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2. ABSTRACT

In Section 4.1 of the deliverable, the focus is on the assessment of multi-hazard scenarios following the collapse of a bridge or other transport links, with particular attention to safety, risk management, and infrastructure resilience. In infrastructure planning and design, the assessment of multi-hazard scenarios that follow the collapse of a bridge—or any other transport link—plays a crucial role in safety, risk management, and resilience. This section provides a framing perspective on the types and methodologies of analyses undertaken in multi-hazard contexts, enabling bridge collapse to be examined in terms of its social, economic, environmental, and human consequences, while highlighting potential cascading and multi-risk effects. The analysis distinguishes between tangible and intangible effects, both direct and indirect, in order to provide an integrated estimation of the consequences of collapse. Particular attention is given to differentiating between immediate and long-term impacts, thereby supporting more informed decision-making in infrastructure safety and risk management. The study concludes with an examination of representative case studies aimed at validating the proposed methodological framework and illustrating, through the application of multi-hazard criteria, the actual economic, environmental, social, and human consequences that have arisen. These case examples also allow comparison of different levels of exposure and vulnerability, underscoring how the multi-risk consequences of collapse may vary significantly depending on the structural characteristics, geographic location, and socioeconomic importance of the infrastructure.

In Section 4.2 of the deliverable, the analysis addresses industrial facilities as complex socio-technical systems exposed to NaTech scenarios, proposing a resilience-based framework for managing risks generated by natural hazards triggering technological accidents. Industrial facilities, once considered isolated entities, are now approached as complex socio-technical systems involving intricate networks operating within the surrounding environment. In particular, the increasing frequency of extreme natural events due to climate change has highlighted the vulnerability of industrial infrastructures to NaTech scenarios, where natural hazards trigger technological accidents. Current methodologies for NaTech risk assessment focus predominantly on immediate consequences, often overlooking the long-term complexities affecting both industrial systems and their surrounding territories. This section proposes a resilience-based framework for NaTech risk management, structured around three main stages—awareness, preparedness, and recovery—together with a continuous learning loop to address the evolving challenges posed by NaTech events. Awareness emphasizes proactive vulnerability detection using a function-location approach and addresses the dynamic interactions between industrial infrastructures and multi-hazard territorial contexts through innovative qualitative and quantitative assessment techniques. Preparedness focuses on forecasting hierarchical safety layers based on detected vulnerabilities, identifying leading indicators to design robust and context-specific safer systems, strengthening barriers, and developing effective emergency plans. The recovery stage is illustrated through a retrospective case of hydrocarbon pollution caused by rainfall, integrating countermeasures and sustainable technological solutions. Overall, this section highlights the need for multidimensional approaches to tackle the evolving challenges posed by NaTech events and presents a comprehensive resilience-based framework to enhance the long-term sustainability of complex industrial systems exposed to multiple natural hazards.

In Section 4.3 of the deliverable, the study examines the interactions and interdependencies among civil critical infrastructures within a multi-hazard risk assessment framework, moving beyond traditional single-infrastructure and single-hazard approaches.

This section analyses the interactions and interdependencies among four civil critical infrastructures—drinking water, sewage and wastewater, railway, and road networks—within a multi-hazard risk assessment framework. The work is motivated by the need to move beyond single-critical-infrastructure and single-hazard risk approaches, particularly in the context of climate change, which simultaneously increases both the probability of individual infrastructure failure and the likelihood of synchronous multi-sector stress. The dependency

analysis characterizes incoming dependencies from electricity, water, and transport systems through structured dependency tables developed via literature review and expert consultation. To move beyond qualitative mapping, the chapter describes a simulation-based framework developed within the project, consisting of a knowledge graph encoding critical infrastructure interdependencies and hazard fragility data, coupled with domain-specific operational simulators and validated through the ReturnLand/ReturnVille Virtual Test Bed. Simulation experiments demonstrate the ability to identify cascading interdependencies that cannot be detected through expert elicitation or literature review alone, thus providing a quantitative and operationally grounded basis for multi-hazard critical infrastructure risk assessment.

In Section 4.4 of the deliverable, the attention is focused on the effects of climate change on critical water infrastructures, including wastewater treatment plants and drinking water treatment plants, with particular emphasis on process resilience and environmental impacts.

Climate change is increasingly affecting critical water infrastructures, including wastewater treatment plants (WWTPs) and drinking water treatment plants (DWTPs), by intensifying the frequency and severity of extreme events such as heat waves, droughts, and intense rainfall. This section analyses the potential concatenation of climate-related risks affecting urban wastewater treatment and drinking water production systems, with specific attention to process performance, environmental impacts, and technological resilience. For WWTPs, two Italian case studies were considered. In Parma, the effects of heat waves on the performance of two wastewater treatment plants were assessed using operational data collected between June and October 2024. The analysis showed that heat-wave events did not lead to exceedances of discharge limits for the main effluent parameters, including suspended solids, COD, nitrogen, and phosphorus. Reactor temperatures remained relatively stable, and no clear evidence of adverse effects on activated sludge settleability was observed. In Palermo, the analysis focused on the impact of intense rainfall and combined sewer overflow activation on microplastic discharge. Results showed that combined sewer overflow events significantly increased microplastic concentrations in wastewater, reaching values approximately twelve times higher than those observed in treated effluent, thus highlighting these events as a relevant pathway for microplastic release into receiving water bodies. For DWTPs, the study addressed the deterioration of surface water quality caused by climate-related stressors, including droughts, high temperatures, water-column stratification, and intense precipitation. These conditions may increase soluble metals, natural organic matter, turbidity, and algal blooms, challenging conventional drinking water treatment processes. In this context, ferrate (VI) was investigated at laboratory scale as an innovative and sustainable treatment option to enhance process robustness under emergency conditions. Experimental results showed that ferrate (VI) can effectively support the removal of manganese, turbidity, and algae, while reducing the demand for conventional coagulants and avoiding the formation of toxic by-products.

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4.1 Main interactions and interdependencies for transportation infrastructures

4.1.1 Analysis Methodologies for Multi-Hazard Scenarios

Multi-hazard scenarios are analytical methodologies that illustrate the probability of occurrence of certain phenomena, whether anthropogenic or natural, which may arise independently, sequentially, or simultaneously, thereby amplifying the overall effects of the event. The methodology is based on the recognition of three fundamental factors: hazard, vulnerability, and exposure (Gill and Malamud 2016). Hazard is defined as the intrinsic danger of a phenomenon, described in terms of its intensity and duration: for example, the probability of an earthquake of a given magnitude and duration. Vulnerability refers to the capacity of an exposed element to resist or sustain damage from a given phenomenon. For instance, a bridge designed according to current seismic regulations will exhibit lower vulnerability to an earthquake compared to an older structure. Exposure concerns the potential consequences in terms of the quantity and value of people, assets, and services that may be affected. The collapse of a bridge connecting two uninhabited towns would represent a significant structural loss, but with limited implications for people, goods, and services. By contrast, the collapse of a bridge linking two metropolitan areas—centres of economic activity and urban life—would have profoundly different consequences due to its high exposure. The integration of these three factors makes it possible to model realistic and complex scenarios, through mathematical and statistical approaches, which are particularly valuable for future infrastructure design, for planning interventions before an event occurs, and for developing maintenance strategies for transport networks. Such strategies are especially crucial for urban and strategic links, where optimized prevention and emergency response are essential.

4.1.2 Current Regulations Applicable to Multi-Hazard Analyses

The application of models to multi-hazard scenarios for the analysis of their interdependencies in design and intervention processes is not yet regulated or uniformly mandated at the global, European, or national level. Although various technical guidelines for infrastructure introduce multi-level approaches that intersect multiple risk factors, a precise and clearly defined regulatory framework is still lacking. Taking the case of transport infrastructures as an example, guidelines have been issued for bridge monitoring, risk management, and risk classification (Ministero delle Infrastrutture e della Mobilità Sostenibili (MIT)., 2022). These include criteria for the assessment of seismic, hydraulic, and geotechnical risks, but they do not prescribe a standardized method for evaluating hazards in a combined manner. This means that, for the time being, the application of such methodologies remains largely dependent on sound engineering practices, research initiatives, and technical recommendations rather than on binding legislative requirements.

4.1.3 Consequences of Bridge Collapse in Multi-Hazard Contexts

When examining specific areas of interest related to the collapse of a bridge—or any strategic transport infrastructure—it is inevitable to identify certain influencing factors that frame the guidelines for interpreting the phenomenon and selecting the appropriate risk scenarios associated with it. The first factor to be assessed is the source and nature of the risk, together with its intensity and duration. Subsequently, attention must be given to the domain of consequences under consideration. Limiting the analysis to local consequences of a collapse - such as the direct damages resulting from the failure of an overpass interrupting a highway at a given point - differs substantially from adopting a broader perspective that incorporates a wider spectrum of factors. It is now well established that the observation of multi-risk consequences can be organized into four main categories:

- Economic consequences;
- Environmental consequences;

- Social consequences;
- Human consequences.

Table 4.1.1: Examples of social, environmental, human and economic consequences (COST Action TU0601).

Consequence categories	Examples
Human	Fatalities Injuries
Economic	Replacement / reconstruction cost Repair costs Loss of functionality/downtime Traffic delay / re-routing costs Traffic management costs Clean up costs Rescue costs Regional economic effect Loss of business Investigations / compensations
Environmental	CO_2 Emissions Energy use Pollutant releases
Social	Loss of reputation / public confidence Changes in professional practice Loss of business

In assessing the severity of consequences, with a specific focus on civil infrastructures, European regulations (European Committee for Standardization., 2002) propose a distinction into three consequence classes, which were later expanded to five in the subsequent supplementary standard (ISO 2394., 2015):

- *CC1- Consequence Class 1*
  Predominantly insignificant material damages.
- *CC2- Consequence Class 2*
  Material damages and functionality losses of significance for owners and operators but with little or no societal impact. Damages to the qualities of the environment of an order which may be restored completely in a matter of weeks.
- *CC3- Consequence Class 3*
  Material losses and functionality losses of societal significance, causing regional disruptions and delays in important societal services over several weeks. Damages to the qualities of the environment limited to the surroundings of the failure event and which may be restored in a matter of weeks.
- *CC4- Consequence Class 4*
  Disastrous events causing severe losses of societal services and disruptions and delays at national scale over periods in the order of months. Significant damages to the qualities of the environment contained at national scale but spreading significantly beyond the surroundings of the failure event and which may only be partly restored in a matter of months.

- *CC5- Consequence Class 5*
  Catastrophic events causing losses of societal services and disruptions and delays beyond national scale over periods in the order of years. Significant damages to the qualities of the environment spreading significantly beyond national scale and which may only be partly restored in a matter of years to decades.

The last distinction (Gajanayake et al., 2017) concerns the classification of effects and consequences into four categories:

- Direct tangible consequences: measurable immediate or delayed damages.
- Indirect tangible consequences: measurable economic losses resulting from the interruption of activities.
- Direct intangible consequences: immediate non-material impacts, such as the suffering of victims' families or the psychological trauma caused by the collapse.
- Indirect intangible consequences: non-material effects that manifest over time, such as the loss of trust in infrastructure safety.

The quantification of consequences - particularly economic ones - is carried out through mathematical-economic models, summarized in **Table 4.1.2** and illustrated in **Figure 4.1.1**, which represent the processes and their segmentation.

Table 4.1.2: Summary of integration techniques (Gajanayake et al., 2017).

Type of impacts incorporated	Method	References
Direct and indirect tangible (Total economic)	Total monetary impact	Cho et al. (2000), Jaiswal et al. (2010), Negi et al. (2013), Winter et al. (2016a), Sohn et al. (2004)
	Cost Benefit Analysis	Maze, Crum & Burchett (2005), Pfurtscheller & Genovese (2016b)
	System risk curve	Shiraki et al. (2007)
Socio-economic	Severity Assessment Tool	Deshmukh et al. (2011)
	Cost Benefit Analysis	Shinozuka et al. (2005), Zhou, Banerjee & Shinozuka (2010)
	Life Cycle Cost	Sobanjo & Thompson (2013), Decò & Frangopol (2011)
Environmental economic	Multi Criteria Analysis	Tapia & Padgett (2016)
Others	Monetary conversion	Dong et al. (2014b), Giunta (2017)
	Multi Criteria Analysis	Padgett, Ghosh & Dennemann (2009), Schweikert et al. (2018)

Figure 4.1.1 shows a simplified workflow for the assessment of possible losses deriving from a structural failure

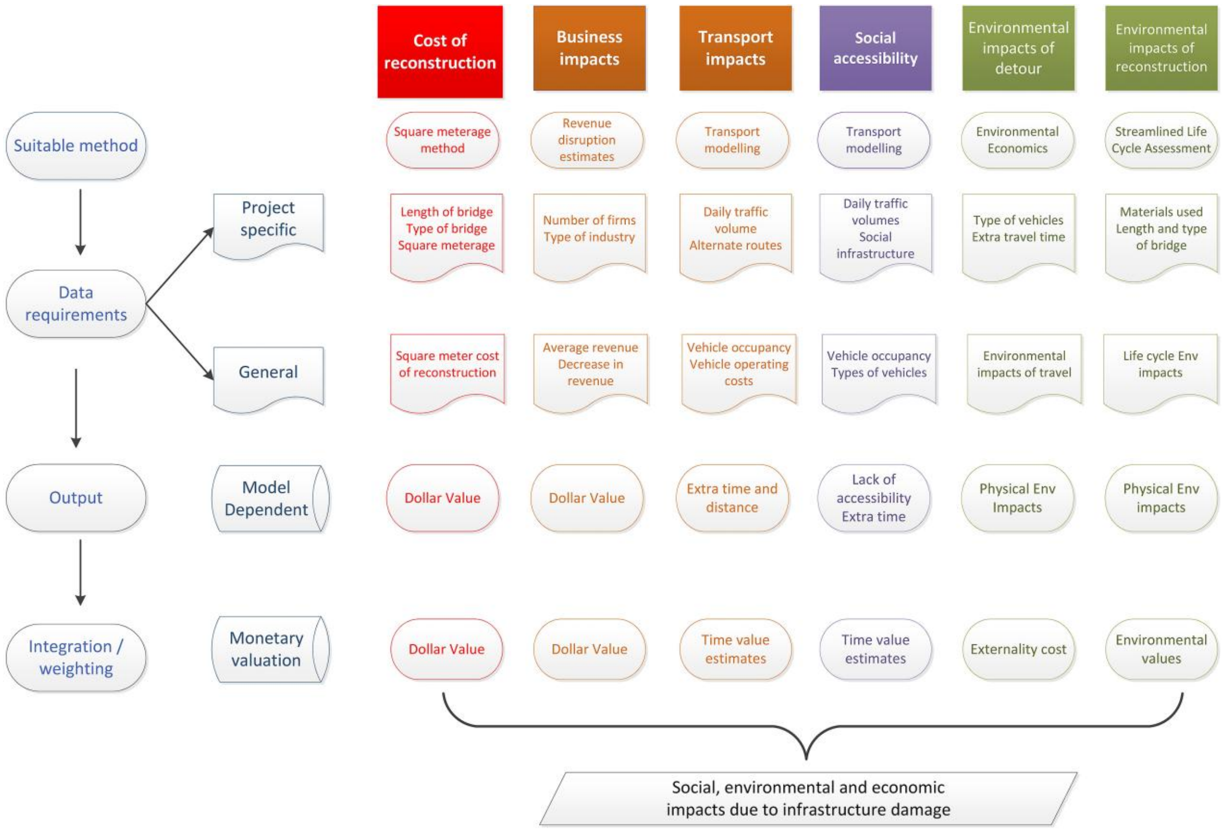


Figure 4.1.1: Simplified diagram for the loss assessment (Gajanayake 2021)

4.1.4 Examples of Analytical Modelling of Multi-Hazard Scenarios Involving Bridge and Infrastructure Collapse

Calculation methods and, subsequently, risk assessment in multi-hazard scenarios initially involve the integration of different types of extreme events and their potential interactions, encompassing all the previously mentioned classes of scenario correlations. The estimation of infrastructure vulnerability and the quantification of the overall impact on critical and strategic systems usually rely on deterministic and probabilistic models, with statistical integration into engineering reasoning. Since the detailed discussion and implementation of mathematical–statistical models for describing multi-hazard scenarios would be too extensive for this essay and would divert from its central theme, **Table 4.1.3** presents some of the main approaches currently established in current scientific literature. However, these approaches do not yet fully cover the area of interest, as they generally conclude the analysis at the moment of bridge failure. As such, they are representative only at a numerical level for the modelling of scenarios. By contrast, our study aims to extend the analysis to the subsequent consequences of bridge collapse, drawing upon real case studies.

Table 4.1.3: Summary of some scientific publications that provide analytical approaches to multi-hazard assessment.

Title	Reference
Multi-hazard fragility modelling framework for bridges with shallow foundations subjected to earthquake, scour, and vehicular loading.	Biazar et al., (2024)
An index-based method for risk assessment of existing bridges subjected to multiple hazards.	Grieco et al. (2024)
Multiple hazard assessment of bridges considering interdependencies.	Stefanidou et al. (2023)

Multi-Hazard Assessment of Bridges in Case of Hazard Chain: State of Play and Application to Vehicle-Pier Collision Followed by Fire.	Petrini et al. (2020)
A Multi-Hazard Probabilistic Framework for Quantifying Bridge Failure Risk Considering Climate Change.	Khandel & Soliman (2019)
Probabilistic Hazard Assessment of Bridges under Multi-hazard Actions during the Life-Cycle Period.	Mei & Soliman (2024)
Multi-hazard risk assessment of highway bridges subjected to earthquake and hurricane hazards.	Kameshwar & Padgett (2014)
Probabilistic multi-hazard fragility analysis of RC bridges under earthquake-tsunami sequential events.	Xu et al. (2021)
Probability of failure estimation for highway bridges under combined effects of uncorrelated multiple hazards.	Fioklou & Alipour. (2022)
Vulnerability of bridges to individual and multiple hazards floods and earthquakes.	Argyroudis & Mitoulis (2021)
Resilience assessment framework for critical infrastructure in a multi-hazard environment: Case study on transport assets.	Argyroudis et al. (2020)

4.1.5 Infrastructure Interdependency Analysis

According to Rinaldi et al. (2001) interdependencies can be defined as "A bidirectional relationship between two infrastructures through which the state of each infrastructure influences or is correlated with the state of the other. More generally, two infrastructures are interdependent when each depends on the other. The term 'interdependencies' is conceptually simple; it refers to the connections among agents in different infrastructures within a general system of systems. In practice, however, interdependencies among infrastructures dramatically increase the overall complexity of the system of systems."
Figure 4.1.2 illustrates what analyses of infrastructure interdependencies entail.

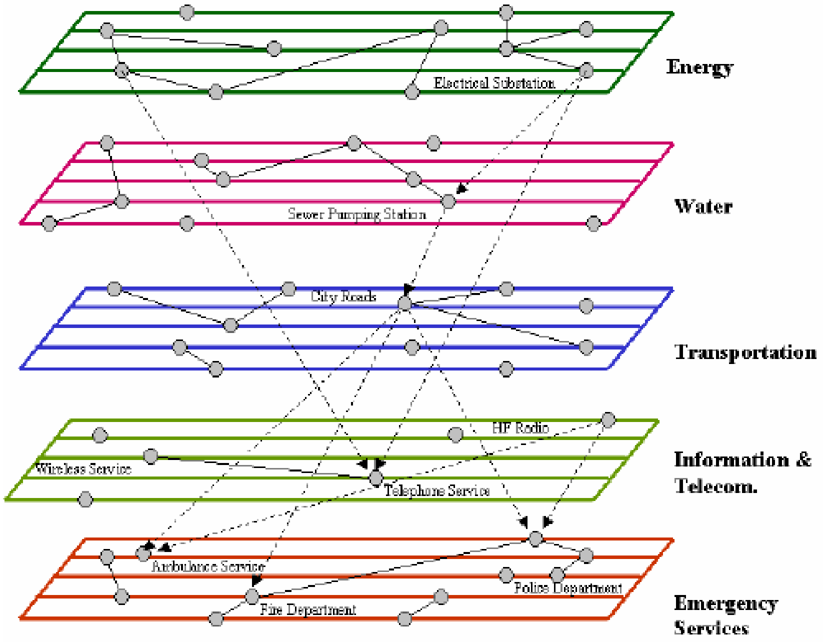
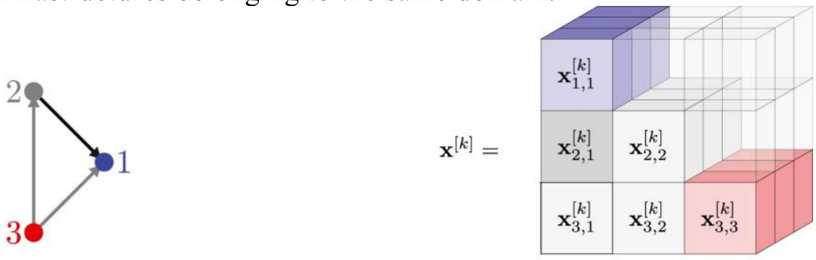


Figure 4.1.2: Infrastructure Interdependencies (Dudenhoefferet al. 2006).

In **Figure 4.1.2**, individual infrastructure networks are represented on a single plane, where parallel lines on the same plane indicate the individual sectors or subsets within a particular domain. The points represent key infrastructure components within a given sector, such as electrical systems or natural gas production and distribution. Solid lines define internal interdependencies between infrastructures within the same sector, while dashed lines indicate interdependencies between infrastructures of different types. The mathematical modelling of this representation leads to the development of threedimensional matrices (**Figure 4.1.3**), which record, for each variable, its relationships within planes that again represent infrastructures belonging to the same domain.



(a) An example network (b) State variables

Figure 4.1.3: Infrastructure Interdependencies as matrix. Source: (Sharma and Gardoni 2022).

According to Denhoeffer et al. 2006, there are several problems in the modelling of the sets and subsets that constitute multi-hazard systems. Indeed, Denhoeffer et al. 2006 identifies three main challenges:

1. Evaluate the impact on a subset of nodes $\{x, y, z, \ldots\}$ given a set of initiating events $\{E(a), E(b), \ldots\}$
2. Evaluate the possible set of events $\{E(a), E(b), \ldots\}$ that may have generated the outcome $\{x, y, z, \ldots\}$
3. 3.Given a set of events $\{E(a), E(b), \ldots\}$ and a set of observed outcomes on nodes $\{x, y, z, \ldots\}$, determine the possible interdependencies?

Thus, a partial or incomplete a priori knowledge of the interactions resulting from a bridge collapse would lead to an incompatibility in defining its consequences, as it would involve correlations and dependencies between structures unknown to the analyst, producing an obscured scenario (**Figure 4.1.4**).

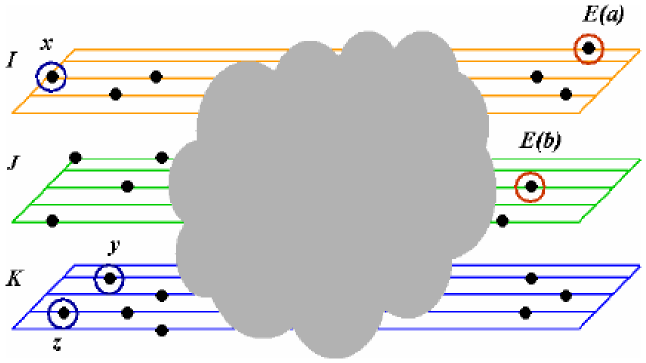


Figure 4.1.4: Interdependency Analysis Problem Space. Source: (Dudenhoeffer, D. D. et al., 2006).

According to Rinaldi et al. (2001), different types of interdependencies can be distinguished, including physical, cyber, logical, and geographic.

- Two infrastructures are physically interdependent if the state of each depends on the material flows or outputs of the other.
- An infrastructure has a cyber interdependency if its state depends on information transmitted through the information infrastructure.
- Infrastructures are geographically interdependent if a local environmental event can induce state changes across all of them.
- Two infrastructures are logically interdependent if the state of each depends on the state of the other through a mechanism that is neither a physical, cyber, nor geographic connection.

Most of the consequences of a CIs collapse primarily involve events affecting electric power networks, infrastructures managing gas distribution, and the environmental and economic damage resulting from the blockage of an underlying road or waterway connection. For example, analysing a case in which a bridge collapse causes the interruption of an electrical line (**Figure 4.1.5**), it is evident that the resulting power outage can potentially trigger further effects, creating a chain reaction of consequences.

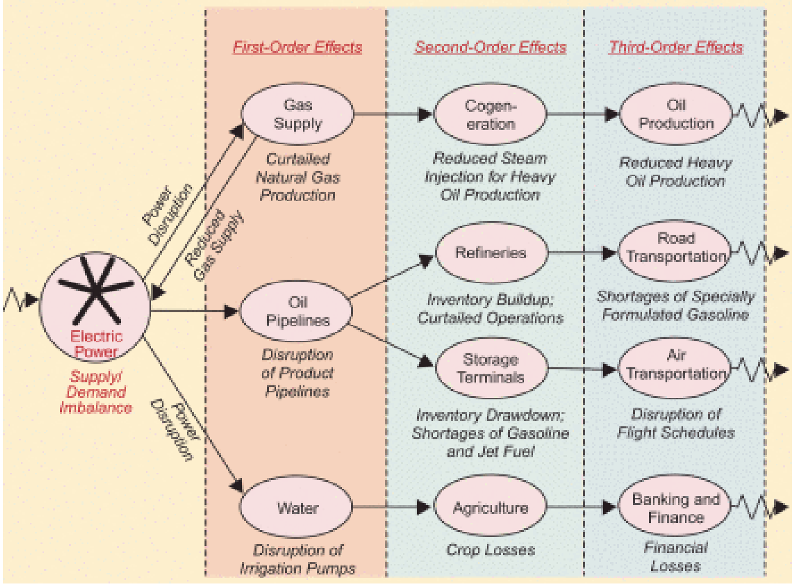


Figure 4.1.5 Examples of nth-order interdependencies and effects (Rinaldi et al. 2001).

This figure (**Figure 4.1.6**) illustrates how not only does the multi-hazard scenario of a bridge collapse, triggered by an initial hazard, cause significant direct consequences such as power outages, but also how this event can hypothetically become a hazard in its own right when studying its interdependencies with other infrastructures.

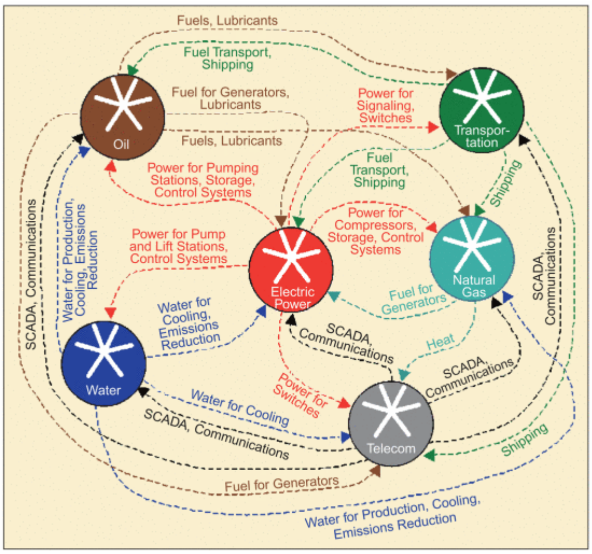


Figure 4.1.6: Examples of infrastructure interdependencies (Rinaldi et al. 2001).

Moreover, by referring to real cases, it is possible to illustrate how the collapse of a bridge spanning a river initially constitutes a direct consequence, which subsequently has repercussions on other infrastructures, such as the river trade network located beneath it, with further economic and logistical impacts on the transportation of goods and passengers. A notable example is the Brazilian bridge case reported in **Table 4.1.4**. Furthermore, bridges are often road bridges, which, if they collapse, can cause direct damage to transportation infrastructures such as highways. In addition to the immediate repair costs, such an event could hypothetically lead to public disruptions, including traffic congestion in other parts of the city and a consequent increase in CO_2 emissions. Continuing, if a bridge were to collapse and damage a gas line running above or below it, immediate hazards such as explosions or fires could occur, along with interruptions in gas supply for households and industries, damage to surrounding infrastructures, and emergency evacuations. Moreover, the event would generate cascading effects on dependent infrastructures, including energy, transportation, and emergency services. Finally, if a bridge spans a railway or tram line, a collapse will not only interrupt the line until reconstruction but also produce economic consequences (for freight transport) and social impacts for the affected city, such as train rescheduling, delays, and isolation of connected urban areas. In theory, one could continue indefinitely listing potential scenarios resulting from a bridge collapse, but this would be of limited utility for the scope of this report. What is crucial to understand is that the sudden collapse of a bridge, triggered by a preceding event, opens up possible scenarios that can be analysed as multi-hazard studies, leading to both direct and indirect consequences connected through their direct or indirect interdependencies. It is therefore essential to study the overlap of urban layers, highlighting the main infrastructures (**Figure 4.1.7**), not only to understand potential scenarios in advance but also to plan maintenance or intervention strategies for a critical infrastructure such as a bridge.

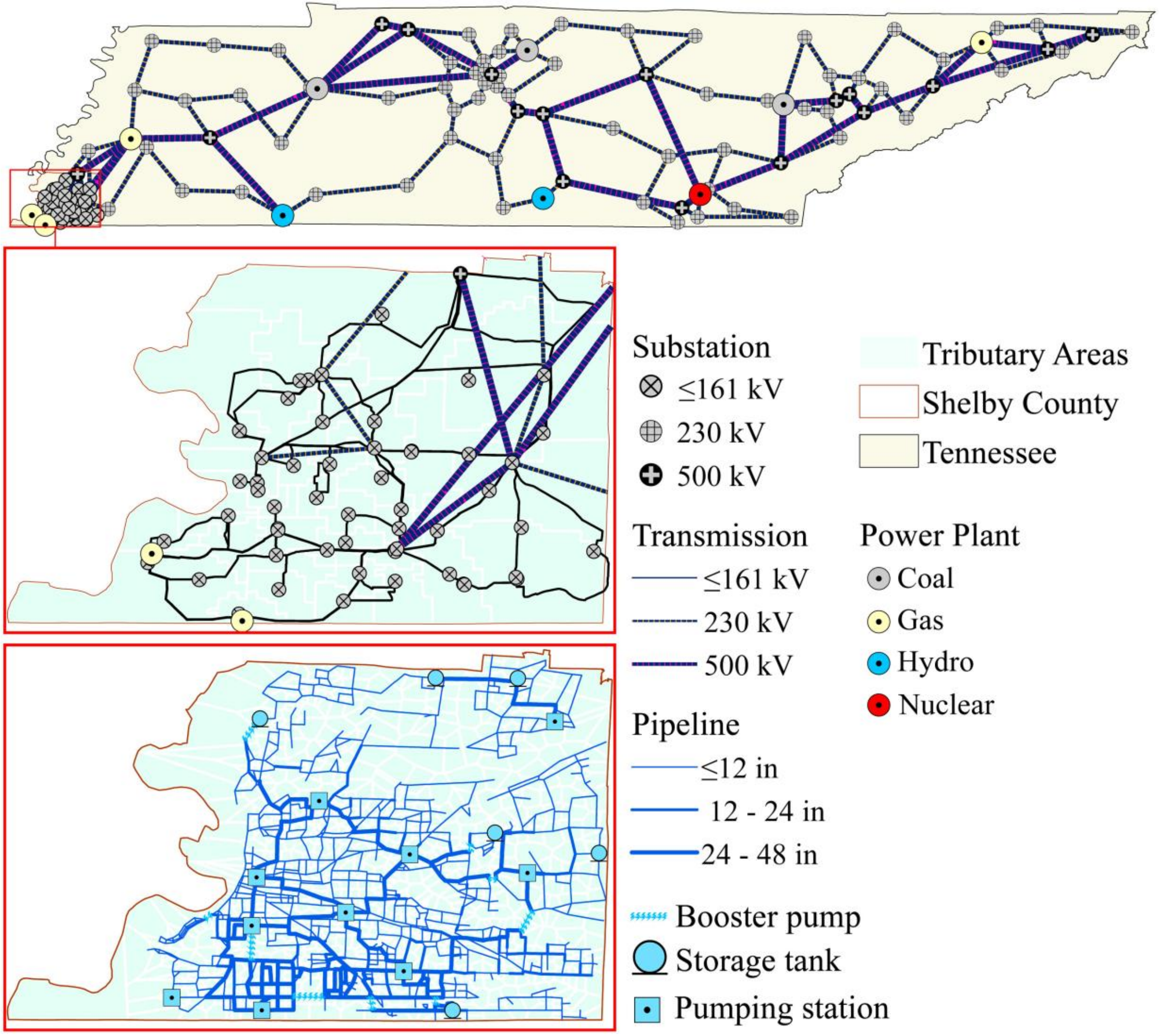
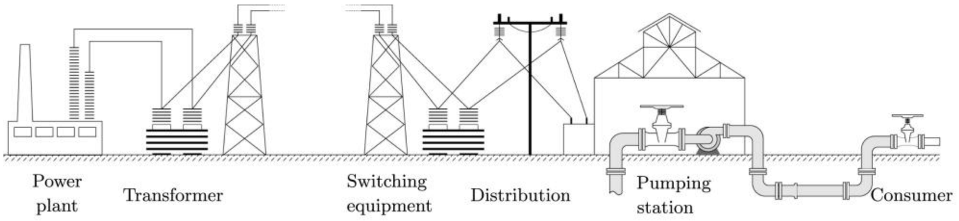
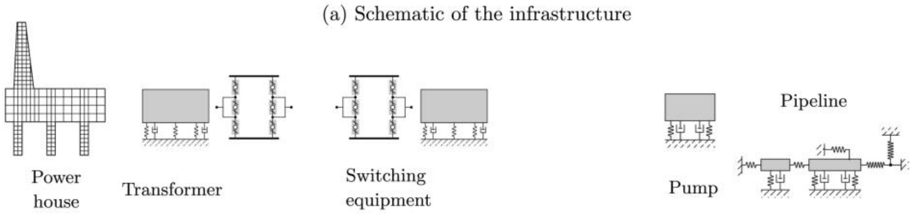


Figure 4.1.7: Modelled infrastructure for Shelby County (Sharma and Gardoni 2022).

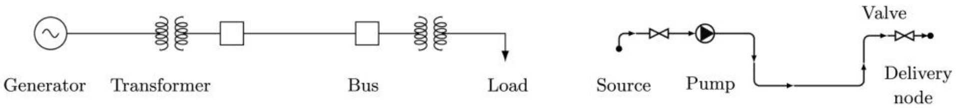
However, as we have seen, this approach may not be sufficiently effective, as it would analyse only the consequences on a single infrastructure. Infrastructures are interconnected due to their interdependence, either on the same layer or across different layers depending on the sector of application. Therefore, it becomes necessary to develop backward-mapping schemes of interdependence for the potentially affected structures, as illustrated in **Figure 4.1.8**.



(a) Schematic of the infrastructure



(b) Structural network (Power) (c) Structural network (Water)



(d) Power flow network (e) Hydraulic flow network

Figure 4.1.8: Networks representing power and potable water infrastructure (Sharma and Gardoni 2022).

4.1.6 Case Studies

In this context, some real facts are reported in which the collapse of a bridge caused different types of consequences on other CIs. For each of the seven infrastructures considered, a data sheet is provided detailing general information about the structure, the initial hazard that led to the bridge collapse, the intrinsic vulnerabilities of the structure, and the resulting consequences in human, social, economic, and environmental terms. The selection of case studies focused on bridge collapses that occurred over the past seven years, specifically chosen in different areas around the world to avoid identifying similar factors and consequences dictated by the same geographical exposure. Among the events listed in the following **Table 4.1.4**, we find the emblematic case of the collapse of the Juscelino Kubitschek de Oliveira Bridge in Estreito, Maranhão, Brazil. This bridge, which spans the Tocantins River, was being crossed at the time of the collapse by a truck carrying sulfuric acid and pesticides, which were entirely released into the river system. This example demonstrates that a bridge does not merely represent the physical road connection between two points; rather, it constitutes a system characterized by interdependencies deriving precisely from its connective function. Consequently, its collapse generates cascading effects across multiple levels or layers, depending on the nature and degree of its exposure. Supporting this argument with another emblematic case, we can refer to the collapse of the Francis Scott Key Bridge. Its direct consequences were, of course, devastating—quantified in economic terms as a reconstruction cost of 1.9 billion dollars—but its indirect effects were equally significant. The collapse forced the closure of the commercial waterway of the Patapsco River, thereby disrupting trade at the Port of Baltimore. This disruption affected more than 40 vessels and resulted in substantial delays in cargo handling and storage operations, in turn compromising, across multiple layers, the systems of communication, goods, and services not only for the city of Baltimore but more broadly for the United States as a whole.

Table 4.1.4: Seven case studies taken as examples of chain reactions caused by interdependencies.

Bridge	Location	Date	Construction Type	Reason of Failure	Consequences			
					Social	**Human**	**Environmental**	**Economic**
Jianzha Yellow River Bridge	Border of Jianzha county, Huangnan prefecture and Hualong county, Haidong city, Qinghai, China	22 August 2025	Steel Bridge	A steel cable used during the tensioning operation of the bridge's central arch snapped. This failure caused the middle section of the arch to collapse into the Yellow River.	The incident deeply affected local communities, raising concerns about construction safety standards. The central government dispatched a task force to investigate the collapse and implement stricter safety measures.	Fatalities:12 construction workers and 4 missing.	Debris from the collapsed bridge entered the Yellow River, potentially affecting water quality and river's ecosystem could be impacted by the introduction of construction materials.	The collapse halted construction, leading to potential delays in the completion of the Sichuan–Qinghai Railway, increasing delays on logistics and transportation. Additional funds required for reconstruction and enhanced safety protocols.
Juscelino Kubitschek de Oliveira Bridge	Estreito, Maranhão – Tocantins, Brazil	22 December 2024	Concrete Bridge	Structural failure (under investigation)	Major disruption of regional transportation; communities on both sides of the Tocantins River isolated; delays in emergency response and daily commuting; local schools and businesses affected.	13 fatalities and 4 missing.	Trucks carrying 76 tons of sulfuric acid and 25,000 Liters of pesticides fell into the river; contamination of water sources posed serious ecological risks, including aquatic life mortality and soil contamination.	Closure of a critical transport route affected trade and local economies; industries dependent on river and road transport experienced losses; costs of clean-up, bridge reconstruction, and environmental remediation estimated in millions of USD.
Red Bridge	Kamloops, British Columbia, Canada	19 September 2024	Wood and Steel Bridge	Suspicious fire that completely destroyed the structure, causing it to collapse into the South Thompson River.	The destruction of the bridge severed a key connection between downtown Kamloops and the Mt. Paul industrial area. Traffic was rerouted to the nearby Halston Bridge, causing significant congestion and delays in commuting and transport. The community faced disruptions in daily mobility and increased travel times, affecting both residents and service providers.	No direct fatalities were reported, but the collapse posed immediate risks to maintenance workers and early morning commuters in the vicinity.	Debris from the collapse entered the South Thompson River. Immediate water quality impacts were minimal, and no significant harm to migrating salmon populations was reported. However, the introduction of wood debris may have altered local river flow and sediment patterns, with potential medium-term ecological impacts.	The Red Bridge had historical and functional value. Its collapse disrupted local logistics and industrial transport, creating delays for businesses relying on this route. Reconstruction costs and emergency response expenses added financial burdens on local authorities, highlighting the economic ripple effects of losing critical infrastructure.
Francis Scott Key Bridge	Baltimore, Maryland, USA	26 March 2024	Steel Bridge	The collapse was caused when the container ship MV Dali lost power and collided with a critical support pier, triggering the failure of the bridge's fracture-critical structure.	The incident prompted a swift response from local, state, and federal agencies. Maryland Governor Wes Moore declared a state of emergency, and the Federal Aviation Administration imposed temporary flight restrictions over the site. The City of Baltimore filed a lawsuit against the ship's owner and operator, alleging negligence in the vessel's operation and seeking damages for the economic losses incurred.	Fatalities: 6 construction workers.	The collapse created a significant obstruction in the shipping channel, requiring extensive efforts to clear debris and restore navigability.	The collapse blocked the Patapsco River shipping channel, halting operations at the Port of Baltimore, a vital hub for international trade. This disruption affected over 40 vessels and led to significant delays in cargo processing. The estimated cost to rebuild the bridge is between $1.7 billion and $1.9 billion, with completion expected by fall 2028.
Tretten Bridge	Tretten, Øyer, Norway	15 August 2022	Wood and Steel Bridge	Failure in one of the timber diagonal members near the western river foundation. This failure led to overloading and subsequent failure of other truss elements.	The bridge carried the E6 highway, a major north-south route. Its closure forced residents and transport operators to take long detours, significantly affecting daily commuting and emergency response times. Access to services, schools, and local businesses in Tretten and surrounding areas was interrupted. The collapse led to an immediate inspection of 14 similar wooden and hybrid bridges across Norway, heightening public awareness and concern about infrastructure safety.	No Fatalities.	Debris from the collapse partially entered the Lågen River, potentially affecting water flow and aquatic ecosystems temporarily.	Immediate repair and temporary bridge construction cost several million USD. The closure of the E6 highway affected commercial transportation, delaying deliveries and increasing fuel and labour costs for logistics companies. The collapse caused disruptions in regional commerce, affecting small businesses relying on the highway and increasing costs for emergency services rerouted due to detours.
Lixinsha Bridge	Lixinsha Bridge, Nansha District, Guangzhou, Guangdong Province, China	22 February 2018	Concrete Bridge	Collision with a barge due to improper operation by the crew.	Isolation of local communities due to closure of a key transport route; disruption of commuting and access to schools and hospitals. Public outrage demanded better safety enforcement.	5 fatalities and 3 injuries.	Minimal immediate environmental impact, but water contamination risk from vehicles submerged in the river and potential fuel leaks.	Disruption of logistics and transport in one of China's busiest manufacturing hubs; temporary halt of port operations; estimated losses in regional trade and supply chains.
Polcevera Viaduct (Morandi Bridge)	Genoa, Liguria, Italy	14 August 2018	Concrete Bridge	The collapse was primarily caused by progressive corrosion and failure of prestressing cables in the central span, exacerbated by structural deterioration and lack of timely maintenance.	The collapse severed a vital transportation link, isolating parts of Genoa and neighbouring areas. Firefighters, police, and civil protection teams were mobilized, highlighting the strain on local emergency services. Italian authorities implemented stricter inspections on other bridges nationwide, revising maintenance protocols and oversight policies.	43 fatalities and 16 injured.	Steel debris fell into the Polcevera river, affecting water quality and potentially harming local ecosystem.	Closure of the A10 highway led to significant detours, affecting freight and commuter traffic with estimated reconstruction and compensation costs exceeded €1 billion. Local industries, logistics companies, and ports experienced delays in shipments and increased transport costs.

4.2 Resilient Framework to cope with Industrial hazards within a Territorial Multi-risk Context

4.2.1 Foundations of resilience applied to the NaTech context

Resilience is a crucial concept in addressing complex systems, involving factors like biophysical and socioeconomic characteristics, infrastructure, land use, the built environment, and external threats from climate and disasters (Hung et al., 2024). Since its development in 2004, resilience engineering (RE) has been introduced in various industrial fields, focusing on anticipating, monitoring, responding, and learning to anticipate, withstand, and recover from disruptions (Hollnagel et al., 2006). However, there is a lack of clarity on the conceptual links between resilience principles and practical procedures in the process industry. Valente et al. (2025) presented a resilience curve, tailored to the evolution of technological accidents triggered by natural hazards involving the release of hazardous substances (NaTech) in the chemical and process industry. The resilience evolution scenario includes six phases of system performance, considering short-term consequences and potential escalation effects, as well as system behaviour during adaptation and recovery phases (**Figure 4.2.1**).

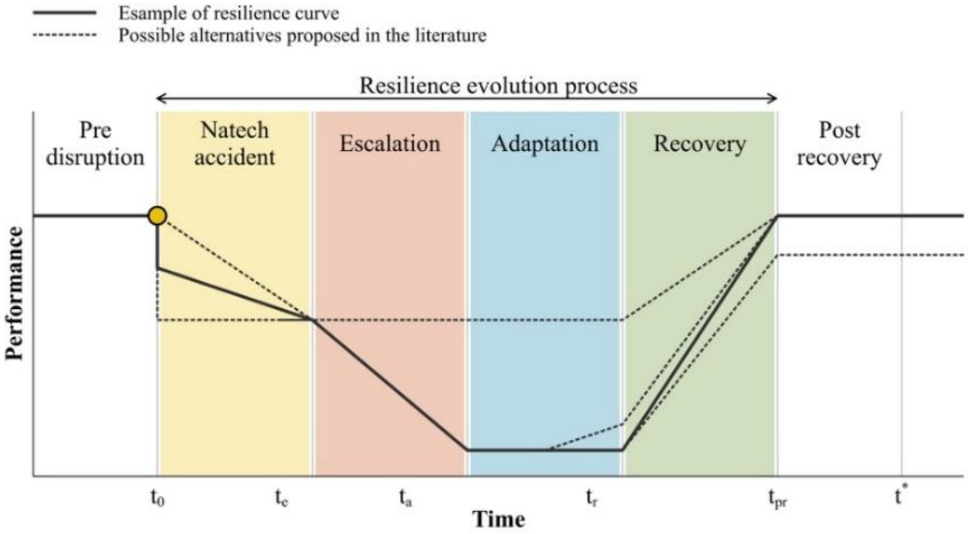


Figure 4.2.1: Generic resilience curve for a NaTech accident, reporting system performance overtime. The time frames are only indicative and do not have the intention to represent a proportion of the duration of the different phases. (t_0: time at which the natural hazard occurs; t_e: time at which escalation is triggered; t_a: time at which adaptation starts; t_r: time at which recovery starts; t_{pr}: time at which recovery ends; t^*: control time). Source: (Valente et al., 2025).

The generic resilience curve aims to establish consensus on phases of NaTech events throughout their lifespan. However, the authors narrowly define the "resilience evolution process" with an arrow during the "disruptive performance period" (after the disruption), overlooking that to build resilience, proactive measures are crucial, anticipating ongoing disruptions and responding during or after such events for survival or recovery. Proactive awareness forms the foundation for identifying, avoiding, or better preparing for future natural hazard challenges by managing vulnerabilities during normal system performance. **Figure 4.2.1** provides a resilience snapshot, limited to a single temporal dimension and often focused solely on metrics related to overall chemical plant performance. This approach fails to account for the multidimensional nature of NaTech events, considering plant integrity and the dynamic location-based interplay of multiple natural factors and their cascading effects on vulnerable elements.

These elements include both internal components within the process plants as well as external entities such as utilities, transportation networks, environmental resources, and other interconnected infrastructure systems, as schematized in **Figure 4.2.2**.

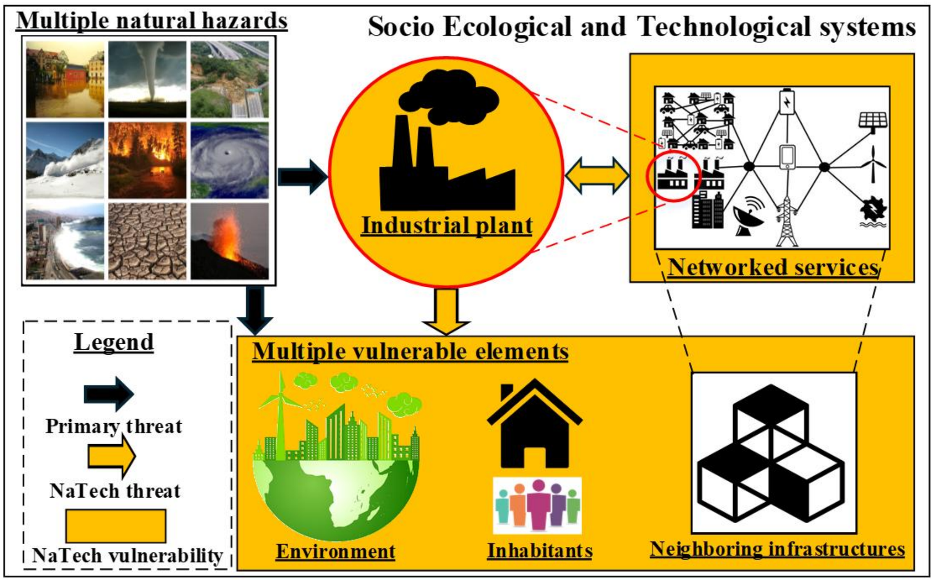


Figure 4.2.2: Representation of the complex interplay among natural hazards, Industrial Critical infrastructures (ICIs), and their interconnected surrounding context.
Source: Castro Rodriguez et al. (2025a)

Table 4.2.1 presents a detailed description of the six phases of the NaTech accident resilience curve, integrating the resilience engineering cycle based on the disruption profile model. Performance behaviours and system targets align with each phase of NaTech evolution, reflecting the state of disruption. The analysis highlights the need for a comprehensive resilience-based framework to enhance NaTech risk management, focusing on industrial infrastructures. This framework should consider the multidimensional complexity of NaTech events, including normal and disruptive performance, and anticipate the spatial-temporal interplay between functional and territorial elements in multi-hazard contexts.

Table 4.2.1 - Comparison of disruption profile states with resilience curve phases for NaTech accidents.

Disruption profile states	Performance	RE principle	Disruption profile states
Normal operations	Steady (avoidance)	Anticipate disruptions and monitoring signals	**Pre-disruption:** it refers to a state where the industrial plant operates at an expected level of performance. Even in the presence of hazards in its surroundings, the current robustness of the system absorbs these threats (Ratthaphong and Andrews 2021). Increasing awareness about the multiple hazards in the plant surroundings and the identification of vulnerable elements is a crucial issue for enhancing the system's preparedness for future NaTech events.
Withstand the disruption	Decrease (absorb-resist)	Response (Short-term)	**NaTech Accident:** The NaTech event constitutes the principal cause of system performance decrease, which may occur instantly or gradually (Valente et al., 2025). It depends on various factors, such as the natural hazard initiator and its multi-hazard dynamics, the propagation pathway (direct or indirect), the infrastructure damaged state, and the barriers to blocking the associated triggered scenarios. However, industrial facilities are often unprepared for such events because of the lack of guidelines on how to apply contextualized countermeasures (El Hajj et al., 2015).
	Abrupt decrease (mitigate-resist)	Response (Short-term)	**Escalation:** The synergy of NaTech may result in a series of interconnected disruptive events (escalation), that may have worse results in the system performance (Zeng et al., 2023). These potential cascading scenarios could involve not only multiple vulnerable elements within the facilities but also those in their surroundings.

Disruption profile states	Performance	RE principle	Disruption profile states
Recover from the disruption impacts	Steady (survive)	Response (transition between short and long-term)	**Adaptation:** When NaTech or its eventual escalation effects stop and the system reaches the point where the worst performance is achieved, operational strategies are introduced to adjust the already degraded state (Zeng et al., 2023). This can be considered the survivability point (Ratthaphong and Andrews, 2021), in those cases in which the system did not completely lose its functionality. Performance may remain constant until the start of recovery activities, or it may eventually experiment with a short-term increment (Valente et al., 2025).
	Increase (recoverability)	Response (Long-term)	**Recovery:** This phase commences when actions are initiated to restore the chemical plant and its surrounding impacted elements to the desired performance level. The recovery speed is determined by a variety of factors, including the response times of proven effective restoration technologies (Castro Rodriguez et al., 2022b), as well as the specifics of each NaTech-triggered scenario. Furthermore, recovery speed is also influenced by the availability and planning of resources (Ratthaphong and Andrews, 2021).
"New" normal operations	Increase (recoverability)	Response (Long-term)	**Recovery:** This phase commences when actions are initiated to restore the chemical plant and its surrounding impacted elements to the desired performance level. The recovery speed is determined by a variety of factors, including the response times of proven effective restoration technologies (Castro Rodriguez et al., 2022b), as well as the specifics of each NaTech-triggered scenario. Furthermore, recovery speed is also influenced by the availability and planning of resources (Ratthaphong and Andrews, 2021).
	Steady (learning and avoidance)	Learning lessons and then starting again to anticipate disruptions and monitoring signals	**Post-recovery:** This stage closes the resilience loop constituting the "new normal" state after the modification achieved by the restoration methods and the introduction of lessons learnt. It can vary across a spectrum of potential outcomes depending on the level of resilience alongside the whole cycle. Thus, the new normal state could exhibit better, similar, or worse performance compared to before the disruption. The system may also completely lose its functionality in the absence of resilience (Castro Rodriguez et al., 2025b).

Source: Castro Rodriguez et al. (2025a)

4.2.2 Framework description

Putting together all the elements discussed above, a novel comprehensive resilient framework is proposed in **Figure 4.2.3** for enhancing NaTech risk management in industrial critical infrastructures. The idea of combining risk and resilience approaches as parallel processes (Schauer et al., 2021), was tailored to simultaneously address both technological and territorial contexts aligned with the concept of territorial resilience (Brunetta et al., 2019). Then, the first application attempt of this framework (Castro Rodriguez et al., 2023), was applied based on 4 steps addressing the application of resilience engineering principles (Hollnagel et al., 2006) aligned with the ones for a continuous improvement cycle aimed at preventing major accidents –prevention, preparation, response, and learning– (European Commission, 2024). Subsequently, these four steps were refined to three stages i) awareness, ii) preparedness, and iii) recovery which align respectively with the state's evolution of the disruption profile–normal operations, withstand and recover from NaTech events– (Cottam et al., 2019). Finally, the bridge concept described in Poljanšek et al. (2017), was introduced to represent the transition from the "current" to a "resilient scenario".

This resilient framework is provided with the spatial-temporal principle consisting of two spatial dimensions and three temporal stages. While the spatial dimensions do not intend to represent the real proportions of the physical area under analysis, they consider the bidirectional relationship between industries and territories at the local scale outlined by Pilone et al. (2017). Similarly, the sequential stages – awareness, preparedness, and recovery – are just indicative of conceptual clusters aiming at the introduction of further methodological procedures, guiding the system to reach resilience consistently with the corresponding target in each NaTech phase. All the concepts addressed in the framework are aligned with the disaster risk reduction terminology (United Nations, 2016).

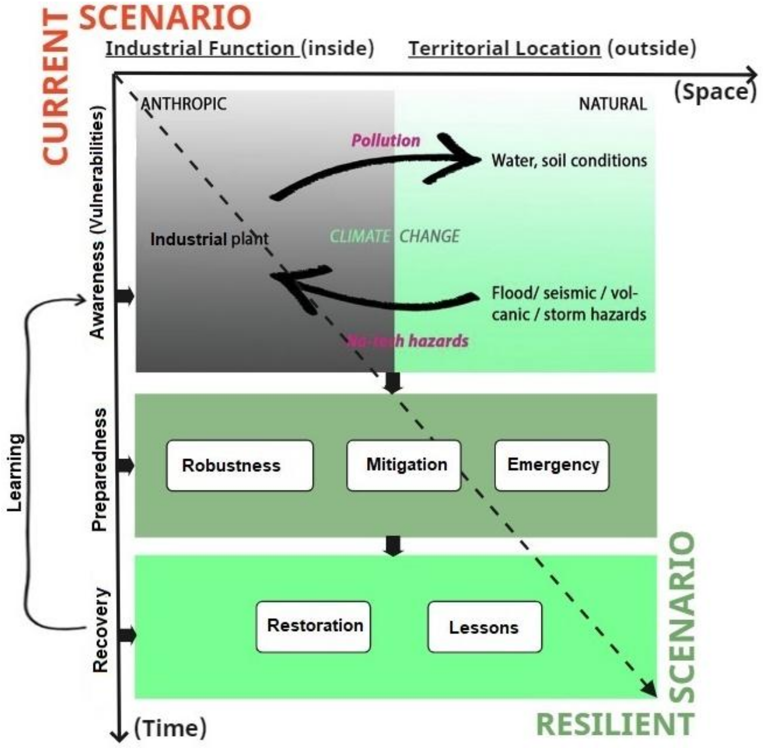


Figure 4.2.3: Multidimensional resilience-based framework for enhancing NaTech risk management in ICIs. Castro Rodriguez et al. (2025a)

The "awareness" is a proactive stage that takes into consideration the RE pillars of "anticipation and monitoring" during the pre-disruption phase. It involves promptly identifying hidden signals to figure out the system's susceptibility to be damaged punctually or gradually by natural events tailoring the definition of vulnerabilities given by the Intergovernmental Panel on Climate Change (2023). Specifically, this stage focuses on identifying the dynamic influence of multiple hazards inherent to the plant location, which can impact vulnerable industrial components and trigger technological scenarios that affect both anthropogenic and natural systems. To achieve this, methodological approaches from the current state-of-the-art of NaTech risk assessment must be incorporated, aligned to the conventional operational safety procedures, and the land use planning, aiming to enhance the overall understanding.

The "preparedness" stage is fed from the already identified vulnerable conditions of the system inherent to the critical natural hazards in the plant surroundings. Consequently, system readiness is achieved through the design and implementation of hierarchical layers of prevention (Amyotte et al., 2018), passing through two different NaTech phases as described below.

During the pre-disruption phase, the objectives are "to absorb" or "to mitigate" the impacts of future natural challenges. The first target involves increasing system "robustness" – the degree to which a system or component can function correctly in the presence of invalid inputs or stressful environmental conditions (Specking et al., 2021)–. Robustness should be achieved through primary prevention measures, such as implementing inherently safer designs (Amyotte and Khan, 2021), tailored to the vulnerable conditions identified earlier. These measures aim to absorb the anticipated impacts of natural hazards effectively. When it is foreseen that the impacts of natural hazards overcome primary layers, or might be amplified by cascading effects, then, secondary layers must be introduced "to mitigate" disruptions, not only strengthening the use of safety barriers but also considering their potential degradation or malfunction during NaTech evolution (Misuri et al., 2023).

On the other hand, emergency plans are critical safety measures designed to mitigate disruptions during NaTech events or their potential escalation effects. While emergency plans are duly implemented within the industry, it is acknowledged that NaTech scenarios often compromise the effectiveness of these traditional response models. For example, emergency responders face numerous challenges during NaTech events, including limited resource availability, communication breakdowns, equipment failures, extended response times, and the complexities of managing dual crises and their cascading effects (Ricci et al., 2024).

These challenges highlight the urgent need for detailed, site-specific NaTech emergency response plans and guidelines for its experimentation, that account for the specific characteristics of each system under consideration. For the design of short-term response plans considering action on-site and off-site at the industrial plant, it is crucial to explore dynamic simulation models and the integration of real-time data devices to predict the progression of events and their impacts. Enhancing the effectiveness of short-term responses can reduce losses to human health, environment, and infrastructures (Zheng et al., 2024).

Although “recovery” is primarily conceived as a corrective stage following a NaTech impact, certain elements of this stage must be addressed in advance to allow immediate intervention once the system reaches its survivability point (adaptation NaTech phase). The specific procedures will vary depending on the triggered NaTech scenarios but typically include damage assessment, primary debris, and contaminant cleanup, modifications to operating conditions, and restoration activities planning (Valente et al., 2025). These activities are premises to assist the system adaptation to its current degraded performance and start the transition to get back to a desired performance state in the long-term (recovery NaTech phase). Therefore, the restoration activities may be implemented immediately or with a delay depending on how fast the system transits from the short-term to the long-term response.

Specifically, the speed and effectiveness of restoration activities depend on several factors connected to the specific characteristics of the NaTech-triggered scenarios. A rehabilitation project should be carried out according to the availability of critical resources. Typical activities include in-deep clean-up activities, maintenance, repair and substitution of components and equipment, simplification of operational procedures for the reduction of human errors, optimization of technological operating conditions to stabilize operations, operational and environmental monitoring, implementation of rehabilitation technologies with proven effectiveness and incorporation of sustainable tendencies.

Finally, the classical resilience engineering pillar of “learning” is incorporated as a feedback loop. This loop is embedded in the NaTech post-recovery phase, enhancing the system’s capacity for continuous improvement by leveraging lessons learned from its own experiences or similar historical events.

4.2.3 Framework implementation

A comprehensive example of this resilience-based conceptual framework is challenging because it requires a long-term period to implement and follow up all the innovative methodological procedures encompassed by the framework described above. This chapter is then organized into three main sections that illustrate the current state of implementation of the proposed stages while emphasizing previously developed test cases focusing on some specific aspects.

The initial section outlines the existing application of methodological approaches aimed at modelling NaTech vulnerabilities in industrial systems within multi-hazard environments to improve "awareness." Subsequently, based on the detected vulnerabilities, essential conceptual ideas are provided as foundational elements for formulating additional recommendations about the "preparedness" phase. Ultimately, the "recovery" phase is addressed through the presentation of restoration actions and insights derived from a decade of research on industrial critical units in Cienfuegos, Cuba. This case specifically examines situations arising from the interaction of persistent rainfall with essential elements of industrial wastewater treatment systems in energy infrastructures, resulting in hydrocarbon contamination of the environment, and may be representative of non-Seveso installations, which may anyway represent a hazardous for the territory.

These presentations of results underscore that, so far, most studies have focused solely on particular phases of resilience management. A comprehensive, multidimensional strategy is absent due to the considerable focus on the resilience cycle concerning NaTech events. Consequently, a transformation in thinking among operators, stakeholders, and practitioners is essential to enhance risk governance and management.

4.2.4 Awareness Phase

The vulnerabilities to NaTech events, considering the bidirectional interaction between ICIs and their multi-hazard territorial context, were conceptualized using the function-location method (**Figure 4.2.4**). The functional factor on the left aligns with the technological vulnerabilities associated with industrial characteristics, categorized into "industrial infrastructure" and "hazardous materials." Shifting to the right side, the geophysical, socio-economic, and environmental aspects include the regional inclination to jeopardize important infrastructure and be affected by technological developments. These territorial vulnerabilities are assessed at several spatial dimensions, illustrating the interaction where the competent authority and stakeholders engage with differing levels of authority and interests. The methodological processes for implementing the function-location strategy are succinctly outlined in the following subsections.

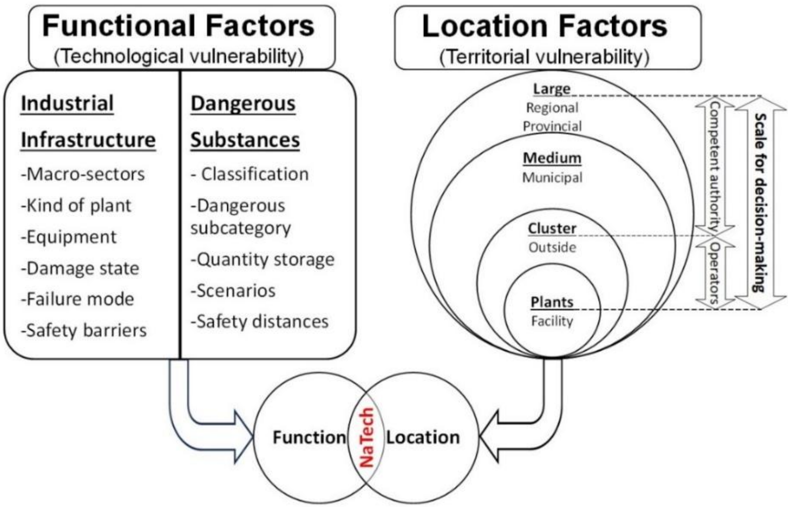


Figure 4.2.4: Function-location approach to characterize NaTech vulnerabilities and support the decision-making process in industrial multi-hazard contexts. Castro Rodriguez et al. (2025b)

The methodological procedures to operationalize each side of the function-location approach presented an intersection with previous tasks and deliverable. Refer to **DV 6.5.2b** to obtain further details on how to model functional vulnerabilities to NaTech in the process industry. On the other hand, refer to **DV 6.5.1b** to obtain further details on how characterize the NaTech territorial vulnerability of industrial infrastructures to multi-hazard.

4.2.5 Preparedness Phase

According to the framework in **Figure 4.2.3** and **Table 4.2.1** system readiness should be achieved through the design and implementation of hierarchical safety layers, building on vulnerabilities identified. To support NaTech risk preparedness, a multi-risk framework was adopted to characterize the vulnerability potential of industrial plants, considering their functional and territorial vulnerabilities. This framework can be used to deploy functional design of safer protection devices or measures to absorb the impacts of natural hazards, strengthen site-specific application of safety barriers, and effectively manage crises, contributing to improved on-site and off-site emergency response plans. This framework was built on the initial proposal by Pilone et al. (2021), which introduced a simplified indicator designed as a pre-screening metric to estimate potential NaTech vulnerability from a multi-risk perspective. Subsequent advancements of this methodology were developed including external context analysis applying GIS-based multi-risk analyses to better characterize vulnerability scenarios of an energetic critical infrastructure (Castro Rodriguez et al., 2023).

Moreover, a substantial step forward in the methodology stressed key opportunities for enhancing the vulnerability NaTech indicator, such as i) flexibility in introducing natural hazards of interest, tailored to the criticalities of the plant location; ii) incorporation of a location priority factor; iii) proposal of vulnerable item categories to standardize consistent with data available in previous NaTech-triggered studies; iv) development of criteria to assess the interaction effects between natural hazards and the dynamic vulnerability of industrial items, considering their proximity and functional interconnections. More details about the discussions of these conceptual ideas can be found in Castro Rodriguez et al. (2025c).

Subsequently, the Industrial Critical Infrastructure Multi-Risk Deployment (ICI-MRD) framework was developed to support the multi-risk assessment of NaTech vulnerabilities in industrial infrastructures. This framework was tested in an energetic critical infrastructure, examining how flooding, lightning, and extreme temperatures could affect eight categories of industrial items. A punctual infrastructural multi-risk value was calculated, with PIMRV = 2.06 falling between minor and moderate importance. The exact weight of each item was determined considering the superposed effects of four hazards, with water treatment basins and storage equipment accounting for around 40% of the total weight. The absolute weight for the four considered hazards provides a rank for hazard-dangerousness, considering their influence on the total of industrial items. Both vulnerable items and dangerous hazard ranks raise awareness and provide data-driven decision-making to support the preparedness of industrial plants and territory. The ICI-MRD framework allows for a deeper level of analysis deploying the vulnerable item in subsequent characteristics of design until obtaining a master plan of interventions to mitigate natural hazards, retrofit industrial equipment, and strengthen safety and emergency response plans. Further description of how to proceed with the ICI-MRD framework can be found in Castro Rodriguez et al. (2025d, 2025e).

The previous analysis, focused on the multi-risk assessment of the complex interactions between infrastructure and territory, is complemented introducing an index designed to evaluate the potential for major industrial accidents based on hazardous substance criteria. This index was developed in alignment with the legal requirements of European regulations (European Commission, 2012) but it extends its scope to include not only major establishments but also the so-called non-Seveso facilities. Further details about this index are provided in Castro Rodriguez (2024) and Castro Rodriguez et al. (2025c).

In this way, the picture of the NaTech definition given by Krausmann et al. (2017) is completed through the analysis of technological accidents contextualized to the natural hazards in the territory and taking also into consideration the hazardous substance criteria. For a comprehensive understanding of the stage to support the preparedness, please refer to **DV 6.5.2c**.

4.2.6 Recovery Phase

This phase is recreated in small-scale distributed power plants of a Cuban case study, which account for over 50% of the country's electricity generation capacity. These plants, strategically located near consumption sites, use fossil fuels to meet energy demands for industrial and residential sectors (Llanes Cedeño, 2017). However, life cycle analyses of distributed electricity generation in Cienfuegos have revealed significant environmental and human health impacts, including hydrocarbon pollution of soil and water (Rodríguez Pérez et al., 2014). This pollution, often caused by daily operations like fuel purification, equipment maintenance, water treatment, and storage tank upkeep, is a persistent stressor for territories (Medel-González et al., 2015). To address this issue, a territorial monitoring program was established, integrating data from industrial activities and their environmental receptors, focusing on facilities across Cienfuegos. **Figure 4.2.5** illustrates the concentrations of total petroleum hydrocarbons (TPH) detected in the environment surrounding industrial facilities in Cienfuegos.

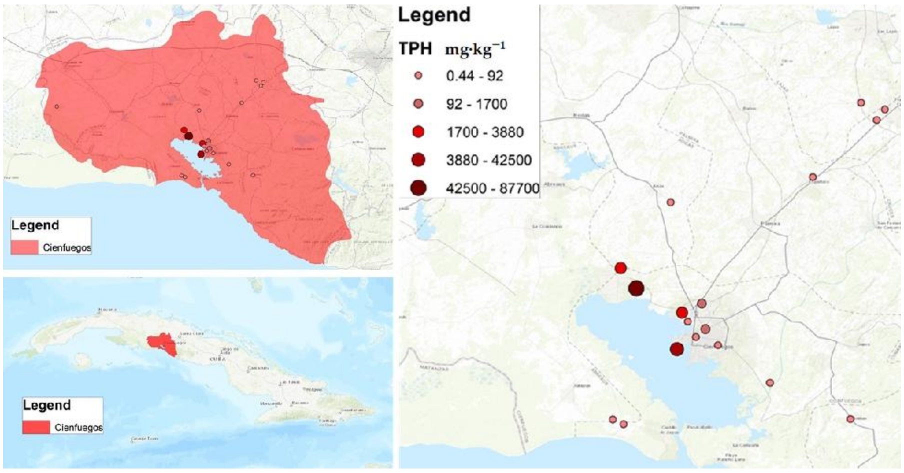


Figure 4.2.5: Concentrations of TPH in the environment surrounding industrial facilities of Cienfuegos, Cuba. Source: (Castro Rodriguez et al., 2022a)

Environmental technological audits have identified key shortcomings in the environmental performance of power generation plants in Cienfuegos, including human errors and deficiencies in stormwater systems (Castro Rodriguez et al., 2020). These findings align with recent research emphasizing the role of human errors and inadequate application of advanced knowledge in technological incidents triggered by natural factors (Hu et al., 2025).

Restoration efforts prioritized returning polluted areas to local communities for safe use and developing sustainable technologies to mitigate oily sludge generation. A systemic approach, integrating industrial and territorial considerations, resulted in the implementation of over 400 measures across individual facilities. Key solutions included source reduction, substitution, process attenuation, and simplification. Improved waste management practices, certification of disposal processes, and employee training were proposed to enhance overall performance Examples of these restoration measures are detailed in Castro Rodriguez et al. (2022a).

A research project was undertaken to develop a bioremediation technique for treating hydrocarbon contamination. This sustainable solution, though taking a long time, has been demonstrated to be simpler and shaped than other alternatives (Castro Rodriguez et al., 2022b; 2022c). It aims to degrade hydrocarbons into oily sludges, which are generated periodically in industrial water treatment systems, stimulating autochthonous microorganisms and valorising other heterogeneous organic wastes from local industries. The systematization of restoration measures addressing operational issues linked to meteorological factors yielded valuable lessons that were standardized for stakeholders to enhance the performance of distributed power generation in Cienfuegos, Cuba. A key recommendation was the development of an in-situ bioremediation technique, specifically bio pile ecotechnology, to manage oily sludges (Castro Rodriguez et al., 2022d).

Despite the restoration measures effectively supporting the long-term recovery of power generation plants, it is important to note that this analysis is retrospective. If a resilient approach had been adopted earlier, the hydrocarbon pollution observed could have been largely prevented.

4.3 Interaction and interdependencies for civil CIs

4.3.1 Background and motivation

Critical Infrastructure Protection (CIP) has increasingly recognized cascading failures – triggered by dependencies and interdependencies across different CI systems and their services – as one of the most significant and structurally complex threat typologies. Unlike direct hazard impacts, cascading effects propagate across sectoral boundaries, amplifying the consequences of an initial disruption well beyond the affected system. Empirical evidence supports the relevance of this concern. TNO (Luijif and Klaver, 2021) developed a comprehensive database tracking over 2.375 serious, publicly reported CI incidents between 2004 and 2018, specifically designed to analyse interdependencies and cascading failures across European critical infrastructure. The analysis reveals that approximately 29% of reported incidents in Europe originate not from a primary hazard acting directly on the affected system, but from failures in other CI services. While anecdotal accounts of cascading events may suggest these are low-probability, high-consequence scenarios, the data indicates they are substantially more frequent than commonly assumed. The same dataset highlights a marked asymmetry in the directionality of cascading dependencies: approximately 60% of all cascade events originate within the energy sector, followed by telecommunications and internet (28%), transport (5%), water (3%), and other CI sectors (4%). This pattern reflects the foundational role of energy supply – and electricity in particular – as an enabling resource for virtually all other infrastructure systems. The same data show that cascading failures do not routinely propagate into deep, multi-sector crises under normal operating conditions. Critical infrastructures are generally designed with redundancy and resilience measures precisely to contain the propagation of localized failures. However, climate change is altering this risk landscape in two compounding ways.

First, it significantly increases the probability of initial failure across multiple infrastructure types through more frequent and intense hazard events such as heatwaves, droughts, extreme precipitation, and windstorms. For example, the electricity sector is exposed to climate-related stressors across its entire supply chain, from generation to transmission and distribution. At the generation level, hydropower output is sensitive to changes in precipitation patterns and snowmelt timing: reduced runoff and earlier snowmelt shift peak production earlier in the year and lower overall availability during summer droughts, precisely when demand peaks. Thermoelectric plants face compounding pressures from higher air and water temperatures, which reduce both efficiency and capacity, while reduced freshwater availability for cooling may force operational curtailments or shutdowns — in some cases mandated by discharge temperature regulations designed to protect aquatic ecosystems. Renewable generation is similarly affected: extreme heat reduces solar panel efficiency, changes in wind patterns alter wind energy output, and wildfires threaten transmission infrastructure. On the demand side, higher summer temperatures drive increased cooling loads, exacerbating peaks in electricity demand at the same time that generation capacity may be constrained. At the transmission and distribution level, extreme winds and wildfires damage lines and towers, extreme heat reduces the capacity of power lines and transformers, and flooding can damage substations, transformers, and underground cables. The combined effect is a sector in which supply-side stress and demand-side pressure may coincide — and in which physical damage to transmission assets can interrupt delivery independently of generation availability.

Second, and more critically, climate-driven hazards have the potential to simultaneously affect multiple infrastructure sectors, effectively neutralizing the redundancy that systems rely upon to absorb isolated shocks. A drought, for instance, simultaneously stresses hydropower generation, thermoelectric cooling capacity, freshwater availability, and agricultural water demand — creating conditions for concurrent multi-sector stress rather than sequential cascading. **Figures 4.3.1** provides a hint of the interaction complexity.

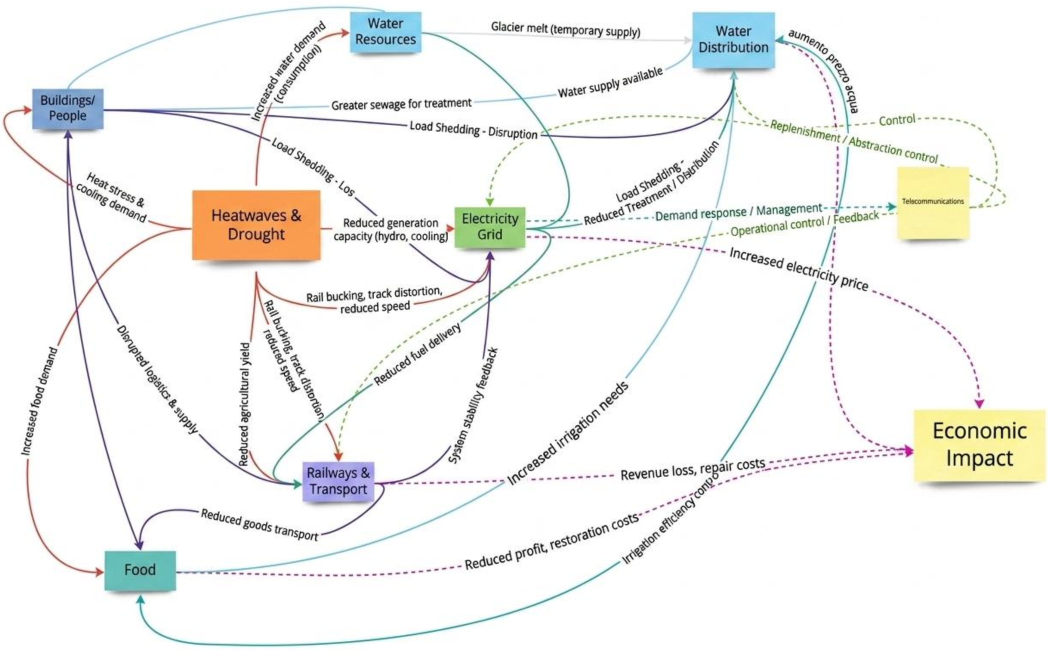


Figure 4.3.1: Infrastructure and natural system interdependencies

This twofold dynamic — higher individual failure probability combined with the potential for synchronous multi-sector impact — substantially elevates the systemic risk associated with CI interdependencies under climate change scenarios, and motivates the analysis presented in the following sections.

4.3.2 Interaction / dependency analysis

The RETURN projects addressed – at different detail level – four of the 11 critical infrastructures included in the CER Directive (Directive (EU) 2022/2557, 2022): the drinking water network, the sewage/wastewater network, the railway network, and the road network. For each of these, incoming dependencies from other CI systems have been characterized through structured dependency tables, developed through a combination of scientific literature review and expert consultation, carried out within Task 6.2.1.

The analysis follows the classification by Rinaldi et al. (2001), already mentioned in section 4.1, which distinguishes four dependency types: physical (a system depends on the material output of another, e.g. electricity supply to water pumps), cyber (dependence on information/ICT flows), geographic (spatial proximity creates coupling, e.g. co-located buried infrastructure), and logical (indirect dependencies mediated by human decisions, procedures, or operational rules).

Drinking water network

The drinking water network exhibits strong dependencies on the electricity distribution network and the road network, with additional geographic couplings to other buried infrastructure.

The most operationally critical dependency is on electricity supply: pumps, valves, chlorination systems, water quality monitoring equipment, and IT/SCADA management systems all require continuous power from secondary substations. Battery backup provides limited autonomy, and its recharge is itself power-dependent. A geographically mediated dependency also arises from the co-location of buried water pipes with electricity cables: electromagnetic interference from transmission lines can affect metallic pipe integrity, and excavation works for electricity maintenance pose accidental pipe break risk.

Road network dependencies are primarily geographic and logical: vehicle loads and traffic induce ground deformation above buried pipes; road maintenance activities (e.g. excavation, de-icing chemicals) can compromise pipe integrity or contaminate groundwater sources. Road accessibility also conditions maintenance and emergency procedures, including water delivery by tanker trucks in case of supply disruption.

The dependency tables for the drinking water network are reported in **Tables 4.3.1–4.3.3**.

Table 4.3.1: Dependency table for the drinking water network from road infrastructure

Infrastructure	OUT Asset	IN Asset	Dependency type	Description	References
Road system	road (condition and stiffness)	(buried) water pipe	geographic	Water pipe integrity depends on the physical characteristics of the ground that supports a road and hence on the physical properties and condition of the road itself (e.g., water infiltration)	(Du et al., 2023)
	road furniture	water pipe	geographic	Road furniture (such as vegetation) influences the physical properties of the ground over the pipe and/or directly the pipe (e.g., roots expansion)	preliminary expert-based consultation
	traffic flow, vehicle load (e.g. trucks)	water pipe	geographic	Traffic affects the ground deformation over the water pipe	(Du et al., 2023)
	road use (goods transportation)	groundwater/water quality monitoring	geographic	Water or substance infiltration caused by road use (spills of pollutants) influence quality of water storage	preliminary expert-based consultation
	underground road/tunnel	groundwater/water quality monitoring	geographic	The condition of the underground road/tunnel influences groundwater quality and dynamics	preliminary expert-based consultation
	road embankment construction	groundwater supply	geographic	road embankment construction influences water level of near groundwater	(Kim et al., 2023)
	viaduct	(overhead) water pipe	Physical	Water pipe integrity under a viaduct depends on the condition of the viaduct	preliminary expert-based consultation
	road (viaduct) maintenance	water pipe maintenance	logical	Road maintenance works influence water pipe maintenance (e.g. accidental breaks)	preliminary expert-based consultation
	road maintenance	groundwater/water quality monitoring	Logical	Road maintenance works (e.g., deicing chemical on road surface) influence quality of water storage (saline intrusion)	(Coletti et.al, 2016) (Weisenhorn, 2020)
	road accessibility	maintenance procedure	Logical	Road accessibility influences accomplishment of maintenance interventions on the infrastructure	preliminary expert-based consultation

	traffic on road, road accessibility	water distribution by tanker trucks	Logical	Road accessibility or traffic influences water transport by tanker trucks	preliminary expert-based consultation
	emergency maintenance procedure of road	water load	Logical	Road integrity (e.g., cooling) influences water demand in emergency cases	(Niggli et al., 2022)
Road system	road accessibility	Maintenance procedure in drinking water treatment plant	Logical	Road accessibility influences accomplishment of maintenance interventions on the infrastructure (reagent transport and sludge disposal)	(Jayasinghe et al., 2023)

Table 4.3.2: Dependency table for the drinking water network from railway infrastructure

Infrastructure	OUT Asset	IN Asset	Dependency type	Description	References
Railways system	rail	(buried) water pipe	geographic	Water pipe integrity depends on the physical characteristics of the ground that supports a rail and hence on the physical properties and condition of the rail (e.g., water infiltration)	preliminary expert-based consultation
	traffic flow, trains load	water pipe	geographic	Traffic/loads affects the ground deformation over the water pipe	(Xie et. al, 2020)
	rail use (goods transportation)	groundwater/water quality monitoring	geographic	Water or substance infiltration caused by rail use (spills of pollutants, vacuum toilet wastewater) influence quality of groundwater and/or water storage	preliminary expert-based consultation
	underground rail/tunnel	groundwater/water quality monitoring	geographic	The condition of the railways/tunnel influences groundwater quality and dynamics	(Baroková et al., 2023)
	railways viaduct	(overhead) water pipe	physical	Water pipe integrity under a railway's viaduct depends on the condition of the viaduct	preliminary expert-based consultation
	rail service availability	water system supplies	logical	Rail availability influences supply services for water system	preliminary expert-based consultation
	emergency maintenance procedure of railways	water load	logical	Rail integrity (e.g., cooling) influences water demand in emergency cases	(Niggli et al., 2022)
	rail maintenance	water pipe maintenance	logical	Rail maintenance works influence water pipe maintenance (e.g. accidental breaks)	preliminary expert-based consultation
	rail maintenance	groundwater/water quality monitoring	logical	Rail maintenance works influence quality of water storage (pollutant intrusion)	preliminary expert-based consultation

Table 4.3.3: Dependency table for the drinking water network from electricity infrastructure

Infrastructure	OUT Asset	IN Asset	Dependency type	Description	References
Electricity distribution/ **transmission system**	(buried) electricity cable	(metallic) water pipe	geographic	Electromagnetic interference generated by the electric line (e.g., transmission) influences the integrity of (near) water pipe	(Ma and Dawalibi, 2006)
	(secondary) substation electrical load	water pump, valve	physical	Water pressure devices such as pumps and valves' efficiency depend on the power supplied by the power substation	preliminary expert-based consultation
	(secondary) substation electrical cable connection	electrical feeder of the water infrastructure	physical	The functioning of the electrical feeder depends on the integrity of the cable	preliminary expert-based consultation
	(secondary) substation electrical load	battery bank	physical	Electricity refurnishing of battery banks depends on power supply	preliminary expert-based consultation
	(secondary) substation electrical load	electrical appliance for water treatment and/or monitoring	physical	The water quality treatment (e.g., chlorination) and monitoring systems require power supply	(Sharif et al., 2019)
	(secondary) substation electrical load	lighting system and IT asset for infrastructure operation and management	physical	The lighting system and IT infrastructure of the water system require power supply	preliminary expert-based consultation
	electricity network maintenance	water system operation	logical	Electricity network maintenance works influence water distribution operation	preliminary expert-based consultation
	electricity network maintenance	water pipe	logical	Electricity assets maintenance works (e.g., excavation) influence integrity of nearby water pipe (accidental)	preliminary expert-based consultation
	emergency procedure of power service	water reservoir/ load	logical	Electricity emergency may cause higher demand of water and affect level of water source	preliminary expert-based consultation

Sewage/wastewater network

The sewage network analysis is organized around two key assets: the drinking water treatment plant and the wastewater treatment plant, which have distinct dependency profiles.

The drinking water treatment plant depends on electricity for all operational processes, and on road accessibility for reagent supply and sludge disposal. Crucially, it is also tightly coupled to the drinking water distribution network itself: a failure in the distribution network downstream (inability to deliver the produced flow) creates a feedback condition that can halt treatment plant operation. Water intake structures and supply pipelines are further upstream dependencies.

The wastewater treatment plant shares the electricity and road dependencies and additionally exhibits internal couplings within the sewage system itself: sewer overflows – most likely to occur due to extreme events like floods – influence treatment plant operation, and illicit or accidental industrial discharges into the sewage network can compromise treatment processes.

The sewage/wastewater network shares the electricity dependency pattern of the drinking water network: treatment plants and pumping stations require continuous power supply, and loss of electricity can lead to untreated discharge with cascading environmental and public health consequences. The network is additionally coupled to the drinking water system via shared hydraulic infrastructure and to the road network for maintenance access and sludge disposal logistics.

The dependency tables for the sewage network are reported in **Table 4.3.4**.

Table 4.3.4: Dependency table for the sewage/wastewater network from external infrastructure

Infrastructure	OUT Asset	IN Asset	Dependency type	Description	References
Electricity network	Electricity network (condition)	Wastewater treatment plant	Physical	Wastewater treatment plant operation depends on the electricity network	
	Electricity network maintenance	Wastewater treatment plant	Logic	Electricity network maintenance works influence wastewater treatment plant operations	
	Wastewater treatment plant	Electricity from cogeneration and heat from district heating	Physical	Biomethane production (where foreseen) is linked to the production of electricity from cogeneration or hot water/steam from district heating	
Road system	road use (goods transportation)	Wastewater treatment plant	Geographic	Substance infiltration caused by road use (spills of pollutants) influences quality of water	(Jayasinghe et al., 2023)
	Road accessibility	Maintenance procedure in wastewater treatment plant	Logic	Road accessibility influences accomplishment of maintenance interventions on the infrastructure (reagent transport and sludge disposal)	(Jayasinghe et al., 2023)
Sewage network	Sewage network maintenance	Wastewater treatment plant	Geographic	Substance infiltration caused by sewage network maintenance	
	Sewage element system (Combined sewer	Wastewater treatment plant	Geographic	Wastewater treatment plant operation depends on the CSO operation	

	overflows CSO)				

Railway network

The railway network depends on electricity for traction, signalling, control systems, station operations, and lighting – making it one of the most electricity-intensive CI in the urban context. These are primarily physical dependencies on secondary substations and electrical feeders.

Dependencies on the drinking water system are predominantly geographic: buried water pipes and water tanks near rail infrastructure influence ground stability and hence rail condition; water infrastructure maintenance (e.g. excavation) can interfere with rail maintenance. A logical dependency also links water availability for inland waterways to rail traffic for goods transport.

Roads condition emergency response and maintenance for all other CI, including railway: their disruption does not cause an immediate functional failure of other CI, but significantly degrades the capacity to restore them after an incident.

The dependency tables for the railway network are reported in **Table 4.3.5** and **Table 4.3.6**.

Table 4.3.5: Dependency table for the railway network from drinking water infrastructure

Infrastructure	OUT Asset	IN Asset	Dependency type	Description	References
Drinking water system	(buried) water pipe	rail	Geographic	Water pipe integrity influences the ground that supports a road and hence the rail integrity	preliminary expert-based consultation
	(overhead) water pipe	rail condition, accessibility	Geographic	Water pipe (e.g., under viaduct) integrity influences the condition and accessibility of the rail underneath	preliminary expert-based consultation
	water infrastructure maintenance	railways infrastructure maintenance	Geographic	Water infrastructure maintenance (e.g., excavation) influences railways infrastructure maintenance (e.g., underground infrastructure)	preliminary expert-based consultation
	groundwater	rail	Geographic	Dynamics of groundwater near rail influences rail condition	preliminary expert-based consultation
	water load	drinking water reservoirs for railways operation and management	Physical	water availability for consumption influences operation of the railways service	preliminary expert-based consultation
	water infrastructure maintenance	rail availability and efficiency	Logical	Water system maintenance works influence rail availability	(Huang et al, 2022)
	water load	traffic	Logical	Water demand influences water level requirements	preliminary expert-based consultation

				for inland waterways with impact on railways traffic (goods)	

Table 4.3.6: Dependency table for the railway network from electricity infrastructure

Infrastructure	OUT Asset	IN Asset	Dependency type	Description	References
Electricity distribution/ transmission system	electricity cable	rail	Geographic	Cable's electricity influences the resistivity of the surrounding soil that supports a rail (e.g., electric rail) and hence the rail condition	(Bongiorno and Mariscotti, 2018)
	electricity infrastructure maintenance	railways infrastructure maintenance	Geographic	Electricity infrastructure maintenance (e.g., excavation) influences railways infrastructure maintenance (e.g., underground infrastructure)	preliminary expert-based consultation
	electricity cable	rail	Geographic	Electromagnetic interference generated by the electricity in the line influences the condition of the (near) rail	(Southey and Dawalibi, 1998)
	(overhead) electricity cable/pole	Rail condition, accessibility	Geographic	Power line (e.g., under viaduct) integrity influences the condition and accessibility of the rail underneath	preliminary expert-based consultation
	secondary substation	rail availability	Physical	The electricity supply is required for the operation on a rail	preliminary expert-based consultation
	(secondary) substation electrical cable connection	electrical feeder of the railways infrastructure	Physical	The functioning of the electrical feeder depends on the integrity of the cable	preliminary expert-based consultation
	electricity load	Railway control system operation (including signal system) and track inspector trains	Physical	Electricity supply influences the operation of the railways control system and track inspectors	preliminary expert-based consultation
	(secondary) substation electrical load	lighting system and IT asset for infrastructure operation and management	Physical	The lighting system and IT infrastructure of the railways system require power supply	preliminary expert-based consultation

	electricity load	access to station	Logical	Electricity supply influences station availability	preliminary expert-based consultation

Road network

Road network dependencies mirror in part those of the railway network, with electricity providing power for lighting, traffic management systems, and communication displays (logical and physical dependencies), and the drinking water system creating geographic couplings through buried pipe proximity, groundwater dynamics, and maintenance interference.

A distinctive feature of the road network is its role as an enabling infrastructure for all other CI: its incoming dependencies are relatively limited in number and severity, but its disruption propagates as a logical dependency across all systems that rely on road access for maintenance, emergency response, and supply logistics. This asymmetry makes the road network a critical node not so much for its own operational continuity, but for the resilience of the entire CI system.

The dependency tables for the road network are reported in **Tables 4.3.7** and **4.3.8.**

Table 4.3.7: Dependency table for the road network from drinking water infrastructure

Infrastructure	OUT Asset	IN Asset	Dependency type	Description	References
Drinking water system	(buried) water pipe	road	geographic	Water pipe integrity influences the ground that supports a road and hence the road integrity	(Jones et. Al 2020)
	(overhead) water pipe	road condition, accessibility	geographic	Water pipe integrity influences the condition and accessibility of the road underneath	preliminary expert-based consultation
	water infrastructure maintenance	road accessibility, traffic	geographic	Water system maintenance works influence traffic on road and road accessibility	(Huang et al., 2022)
	water distribution by tanker trucks	road	geographic	Frequency of tanker trucks influences road condition/ integrity	preliminary expert-based consultation
	groundwater	road	geographic	Dynamics of groundwater near road influences road condition	preliminary expert-based consultation
	water load	traffic	logical	Water demand influences water level requirements for inland waterways logistics with impact on road traffic	preliminary expert-based consultation

Table 4.3.8: Dependency table for the road network from electricity infrastructure

Infrastructure	OUT Asset	IN Asset	Dependency type	Description	References

Electricity distribution/ transmission system	electricity infrastructure maintenance	road maintenance	Geographic	Electricity infrastructure maintenance (e.g., excavation) influences roads infrastructure maintenance (e.g., road break)	preliminary expert-based consultation
	(overhead) electricity cable/pole	rail condition, accessibility	Geographic	Power line (e.g., under viaduct) integrity influences the condition and accessibility of the road underneath	preliminary expert-based consultation
	(secondary) substation electrical cable connection	electrical feeder of the road infrastructure	Physical	The functioning of the electrical feeder depends on the integrity of the cable	preliminary expert-based consultation
	(secondary) substation electrical load	lighting system and IT asset for infrastructure operation and management	Physical	The lighting system and IT infrastructure of the road system require power supply	preliminary expert-based consultation
	electricity load	communication services/traffic	Logical	Electricity supply for communication services (e.g., displays) influence viability	preliminary expert-based consultation

To summarize and pointing out key idea for the framework, cascading failures occur when the disruption of one CI propagates to one or more dependent systems, triggering a chain of secondary failures that may amplify the consequences of the original event well beyond the directly affected infrastructure. Three general mechanisms are relevant for the civil CI considered here:

- **Functional cascade**: the loss of a service provided by CI-A removes a necessary input for CI-B (e.g. power loss disables water pumping).
- **Geographic cascade**: physical damage to the assets of CI-A affects the structural integrity of co-located assets of CI-B (e.g. pipe burst destabilizes road foundation).
- **Procedural cascade**: the disruption of CI-A prevents the execution of maintenance or emergency operations on CI-B (e.g. flooded roads block repair crews from reaching a substation).

In practice, real-world cascading events combine these mechanisms, and their propagation speed and depth depend on the redundancy available in each system at the time of the triggering event.

It should be noted that – while telecommunications network has not been taken into account by the projects due to its complexity in modelling and the need of engaged operators – the electricity distribution network emerges recurrently across all dependency tables as primary source infrastructures — i.e., infrastructures upon which the four analysed CI critically depend. Although a more complete characterization of this network would require dedicated data collection and operator engagement and was beyond the scope of the project, its role is accounted for in the dependency analysis as external input nodes, and its potential failure is considered in all the cascading effect scenarios (see also deliverable DV6.2.4 for simulation results in the drinking water and railway domain).

4.3.3 Towards a Multi-Hazard Risk Assessment Framework

The analysis of interactions and interdependencies among civil CI presented in the previous section has direct implications for a multi-hazard risk assessment framework.

1. Interdependencies amplify hazard-specific risk estimates. Risk assessments conducted at the level of individual CI — however detailed — systematically underestimate the actual consequences of a disruptive event if interdependencies are not accounted for. The dependency tables in Section 4.3.2 show that each of the four CI analysed has multiple incoming dependencies from electricity and, to a lesser extent, from road accessibility and the water system. This means that the impact of a hazard on any one of these source infrastructures propagates as an additional, indirect stressor on all dependent CI – even if those CI are not directly exposed to the hazard. A flood that damages a substation, for instance, generates consequences for water, wastewater, and rail that would not appear in a single-CI flood risk assessment.
2. The climate change scenarios challenge the CI redundancy design assumption in two ways. First, they increase the frequency and severity of events that can trigger simultaneous multi-CI stress, reducing the effectiveness of redundancy. Second, slow-onset stressors such as drought create background degradation conditions that lower the threshold at which a subsequent acute event triggers a cascade. The multi-hazard framework must therefore account not only for the co-occurrence of hazards, but for the sequential and cumulative interaction between slow-onset and acute events.

Therefore, a robust multi-hazard risk assessment for civil CI should incorporate at minimum three elements that go beyond standard single-hazard, single-CI approaches: (i) a system-of-systems perspective that tracks how hazard impacts propagate across CI boundaries via the dependency links characterized here; (ii) explicit modelling of the temporal dynamics of cascades, distinguishing between near-instantaneous functional cascades (e.g. power loss → pump failure) and slower geographic or procedural propagation pathways; and (iii) scenario-based stress testing that combines climate hazard projections with CI dependency structures to identify the combinations of conditions most likely to overwhelm system redundancy.

The qualitative dependency analysis presented in the previous sections provide a conceptual map of the interdependency risk landscape. Translating this map into actionable, quantitative risk estimates requires a computational framework capable of representing the system-of-systems structure of civil CI and simulating the propagation of failures across interdependent networks. This section quickly summarizes the simulation-based approach developed within the project to this end. For more details about the design and preliminary analysis, see deliverables DV6.2.3 and DV6.2.4, whereas scenarios results are in deliverable DV PoC1 and have been submitted for a publication under review.

Knowledge graph and domain simulators

The proposed framework integrates two complementary components: a knowledge graph and a set of domain-specific simulators, coordinated by a simulation manager (**Figure 4.3.2**, see also deliverable DV6.2.3).

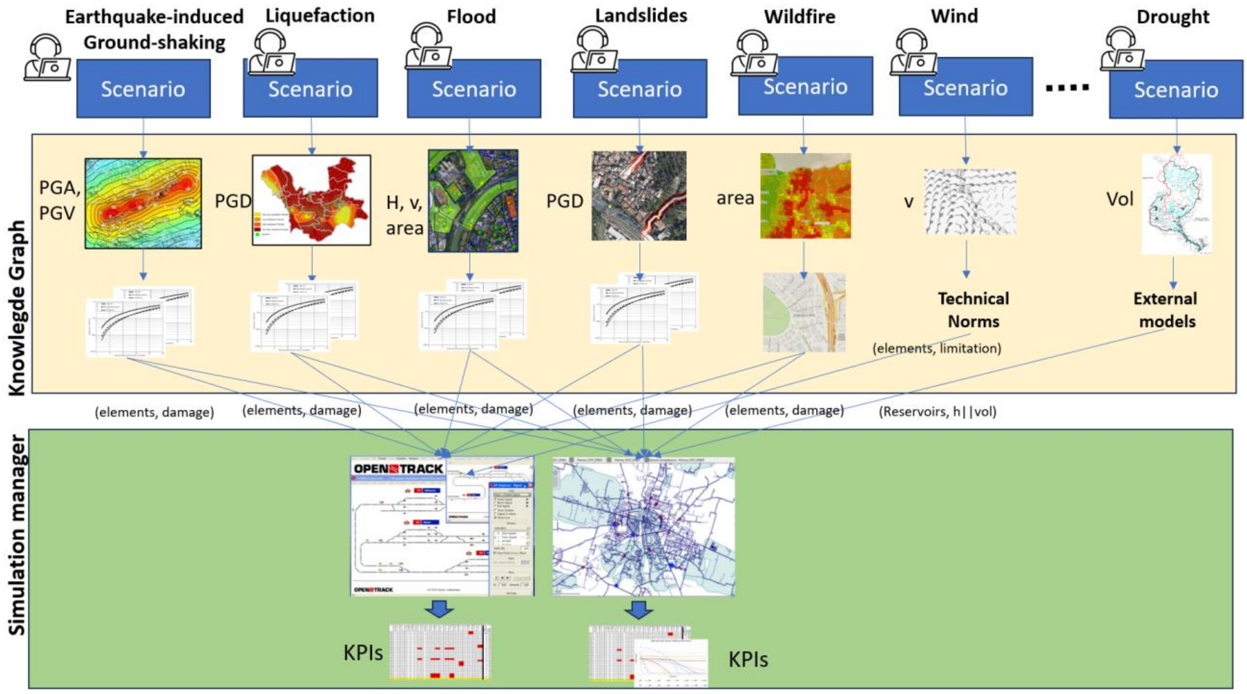


Figure 4.3.2: Workflow of the information processing in the simulation environment (DV6.2.3)

The knowledge graph serves as a resilience-oriented semantic layer that connects heterogeneous data sources – hazard maps and intensity parameters, infrastructure component data, fragility curves linking hazard intensity to damage probability, and technical performance norms – into a unified, queryable representation of the CI system-of-systems. Crucially, it encodes not only the properties of individual infrastructure components but also their interdependencies, enabling the formal representation of the dependency relations characterized in Section 4.3.2 and its quantitative assessment, whenever possible. The ontological structure of the knowledge graph is grounded in established frameworks (including OntoCAPE, OntoPowSys, and the Social-Ecological-Technological Systems model of McPhearson et al., 2022), extended with modules specifically developed for resilience analysis of civil CI under natural hazard scenarios.

Given a hazard scenario as input — characterized by intensity parameters such as peak ground acceleration for earthquakes, water height and velocity for floods, or volume deficit for droughts — the knowledge graph evaluates fragility functions for each exposed infrastructure component, producing damage estimates that are then passed to the simulation manager. The simulation manager configures and runs domain-specific operational simulators: OpenTrack for railway networks, InfoWorks WS Pro for water distribution systems, and equivalent tools for other CI. These simulators model infrastructure performance under damaged conditions, accounting for both internal cascades (e.g. loss of power affecting water pumps within the water system) and cross-system cascades (e.g. railway delays caused by power outage propagating from the electricity network).

The output of each simulation run consists of Key Performance Indicators (KPIs) — service availability, performance degradation, recovery times — that quantify the resilience of the CI system under the given scenario.

Simulation as a tool for discovering hidden interdependencies

A distinctive feature of the simulation-based approach is its capacity to surface interdependencies that are not apparent from expert elicitation or literature review alone. Static dependency tables, however, carefully constructed, necessarily reflect known relationships. Simulation, by contrast, can reveal emergent behaviours: combinations of partial failures that interact in unexpected ways, threshold effects in network hydraulics or capacity, or feedback loops between CI that only manifest under specific loading conditions.

This capability has been demonstrated in the context of the ReturnLand/ReturnVille Virtual Test Bed (Digital Ecosystem RETURNLAND&RETURNVILLEs, 2026 and related hazard packages) developed within the project – a digital representation of the study territory that integrates the physical environment and its hazard dynamics with the urban system: infrastructure networks, hospitals, schools, and economic activities. Simulation experiments conducted within the VTB have identified cascading interdependencies not previously captured in the qualitative dependency analysis, providing a concrete illustration of the added value of the computational approach for multi-hazard CI risk assessment (Villani, M.L. and Lavalle L., under review).

The simulation framework operationalizes the three elements identified as necessary for an integrated multi-hazard risk assessment: it implements a system-of-systems perspective through the knowledge graph structure; it captures the temporal dynamics of cascade propagation through sequential simulation steps; and it supports scenario-based stress testing by allowing systematic variation of hazard parameters and CI initial conditions.

4.4 Analysis of the potential concatenation of risks on drinking water production plants and urban wastewater treatment plants

4.4.1 Climate change effects on WWTP: Parma Case Study

Water infrastructures, including WWTPs, are vulnerable to the effects of climate change. Such infrastructures are referred to as "critical infrastructures" meaning systems that are essential for supporting key operations in society, as well as the health, safety and economic or social well-being of citizens (Stamou et al., 2024). Climate change leads to extreme weather conditions that place significant pressure on WWTP (Tolkou & Zouboulis, 2015; Hughes et al., 2021; Li et al., 2023). The impact of climate change (**Figure 4.4.1**) was analysed, particularly: the evaluation of the influence of heatwaves on the treatment process and the combined sewer overflow (CSO) as a source of microplastic input into water bodies following intense weather events.

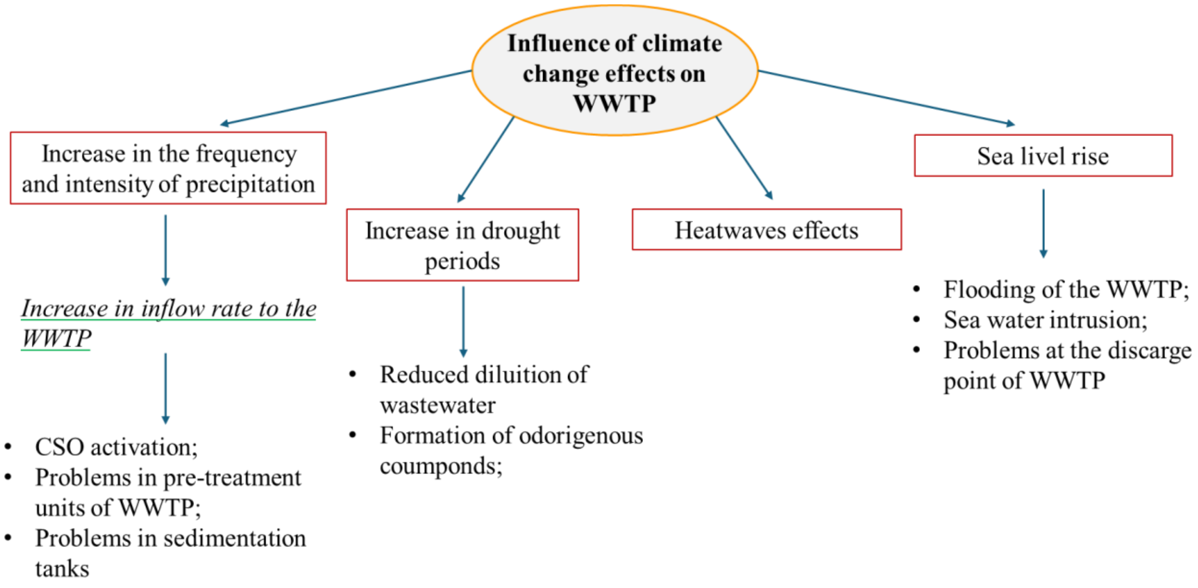


Figure 4.4.1: Impact of climate change on WWTPs.

The alternation of extreme weather events, such as very intense but short-duration rainfall and prolonged heat waves, not only places biological and physicochemical treatment processes under stress but also acts as a trigger for so-called NaTech events, Natural Hazard Triggering Technological Disasters, namely technological disasters caused by natural hazards. The increase in rainfall intensity has a direct and devastating impact on urban drainage networks and wastewater treatment plants, particularly with regard to emerging pollution from microplastics, MPs (Di Nunno et al., 2021; Zhou et al., 2023). During intense rainfall events, a massive surface runoff phenomenon is generated, washing urban impervious surfaces and collecting plastic debris derived from tyre wear, road markings and the degradation of plastic waste. In addition, contaminated sediments within sewer collectors are rapidly resuspended. When the incoming water volumes exceed the design capacity of the wastewater treatment plant, a limit typically estimated at between three and five times the average daily dry-weather flow, combined sewer overflows, CSOs, are activated. These emergency infrastructures discharge the mixture of stormwater and urban wastewater directly into receiving water bodies, bypassing the treatment processes.

In collaboration with IREN S.p.A, the influence of heatwaves on the wastewater treatment plants in Parma was analyses. The historical data relating to the Parma Est and Parma West wastewater treatment plants refer to the period June-October 2024 and concerns the plant inlet section, the biological treatment compartment, and the outlet section. These data are supplemented by additional information on sludge characteristics, including the volatile solids content, the presence of microbial species, and oxygen consumption kinetics.

Temperature data were also used, specifically the daily maximum and average temperatures, which were necessary to identify heat waves during the period considered. A heat wave was defined as a period of at least two consecutive days in which the daily maximum temperature exceeded the 90th percentile threshold, calculated over a 5-day moving window centred on each day using data from the reference period 2003–2024.

The data analyses showed that discharge limits were consistently complied with throughout the observation period. During heat waves (**Figure 4.4.2**), the parameter values almost always fell within the IQR, with only a few exceptions. The analysis of WWTP operational data showed that air and reactor temperatures followed a similar trend, with reactor temperature remaining relatively stable. Heatwaves generally did not cause exceedances of regulatory limits for SS, COD, N, and P in the effluent. However, the SVI trend did not provide clear evidence of a heatwave effect on activated sludge settleability.

Period	June-september
of identified events	2
Event 1	12-13 July 2024
Event 2	29-30 July 2024

a) Short duration of the heat wave
b) Lack of plant data for Event 2

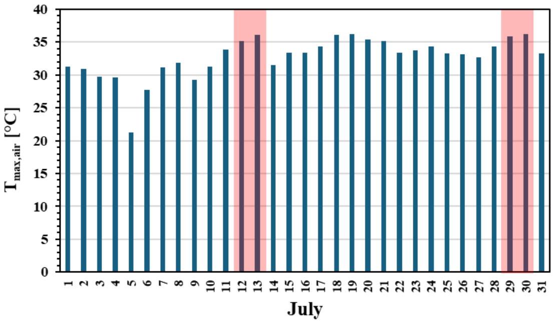


Figure 4.4.2: Identified heat-wave events during the observation period

4.4.2 Climate change effects on WWTP: Parma Case Study

Since no anomalies or equipment failures were recorded during or after the heat-wave events, a further analysis was carried out to assess another potential source of environmental impact related to wastewater treatment plants: the release of microplastics during combined sewer overflow events. For this reason, an experimental campaign was conducted at the municipal WWTP of Palermo, Italy, from September 2023 to August 2024. Wastewater samples were collected under different weather conditions, including dry weather, wet weather with and without CSO activation, as well as from the WWTP effluent. The aim of the analysis was to evaluate how rainfall events and CSO activation affect microplastic concentrations in wastewater and to better understand their potential contribution to microplastic discharge into receiving water bodies.

The extraction of microplastics from wastewater was carried out according to the methods described by Hu et al. (2022), Yang et al. (2022) and Ross et al. (2023), as shown in **Figure 4.4.3**. The number of microplastics were manually counted and then classified by shapes into 4 classes: spheres, fibers, fragments, and films. Finally, the MPs concentrations were expressed as number of elements per L.

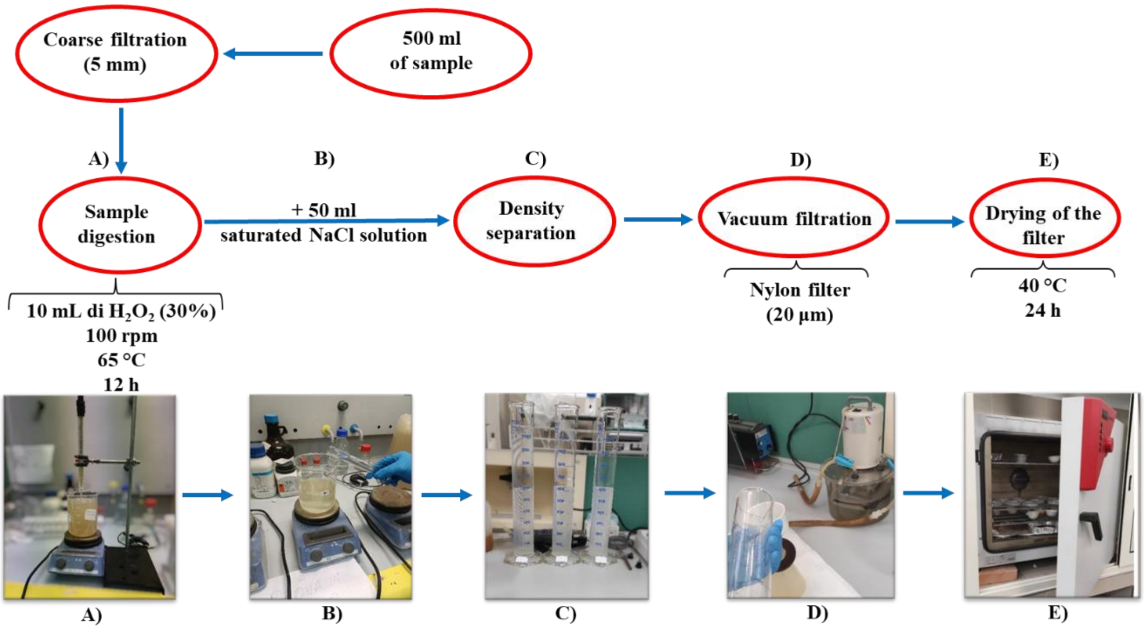


Figure 4.4.3: Microplastics extraction

Figure 4.4.4 shows that the highest microplastic concentration was detected in CSO samples, followed by wet-weather samples without CSO activation and dry-weather samples. The WWTP effluent showed much lower concentrations, indicating good microplastic removal efficiency by the treatment plant.

Microplastic concentrations during CSO events were almost twice those observed under dry-weather conditions and about 50% higher than during rainfall events without CSO activation. This suggests that urban runoff significantly increases microplastic loads in wastewater, especially during intense rainfall events, when runoff and sediment resuspension in sewer collectors may further enhance microplastic transport.

Fragments were the most abundant microplastic shape in influent samples, while fibers dominated in the effluent. The increase in fragments and spheres during CSO events may be related to runoff from road surfaces, plastic waste degradation, and tire wear.

Overall, CSO samples showed microplastic concentrations about 12 times higher than WWTP effluent samples, suggesting that although CSO events are less frequent, they may represent a relevant source of microplastic discharge into receiving water bodies.

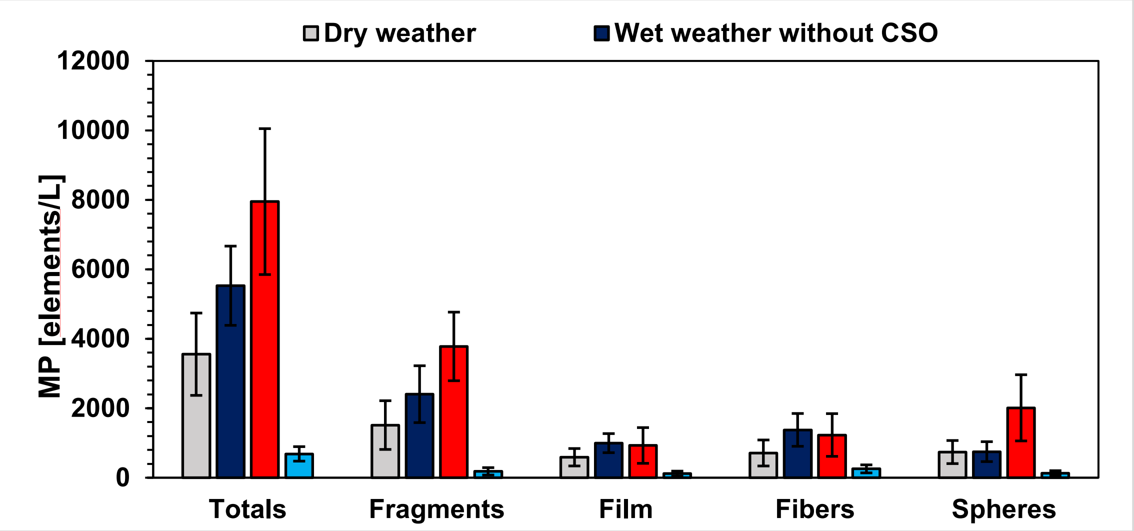


Figure 4.4.4: Concentration of MPs in the collected samples distinguished by total and shape

4.4.3 Climate change effects on WWTPs

Drinking water treatment plants supplied by surface waters, particularly artificial reservoirs, are especially exposed to the effects of climate change (Graham et al., 2024). The alternation of drought periods, heat waves, and intense precipitation events can lead to a deterioration in the quality of raw water, with consequent impacts on treatment processes. In particular, the literature shows that climate change may promote an increase in the concentration of soluble metals, such as iron and manganese (Freeman et al., 2017; Jarsjö et al., 2020), as well as an increase in natural organic matter (Hashempour et al., 2020), turbidity, and the frequency of algal blooms (Gobler, 2020). These phenomena represent a critical issue for conventional drinking water treatment plants, as they may reduce treatment efficiency, increase reagent consumption, and make compliance with drinking water quality standards more challenging.

In this context, the case study considered the use of ferrate (VI) as an innovative and sustainable treatment to address emergency conditions related to the deterioration of raw water quality (Li et al., 2021; Marbaniang et al., 2023). Ferrate (VI) was investigated both as an alternative to and as a support for conventional treatments, with reference to the removal of manganese, natural organic matter, turbidity, and algae. These parameters were selected because they represent some of the main critical issues that may occur in surface reservoirs as a result of the combined effects of drought, increasing temperature, water-column stratification, and intense precipitation events.

The analyses on the effectiveness of ferrate (VI) were carried out at laboratory scale, simulating the main treatment processes of drinking water treatment plants through jar tests (**Figure 4.4.5**). The procedure included a rapid mixing phase, a slow mixing phase, and a subsequent sedimentation phase, after which samples were collected from the supernatant for analysis.

Several critical issues typical of surface waters intended for drinking water production were evaluated. The removal of soluble manganese was analysed by filtering the samples and subsequently measuring them using ICP-OES, including kinetic tests. The removal of natural organic matter was assessed by measuring TOC, while turbidity was evaluated on real inlet water samples from a drinking water treatment plant using a turbidimeter. To simulate algal blooms, the water was contaminated with natural algae, mainly Chlorella sp., and the removal efficiency was determined by measuring chlorophyll-a.

Finally, the residual concentration and stability of ferrate(VI) were monitored by UV-VIS spectrophotometry, measuring the absorbance of Fe(VI) and its reduction products as a function of pH.

Figure 4.4.5: Jar test

The available results (**Figure 4.4.6**) show that ferrate (VI) can contribute to improving the robustness of the drinking water treatment process.

In particular, for the removal of soluble manganese, ferrate (VI) showed good oxidative performance, with a reagent demand similar to that of other commonly used oxidants, but with the advantage of not generating toxic by-products and producing a lower amount of sludge compared to permanganate. The effectiveness of the process was higher under slightly alkaline conditions, whereas at neutral pH ferrate tended to lose stability.

Regarding natural organic matter, ferrate (VI) used alone showed limited effectiveness; however, in the presence of soluble manganese, TOC removal increased significantly due to the formation of more reactive intermediate iron species.

In the case of turbidity, the use of ferrate (VI) in combination with the conventional coagulant made it possible to achieve values below the European regulatory limit, while reducing the required PACl dosage by more than 50%.

Finally, for algae removal, ferrate (VI) proved to be more effective than permanganate, especially at low dosages. Its action combines oxidation and flocculation, due to the formation of Fe (III), thus also allowing a significant reduction in the need for conventional coagulants.

This aspect is particularly relevant under climate emergency conditions, where a sudden deterioration in inlet water quality may require rapid adaptation of the treatment line.

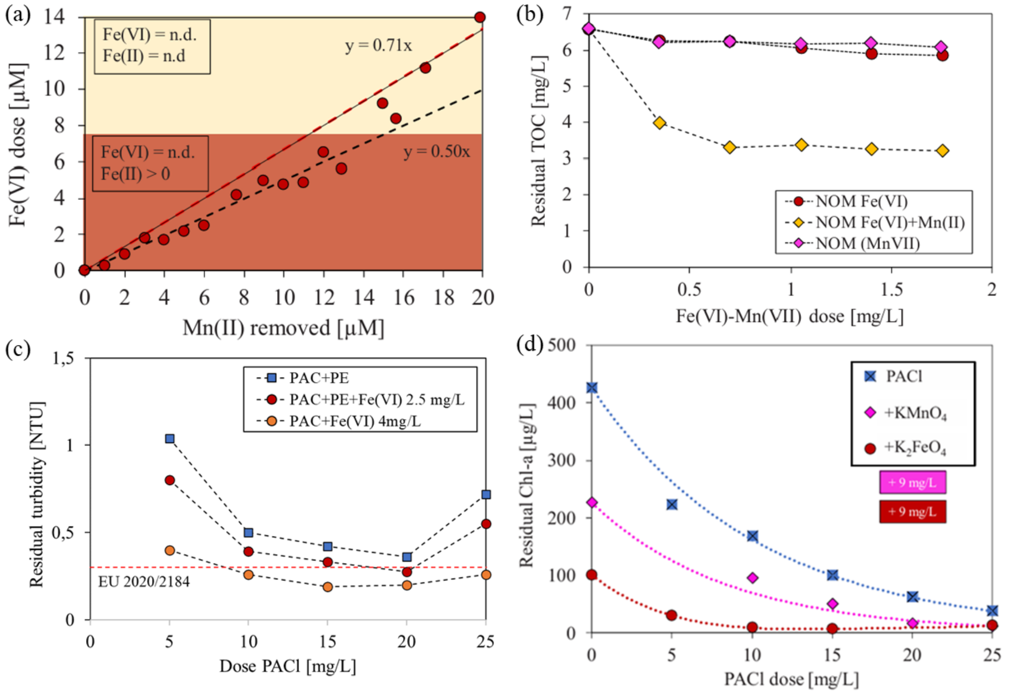


Figure 4.4.6: Results: (a) manganese removal; (b) NOM removal; (c) turbidity removal; and (d) algae removal.

5. Conclusions

Considering the analyses presented in Section 4.1, it can be concluded that bridge collapses generate complex and interconnected consequences at the social, economic, environmental, and human levels, highlighting the need for integrated and resilient infrastructure management strategies. The analysis of bridge collapses has highlighted, despite the limited number of case studies examined, certain recurring patterns in the consequences generated at the social, economic, and environmental levels, offering several significant insights. The data show, first of all, that the consequences in terms of loss of human life are often a critical element, not only because of the fatalities themselves, but also due to the psychological damage inflicted on the population, which reduces trust in modern infrastructure. This is closely linked to the social consequences experienced by local communities: isolation caused by disrupted connections and difficulties in accessing essential services such as schools and hospitals—further exacerbated by rerouted traffic on roads not designed to accommodate such high traffic volumes—have frequently triggered public protests demanding accountability and transparency in infrastructure management. Regarding environmental consequences and the resulting chain reactions, a recurring exposure to pollution risks emerges, particularly when collapses involve the transport of chemicals or hazardous goods. This was demonstrated in the case of the Juscelino Kubitschek de Oliveira Bridge in Estreito, Brazil, where the collapse compromised water quality and river ecosystems. From an economic perspective, the impacts are significant, both because of the interruption of trade and logistics flows and the substantial costs associated with reconstruction and damage mitigation. It is also important to note that bridge collapses often produce different cascading effects depending on the type of infrastructure affected. Statistically, small- and medium-sized bridges connecting smaller urban areas tend to generate greater social consequences, isolating communities from essential goods and services while producing comparatively limited economic repercussions, typically confined to reconstruction costs. By contrast, the loss of a major infrastructure link between two metropolitan areas causes severe social disruption and equally significant economic losses. These recurring patterns underline the necessity of addressing bridge design, maintenance, and management through an integrated and resilient approach that considers not only structural safety, but also the broader interconnections with society, the environment, and the economy. This confirms the importance of predictive models based on multi-hazard analyses and decision-making frameworks aimed at reducing the risk of future collapses and enhancing the resilience of strategic infrastructure.

Based on the findings discussed in Section 4.2, it can be concluded that a resilience-based framework is essential for improving NaTech risk management in industrial critical infrastructures exposed to natural hazards and technological accidents. This report presents a comprehensive resilience-based framework designed to enhance NaTech risk management in industrial critical infrastructures. The framework integrates both established and innovative approaches, accounting for system disruptions and performance behaviours, and is structured around three core stages: awareness, preparedness, and recovery. Awareness involves proactively identifying system vulnerabilities, with particular emphasis on the complex interplay between technological systems and natural hazards. Preparedness focuses on enhancing system readiness by implementing hierarchical safety layers, improving robustness, strengthening the targeted use of safety barriers, and refining emergency response plans. Recovery addresses both short-term and long-term restoration challenges through corrective actions such as clean-up operations, process simplification, and sustainable rehabilitation technologies. The framework also includes a final feedback loop for continuous learning, allowing adaptation to the dynamic challenges posed by NaTech events. The case study on hydrocarbon pollution in Cienfuegos, Cuba, exemplifies the importance of adopting a proactive resilience-based approach. This framework not only strengthens the resilience of industrial infrastructures but also contributes to the broader objective of sustainable development by minimizing the environmental and societal impacts of industrial accidents. Future efforts should focus on validation through additional case studies and real-world applications to ensure its practical effectiveness across different industrial contexts.

From the results presented in Section 4.3, it emerges that multi-hazard risk assessment of critical infrastructures must include interdependencies and cascading effects in order to provide realistic and effective support for infrastructure planning and emergency preparedness. This chapter examined the interactions and interdependencies among four civil critical infrastructures—drinking water, sewage and wastewater, railway, and road networks—within a multi-hazard risk assessment framework. Three main findings emerge from the analysis. First, cascading failures across critical infrastructure boundaries are not rare events: with 29% of serious European critical infrastructure incidents originating from failures in other services, any risk assessment limited to a single infrastructure systematically underestimates both the probability and the magnitude of adverse outcomes. The dependency tables developed provide a structured basis for extending risk estimates across infrastructure boundaries. Second, climate change significantly alters the interdependency risk profile. In addition to increasing the probability of individual infrastructure failures through more frequent and intense hazard events, climate-driven stressors may simultaneously degrade multiple infrastructures, reducing the redundancy that systems rely upon to manage isolated failures. Electricity supply is consistently identified as a systemic vulnerability whose failure generates disproportionate cross-sector consequences. This finding strongly supports the inclusion of the electricity network in future integrated critical infrastructure risk assessments. Finally, the simulation-based framework developed within the project—integrating a knowledge graph with domain-specific operational simulators and validated through the ReturnLand/ReturnVille Virtual Test Bed—demonstrates that quantitative cascade analysis is both feasible and necessary. Simulation makes it possible to identify emergent interdependencies that qualitative analysis alone cannot capture and provides KPI-based resilience metrics needed to support evidence-based infrastructure planning and emergency preparedness.

In light of the results described in Section 4.4, it can be concluded that climate change poses significant and interconnected risks to critical water infrastructures, requiring adaptive and sustainable solutions to ensure long-term operational resilience. This report analysed the potential concatenation of climate-related risks affecting critical water infrastructures, with particular reference to urban wastewater treatment plants and drinking water treatment plants. The results show that climate change can generate several interconnected impacts through heat waves, droughts, intense rainfall, and the deterioration of raw water quality. These phenomena may affect process performance, environmental protection, and the overall resilience of water services. For wastewater treatment plants, the Parma case study showed that heat-wave events did not cause exceedances of discharge limits for the main effluent parameters, including suspended solids, COD, nitrogen, and phosphorus. Reactor temperatures remained relatively stable, and no clear negative effect on activated sludge settleability was observed. This suggests that, under the analysed conditions, the plants were able to maintain adequate operational performance, although more severe or prolonged heat waves could still represent a future risk. The Palermo case study highlighted a different vulnerability related to intense rainfall and combined sewer overflow activation. Combined sewer overflow events significantly increased microplastic concentrations in wastewater, reaching values much higher than those found in treated effluent. This confirms that, during extreme rainfall, untreated or partially treated flows may become an important pathway for microplastic discharge into receiving water bodies. Regarding drinking water treatment plants, the analysis showed that droughts, high temperatures, reservoir stratification, and intense rainfall can worsen raw water quality by increasing manganese, turbidity, natural organic matter, and algal blooms. In this context, ferrate (VI) proved to be a promising and sustainable treatment option, improving the removal of manganese, turbidity, and algae while reducing the need for conventional coagulants. Overall, the study confirms the need for an integrated and resilience-based approach to water infrastructure management. Future strategies should strengthen monitoring systems, improve emergency planning, control CSO impacts, and adopt flexible treatment technologies to enhance the resilience of critical water infrastructures under climate change conditions.

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