current state of District Heating (DH) in the Netherlands. https://vb.nweurope.eu/media/5541/netherlands_heatnet-nwe_lt-wp11_final.pdf

IWEPS – Institut wallon de l'évaluation, de la prospective et de la statistique (2025). *Le portail d'informations statistisques locales sur la Wallonie* [Data set]. WalStat. https://walstat.iweps.be/walstat-fiche-entite.php?entite_id=62063

JCAR ATRACE (2025). *Roer*. https://www.jcar-atrace.eu/en/basins/roer

Landesbildungsserver Baden-Württemberg. (n.d.). *Die Bundesländer und ihre Aufgaben* [The federal states and their responsibilities]. https://www.schule-bw.de/faecher-und-schularten/gesellschaftswissenschaftliche-und-philosophische-faecher/gemeinschaftskunde/materialien-und-medien/staat/land

Leal Filho, W., Abeldaño Zuñiga, R.A., Sierra, J., Pimenta Dinis, M. A., Corazza, L., Nagy, G. J., & Aina, Y. A. (2024). An assessment of priorities in handling climate change impacts on infrastructures. Science Report 14, 14147. https://doi.org/10.1038/s41598-024-64606-3

Littooij, A., & van Eck, M. (2015, December 4). *Handreiking 'De veiligheidsregio bij dreigende verstoring/uitval van vitale voorzieningen' [Guidance 'The safety region in the event of imminent disruption or failure of vital facilities']*. Veiligheidsberaad en Ministerie van Veiligheid en Justitie [Security Council and Ministry of Justice and Security]. https://nipv.nl/wp-content/uploads/2022/06/20151204-VB-VenJ-Handreiking-De-veiligheidsregio-bij-dreiging-verstoring-uitval-vitale-voorzieningen.pdf

Medicines and Healthcare Products Regulatory Agency. (2013). *Guidance – Decide if your product is a medicine or a medical device*. GOV.UK. https://www.gov.uk/guidance/decide-if-your-product-is-a-medicine-or-a-medical-device

Menoni, S., Faiella, A., Gazzola, V., Boni, M. P., Eklund, L. G., Corban, C. (2023). *Cross-border impacts on Networks due to natural hazards*. Joint Research Institute. https://publications.jrc.ec.europa.eu/repository/handle/JRC133171

Minister van Binnenlandse Zaken en Koninkrijksrelaties [Ministry of the Interior and Kingdom Relations]. (n.d.). *Provinces, municipalities and water authorities*. Government of the Netherlands. https://www.government.nl/topics/public-administration/provinces-municipalities-and-water-authorities

Ministerie van Infrastructuur en Waterstaat. (2025, October 15). *Handreiking klimaatbestendige vitale infrastructuur voor het bepalen van klimaatrisico's* [Guideline for climate-resilient critical infrastructure for determining climate risks]. Rijksoverheid. https://www.rijksoverheid.nl/documenten/rapporten/2025/10/15/handreiking-klimaatbestendige-vitale-infrastructuur-voor-het-bepalen-van-klimaatrisico-s

Mondzech, J., & Sester, M. (2011). Quality Analysis of OpenStreetMap Data Based on Application Needs. *Cartographica The International Journal for Geographic Information and Geovisualization, 46*(2), 115-125. https://doi.org/10.3138/carto.46.2.115

Mülhofer, E., Koks, E. E., Kropf, C. M., Sansavini, G., & Bresch, D. N. (2023). A generalized natural hazard risk modelling framework for infrastructure failure cascades. *Reliability Engineering & System Safety, 234*. https://doi.org/10.1016/j.ress.2023.109194

NATO – North Atlantic Treaty Organization. (2024, November 13). *Resilience, civil preparedness and Article 3*. . https://www.nato.int/en/what-we-do/deterrence-and-defence/resilience-civil-preparedness-and-article-3

NATO – North Atlantic Treaty Organization. (2025a). Overview - 2025 NATO Summit in The Hague. https://www.nato.int/en/news-and-events/events/2025/6/overview---2025-nato-summit-in-the-hague

NATO – North Atlantic Treaty Organization. (2025b, June 25). The Hague Summit Declaration – issued by the NATO Heads of State and Government participating in the meeting of the North Atlantic Council in The Hague 25 June 2025. https://www.nato.int/en/about-us/official-texts-and-resources/official-texts/2025/06/25/the-hague-summit-declaration

NATO Energy Security Centre of Excellence. (2025, April 3). *Impact of Critical Energy Infrastructure Security on Military Resilience and Energy Security within NATO*. NATO ENSECCOE. https://www.enseccoe.org/publications/impact-of-critical-energy-infrastructure-security-on-military-resilience-and-energy-security-within-nato/

NCTV – Nationaal Coördinator Terrorismebestrijding en Veiligheid (2025, July 24). Toenemende en veranderende dreigingen op vitale infrastructuur [Increasing and changing threats to critical infrastructure]. https://www.nctv.nl/actueel/nieuws/2025/07/24/toenemende-en-veranderende-dreigingen-op-vitale-infrastructuur

NCTV – Nationaal Coördinator Terrorismebestrijding en Veiligheid (2025, July 24). Dreigingslandschap Vitale Infrastructuur (2025) [Threat Landscape Critical Infrastructure (2025)]. *Ministerie van Justitie en Veiligheid*. https://www.nctv.nl/documenten/2025/07/23/dreigingslandschap-vitale-infrastructuur

NCTV – Nationaal Coördinator Terrorismebestrijding en Veiligheid. (2018, February 1). *Factsheet Critical Infrastructure – Resilient critical infrastructure*. Ministry of Justice and Security https://english.nctv.nl/documents/2018/02/01/factsheet-critical-infrastructure

NCTV – Nationaal Coördinator Terrorismebestrijding en Veiligheid. (n.d.-a). *Critical Infrastructure (protection)*. Ministerie van Justitie en Veiligheid. https://english.nctv.nl/topics/c/critical-infrastructure-protection

NCTV – Nationaal Coördinator Terrorismebestrijding en Veiligheid. (n.d.-b). *Vragen en antwoorden [Questions and answers]*. Ministerie van Justitie en Veiligheid. https://www.nctv.nl/onderwerpen/w/wet-weerbaarheid-kritieke-entiteiten/vragen-en-antwoorden

NCTV – Nationaal Coördinator Terrorismebestrijding en Veiligheid. (n.d.-c). Welke organisaties vallen onder de Wet weerbaarheid kritieke entiteiten [Which organisations fall under the Critical Entities Resilience Act]. https://www.nctv.nl/onderwerpen/w/wet-weerbaarheid-kritieke-entiteiten/welke-organisaties-vallen-onder-de-wet

NCTV – Nationaal Coördinator Terrorismebestrijding en Veiligheid. (n.d.-d). Wetsvoorstellen in ontwikkeling [Bills in development]. Ministerie van Justitie en Veiligheid. https://www.nctv.nl/onderwerpen/w/wet-weerbaarheid-kritieke-entiteiten/wetsvoorstellen-in-ontwikkeling

Nick, F. C., & Sandholz, S. (2022). Critical infrastructures and flood risk governance. *UNU-MERIT*. As cited by Meijer, L., & Juch, S. (2024, February 26). Critical Infrastructure in Transboundary River Basins. *Deltares*. https://storymaps.arcgis.com/stories/39696d2773e241f2a6c2cec2a2ad0426

NVZ – Nederlandse Vereniging van Ziekerhuizen (n.d.). Over de leden [About the members]. https://nvz-ziekenhuizen.nl/over-de-leden

OpenKRITIS. (2025a). *KRITIS-Dachgesetz* [Critical Infrastructure Umbrella Law]. https://www.openkritis.de/it-sicherheitsgesetz/kritis-dachgesetz-sicherheitsgesetz-3-0.html

OpenKRITIS. (2025b). *KRITIS-Verordnungen* [Critical infrastructure regulations]. https://www.openkritis.de/it-sicherheitsgesetz/kritis-verordnung-2-0.html

OpenKRITIS. (2025c). *Kritische Sektoren* [Critical Sectors]. https://www.openkritis.de/it-sicherheitsgesetz/kritis-sektoren.html

OpenKRITIS. (2025d). *Kritische Anlagen* [Critical Facilities]. https://www.openkritis.de/it-sicherheitsgesetz/kritis-anlagen.html

OpenKRITIS. (2025e, December 5). *NIS2-Umsetzungsgesetz* [NIS2 Implementation Act]. https://www.openkritis.de/it-sicherheitsgesetz/nis2-umsetzung-gesetz-cybersicherheit.html

Parker, J. (2026, January 8). Berlin power outage highlights German vulnerability to sabotage. *BBC*. https://www.bbc.com/news/articles/cvgrpzn6gz4o

Pescaroli, G., & Alexander, D. (2015). A definition of cascading disasters and cascading effects: Going beyond the “toppling dominos” metaphor. *GRF Davos Planet@Risk, 3*(1). https://www.preventionweb.net/publication/definition-cascading-disasters-and-cascading-effects-going-beyond-toppling-dominos

Pursiainen, C., & Kytömaa, E. (2023). From European critical infrastructure protection to the resilience of European critical entities: what does it mean? *Sustainable and Resilient Infrastructure, 8*. https://doi.org/10.1080/23789689.2022.2128562

Rathnayaka, B., Siriwardana, C., Robert, D., Amaratunga, D., & Setunge, S. (2022). Improving the resilience of critical infrastructures: Evidence-based insights from a systematic literature review. *International Journal of Disaster Risk Reduction, 78*. https://doi.org/10.1016/j.ijdrr.2022.103123

Rijksinspectie Digitale Infrastructuur. (2025, June 18). *Cyberbeveiligingswet en Wet weerbaarheid kritieke entiteiten ingediend bij de Tweede Kamer [Cybersecurity Act and Critical Entities Resilience Act submitted to the House of Representatives]*. Ministerie van Economische Zaken [Ministry of Economic Affairs]. https://www.rdi.nl/actueel/nieuws/2025/06/18/cyberbeveiligingswet-en-wet-weerbaarheid-kritieke-entiteiten-ingediend-bij-de-tweede-kamer

Rijksoverheid (2019). Veiligheidsregio's [Safety regions]. https://www.rijksoverheid.nl/onderwerpen/veiligheidsregios-en-crisisbeheersing/veiligheidsregios

Rijkswaterstaat Mission. Rijkswaterstaat Ministerie van Infrastructuur en Waterstaat [Executive Agency of the Ministry of Infrastructure and Water Management]. (n.d.). https://www.rijkswaterstaat.nl/over-ons/onze-organisatie/onze-missie

Schneider, M., Halekotte, L., & Mentges, A. (2025). Dependent Infrastructure Service Disruption Mapping (DISruptionMap): A method to assess cascading service disruptions in disaster scenarios. *Scientific Report, 15,* 5736. https://doi.org/10.1038/s41598-025-89469-0

Schneider, M., Priesmeier, P., Fekete, A., Lichte, D., & Fiedrich, F. (2024). Cascading Effects of Critical Infrastructures in a Flood Scenario: A Case Study in the City of Cologne. *21st International ISCRAM Conference*. https://dx.doi.org/10.59297/ws32ka31

Schotten, R., & Bachmann, D. (2023, April 13). Critical infrastructure network modelling for flood risk analyses: Approach and proof of concept in Accra, Ghana. *Journal of Flood Risk Management, 16*(3). https://doi.org/10.1111/jfr3.12913

Schotten, R., & Bachmann, D. (2023). Integrating Critical Infrastructure Networks into Flood Risk Management. Sustainability 2023, 15(6), 5475. https://doi.org/10.3390/su15065475

Sociale Verzekeringbank (n.d.). Verschil Wlz en Zvw. *SVB voor het leven*. https://www.svb.nl/nl/wlz/uitleg-over-de-wlz/verschil-wlz-en-zvw

StatLine CBS (2025). Bevolkingsontwikkeling; regio per maand. https://opendata.cbs.nl/statline/#/CBS/nl/dataset/37230NED/table

Sun, Y., Meng, L., Camero, A., Auer, S., & Zhu, X. X. (2026, January 3). A deep dive into OpenStreetMap research since its inception (2008–2024): contributors, topics, and future trends. *International Journal of Geographical Information Science*, 1–55. https://doi.org/10.1080/13658816.2026.2613347

Tagesspiegel (2026, January 8). Nach Stromausfall in Berlin: Landkreistag: Sicherheitslücke im Kritis-Gesetz schließen. https://www.tagesspiegel.de/berlin/nach-stromausfall-in-berlin-landkreistag-sicherheitslucke-im-kritis-gesetz-schliessen-15115680.html

TenneT Holding (2025, December 31). GB Onshore Corporate Map. https://tennet-drupal.s3.eu-central-1.amazonaws.com/default/2026-01/GB_DEC2025_Onshore_Corporate.pdf

TenneT Holding (2026, January 13). Grid maps. https://www.tennet.eu/grids-and-markets/grid-maps

Tidey, A. (2025, May 2026). EU to deploy 650 firefighters to wildfire high-risk zones. *Euronews*. https://www.euronews.com/my-europe/2025/05/26/eu-to-deploy-650-firefighters-to-wildfire-high-risk-zones

Tweede Kamer der Staten-Generaal. (2025a, June 2). *Cyberbeveiligingswet* – Cbw [Cybersecurity Act] (36764-2). https://www.tweedekamer.nl/kamerstukken/wetsvoorstellen/detail?cfg=wetsvoorsteldetails&qry=wetsvoorstel%3A36764

Tweede Kamer der Staten-Generaal. (2025b, June 4). *Wet weerbaarheid kritieke entiteiten – Wwke [Critical Entities Resilience Act]* (36765-2). https://www.tweedekamer.nl/kamerstukken/wetsvoorstellen/detail?cfg=wetsvoorsteldetails&qry=wetsvoorstel%3A36765

van Gastel, E. (2024, July 3). Nieuw kabinet beëdigd, Sophie Hermans eerste minister van Klimaat en Groene Groei [New cabinet sworn in, Sophie Hermans first minister of Climate and Green Growth]. *Solar Storage Magazine*. https://solarmagazine.nl/nieuws-zonne-energie/i37942/nieuw-kabinet-beedigd-sophie-hermans-eerste-minister-van-klimaat-en-groene-groei

Verbond van Verzkeraars (2022). *Watersnood Limburg: ruim 95% particuliere schades afgehandeld door verzekeraars*. https://www.verzekeraars.nl/publicaties/actueel/watersnood-limburg-ruim-95-particuliere-schades-afgehandeld-door-verzekeraars

Vewin – Vereniging van Waterbedrijven in (n.d.). Over Vewin Den Haag [About Vewin Den Haag]. https://www.vewin.nl/over-vewin-den-haag/

Wang, W., Yang, S., Hu, F., Stanley, H. E., He, S., Shi, M. (2018). An approach for cascading effects within critical infrastructure systems. *Physica A: Statistical Mechanics and its Applications, 510*. https://doi.org/10.1016/j.physa.2018.06.129

Wegweiser Kommune (2025). Kommunale Daten. https://www.wegweiser-kommune.de/daten/demografische-entwicklung+aachen+2019-2023+tabelle

Wet kwaliteit, klachten en geschillen zorg [Healthcare Quality, Complaints and Disputes act] (2022). https://wetten.overheid.nl/BWBR0037173/2022-01-01

Wintershall Dea (2023, December 6). Fluxys, OGE and Wintershall Dea are teaming up to create a CO2 corridor from Southern Germany to Belgium's CO2 export hubs. https://wintershalldea.de/en/newsroom/pi-23-42

Zanaga, D., Van De Kerchove, R., Daems, D., De Keersmaecker, W., Brockmann, C., Kirches, G., Wevers, J., Cartus, O., Santoro, M., Fritz, S., Lesiv, M., Herold, M., Tsendbazar, N.-E., Xu, P., Ramoino, F., & Arino, O. (2022). ESA WorldCover 10 m 2021 v200 (Version v200) [Data set]. *Zenodo*. https://doi.org/10.5281/zenodo.7254221

Appendix

A. Terms Definition

Concept	Synonyms	Definitions
Cross-border	Transboundary, Transnational	Relating to activities or events crossing national borders
Critical Infrastructure(s)	Vital Infrastructure	*See Chapter 2.2 Legal Framework*
Health (CI sector)	Healthcare (services) sector, emergency response (services) sector	In legal and regulations context, the health CI sector encompasses (in the present study) any infrastructure having a relation to the protection of civilians, meaning the care of patients (i.e. as defined by most nations in Ch. 3: hospitals, care centres, clinics, pharmacies, production facilities for medical devices or pharmaceutical products) as well as the rescue of civilians during emergencies from natural catastrophes (i.e. fire departments or police stations). In geospatial analyses, the health sector only considers consistent OpenStreetMap data, being hospitals, clinics, care centres, pharmacies, fire departments and police stations.
Network	System	Group of physical or virtual assets (points/nodes) of a CI sector, with known or hidden interconnections and interdependencies (links/edges)
Cascading effect	Cascading / chain / spreading disruption / failure / disaster, Domino effect	In the present study, a cascading effect is the result of an event occurring in one node of a network, having an effect on another –often unexpected and far– node of the same network, or of another network linked to the former. For a comprehensive review of the different terms' definition, the ready is referred to the papers of Barquet et al. (2023) and (Pescaroli & Alexander, 2015)

Table 0.1: Definitions of Concepts central to the Study

B. Resources Overview

Literature Review

- Academic, research and journal paper portals and data bases;
- Library and university portals.

Critical Infrastructures – Definition Search & Data

- **Germany**: Federal Ministry of the Interior (BMI), Federal Office for Population Protection and Catastrophes Help (BBK), Federal Association for the Protection of Critical Infrastructures (BSKI), German Domestic Intelligence Services (BfV), Federal Agency for Technical Relief (THW), GeoPortal StädteRegion Aachen (inkasPortal), GEOportal NRW (NRW, TIM-online), RWE Global (RWE);
- **Netherlands**: National Coordinator for Security and Counterterrorism (NCTV), Netherlands Institute for Public Safety (NIPV), Netherlands Organisation for Applied Scientific Research (TNO);
- **Both**: websites of states and governmental agencies, local authorities (police or firework departments, hospitals and emergency service organisation), Directorate-General Home (link), EUR-Lew (link), Joint Research Center (JRC), Airbus Defence and Space (reach out in current job), Earth Engine Data Catalog (GPPD).

Floods – Data

- **Germany**: DLR and partners, German Research Centre for Geoscience (GFZ), German Committee for Disaster Reduction (DKKV), German Weather Service (DWD), Federal Institute of Hydrology (BfG), Land-wide Flooding Portal (LHP), Academy of Flood Protection (Akademie Hochwasserschutz);
- **Netherlands**: Deltares and partners (TU Delft, RWTH Aachen, Osnabrück University, JCAR research partners), Royal Netherlands Meteorological Institute (KNMI), Ministry of Infrastructure and Water Management (MIW);
- **Both**: local authorities (police or firework departments, hospitals and emergency service organisation), EU Directorate-General for Environment (DG-ENV), Joint Research Center JRC, Copernicus Emergency Management Service (CEMS) with the European- and Global Flood Awareness System (EFAS & GloFAS), European Environment Agency (EEA), European Geosciences Union (EGU), Airbus Defence and Space (reach out to colleagues).

C. Legal Sources

Section 1 (“Netherlands – overview of relevant (sub)sectors”)

Citation	Reference
Tweede Kamer der Staten-Generaal (2025b) – p.4 & Art.6 para.1 & Art.7 & p.20 NCTV (n.d-a) NCTV (2018) Tweede Kamer der Staten-Generaal (2025b) – p.6 Tweede Kamer der Staten-Generaal (2025a)	*See bibliography*

Section 2 (“Ministries and Responsibilities”)

Citation	Reference
BBK (n.d.-a) BMI (n.d.-b) BMI (n.d.-c) BMI (n.d.-e) BSI (n.d.-a)	*See bibliography*

Section 3 (“Germany – Overview of Relevant (sub)Sectors”)

Citation	Reference
BBK (2008; n.d.-d; n.d.-e) BMI (2024; n.d.-e) BSI (2024-a; 2025; 2026; n.d.-d) Bundesministerium der Justiz und für Verbraucherschutz (2016; n.d.) Die Bundesregierung (2025) OpenKRITIS (2025b; 2025c; 2025d)	*See bibliography*

D. Data Sources for Legal Documentations

Section 1: For Legal Documentation

Jurisdictions	Online Sources
European Union	- EUR-Lex - European Commission (EC) - EC’s Joint Research Center (JRC) - EC’s DG Migration & Home affairs - OpenKRITIS - CER
Netherlands	- Nationaal Coördinator Terrorismebestrijding en Veiligheid - Rijksinspectie Digitale Infrastructuur (Ministerie van Economische Zaken) - Overheid / Rijksoverheid - Algemene Inlichtingen- en Veiligheidsdienst (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties) - Eerste Kamer der Staten-Generaal - Ministerie van Infrastructuur en Waterstaat - Ministerie van Volksgezondheid, Welzijn en Sport - Nederlands Instituut Publieke Veiligheid
Germany	- Bundesministerium des Innern (BMI) - Bundesministerium der Justiz und für Verbraucherschutz - Bundesamt für Bevölkerungsschutz und Katastrophenhilfe (BBK) - Bundesamt für Sicherheit in der Informationstechnik (BSI) - Bundesregierung - Deutscher Bundestag - OpenKRITIS - Frauenhofer-Gesellschaft - Deutsches Zentrum für Luft- und Raumfahrt

Table 0.2: Overview of Sources for Legal Documentations (Debelle, 2026)

Section 2: For GIS Data

Jurisdictions	Geoportals / Sources for GIS Data	Geoportals / Sources for Flood Data
European Union (NL + DE + BE)	- OpenStreetMap - INSPIRE Geoportal - Europe data	/
Netherlands	- OpenStreetMap - PDOK	- Atlas Leefomgeving - Landelijk Informatiesysteem Water en Overstromingen (LIWO) - Klimaateffecatlas - Risicokaart - Waterschap Limburg[12]
Germany	- OpenStreetMap - Geoportal.de - GEOportal.NRW - Geobasis NRW - TIM-online.nrw - ELWAS-WEB	- Bundesamt für Kartographie und Geodäsie (BKG) - open.nrw & Klimaatlas NRW - Umweltportal NRW - OpenGeodata.NRW
Belgium	- OpenStreetMap - Metawal	- Datavindtplaats - L'Environnement en Wallonie - Géoportail de la Wallonie

Table 0.3: Overview of Geoportals and Sources for GIS Data (Debelle, 2026)

E. Data Categories and Spatial Models for GIS Data

Section 1: Data Sought and File Types

Data Category	Spatial Data Models (Geometry)	File Types
Critical Infrastructures	Points, Lines, Polygons (vectors)	.SHP, .GPKG
Floods	Polygons (vectors) Grid of cells / pixels (rasters)	.SHP, .GPKG .TIFF, .GeoTIFF
Land use, Population Density	Grid of cells / pixels (rasters)	.TIFF, .GeoTIFF

Table 0.4: Overview of Data Sought and File Types (Debelle, 2026)

[12] Personnel from the Waterschap Limburg were kind enough to provide some downloadable file

Section 2: Data Selection Criteria

Data Category	Spatial Data Models (Geometry)
Critical Infrastructures	OSM* All OSM data respecting the following criteria is retrieved: – The vector geometry type is Node, Way, Relation, Points, Lines, Multilinestrings, Multipolygons – The OSM keys and values related to any of the definition of any of the 3 jurisdictions (EU/NL/DE), which are listed in Appendix F. Geoportals and Online sources Any data providing point locations of critical infrastructures falling under the definition of any of the 3 jurisdictions (EU/NL/DE) is retrieved.
Floods	Flood data is collected from all sources mentioned in 4.2.2 Data Sources, both from fluvial or pluvial sources, with only criterion to indicate the return period HQ, or the scenario level of likelihood to happen**.
Land use, Population Density	The data is retrieved from the single sources mentioned in 4.2.2 Data Sources, and is not cross-validated with other data given the agencies' credibility.

Table 0.5: Overview of Data Selection Criteria (Debelle, 2026)

* Data is retrieved via the QuickOSM QGIS plug-in, using different keys (categories of OSM data) and values (subcategories within keys) and restraining the data query to the extent of the canva layer. Despite the state police partially omitted in EU, Dutch and German legal CI frameworks, both are regularly described in flood risk response reports (Hagenlocher et al., 2023), and are therefore also included in the retrieved OSM key-value combinations. N.B.: Some combination of the stated keys and values in Table 0.6 of the Appendix F provide an empty output in the region of the canvas.

** The scientific and political community generally agrees to categorise floods using a specific classification of exceedance probability, more often "return period", indicating the amount of years (i) in which a flood is prone to happen. English terminology uses the abbreviation Q_i (annual recurrence interval), German HQ_i (HochwasserQuantil), and Dutch T_i (Terugleertijd). From the remaining of the paper, the terminology HQ is adopted and favoured. A geographical element located in a flood scenario map with a return period of 100 signifies that the flood is prone to occur at least once in the upcoming 100 years. While a broad consensus prevails to classify flood hazards by 'low', 'medium' or 'high' likelihood, or 'rare', 'possible" or 'frequent' occurrence, specific thresholds vary between jurisdictions: some will consider $i = 500$ as low likelihood, others as $i = 1{,}000$.

F. OpenStreetMap – Keys and Values for Data Extraction

To find relevant keys and values, the following online tool is used:

https://taginfo.openstreetmap.org/keys

Keys	Values
amenity	clinic fire_station hospital pharmacy police
emergency	ambulance_station emergency_ward_entrance air_rescue_service disaster_response rescue_station drinking_water
healthcare	clinics hospitals laboratory pharmacy
industrial	oil gas
police	offices

Keys	Values
man_made	dyke pumping_station wastewater_plant water_tower water_well water_works storage-tank chimney gasometer mineshaft monitoring_station
pipeline	valve substation
power	compensator generator line plant portal substation switch switchgear terminal tower transformer
reservoir_type	sewage water_storage
substation street_cabinet	/

Table 0.6: Combination of Keys and Values for OSM Data (Debelle, 2026)

Relevant tags, keys and values were manually search on the OpenStreetMap wiki platform: https://wiki.openstreetmap.org/wiki/Main_Page

G. Geospatial Data Sets Retrieved from Online Sources and Geoportals

- NL_LIM: Manufacturing facilities, Hospitals, Dams (big), Dams (small), Dike closure devices, Pipe closure devices, Pipe access points, Pipes under obstacle, Pipes under obstacle (sealed), Water producing facilities, Pumping stations, Sand traps;
- DE_NRW: Buildings with photovoltaic panels, Water power facilities, Wind energy, Wind energy allowed, Hospitals, Basins locations, Protective infrastructure;
- BE_ALL: Hospitals, Wastewater treatment plants.

H. Major Rivers and Waterways of the Canvas

Number	*Name*	*Size*	*Description*
1	Albert Canal	Large	Artificial canal connecting Antwerp, Liège and the Meuse
2	Demer	Small	Long narrow river spanning from the Canvas to the Dyle and Antwerp
3	Jeker (Geer)	Small	Tributary river to the Meuse
4	Briegden-Neerharen Canal	Large	Dugged with the Albert Canal for freight transport purposes
5	Meuse & parallel Juliana Canal	Large	Main and largest river of the canvas, and key to the Euregio Meuse-Rhine
6	Geleenbeek	Small	River connecting Heerlen to Geleen, before discharging into the Juliana Canal
7	Kleine Geul	Small	River originating in the Belgian Ardennes and discharging in the Juliana Canal
8	Wurm & tributaries	Small	Urban-crossing river flowing through Aachen and discharging into the Roer
9	Inde	Small	River originating in the Belgian Ardennes and crossing the Eifel region to then discharge in the Roer.
10	Roer	Large	Major river of the Euregio Meuse-Rhein, tributary to the Meuse river.

Table 0.7: Major Rivers and Waterways of the Canvas (Debelle, 2026)

I. TenneT TSO's On- and Offshore Grid Map

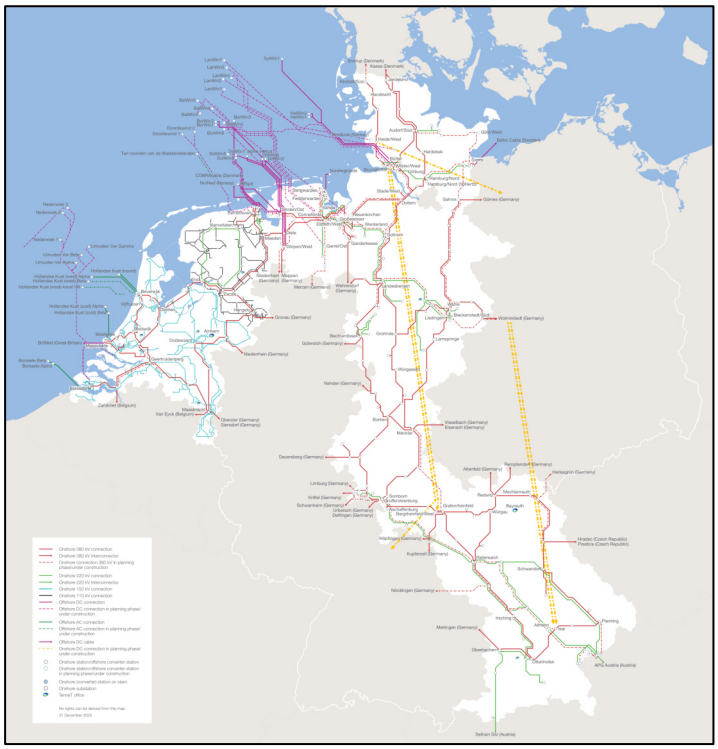


Figure 0.1: TenneT TSO's On- and Offshore Grid Map (TenneT, 2026)

J. GIE & ENTSOG Gas Grid Maps

Given the high degree of spatial detail in the GIE gas grid maps, a reproduction in the present report compromises the maps' legibility. Consequently, the reader is advised to refer to the following URL link for an overview and download links of relevant GIE and ENTSOG gas grid maps: https://www.gie.eu/publications/maps/

K. Elia Group's Electricity Grid Map

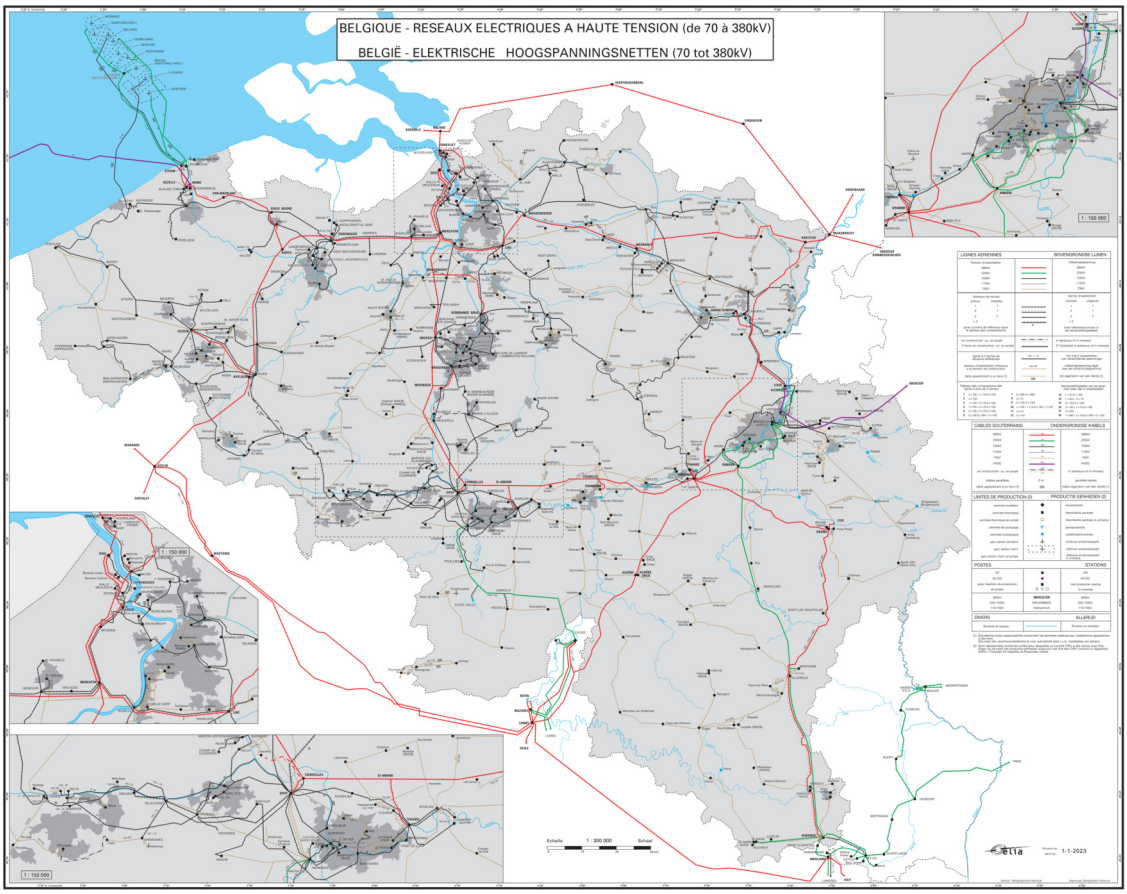


Figure 0.2: Elia Group's Electricity Grid Map (Elia Group, 2023)

L. Sum of Inhabitants per Hospitals (National vs. International Voronois)

Hospital Institution	Inhab. Nat.	Inhab. Internat.	Change to Internat.
Uniklinik RTWH Aachen	37,910	70,490	+85.9%
Medish Centrum Maastricht Annadal	45,647	64,527	+41.4%
Zorgcentrum Schuttershof	15,438	20,968	+35.8%
Franziskushospital	15,669	19,626	+25.3%
VIALIFE Reha Bardenberg GmbH	100,333	121,317	+20.9%
Openbaar Psychiatrisch Zorgcentrum Rekem	40,600	48,507	+19.5%
Marienhospital Aachen	89,746	101,243	+12.8%
Luisenhospital Aachen	4,628	4,628	0.0%
Bethlehem Gesundheitszentrum Stolberg GmbH	77,944	77,944	0.0%
Rhein-Maas Klinikum GmbH	59,364	59,364	0.0%
St.-Antonius-Hospital Eschweiler	38,103	38,103	0.0%

ZOL Ziekenhuis Oost-Limburg Campus Sint-Jan	29,265	29,265	0.0%
Medisch Centrum St-Jozef Nord	7,308	7,308	0.0%
Clinique Andr√© Renard	44,199	44,199	0.0%
Clinique du Ch√¢teau Rouge	25,900	25,900	0.0%
Centre Medical Mosan	57,538	57,538	0.0%
Alexianer Krankenhaus	32,421	32,421	0.0%
Adelante Ziekenhuis	58,011	58,011	0.0%
Zuyderland Medisch Centrum	44,754	44,436	-0.7%
Zuyderland Medisch Centrum	80,321	78,864	-1.8%
Clinique CHC Hermalle	57,114	53,776	-5.8%
Maastricht UMC	48,880	45,867	-6.2%
St. Elisabeth-Krankenhaus Geilenkirchen GmbH	83,731	77,864	-7.0%
Vijverdal	80,526	74,654	-7.3%
Medisch Centrum St-Jozef Zuid	34,492	28,836	-16.4%
Zuyderland Medisch Centrum Nord	104,367	83,488	-20.0%
ZOL Ziekenhuis Oost Limburg Campus Sint-Barbara	23,763	16,778	-29.4%
Zuyderland Medisch Centrum Zuid	56,773	31,774	-44.0%

Table 0.8: Inhabitants Serviced by Hospitals of the Canvas, in Border-Restricted vs. Border-Blind Contexts (Debelle, 2026)

M. Sum of Inhabitants per Electricity Hubs (National vs. International Voronois)

Electricity Hubs	Inhab. Nat.	Inhab. Internat.	Change to Internat.
Chemelot	15,980	41,092	+157.2%
Herzogenrath	20,928	44,812	+114.1%
Hombourg	15,048	30,337	+101.6%
Walheim	28,579	40,231	+40.8%
RueLongue	22,529	28,334	+25.8%
Limmel	103,765	127,910	+23.3%
Heidberg	23,024	27,135	+17.9%
DerbyArena	38,110	42,902	+12.6%
Beek	44,364	49,608	+11.8%
GruenerWeg	119,190	124,068	+4.1%
Lutterade_North	21,289	21,310	+0.1%
Treebeek	73,153	73,190	+0.1%
AndreDumont	4,710	4,710	0.0%
Hauts-Sarts	65,673	65,673	0.0%
RueMalvoye	59,799	59,799	0.0%
Alsdorf	29,963	29,963	0.0%
Baesweiler	22,366	22,366	0.0%
BranderWald	56,325	56,325	0.0%
FischerStr.	22,703	22,703	0.0%
Geilenkirchen	14,279	14,279	0.0%
KrauthausenerHeide	21,083	21,083	0.0%

MoselStr.	23,552	23,552	0.0%
PV_B57	2,615	2,615	0.0%
SchHalGmbH	15,687	15,687	0.0%
Siersdorf	12,978	12,978	0.0%
Stalberg	4,767	4,767	0.0%
StationAltenrath	12,279	12,279	0.0%
StationVelau	21,456	21,456	0.0%
UW-Gereonsweiler	2,823	2,823	0.0%
UW-Merzenhausen	2,697	2,697	0.0%
Verlautenheide	6,275	6,275	0.0%
Wuerselen	27,842	27,842	0.0%
Lutterade_South	8,316	8,316	0.0%
Swentibold	4,397	4,397	0.0%
ENCI	48,613	48,284	-0.7%
StaheAmWasberg	10,327	10,257	-0.7%
Beersdal	51,816	51,052	-1.5%
Lixhe	22,973	20,920	-8.9%
Tongersesteenweg	34,078	28,769	-15.6%
RansdalerStr.	46,898	38,041	-18.9%
LuetticherStr.	36,512	25,990	-28.8%
OudeTongersesStr.	37,471	26,581	-29.1%
Terwinselen	116,129	71,173	-38.7%
Elia Stalen	28,957	14,165	-51.1%
Langerlo	43,926	17,465	-60.2%

Table 0.9: Inhabitants Serviced by Electricity Hubs of the Canvas, in Border-Restricted vs. Border-Blind Contexts (Debelle, 2026)

N. Methodology for General Statistical Numbers of Health CIs

All 510 point-elements of healthcare and emergency services are individually and manually verified to determine their service capacity, similar to the electricity hubs: if a facility's node itself is marked in blue in the underlying flood raster layer, or its access roads or surroundings are heavily affected, then the facility is considered as flooded and unable to provide its core service(s). It must be noted that the visual analysis is deemed as most accurate for the present study, as complex geographic and geometric tool –or thereof combination– are required to gain enough flood insights of the facility's surrounding environment.

Given the missing flood depth values for some region (necessary to determine the road accessibility of an infrastructure), and to keep a uniform assessment of the floodings, water levels are considered too deep (hence a facility not reachable) if large contiguous pixel aggregates exist around the location or cover the full width of connected roads. Of course, this assumption omits the possibility of some vehicles possessing sufficient height clearance to drive through deeper flood levels, a parameter that cannot be reasonably quantified. Figure 0.3 show why sampling the flood raster layer below nodes is not sufficient, as that would consider the fire station not flooded an operatable. Building a point layer with the closest three roads in a perimeter of 50 metres would also return the Molensingel road being not flooded, neglecting the reality that the road fully flooded both up north and down south.

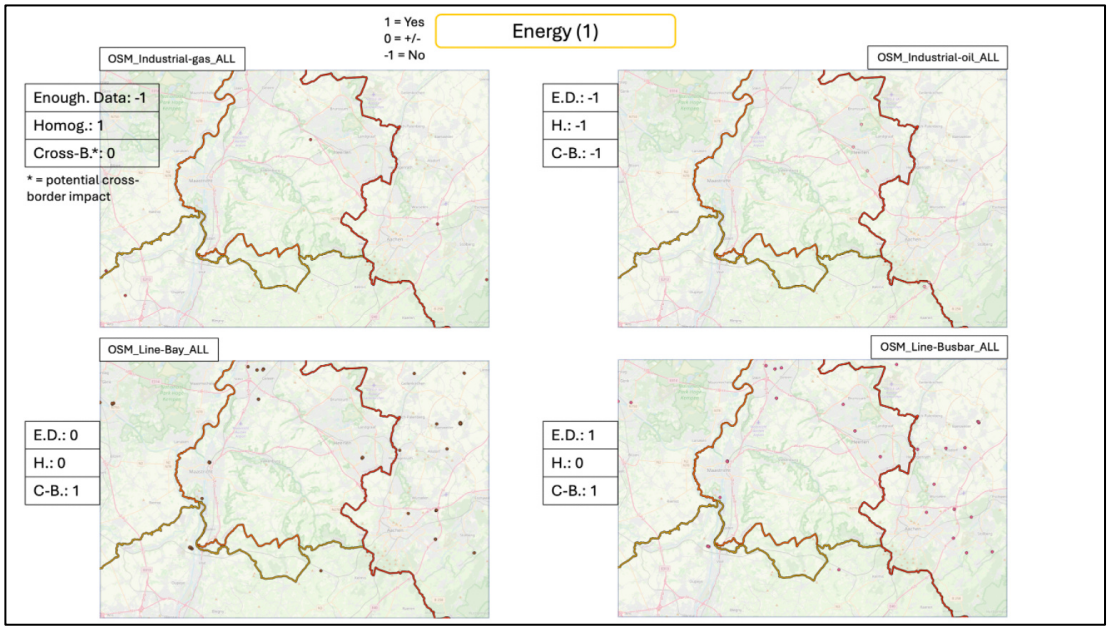


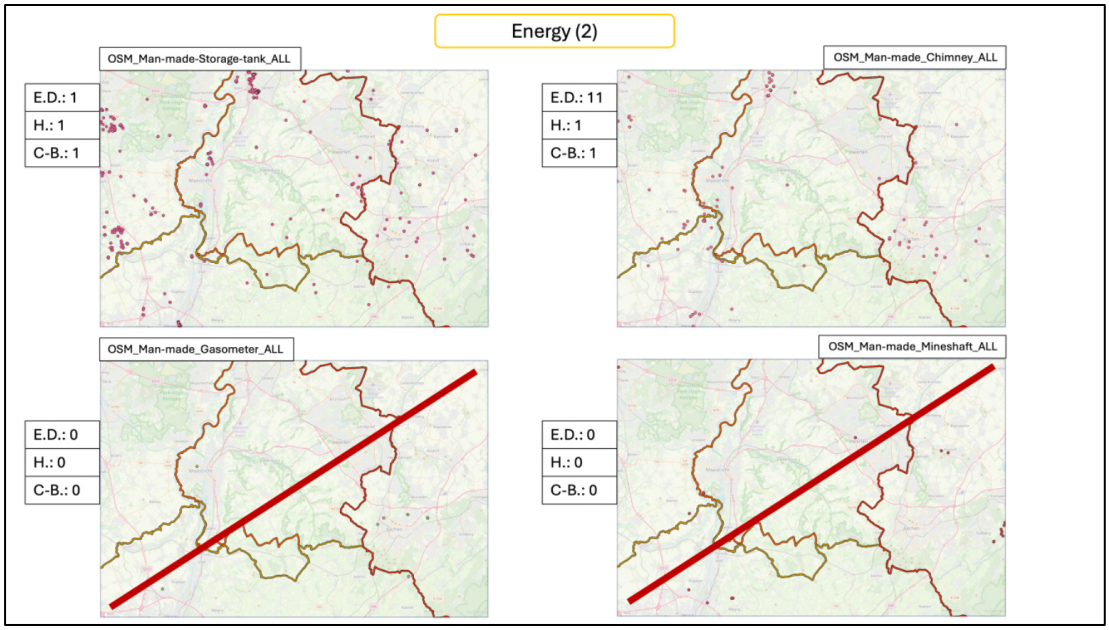
Figure 0.3: Example of Node not Considered as Flooded if Sampling the Flood Raster Layer (Debelle, 2026)

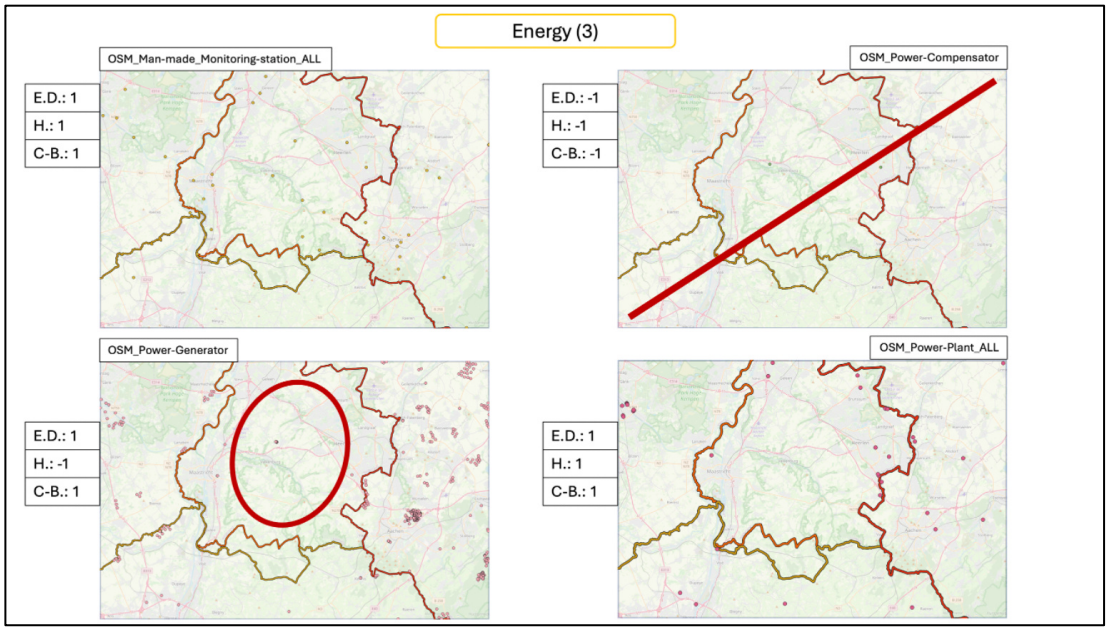
Country (CI)	Total	Node Flooded		Visually Flooded		CI Density
	#	#	%	#	%	(# / 100km^2)
Belgium	**157**	**18**	**11.5%**	**35**	**22.3%**	
Hospital (H)	10	2	20.0%	3	30.0%	0.4
Hospital (CC)	3	0	0.0%	0	0.0%	0.2
Hospital (ES)	2	0	0.0%	1	50.0%	1.3
Fire Station	11	0	0.0%	3	27.3%	1.2
Police	24	5	20.8%	5	20.8%	12.6
Pharmacy	107	11	10.3%	23	21.5%	2.8
Netherlands	**116**	**5**	**4.3%**	**75**	**64.7%**	
Hospital (H)	9	0	0.0%	7	77.8%	3.0
Hospital (CC)	18	0	0.0%	11	61.1%	4.1
Fire Station	25	1	4.0%	21	84.0%	1.5
Police	13			7	53.8%	8.4
Pharmacy	51	4	7.8%	29	56.9%	2.1
Germany	**237**	**11**	**4.6%**	**79**	**33.3%**	
Hospital (H)	14	2	14.3%	5	35.7%	1.6
Hospital (CC)	9	0	0.0%	4	44.4%	11.7
Fire Station	68	5	7.4%	31	45.6%	2.4
Police	23	0	0.0%	5	21.7%	21.2
Pharmacy	123	4	3.3%	34	27.6%	4.0
Grand Total	**510**	**34**	**6.7%**	**189**	**37.1%**	

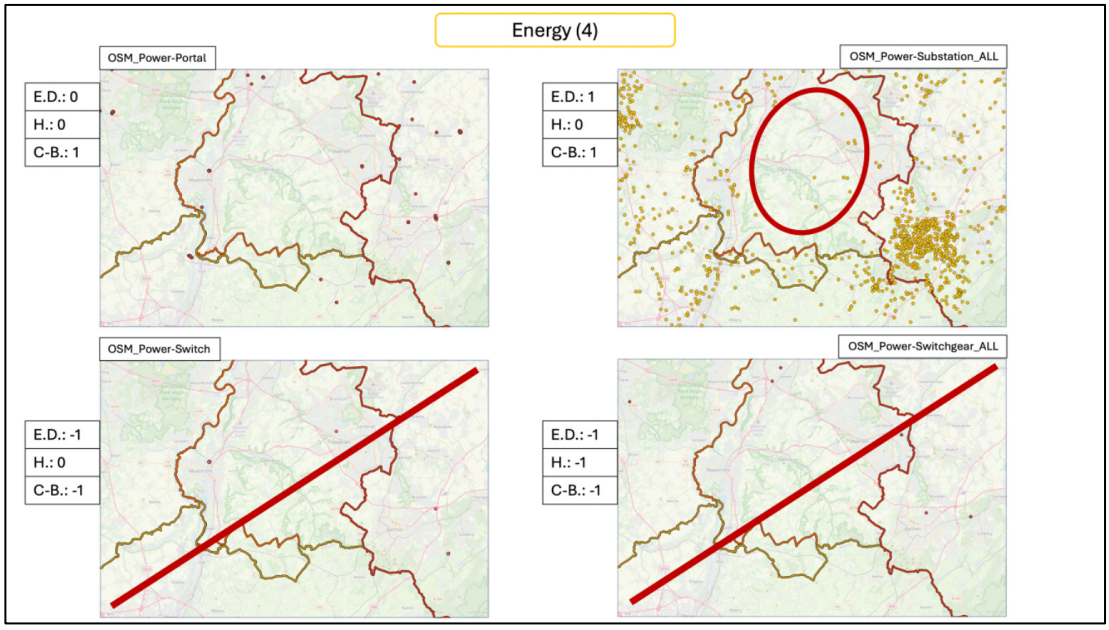
Table 0.10: Statistical Numbers on Flooded CIs (HQ100) from the Healthcare and Emergency Response Services Sector (Debelle, 2026)

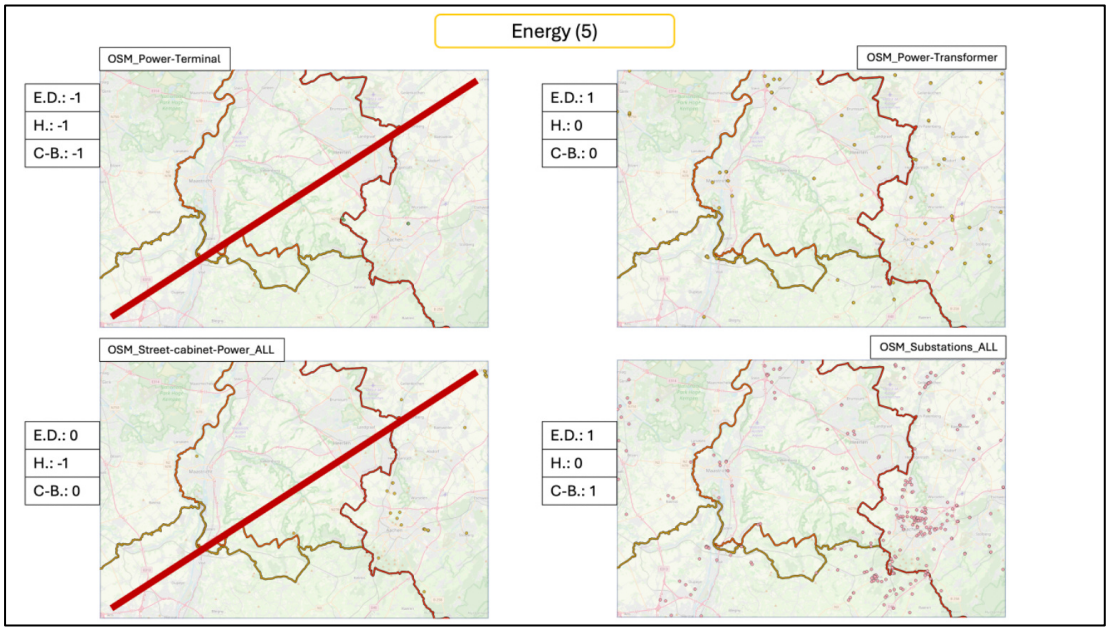
O. Selected OSM Layers

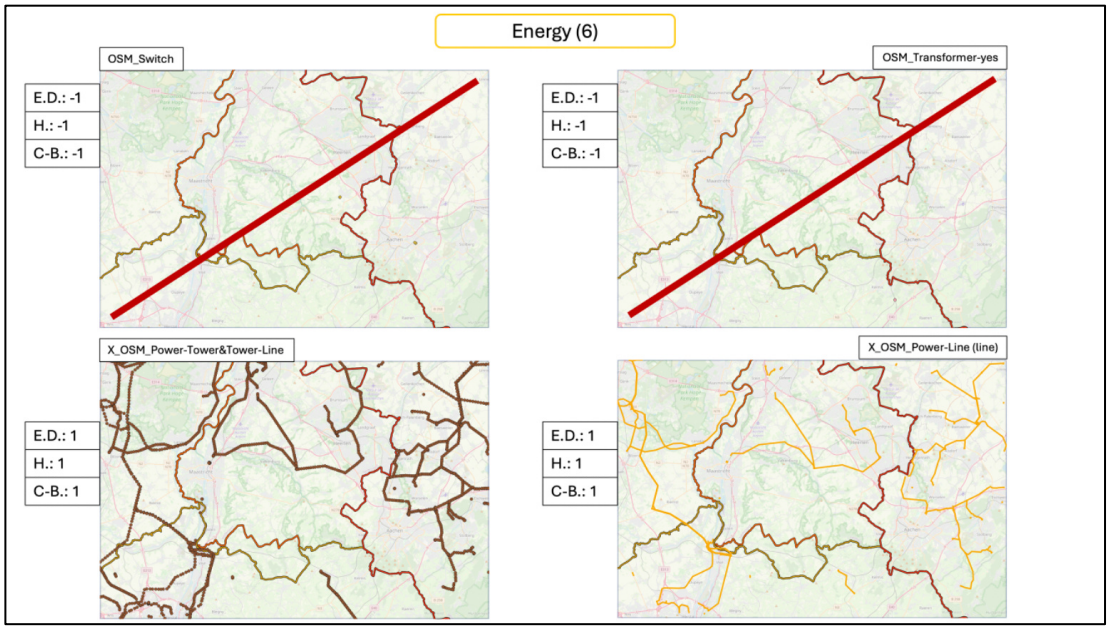


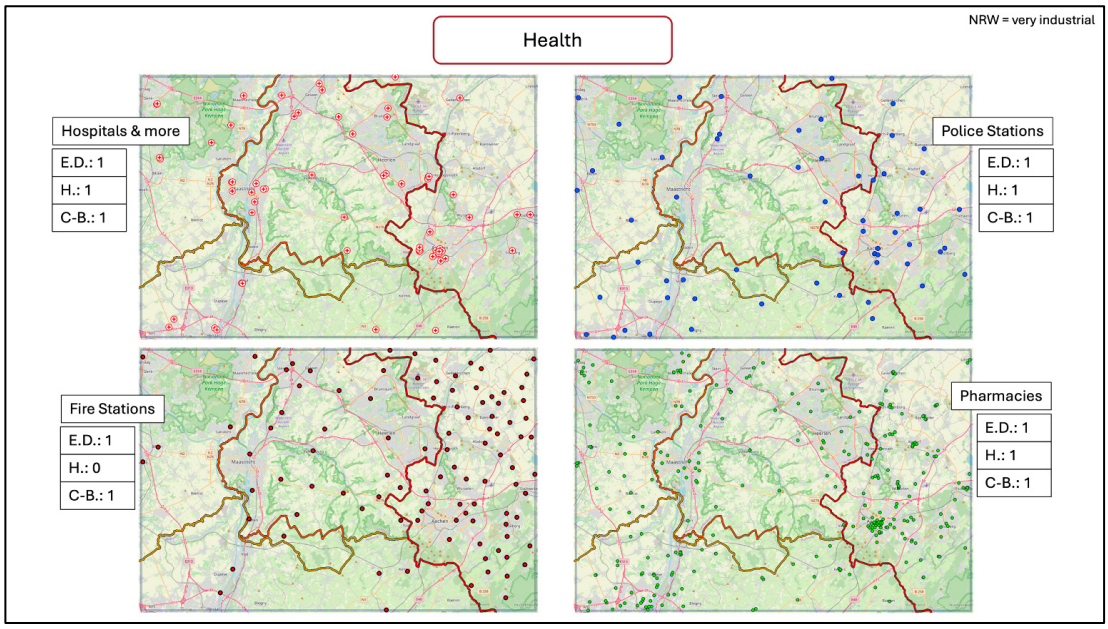


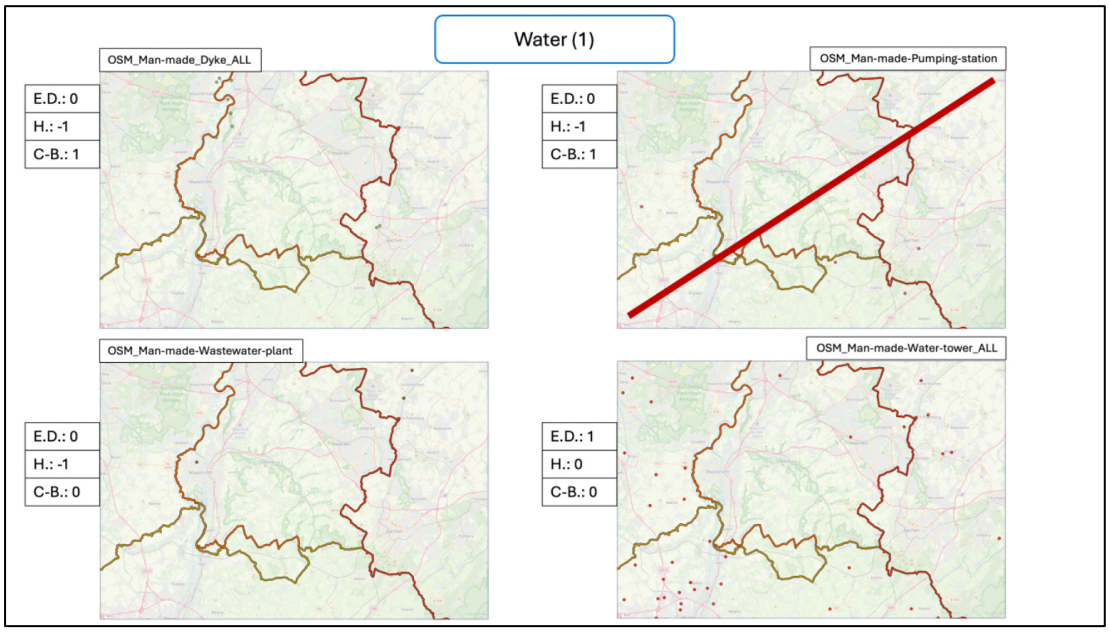

Energy (3)
OSM_Man-made_Monitoring-station_ALL
E.D.: 1
H.: 1
C-B.: 1
OSM_Power-Compensator
E.D.: -1
H.: -1
C-B.: -1
OSM_Power-Generator
E.D.: 1
H.: -1
C-B.: 1
OSM_Power-Plant_ALL
E.D.: 1
H.: 1
C-B.: 1

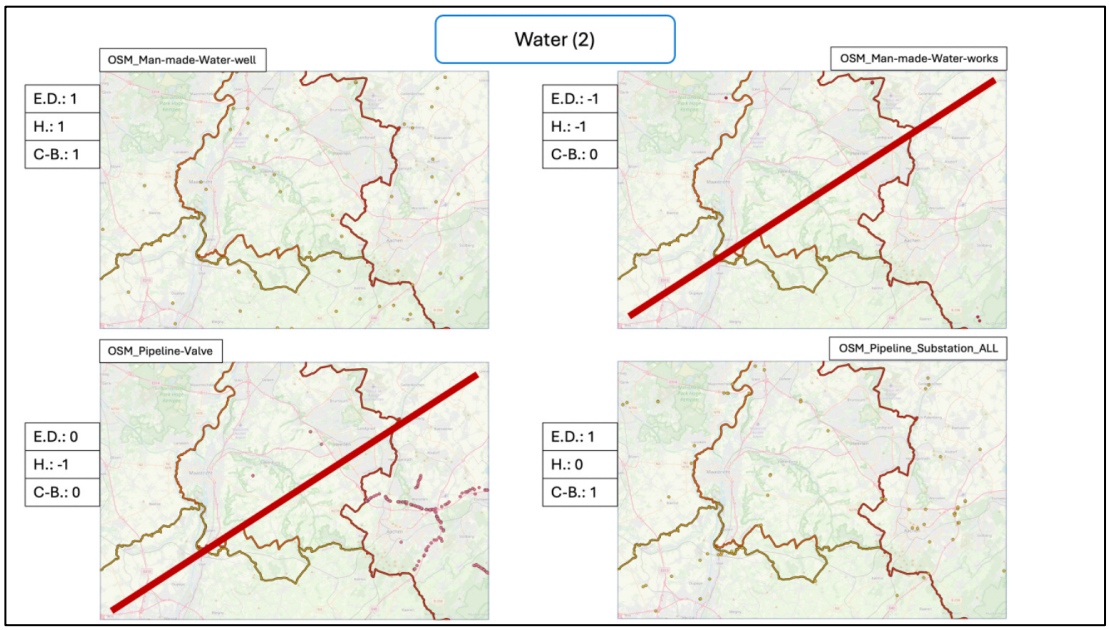

Energy (4)
OSM_Power-Portal
E.D.: 0
H.: 0
C-B.: 1
OSM_Power-Substation_ALL
E.D.: 1
H.: 0
C-B.: 1
OSM_Power-Switch
E.D.: -1
H.: 0
C-B.: -1
OSM_Power-Switchgear_ALL
E.D.: -1
H.: -1
C-B.: -1

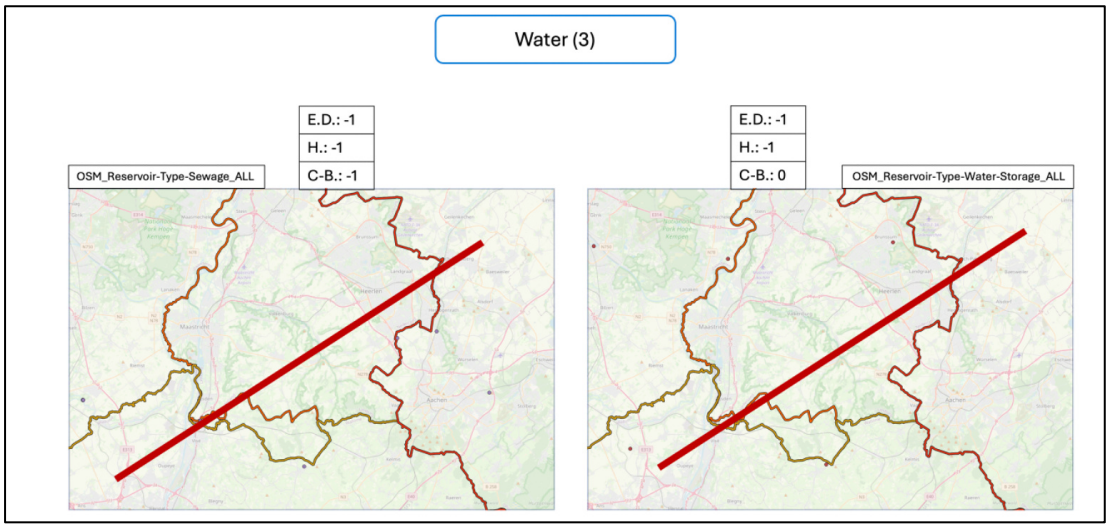

Energy (5)
OSM_Power-Terminal
E.D.: -1
H.: -1
C-B.: -1
OSM_Power-Transformer
E.D.: 1
H.: 0
C-B.: 0
OSM_Street-cabinet-Power_ALL
E.D.: 0
H.: -1
C-B.: 0
OSM_Substations_ALL
E.D.: 1
H.: 0
C-B.: 1


Energy (6)
OSM_Switch
E.D.: -1
H.: -1
C-B.: -1
OSM_Transformer-yes
E.D.: -1
H.: -1
C-B.: -1
X_OSM_Power-Tower&Tower-Line
E.D.: 1
H.: 1
C-B.: 1
X_OSM_Power-Line (line)
E.D.: 1
H.: 1
C-B.: 1


Health
NRW = very industrial
Hospitals & more
E.D.: 1
H.: 1
C-B.: 1
Police Stations
E.D.: 1
H.: 1
C-B.: 1
Fire Stations
E.D.: 1
H.: 0
C-B.: 1
Pharmacies
E.D.: 1
H.: 1
C-B.: 1


Water (1)
OSM_Man-made_Dyke_ALL
E.D.: 0
H.: -1
C-B.: 1
OSM_Man-made-Pumping-station
E.D.: 0
H.: -1
C-B.: 1
OSM_Man-made-Wastewater-plant
E.D.: 0
H.: -1
C-B.: 0
OSM_Man-made-Water-tower_ALL
E.D.: 1
H.: 0
C-B.: 0





P. Questions for Expert Interviews

Q1 : What are your preferences or requirements regarding how your intervention in and contribution to this study is cited or attributed?

Q2 : Could you describe your role within [employer], and the primary responsibilities this entails?

Q3.1 : From your employer's respective CI sector and thereof network, what are potential, existing or missing interactions creating synergies or conflicts for the management and governance of the CI network?

Q3.2 : Are there existing agreements between your and partnering institutions / governmental bodies, and if so, how do they apply or interact with the previous questions?

Q4 : Are you, or is your institution, generally aware of applying laws and regulations such as the CER-Directive, Wwke or KRITIS-D. acts? If so, how do these influence your role or your institution's daily operations?

Q. Summaries of Expert Testimonies

Organisation (Country)	***Expert***	***Current Role(s)***	***Interview Format***
Uniklinik Aachen (DE)	Johannes Wilde	- Head of the plant fire brigade of the Aachen University Hospital - Lecturer at Technical School of Cologne	Phone call (23/01/2026)
EMRIC (BE, NL, DE)	Giulia Stroink	Programme manager at EMRIC, coordinating the collaboration between partnering institutions	Online meeting (29/01/2026)
Waterschap Limburg (NL)	Sven Robertz	- Project manager of the Euregio Meuse-Rhine Interreg Flood Wisdom project - Employee at Waterschap LIM.	Online meeting (11/02/2026)
	Sophie Verstraelen	Advisor in international relations and coordinator at Waterschap LIM., specifically for collaboration with German partners and in water quality topics	
Noodplanning Crisisbeheer Limburg (BE)	Michel Carlier	Director of the emergency planning and crisis management dept. at the Governor of Limburg (BE)	Email exchanges (06/02/2026)

Table 0.11: Experts Agreeing to an Interview (Debelle, 2026)

a) Johannes Wilde (Uniklinik Aachen) – DE

The interview was conducted via a phone call. The following points summaries the primary insights and perspectives provided by the expert. The points are AI-assisted syntheses of unstructured notes recorded during the interview, remaining faithful to the raw notes and insights gathered. The Q1 question in principally answered on the expert's website: https://johanneswilde.de/.

- The EMRIC (Euregio Meuse-Rhine Incident Response and Crisis Management) framework is not a concept but a fully operational reality. All necessary protocols for collaboration already existed and functioned before the 2021 flood disasters. Nonetheless, improvements are always possible.
- Cooperation is particularly occurring at local levels, between specific Landkreise (German districts) or municipalities. A practical example of the functionality is the seamless deployment of fire engines across borders, where technical and procedural barriers have already been largely overcome.
- The topic of critical infrastructures (KRITIS in Germany) is not a secondary task, but a core pillar of the expert's daily professional duties and operations. The German legislative regulations and frameworks (KRITIS-Dachgesetz) already dictate the expert's workload. A significant and ongoing requirement exist to adapt local processes and procedures, and undertake new projects.
- When identifying specific CI that may trigger a regional cascade of disruptions, the expert singled out the Uniklinik RWTH Aachen. The expert asserts that the existence of this hospital is not only relevant to the neighbouring regions of Liège or the Dutch Limburg, but to much further cities and populations of the respective neighbouring countries. This illustrates the criticality of this very infrastructure.

- Resilience projects are driven more by the NATO than other intergovernmental bodies such as the EU, and less by national authorities. Further details may not be provided or shared.
- By email: The provision of electricity by emergency generators at times of outages is generally not considered as sufficient enough to keep the Uniklinik RWTH Aachen's regular services levels at 100% of its capacity, like in normal times. The Uniklinik RWTH Aachen has sufficient emergency power capabilities for self-sufficient operation to maintain patient care for 72 hours.

b) Giulia Stroink (EMRIC) – BE, NL, DE

The interview was conducted via an online meeting. The following points synthesise the primary insights and perspectives provided by the expert. The points are AI-assisted syntheses of unstructured notes recorded during the interview, remaining faithful to the raw notes and insights gathered.

- The core coordination office acts as a connective tissue for a vast network of regional partners. Cooperation projects includes multiple partners across all sectors and from the entire Euregio, including fire services, emergency medical services, infectious disease control, and flood crisis management.
- EMRIC does not command operations during crises, their role is in the partners' preparation prior to crisis events: creating plans, developing tools and facilitating post-incident feedback loops. This ensures the technical readiness –connectivity of dispatching centres, verified contact lists, communications protocols– is operational before crisis occurrence.
- The coordination is maintained through 10 specialised working groups, meeting two to four times annually to discuss crisis management and prepare joint exercises with regards crisis scenarios such as forest fires or CBRN (chemical, biologic, radioactive and nuclear) incidents.
- Help requests are submitted by "packages", based on capacity rather than specific inventory. For example, fire departments may request help for an intervention necessitating enough water to turn out a manufacturing plant fire: There, the request for help is not for a specific truck model, rather for a package capable and sufficient enough for delivering the specific volumes of water (e.g. litres per minute). The standardisation of these packages is an ongoing project. Packages are requested directly between partners at time of crises, without any EMRIC intervention, to ensure a prompt provision of help.
- There is no legal obligation to send aid packages. Each partner's primary mandate is the protection of their own domestic territory. A help package is only accepted if the providing region has sufficient surplus activity. During the 2021 floodings, no package request was used or accepted, given the regional forces were engaged at their full capacities in their local duties. Throughout the 2021 crisis, the most critical "infrastructure" was the information flow, pre-planned by EMRIC with dedicated communication channels essential for data exchanges, even when physical equipment could not be shared. In this context, key contacts and intervenors are identified, and provided with a specific phone number and email address to be reachable 24h/24, 7d/7.
- To avoid linguistic or procedural confusion, teams are not mixed at the ground level during operations. Instead, foreign teams accepting a package request are assigned to a specific autonomous task (e.g. evacuate and save injured commuters from a specific derailed train car), with coordination occurring only at leadership levels.

- The EMRIC initiative was largely driven by the Netherlands and the Dutch region of Limburg, where waiting for domestic aid from the north took longer than receiving aid from across German and Belgian borders.
- While catastrophes are rare, daily cooperation is common, with 638 cross-border ambulance deployments and 67 fire service interventions in 2024 alone. Such daily cooperation sending teams across borders does not require formal requests for help packages.
- A recent forest fire (in Brunssummerheide near Heerlen, August 2025) illustrated the “ad-hoc” nature of cooperation. As hydrants were unavailable, teams laid kilometres of hoses across the Dutch-German border to bring water from Germany to the Netherlands.
- For EMRIC, the primary focus is the protection of population less of critical infrastructure. While CI failures may trigger crises, the expert notes that their daily work is not specifically influenced by European directives or thereof national transposition laws. Additionally, the expert asserts that NATO readiness requirements for population protection often carry more weight than European or national directives. Whether an emergency response directly serves a household or a critical infrastructure, no specific framework exist for the latter.
- Financial topics are discussed upstream and are dictated over pre-existing contracts and agreements (available on the EMRIC website). Generally, costs are absorbed by the respective fire departments or thereof insurers, even if participating in cross-border interventions. Some contracts may include “fair use” clauses (e.g. the first X interventions per year are free, then billing starts), preventing one region from subsidising another’s safety budget indefinitely.
- Previously funded by the EC and it European Regional Development Fund (ERDF), EMRIC is now independent and financed by the partnering institutions. EMRIC also provides expertise insights to other comparable initiatives across other European borders. While institutions are typically open to collaborative learning, a preference is marked for self-directed rather than externally enforced protocols.

EMRIC 2024 Report: https://www.emric.info/sites/default/files/2025-05/EMRIC%20Jahresbericht%202024%20DE.pdf

c) Sven Robertz & Sophie Verstraelen (Waterschap Limburg - WL) – NL

The interview was conducted via an online meeting. The following points synthesise the primary insights and perspectives provided by the expert. The points are AI-assisted syntheses of unstructured notes recorded during the interview, remaining faithful to the raw notes and insights gathered. The synthesis is then commented and corrected by the experts.

- Sophie Vestraelen acts as the Germany coordinator for Waterschap Limburg, focusing on water quality (specifically chemical and ecological, rather than drinking water, cf. the German Wasserrahmenrichtlinie directive [WRRL]).
- Sven Robertz leads the FLOOD WISDOM project from the Interreg Meuse-Rhine initiative, co-funded by the European Union. His work involves research to improve regional understanding of water behaviour, construction projects for measuring devices, and creating digital GIS twins and flood risk models.
- The WL’s relationship include the Rijkswaterstaat and LANUK, but also Dutch and German regions, municipalities, water boards, etc. The federal ministries of Germany and Belgium are generally less involved. Collaboration is stronger at regional levels, because the NRW’s size is comparable to the entire country of

the Netherlands. Consequently, Den Haag communicates more with Düsseldorf than Berlin. Additionally, the NRW authorities show greater interest in flood data from the 2021 crisis than the federal German authorities.

- The Meuse river is managed by the Rijkswaterstaat, while the Roer river is primarily under the supervision of the WL (similarly to the distinction between national highways and regional roads). The WL and the NRW region share 14 WRRL border crossing water bodies / stretches. The WL is responsible for wastewater and general water infrastructure, but not drinking water, and its functions effectively stop at the Dutch borders. Additionally, the WL only informs population and issues danger warnings: Safety remains the responsibility of concerned Veiligheid's regions (a similar system applies in NRW). The Roer and the Meuse river are vital the region, and recent incidents include water quality.
- While cross-border communication existed during the 2021 floods, improvement possibilities were identified. Belgian rainfall forecastings proved more accurate and closer to observed quantities than Dutch and German previsions. A major issue is the lack of downstream communication from upstream countries, often due to a lack of structural processes or political will. Bureaucracy is a significant bottleneck, reportedly more in Germany than in the Netherlands. For example, logistical hurdles exist, where employees and workers may not carry and use their working laptops or phones across border, due to data confidentiality protocols.
- The guiding motto is that "water knows no borders", but the reality imposes challenges. Regions model their domestic geographical catchment, and despite using neighbouring data, no unified global plan exists for cross-border infrastructure. There is little national or federal push for system unification and integration, collaboration is rather driving bottom-up by regions.

d) Michel Carlier (Noodplanning Crisisbeheer Limburg) – BE

The testimony was collected via email exchanges. The following original transcript of the received response is provided:

Question 1

I am the director of the Emergency Planning and Crisis Management Department at the Governor of Limburg.

This department supports the Governor in his security duties.

The department operates in two phases:

- Cold phase: planning, training local authorities and other partners, exercises, networking, and collaboration.

- Hot phase: crisis management.

In short, we are strongly committed to professionalizing the operations at the local level and promoting collaboration between all partners.

Question 2

This depends on the crisis management approach. In Belgium, this approach takes place at three (four) levels:

- During the operational phase (the crisis management approach is the responsibility of the emergency services) we always contact the mayors to ask whether they are

aware of the situation and whether they have thought about communication, support, etc.

- In the municipal phase, the mayor is responsible for contact with the adjacent region, municipalities, and province. We support local operations remotely, and they can always rely on our knowledge, experience, networking, and relationships. If desired, we join the municipal crisis unit.

- In the provincial phase, the governor is responsible. We fully support the governor in his approach to the crisis, including in relation to neighboring regions and provinces.

- In the federal phase, the federal minister is responsible, and we support and strengthen the federal approach from the governor's perspective.

To prepare for potential crisis situations, we strongly focus on networking and good relations with neighboring domestic and international regions.

- In Belgium, we border the Dutch-speaking provinces of Antwerp and Flemish Brabant and the French speaking province off Liège. We have direct contacts with the EPCM of the governors of Antwerp, Flemish Brabant and Liège. We also collaborate together on some plans. An example of this collaboration is the nuclear plan for

the Mol-Dessel nuclear installations that impact . We have a similar collaboration with Liège, for example, regarding the preparation of the plans for the Tihange nuclear installation. Further more we have a direct line to the Walloon crisis center Cortex. This is especially important in the context of flooding in the Meuse basin.

- At the Dutch Limburg border, our partners are the safety regions. We also have agreements with them regarding notification and information sharing (e.g., via Emric). With EPICC, we have less to do because we are multidisciplinary.

- Agreements with all these partners are laid down in the emergency plans.

- In crisis situations of any nature that impact one of the neighboring provinces or Dutch Safety Regions, we share the reports and decisions of our crisis unit.

Question 3

We are aware (though not in detail) of each other's risks through risk maps and analyses.

Dutch legislation differs from Belgian legislation, but we are familiar with their approach and scaling methods, and so on.

Because we are familiar with them, the impact on daily operations is minimal. It is sometimes strange, for example, that during a provincial phase, our governor can't consult his Dutch counterpart (the King's Commissioner), but must make arrangements with the chairman of the safety region, who is a mayor. But I can assure you that these differences do not cause any problems.

I am aware of the list with critical entities form my province.

The NCCN (National Crisis Centre) coördinates the CER-directive.

The governor can, if he thinks that this is necessary, include specific measures in the general emergency plan of the province in accordance with the NCCN