Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

multi-Risk sciEnce for resilienT commUnities undeR a changiNgclimate

Codice progetto MUR: **PE00000005** – CUP LEAD PARTNER: I33C22006910006

Return

Deliverable title: **Analysis of different infrastructures and their interdependencies from a systemic and functional point of view**

Deliverable ID: **DV6.2.3**

Due date: **28/02/2025**

Submission date:

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Approved by Luisa Lavalle (WP leader)

Technical references

Project Acronym	RETURN
Project Title	multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate
Project Coordinator	Domenico Calcaterra UNIVERSITA DEGLI STUDI DI NAPOLI FEDERICO II domcalca@unina.it
Project Duration	December 2022 – November 2025 (36 months)

Deliverable No.	DV6.2.3
Dissemination level*	PU
Work Package	WP2 - Asset systems definition and characterization
Task	T2.3 - Modelling and analysis of different infrastructure systems and their interdependencies from a systemic and functional point of view
Lead beneficiary	ENEA
Contributing beneficiary/ies	

* PU = Public

PP = Restricted to other programme participants (including the Commission Services)

RE = Restricted to a group specified by the consortium (including the Commission Services)

CO = Confidential, only for members of the consortium (including the Commission Services)

Document history

Version	Date	Lead contributor	Description
0.1	17.02.2025	Luisa Lavalle, Maria Luisa Villani (ENEA)	First Draft
0.2	24.02.2025	Luisa Lavalle (ENEA)	Critical review and proofreading
0.3	26.02.2025		Edits for approval
1.0	28.02.2025		Final version

ABSTRACT

Critical infrastructures (CIs) are the backbone of modern society, ensuring public safety, economic stability, and essential services. However, these systems are increasingly vulnerable to climate change, which amplifies the frequency and intensity of natural hazards such as floods, droughts, wildfires, and extreme temperatures. Traditional risk assessments, which focus on isolated hazards, fail to capture the cascading failures and interdependencies that characterize real-world disasters. To address this gap, this study presents an integrated multi-risk assessment framework that advances the state of the art by combining domain-specific simulators, knowledge graphs, and high-fidelity data models.

The framework enhances commercial simulation tools – such as InfoWorks WS Pro for drinking water networks and OpenTrack for railways – by interfacing them with external analytical layers. While commercial simulators provide trusted and operator-friendly results, they are typically designed for planning purposes rather than real-time emergency response. Our approach allows the injection of scenario-relevant failures, dynamic network evolution, and cascading failure modelling, overcoming the mentioned limitation and ensuring a more realistic resilience assessment and enhanced decision support.

A knowledge graph is introduced to represent interdependencies between infrastructures and their environment, bridging hazard data with technical norms and vulnerability models. This novel component enables a system-of-systems analysis, supporting decision-makers in quantifying the multi-risk impacts on critical infrastructure and evaluating mitigation strategies.

The simulation environment produces key performance indicators (KPIs) that quantify service availability, delays, and operational resilience, supporting risk-informed decision-making. The modular design ensures scalability, allowing integration of emerging technologies and evolving threats in future iterations.

To validate the framework, two case studies were implemented: Drinking water networks and Railway networks.

This study represents a significant advancement in infrastructure resilience assessment, offering a comprehensive, adaptable, and operator-trusted methodology that supports data-driven strategic investment planning and resilience strategies.

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1. Introduction

1.1 Problem Statement

Critical infrastructures (CIs) form the backbone of modern society, playing an indispensable role in ensuring public safety, economic stability, and the continuous provision of vital services. Recognizing their importance, numerous directives, strategic agendas and policy frameworks at national and international levels emphasize the need to strengthen their capacity to prevent, protect against, respond to, resist, mitigate, absorb, accommodate and recover from incidents that could disrupt essential services (Directive (EU) 2022/2557, 2022).

Yet, in an era of increasing climate uncertainty, the systems supporting vital societal functions and economic activities are more fragile than ever before. As highlighted in DV6.2.1, climate change has emerged as a rapidly escalating threat – both directly and through cascading effects – characterized by more frequent, prolonged, and unpredictable severe storms, floods, droughts, heatwaves, and wildfires. These events not only trigger large-scale disasters, but also contribute to chronic stressors. Combined with aging infrastructure that is vulnerable to climate impacts, these trends put countless communities at heightened risk.

Furthermore, traditional risk assessments often focus on single hazards, such as flooding or earthquakes, in isolation. However, real-world disasters rarely occur in isolation: a wildfire may be followed by a storm, increasing contamination risks; an earthquake may trigger liquefaction, leading to widespread pipeline failures. To improve resilience, a multi-hazard approach is essential.

While the need to better prepare for the inevitable effects of climate change is widely acknowledged, to date no comprehensive assessment exists that addresses the climate-related vulnerabilities of critical infrastructures, the potential resulting damages, or the cost of reconstruction and recovery. Also, because such protracted exposure to extreme natural events is extraordinary compared to events experienced in the 20th century, they are not yet incorporated in infrastructure management principles and practice.

Understanding the vulnerabilities of critical infrastructures to natural hazards is a crucial step and is addressed in WP4. The next crucial phase is to develop a structured, trusted methodology for quantifying risk, ensuring that investments are directed toward the most critical areas.

Strategic investment plays a pivotal role in enhancing the resilience of critical infrastructures. By directing resources effectively, it ensures risk reduction through the strengthening of vulnerable systems to withstand extreme events, promotes cost efficiency by allocating funds where they yield the highest impact, and safeguards service continuity to maintain uninterrupted access to essential services during crises. This integrated approach not only addresses immediate threats but also supports long-term sustainability and resilience.

The key requirements to better equip CI operators with the knowledge and tools needed to navigate a dynamic threat landscape – enabling strategic investment decisions that balance risk, cost, and long-term benefits – were identified in DV6.2.1 and presented to the Consortium's experts. The activities outlined in this document focus on Requirements DW-RR1 for the drinking water sector and RL-RR1 for railway networks.

1.2 Vision to advance the State-of-the-art

The current state of the art in infrastructure resilience assessment concerning natural hazards is exemplified by the Hazus methodology developed by FEMA (FEMA, 2024). Hazus employs predominantly empirical fragility curves at the component level (e.g., facilities, control stations, pipelines, tanks, water treatment plants) to estimate the potential impacts of natural hazards. These impacts are assessed qualitatively through defined damage states (None, Slight, Moderate, Extensive, Complete) for many system components, while for others (e.g, pipelines), the repair rate – measured in repairs per kilometer – serves as the key parameter. Fragility curves are developed for each classification of water system components, illustrating the probability of reaching or exceeding specific damage states based on the severity of ground motion or ground failure. Using these curves, Hazus provides a method for assessing the functionality of individual system components and offers a simplified approach for evaluating overall network performance.

However, Hazus has notable limitations, which are clearly identified and stated in their report: it does not account for direct utility outages, cascading effects, or detailed system performance, nor does it address interdependencies between different infrastructures.

To overcome these limitations, we propose an advanced framework that integrates fragility curves into domain-specific simulators. This integration enables a more comprehensive assessment of natural hazard impacts, capturing not only the physical vulnerabilities of individual components but also the dynamic operational impacts across entire systems. Additionally, we introduce the use of knowledge graphs to represent and analyse interdependencies, both among critical infrastructures and within their broader environmental context. This approach also facilitates the assessment of compound risks arising from concurrent natural hazards, providing a holistic understanding of systemic vulnerabilities.

Our architectural design envisions modular, yet seamlessly integrated, components. This modularity ensures flexibility, allowing the incorporation of cutting-edge algorithms for hazard impact assessment as they become available, while the deployment of domain simulators is pivotal for maintaining an operator-friendly and trusted tool, enabling continuous updates aligned with infrastructure modifications to preserve the relevance and accuracy of resilience assessments over time.

This multi-hazard simulation environment will allow to:

- Evaluate infrastructure responses to varying hazard intensities and combinations.
- Account for cascading failures triggered by successive disasters (e.g., an earthquake causing pipe ruptures, followed by flooding that exacerbates contamination risks).
- Assess the effectiveness of mitigation strategies in a virtual environment before real-world implementation.

To enhance the resilience of critical infrastructures, it is essential to follow a structured process that includes the following key steps:

- Model the effects of natural hazards on CIs accurately.
- Build a model that enables the chain of events to emerge naturally during crisis evolution, capturing cascading effects across interconnected infrastructures.
- Quantify multi-risk impacts on critical infrastructures, moving beyond guesswork to support data-driven decision-making for investments and resilience strategies.

1.3 Scope and Relation with the other activities in the project

Within the RETURN project, the overarching goal of the Transversal Spoke TS2 (Spoke 6) is to strengthen Italian governance in disaster risk management by enhancing the understanding of environmental, natural, and anthropogenic risks affecting Critical Infrastructures.

Building on the requirements DW-RR1 and RL-RR1 outlined in DV6.2.1, this deliverable reports the analysis and modelling activities conducted in WP2, focusing on the drinking water distribution network and the railway network. It examines the impacts of natural hazards on these infrastructures and their implementation within a simulation environment. Notably, the same approach can be applied to other infrastructures. In some cases, such as the wastewater network, similar commercial tools (e.g., a different module of Infoworks) and shared fragility curves related to earthquakes and ground instabilities can be utilized.

The simulation environment is designed to accommodate inputs on natural hazards from WP3 and the Vertical Spokes, as well as integrate insights on factors compromising structural integrity over time from T6.2.2 and WP4. The extensive simulation results for various failure scenarios fall within the scope of Task 2.4 (and deliverable D2.4), while scenario-based applications are addressed in WP5. The assessment of different mitigation measures will be detailed in DV6.6.2. Additionally, the KPIs derived from the extensive simulation campaign will be integrated into the platform developed in WP6, providing a broader geographical and general overview.

It is important to note that the development of a graphical user interface was not planned; analyses are conducted directly within the development environment. As of this deliverable's release, modelling activities for the drinking water domain have been completed, while the modelling of the railway network is still ongoing due to significant setbacks in finalizing the NDA agreement for data access.

1.4 Document Structure

The report is organized as follows. Section 2 outlines the general architecture of the simulation environment, highlighting the workflow and detailing the general aspects about the knowledge graph and the employment of commercial simulators. In Section 3, the modelling of the drinking water distribution network is detailed, taking into account both the hydraulic model, the effects of the natural hazards, and the integration of their model into the commercial simulator, whereas in Section 4 the process is repeated with respect with railways domain. Section 5 draws some conclusions.

2. The implemented framework

The interconnected nature of critical infrastructures has made them robust under normal conditions; however, natural hazards often trigger multiple simultaneous failures, overwhelming even redundant networks that are not designed to withstand compounded stress. These failures are not merely inconvenient – they can be catastrophic, affecting public health, economic stability, and national security.

As highlighted in Section 1.2, an advanced simulation environment, accessible to critical infrastructure operators, would be highly beneficial. Such an environment would accurately evaluate infrastructure responses to varying hazard intensities and combinations, account for cascading failures triggered by successive disasters, and enable decision-makers to transform trusted model data into actionable strategies. These strategies could inform infrastructure operations, mitigation measures, and investment priorities.

A comprehensive multi-hazard assessment framework integrates multiple scientific disciplines, datasets, and modules to assess vulnerabilities and predict system failures. Key components include:

1. **Hazard Identification:** Determining which natural hazards pose risks to critical infrastructure based on historical data and climate projections, and understanding how different hazards can co-occur and amplify each other. Operators continuously perform this task but highlight the need for more accurate methods, algorithms, and climate change forecasts. These tools are currently under study by the Vertical Spokes and WP3.
2. **Exposure Analysis:** Mapping physical infrastructure to identify assets at risk, alongside population and economic assets, for a comprehensive risk assessment.
3. **Resilience Scoring Systems:** Ranking infrastructure assets based on their ability to withstand disruptions to identify components requiring immediate attention.
4. **Vulnerability Assessment:** Evaluating the susceptibility of each component to various hazards, considering material properties, design standards, and historical failure records.
5. **Interdependency Analysis:** Examining how failures in one part of the system can affect other components, revealing critical interconnections.
6. **Impact Modelling:** Simulating hazard scenarios with computational models to estimate physical damage, service disruptions, and economic losses.
7. **Risk Quantification:** Assigning numerical values to the probability and consequences of failures, helping decision-makers prioritize investments in mitigation and adaptation strategies.
8. **Cost-Benefit Analysis:** Comparing the costs of investments with the expected long-term benefits to guide resource allocation effectively.

To achieve these objectives, it is essential to follow a structured process that includes the following key steps:

- **Build a modelling and simulation environment** that provides accurate and trusted information about the physical behaviour of the infrastructure, while enabling the natural emergence of event chains during crisis evolution and capturing cascading effects across interconnected infrastructures.
- **Model the effects of natural hazards on critical infrastructures** with high accuracy.
- **Quantify multi-risk impacts** on critical infrastructures, using relevant KPIs identified in collaboration with operators.

The following sections of this chapter describe the general approach adopted, while the application of this approach to specific case studies is detailed in the subsequent chapters.

2.1 Simulation Strategy: Enhancing Commercial Tools for Hazard effects prediction

2.1.1 Using commercial domain simulators for accurate and trusted results

Simulation strategies play a crucial role in hazard prediction and enhancing the resilience of infrastructures. They provide a controlled environment for testing various hazard scenarios and understanding their potential impacts. By leveraging advanced computational models and commercial simulation tools, decision-makers can anticipate risks, optimize infrastructure investments, and develop robust mitigation strategies. More specifically, the benefits include:

- **Risk Identification:** Simulations help detect vulnerabilities in critical infrastructure before they lead to failures.
- **Scenario Planning:** Decision-makers can model different disaster scenarios and develop targeted response plans.
- **Cost-Effective Testing:** Infrastructure modifications can be evaluated virtually before implementation, saving time and resources.
- **Improved Accuracy:** Combining simulations with real-world data enhances predictive accuracy and reliability.

Given the complexity of domain-specific physics-based analyses – usually involving differential equations for hydraulic behaviour, power flow, or speed and distance – which can be time-consuming, data-intensive, and require specialized expertise, many researchers have developed simplified models to assess the serviceability of networks under varying levels of damage. However, while these simplified models may provide qualitative insights, they often fail to capture the complete system behaviour. For example, closely related to reliability is redundancy, a critical yet often overlooked characteristic of overall system performance. Redundancy in a water supply network, for example, refers to the system's reserve capacity and the availability of alternative routing (i.e., supply paths to demand nodes in case primary supply links fail) but simply considering the available paths is not always sufficient to fully understand system resilience.

The deployment of domain-specific simulators is pivotal for maintaining an operator-friendly and trusted tool. This enables continuous updates aligned with infrastructure modifications, preserving the relevance and accuracy of resilience assessments over time. Computational simulations offer a physics-based approach to modelling complex hazard interactions, providing valuable insights into system behaviour under stress. Employing trusted (commercial) simulators is essential for:

- **Ensuring Accuracy:** Comparing model predictions with real-world observations to improve reliability.
- **Enhancing Decision-Making:** Providing confidence in models used for infrastructure planning and disaster management.
- **Refining Assumptions:** Identifying discrepancies between theoretical models and actual system behaviour.
- **Improving Stakeholder Trust:** Gaining acceptance from infrastructure operators and policymakers.

In the water domain, the chosen commercial simulator is **InfoWorks WS Pro**, as it is already employed by IREN, a partner of the project and a multi-utility operating in the water sector.

InfoWorks WS Pro is an advanced hydraulic modelling software developed by Innovyze, now part of Autodesk. It is specifically designed for water distribution network analysis and management, offering comprehensive tools to simulate, plan, and optimize the performance of complex water supply systems. The software allows users to model water networks of any size and complexity. Its hydraulic and water quality modelling features simulate water flow, pressure, and quality within the network, accounting for factors such as demand variations, pump operations, and valve settings. It can simulate daily or multi-day cycles, effectively analysing the distribution of pressures, flow rates, and storage volumes under gradually varied flow conditions. The software provides detailed representation of individual consumers, categorizing demand based on usage types such as domestic, commercial, and industrial. A key feature is its ability to model demand as partially or fully dependent on network pressure, which is crucial for accurately representing water losses and conducting fire protection system checks. The software can also handle highly complex systems, including those with pressure-reducing or pressure-sustaining valves, multi-pump stations regulated by inverters, and other sophisticated hydraulic components. Its robust numerical algorithms ensure stable and reliable calculations, delivering rapid simulation times even for extensive and intricate network models.

InfoWorks WS Pro is widely adopted by operators in Italy, including CAP, Hera, MM, Acea, Gori, and SMAT, in addition to IREN. Collectively, these operators serve approximately 23.5 million residents across 13 regions: Liguria, Emilia-Romagna, Valle d'Aosta, Piemonte, Lombardia, Veneto, Friuli, Marche, Lazio, Toscana, Umbria, Molise, and Campania.

It is worth noting that, beyond the general advantages of using commercial simulators, employing those already used by our collaborating operators offers specific benefits. It facilitates easier interaction, as all parties are familiar with the required information and software capabilities. Moreover, it significantly enhances model exchange and result usability, fostering greater trust and enabling seamless integration into existing operational systems. This familiarity not only improves efficiency but also ensures that simulation outputs are directly relevant and actionable for the operators involved.

However, past successful use of PSS Sincal by Siemens (Lavalle et al., 2020) demonstrates that this approach is generalizable and can be extended to other domain-specific simulators by adapting the interface module.

In the railway domain, OpenTrack has been chosen. OpenTrack is a well-established railway planning software widely used by railways, the railway supply industry, consultancies, and universities across various countries. It enables the modelling, simulation, and analysis of diverse rail systems.

OpenTrack supports several key tasks, including:

- Infrastructure Planning: Determining the requirements for a railway network's infrastructure.
- Capacity Analysis: Analyzing the capacity of lines and stations.
- Headway Calculation: Calculating minimum headways.
- Failure and Delay Analysis: Assessing the effects of system failures (such as infrastructure or train failures) and delays.

Predefined trains operate according to the timetable on a simulated railway network. During the simulation, OpenTrack calculates train movements based on the constraints imposed by the signalling system and timetable. The simulation results are presented through diagrams, train graphs, occupation diagrams, and statistical data. The core of OpenTrack's simulation relies on differential equations for speed and distance to model train movements accurately. Trains strive to adhere to the timetable, but their progress can be impeded by occupied tracks and restrictive signal aspects imposed by the signalling system. Throughout the simulation, data such as speed, acceleration, position, and power consumption is continuously recorded for each train, providing detailed insights that can be evaluated post-simulation.

In addition to RFI - Rete Ferroviaria Italiana, partner of the project, key operators using OpenTrack in Italy include Ferrovie Nord Milano, Circumvesuviana, Ferrovie Nord Barese, Ferrovie del Sud Est, Ferrovie del Gargano, FAL - Ferrovie Appulo Lucane, FCU - Ferrovie Centrale Umbria and Ferrovie Emilia Romagna. Additionally, OpenTrack is employed by numerous operators across Europe and worldwide.

It is worth noting that while other commercial transport planning software has been evaluated, macroscopic modelling of transport networks lacks the ability to accommodate local failures caused by natural hazards or to simulate cascading effects. Furthermore, such models are not suitable for assessing mitigation manoeuvres that operators might consider.

Despite their benefits, advanced modelling approaches face several challenges:

- **Data availability**: Incomplete, outdated, or biased datasets can significantly reduce model accuracy. However, initiatives like SINFI (see Section 2.1.2) are actively working to address these challenges. Moreover, the procedure developed in this study can be reasonably extended to scenarios with minimal data availability, as discussed in Section 3.1.1, and can be further supported by targeted testing campaigns to enhance data reliability and model performance.
- **Integration with Existing Systems**: Legacy infrastructure may not be fully compatible with "external" solutions. To address this, we have utilized a commercial simulator and validated its reliability using a real-world network.
- **Accessibility and Cost**: Some advanced commercial tools may be prohibitively expensive for smaller municipalities and organizations. This challenge has been mitigated by employing commercial tools already in use by the operators involved in this project, ensuring cost-effectiveness and operational compatibility.

2.1.2 Dealing with the quality of data

Ensuring high-quality data is paramount for achieving accurate and reliable results in infrastructure resilience modelling. High-fidelity simulations and the effective use of commercial domain simulators depend heavily on the integrity, completeness, and precision of the input data. Poor data quality can lead to flawed risk assessments, misguided decision-making, and ultimately, ineffective mitigation strategies that fail to protect critical infrastructure from climate-driven natural events. For example, the material used to construct pipelines might be unknown unless original pipeline drawings are available. Since pipeline performance is often influenced by construction materials, analysts may assume "average" quality construction and select fragility curves representing average material performance. While this increases uncertainty in the analysis results, it may be acceptable for preliminary, rough-cut evaluations.

While data gaps and inconsistencies present challenges, it is important to recognize that the absence of complete datasets does not necessarily render simulations ineffective. In many cases, partial datasets can still offer valuable insights, especially when leveraged through domain-specific simulation models. These models can identify trends, highlight vulnerabilities, and guide preliminary risk assessments, serving as a catalyst for targeted data collection efforts. This approach was applied in the case study described in Section 3.1, demonstrating how working with partial real-world data and realistic assumptions can yield outputs that, while not fully accurate, offer valuable clues about network behaviour. This iterative approach encourages continuous improvement in data quality over time, enhancing the robustness of resilience assessments.

Moreover, national initiatives such as SINFI (Federated National Information System of Infrastructures), established by the Ministry of Economic Development, play a crucial role in improving data availability and accessibility. SINFI aims to create a comprehensive, federated national registry of both underground and above-ground infrastructures across Italy and requires operators to upload technical data related to maintenance and planning interventions, making it plausible that more comprehensive information will become available in the near future.

Additionally, historical inventories of construction techniques (similar to the analysis conducted on roads in Task 6.2.2, see Deliverable DV6.2.2) provide a rich source of contextual information, supporting more realistic modelling assumptions when direct data is scarce. These resources help bridge data gaps by offering reference points for infrastructure characteristics, performance expectations, and potential vulnerabilities.

Looking ahead, advancements in data collection technologies, coupled with regulatory frameworks promoting data sharing and standardization, suggest that access to high-quality infrastructure data will become increasingly feasible. As data availability improves, the accuracy and reliability of high-fidelity simulations will continue to strengthen, further solidifying domain-specific simulation as a viable and effective strategy for enhancing infrastructure resilience in the face of evolving climate threats.

2.1.3 Interfacing commercial simulators for custom semi-automated analysis

Commercial simulators are widely recognized for providing reliable and trusted simulation results, primarily due to their rigorous development and validation processes tailored for specific industry needs. However, these tools are typically designed with a focus on planning and design purposes, rather than for simulating the dynamic evolution of emergency situations. This inherent design focus introduces critical limitations when attempting to analyse complex scenarios, such as those arising from climate-driven natural disasters.

For example, **water domain simulators** often operate under the assumption of **unlimited water availability** in reservoirs, a condition suitable for long-term infrastructure planning but unrealistic during crises where supply disruptions are likely. Similarly, many commercial simulators adhere to the n-1 criterion, which assumes the failure of a single component while the rest of the system remains operational. While effective for standard resilience assessments, this approach falls short in capturing the cascading failures typical of natural disasters, where multiple interdependent components can fail simultaneously or sequentially.

These limitations are not flaws per se; rather, they reflect the original purpose for which these tools were developed. Nevertheless, in the context of resilience assessment and emergency scenario simulation, it becomes essential to **interface commercial simulators** with external systems or custom scripts. This interfacing capability enables users to:

- **Introduce Scenario-Relevant Failures**: Inject specific failure conditions that go beyond the standard assumptions, such as multiple simultaneous outages or progressive infrastructure degradation due to cascading effects.
- **Control Network Evolution**: Dynamically manage the operational status of network components based on real-time conditions. For instance, a pumping station can be automatically set out of service if its power supply is disrupted due to the failure of an upstream electrical substation without backup power. Conversely, the presence of backup systems can be modelled with appropriate delays and operational constraints.
- **Simulate Cascading Effects**: Model the interdependencies between different infrastructure systems, allowing for a more realistic representation of how failures in one domain (e.g., the electrical grid) can propagate and impact other sectors (e.g., water distribution).

By enabling the integration of custom analytical layers on top of commercial simulation engines, this approach ensures that the tools remain **operator-friendly and trusted** while significantly expanding their applicability to complex, real-world scenarios. The ability to "inject" the necessary features through interfacing is therefore critical to advancing the state of resilience modelling and supporting more informed decision-making in the face of evolving risks.

It is worth noting that InfoWorks WS Pro supports automation and customization through the use of **Ruby scripting**, a dynamic programming language integrated within the software. This feature allows users to enhance workflows, automate repetitive tasks, and create customized analyses tailored to specific project needs.

While Ruby is typically launched from within InfoWorks, we needed to run it externally (as detailed in the architecture, see Section 2.4 and 3.1.2). To achieve this, we successfully accessed a hidden application that previously supported APIs but had been disabled for business reasons a few years ago.

On the other hand, OpenTrack offers an application programming interface (API) to connect other applications with OpenTrack. The other application can send standardized commands to OpenTrack and gets defined status messages back from OpenTrack. Technically, SOAP-Messages are exchanged via HTTP (SOAP over HTTP).

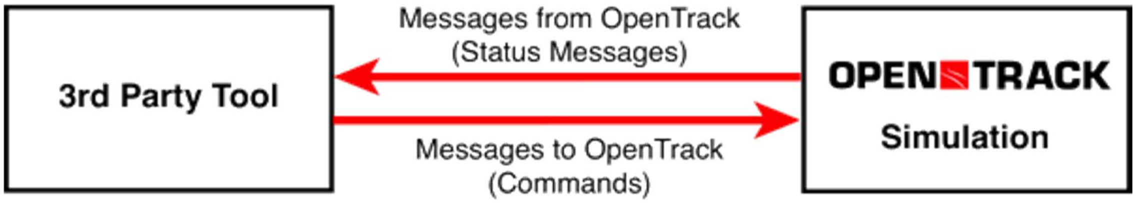

Figure 1: Interfacing mechanism with OpenTrack

2.1.4 Adopted Key Performance Indicators (KPIs)

The ultimate goal of a risk assessment methodology is to evaluate the performance – or the expected loss – of infrastructure, including its systems and components, when exposed to hazards. This performance is quantitatively measured using Key Performance Indicators (KPIs), which numerically represent factors such as the comparison between demand and capacity, the effectiveness of mitigation actions, or the cumulative impact of all damages. The functionality and performance of each component are directly linked to the anticipated levels of damage. Individual utility owners and operators need to identify the components of their utilities (e.g., pumps, generators, and SCADA systems) that are of higher consequence and concern in the event of an incident.

Drinking water domain

Water system failures can affect various components, with the extent of the impact depending on the redundancy and criticality of each element. Failures are categorized based on the system's operational phase (normal, crisis, or recovery) and may involve the inability to supply adequate water for firefighting, meet peak consumption demands, or serve all customers.

Key performance metrics in the water domain typically include the percentage of the population served within a specific timeframe, measured in terms of service connections, population coverage, or water volume. The importance of each component is assessed using the Component Criticality Rating (CCR), which accounts for factors such as life safety, fire flow, drinking water supply, and potential risk of damage to adjacent facilities.

The simulation environment developed within the RETURN project calculates all hydraulic parameters for the drinking water distribution network, enabling the generation of any hydraulic KPI with a minimum post-processing. The selected Key Performance Indicators (KPIs) focus on:

- The number of isolated users and unserved water flow (m^3/h).
- The number of users experiencing inadequate pressure and unserved water flow (m^3/h).

Custom reports can highlight isolated or unserved critical customers and assess the economic impact of service disruptions, if required.

Railway

In the railway domain, a parallel analysis can be drawn with the water domain. From a functional perspective, as examined by the simulation environment, failures in the railway system manifest as service delays, route limitations, or complete cancellations.

Key Performance Indicators (KPIs) for railway infrastructure have been previously identified in DV6.2.1. These KPIs are designed to assess the impact of disruptions on service quality and operational efficiency. The primary metrics used to quantify service impacts include:

- The number of trains affected.
- The total minutes of delay.

- The number of cancelled trains (trains that do not complete their entire route).
- The number of limited trains (trains that do not cover a portion of their intended route).

The simulation environment developed within the RETURN project enables the calculation of these KPIs, providing a clear assessment of how different failure scenarios affect railway operations.

2.2 Interdependency modelling: The Knowledge Graph

2.2.1 Motivation and Scope

A knowledge graph specifically devoted to resilience analysis of the critical infrastructures in the scope of RETURN is one of the new software artifacts designed to support the studies of WP5 and WP6. A knowledge graph consists of data, containing specific information, and an ontology, a logical model defining the meaning and context of that information. Additionally, inference rules can be defined to automatically derive (make explicit) further information or relationships based on the existing data. The aim of the knowledge graph is to build a resilience-oriented semantic layer devoted to the analysis of critical infrastructures by integrating data to interconnect natural KPIs (e.g., climate projection KPIs or geo-hazard KPIs), critical infrastructure vulnerable components (including their interdependencies), and impact KPIs relevant for assessing resilience strategies. Additionally, it aims to support configure tools, such as simulation environments, typically used by operators for infrastructure analysis, using parameters derived from climate and location-specific studies.

It should be noted that the knowledge graph is being developed to support the specific analyses needed for the project, i.e., the evaluation of the impact of natural events on the infrastructure services, although the focus is on designing a more general structure that can be useful for further studies related to resilience of critical infrastructures.

2.2.2 Methodology

To build a knowledge graph aimed at integrating data from different sources and supporting integrated analyses, it is necessary to balance the representation of the domain through existing ontologies with the abstraction of the data semantics from the infrastructure-specific datasets. This can be challenging because ontologies to be reused are often designed specifically for knowledge representation within a given domain, while infrastructure data models, on the other hand, are typically not conceived with generalization in mind. For example, the data model of a water infrastructure often is not designed to generalize to the representation of other critical infrastructures.

To address this challenge, both the complexity associated with the scale of the knowledge graph and the need for its extensibility and manageability, it was essential to establish a development process and general requirements for the ontology structure and realization.

2.2.2.1 Development process of a knowledge graph

An incremental process has been adopted, which includes the following steps:

1. Searching for upper-level semantic models to represent a system-of-systems while focusing on the perspective of a specific infrastructure.
2. Refining these models to populate (or link) the ontology representing the infrastructure with raw data, i.e., abstracting conceptual representations from the source dataset models and testing the annotations and requirements.
3. Paving the way to incorporate the semantic representation of other infrastructures and their interdependencies within the system-of-systems model.

The first iteration focused on defining and detailing the system-of-systems model with the drinking water infrastructure, which is described in Subsection 2.3.3. Subsequent iterations will focus on steps 2 and 3, applying them to the other infrastructures, i.e., transportation infrastructures, refining their models, and integrating their interdependencies into the overall system-of-systems framework.

2.2.2.2 Requirements for the ontology and its structure

The aim of the semantic layer of the knowledge graph, i.e., the ontology, is to create a backbone that collects, connects and structures parts of the domain related to the resilience analyses of the critical infrastructures in the scope of RETURN. As the development of the knowledge graph cannot be complete, given the complexity and dynamic feature of the domain, the result ontology provided within the project deadline should allow the development of one or more prototypes for specific case studies while facilitating future extensions and enhancements such as other studies, other (sub)systems and/or other critical infrastructures.

After the *definition of the scope of the model*, needed for the identification of the reference domain(s), corresponding to the critical infrastructures and natural systems to be represented, the following criteria have been established for the selection and adoption of ontologies.

Selections have been made to meet the following general requirements:

[GR1] The ontology needs to be open-source, or detailed in scientific documents, stable and mature.

[GR2] The ontology needs to be supported by good scientific publications that demonstrate its validity in the domain.

[GR3] The ontology should have been already used in software applications related to the analysis of critical infrastructures.

Requirements for the ontology structure have been set as follows:

[GR4] The overall ontology should be modular in its structure, with different OWL files for the various aspects/infrastructures or sub-ontologies. This modularization facilitates maintenance and management.

[GR5] Realization of design patterns i.e., high level model fragments, as method of development, based on competency questions, i.e., queries the models need to satisfy. These patterns allow to structure the ontology and guide for subsequent refinements.

2.2.3 The semantic layer

This section first presents the system-of-systems ontology and then details the critical infrastructure model.

2.2.3.1 The system-of-systems model

The social-ecological-technological system (SETS) framework described in (McPhearson et al., 2022) is a general model of a systemic representation of infrastructures, as part of the technological-infrastructure domain, to analyze direct and indirect, positive and negative influences from the other domains. This framework has been considered to define an upper-level model of an extensible and modular ontology to represent critical infrastructures embedded in a social-ecological-technical system and to model resilience as their ability to cope with all kinds of hazardous interactions, e.g., ecological, as a natural perturbation propagating through the ecological-technological interaction. Cascading failures originated by natural events are intended as (internal) propagations in the infrastructural domain by considering direct (technical) interdependencies. The different interdependencies analyzed in RETURN have been described at conceptual level in DV6.2.1.

The selection of an ontological model addressing the domain and structural requirements has been towards:

- OntoCAPE (Morbach et al., 2008), in the way it has been re-used in the wider open-source project 'The World Avatar' (Kraft, 2023), aiming at the creation virtual models and digital twins to foster interoperability between conceptually connected domains, both in terms of knowledge and data.

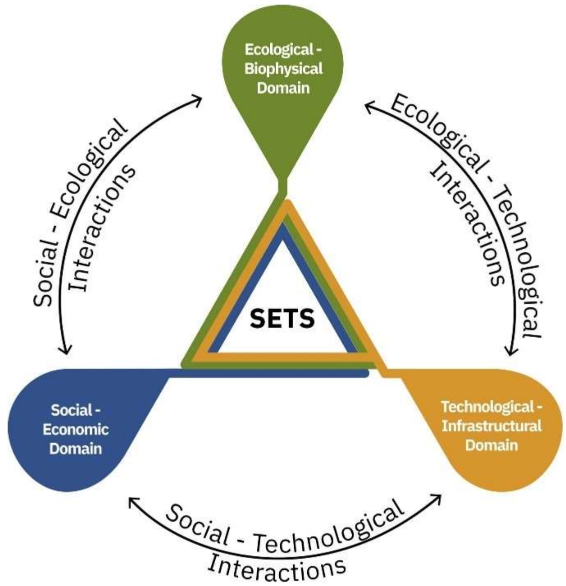

Figure 2: SETS Conceptual framework (McPhearson et al., 2022)

- OntoPowSys (Devanand et al., 2020) – The ontology details the electricity system, which will not be directly analyzed in RETURN. However, the semantic model defined in OntoPowSys to represent a technological infrastructure has been re-used for the RETURN network infrastructures. Furthermore, this ontology is also useful to eventually analyze the dependencies from the electricity system of the water and transportation systems. Finally, the use of this ontology has been demonstrated by the authors to support agent-based analysis in various applications.
- ATU (Du et al, 2023) – A set of open ontologies to represent properties and processes of urban infrastructures to the purpose of sustainable urban infrastructure planning. In particular, the GroundOntology, the PipeOntology and the RoadOntology have been considered and adapted for RETURN.
- SWEET (Raskin and Pan, 2005) and ENVO (Buttigieg et al, 2016) – Represent ecosystems and natural phenomena/processes. These ontologies are largely used as reference in various scientific publications.
- TERMINUS (Coletti et al, 2016) – Provides the ontology model for infrastructure system risk from climate change based on the IPCC risk model.

More specifically, the layered and modular structure of the first two ontologies has been re-used. The layers refer to levels of abstraction from meta-layer (defining a meta-model based on general systems theory) to the application-specific layer (dealing with specific systems such as technical infrastructures). Each layer consists of modules. A module is a model with a few interrelated classes, relations, and axioms, which jointly conceptualize a particular topic (e.g., the module network_system holds a conceptualization of a technical system as a network).

Meta-model layer

This comprises a set of ontologies, mostly taken from OntoCAPE, that provide abstract entities and modelling patterns (i.e., re-usable models) related to design of systems and processes. For example, the model package is concerned with the description of mathematical models, including model variables and items pertaining to sub-models and their connections. Models can be instantiated at application level to defined cost models in economic systems, or equations for load flow analysis. Furthermore, the system ontology is a conceptualization of system and properties, its composition in sub-systems and its relationship with other systems. It also introduces the concept of an aspect system to refer to a particular viewpoint and thus allows partitioning a complex system into manageable parts. The other modules of interest comprise the module network_system to represent a distributed system as a network, the module coordinate_system, as a frame of reference for geolocalized objects, and the module technical_system, defining a technical system as a system that has been developed through an engineering design process. A *technical system*, is modelled through the requirements, functions, realization, and behavior aspect systems. To meet the objective of RETURN:

- *natural_system* and a *socio-economic_system* packages have been added that import the system ontology, to contain modules to describe natural entities and socio-economic entities as systems.
- The *resilience aspect* in the aspect_system package has been added as a new module.

The system ontology also specifies constructs to represent the relation of a system with its environment.

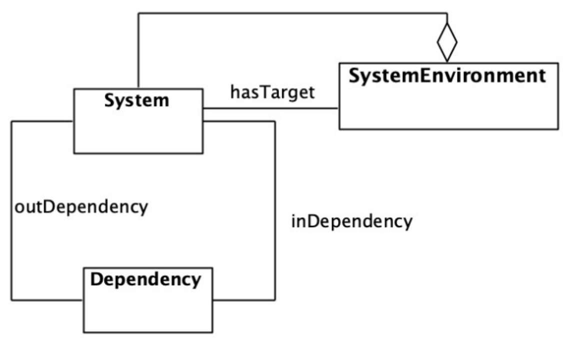

Figure 3: System environment

Figure 3 illustrates an ontological sub model (left side) at the basis of the SETS model. Given a system, its system environment is any aggregation of other (sub)systems that have direct dependency relations (in or out) with the given system. As the environment concept is relative, such class must be further specified for each system instance, e.g., if the focus is on drinking water system, the system environment targeting at that includes the ground system, the electricity system and so on; if the focus is on the road transportation system, its system environment includes the energy system and the weather system. The in and out dependencies allow to formally represent those described in DV6.2.1 – Inventory, Description and Classification of Interdependent Infrastructures and their Critical Assets.

Application layer

This comprises the ontologies that details the specific systems, and their components, of interest to support the analyses of WP5 and Task 6.6.2 of RETURN. An overview of the package organization is provided in Figure 4. Note that the ontology packages specified at the application layer are not exhaustive. The aim is to show that the modular structure allows for the enhancement of the overall ontology by adding new modules and without modifying the existing ones.

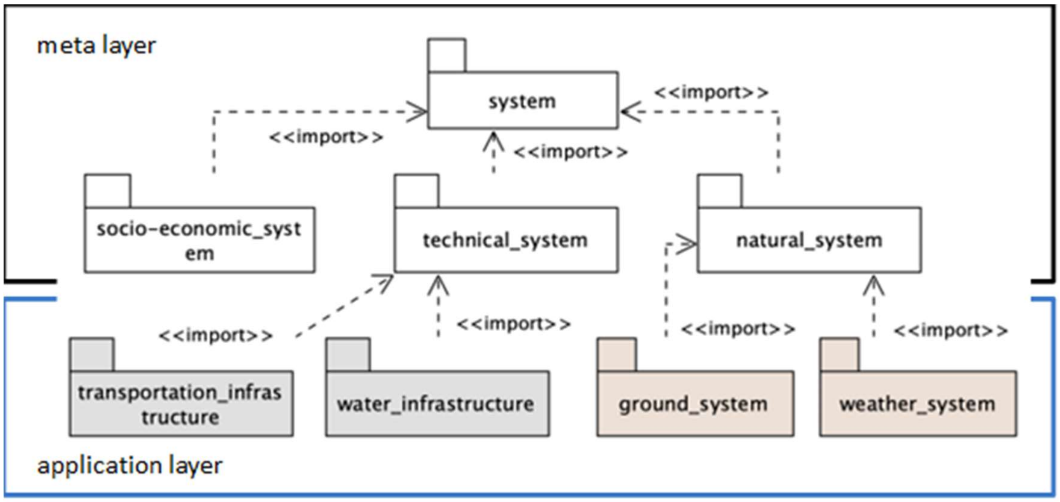

Figure 4: Layered structure of the ontology packages organization

2.2.3.2 The critical infrastructure model

For the semantic representation of a critical infrastructure, we adopted and abstracted OntoPowSys, which is publicly available and was originally defined for power systems, to be applicable to other infrastructures. In particular, the aspect_system allows to differentiate between: *SystemRealization*, i.e., the representation of the physical components and their properties; *SystemFunction*, i.e., the representation of the functions provided by the physical devices; *SystemBehaviour*, i.e., the description of the state model of the system; *SystemModel*, i.e., the analysis models; *SystemPerformance*, i.e., the description of performance KPI; and the additional aspect *SystemResilience* as a sub-class of *SystemPerformance* to highlight the resilience KPIs.

Note that not all these aspects necessarily need to be detailed and evaluated for each critical infrastructure; depending on the specific application, one may choose which ones to use.

As an example, Figure 5 presents a fragment of the drinking water system realization model.

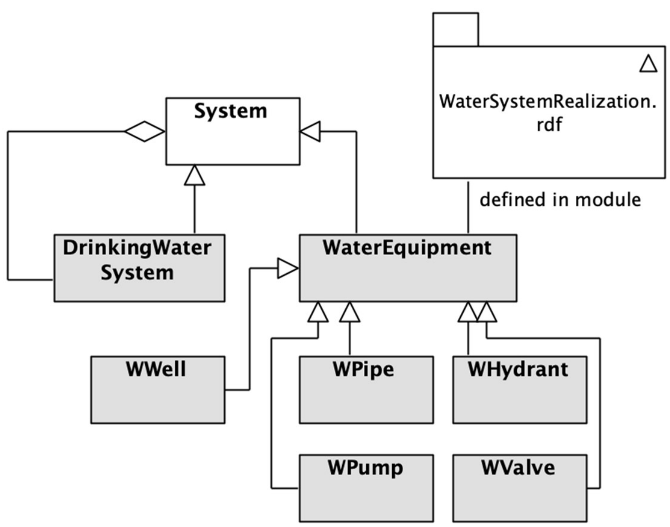

Figure 5: Main components of the drinking water system realization

By means of the NetworkSystem ontology constructs it is possible to represent the network structure of the DrinkingWaterSystems, where the components are all of type Node and connections are specified through the property isDirectlyConnectedTo, e.g., a pipe is directly connected to two other nodes. This representation could be useful to annotate the model used by a simulator of a drinking water system. Currently, the semantic annotation of the simulation network model is not required to support the planned analyses for the case study, hence such annotation has not been created.

The Property class of the system ontology allows to detail the various properties that are of interest for the application domain. The ATU ontology provides such models for pipes in the PipeOntology, namely the PipeProperty taxonomy and the PipeProcess types, which describes the processes influencing the properties (e.g., pipe cracking influences the pipe leakage rate)

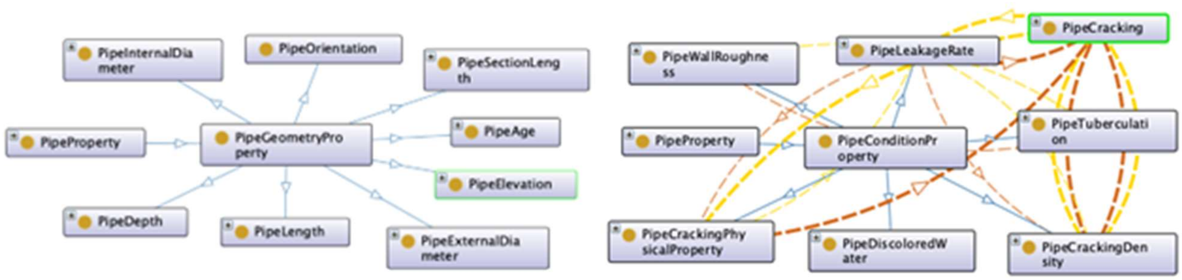

Figure 6: Fragments of semantic models of the pipe property entity adopted from ATU ontology: (left) the pipe geometry property hierarchy; (right) the pipe conditions and their links.

Other than the geometry, other properties of interest refer to the material and the condition of operation, e.g., the pipe cracking process impacts on the failure rate property of the pipe.

The *SystemModel* aspect allows linking the type of analysis model, e.g., a specific mathematical model, to an entity of the system to support analyses. This linkage is useful to an analyst both for identifying which models are available to compute a certain quantity related to a given entity (e.g., the impact model of a pipe leakage used by a simulator) and for tracing the results of analyses back to the originating models.

2.2.3.3 The systemic risk scenario model

One objective of the knowledge graph is to support hazard scenario impact analyses that may involve one or more on critical infrastructures, leveraging their interdependencies. A fragment of the scenario model that focuses on the hazard assessment is represented in Figure 7. The class HazardEvent, is intended for the occurrence in time and space of some critical (external) event for a system, related to some Hazard. An HazardEvent may trigger a perturbation in the SystemEnvironment, (negatively) influencing the relation between the system at hand and its environment. For example, strong wind may cause a damage to the electricity system, hence interrupting the supply to the water system (the focus of the analysis). The extent of such a perturbation, i.e., the intensity of the stress, may be assessed through a mathematical model, if any.

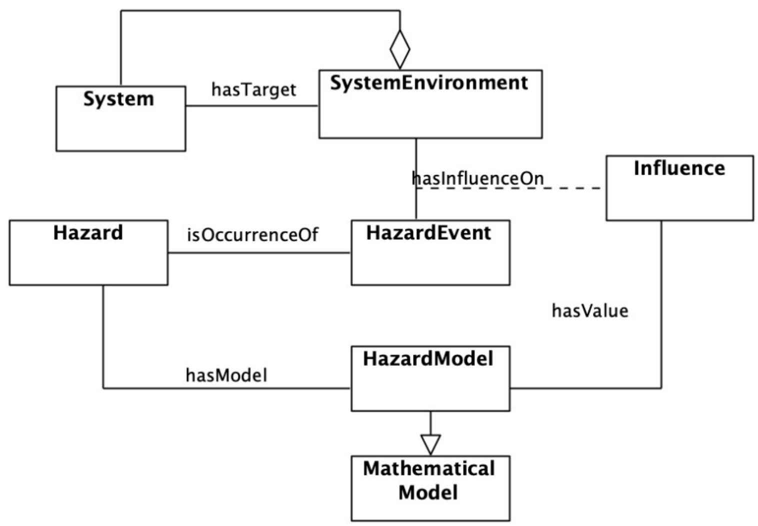

Figure 7: Hazard scenario

The evaluation of the impact of such a perturbation on the system functioning requires vulnerability models associated with the various system components. For hazards such as earthquakes and landslides, these models are named fragility functions, they are hazard-specific and allow to compute possible damage values (and hence serviceability based on functional, physical and contextual properties. The semantic model to represent fragility functions associated with system components is shown in Figure 8.

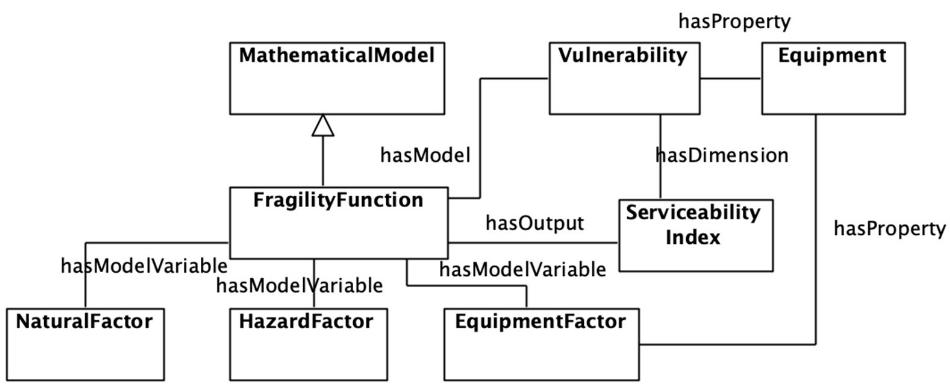

Figure 8: Vulnerability model

The foreseen physical damage, or the related serviceability index, is then used as input for a numerical/simulation model of the infrastructure to assess the impact of equipment disruptions on the service. The knowledge graph is useful here to trace the results of the overall scenario analyses. As shown in Figure 9, a Scenario is defined by a HazardEvent and evaluates resilience performance metrics by considering (impacted) equipments and consequent service loss computed through system simulations.

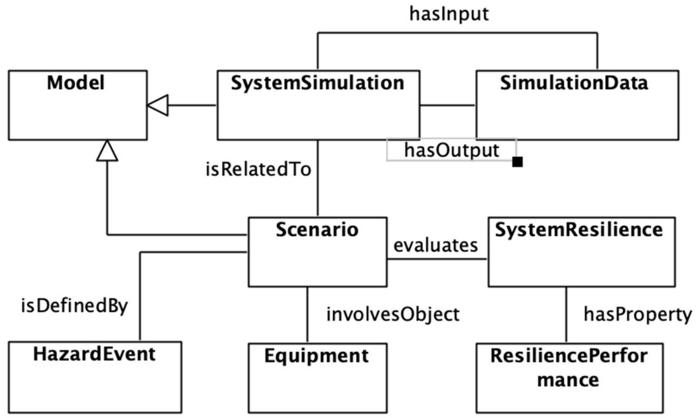

Figure 9: Scenario model for resilience analysis

It should be noted that the detailed configuration of the simulations is out of the scope of the knowledge graph, i.e., the simulation data may consist of a descriptive text or a link to text files containing the simulation parameters.

2.2.4 Knowledge graph application

A software prototype application for generating earthquake scenarios and configuring the drinking water infrastructure simulator of the city of Parma with damage predictions has been developed based on the semantic models presented in Subsection 2.3.3. The software architecture and the implemented process are described in the following.

2.2.4.1 Software architecture

While the design of the ontological component of the knowledge graph is being updated and refined through an iterative development process, a concrete architecture outlining the enabling technologies and data flow for the knowledge graph has been defined, as shown in Figure 10.

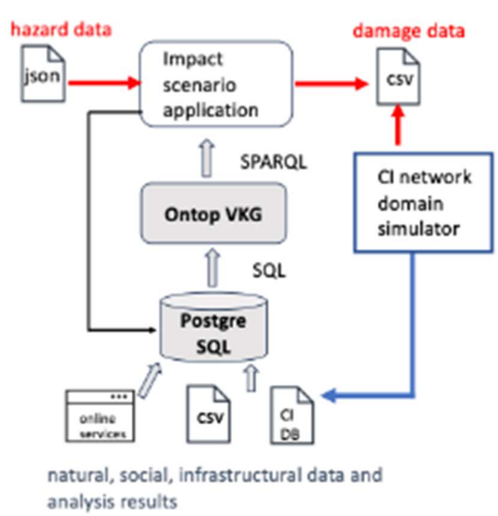

Figure 10: Software architecture for impact scenario generation

The architecture has been broadly designed to support interaction with various CI network domain simulators, although the current goal is to test it on a specific case study with the simulator of a drinking water network.

The technical solution requires the import of data from various sources into a Postgres/PostGIS database and the mapping of these data to the semantic layer of the knowledge graph by means of the Ontop technology (Xiao et al., 2020). The last is a mature open-source technology designed for creating virtual knowledge graphs. It enables seamless access to data stored in their original databases by automatically translating semantic queries (written in SPARQL) into SQL queries. This approach allows us to keep the data of the analysed infrastructure in the same database schema as that used by the domain simulator, thus making data alignment easier during analyses.

The *Impact scenario application* is a software component designed to identify the infrastructure components most vulnerable to a specific hazard by supporting a what-if scenarios approach. Given a hazard event specification as input for a risk scenario, the application supports the evaluation of fragility functions associated with the infrastructure components to quantify their potential damage levels. This data is used to configure simulation runs for impact analysis. The results of the analysis of the performed simulations can be stored in the knowledge graph database for future use. The communication between the application and the domain simulator is done through files (e.g. in json or csv format), as the simulations need to be run in batch mode and the analysis of the results is not automatic.

2.2.4.2 Data Ingestion for the case study

For the specific application regarding the impact of earthquake scenarios on the pipes of the drinking water system of Parma, the following data have been provided to the knowledge graph.

Database of the CI structure used by the network simulator. This has been obtained through a specific DB export function provided by InfoWorks WS Pro (see Section 2.1.1). The data schema is aligned with the model presented in Figure 5. In particular, the following properties have been provided for the pipes: material, length, diameter and location area.

Ground motion models. A Ground Motion Model (GMM) is a mathematical model used to estimate the expected level of ground shaking during an earthquake. Thus, this model is suitable to implement what-if impact scenarios given hypothetical earthquake events. The model predicts some transient ground motion parameters, such as peak ground acceleration (PGA), and peak ground velocity (PGV), which are the commonly used parameters to evaluate vulnerabilities of CI physical assets.

Various GMM implementations exist, produced empirically from studies of specific earthquakes. Some of these implementations are provided by the ITACA GMM web service managed by INGV (Italian National Institute of Geophysics and Volcanology) at the URL https://itaca.mi.ingv.it/itaca40ws/gmm/1/query-options.html. The implemented models include the well-known model ITA18 (Lanzano et al., 2019) for Italy, which outputs the predicted values of PGA and/or PGV and the associated total standard deviation in specified geographical locations, given an earthquake event message, described by: magnitude and rrup (rupture distance), the shortest distance between the site of the pipeline and the surface of the earthquake rupture, or the rjb (reverse-joint boundary distance), the distance from the surface projection of the seismic source (hypocenter) to the site of the pipeline. These metrics are illustrated in Figure 11, where the station is a generic location near the surface, for example the centroid of a pipeline.

Once identified a set of earthquake events for the case study, e.g., from historical records of the INGV database, the ITACA service can be used at run time by our system to retrieve the PGV (or PGA) parameters associated with the pipelines locations.

Another relevant metric for earthquake ground motion assessment is PGD (Peak Ground Displacement), which refers to the maximum displacement of the ground during an earthquake. This metric is not provided by the ITACA web service, however plausible values for the simulations could be pre-defined with support by the experts of the RETURN project.

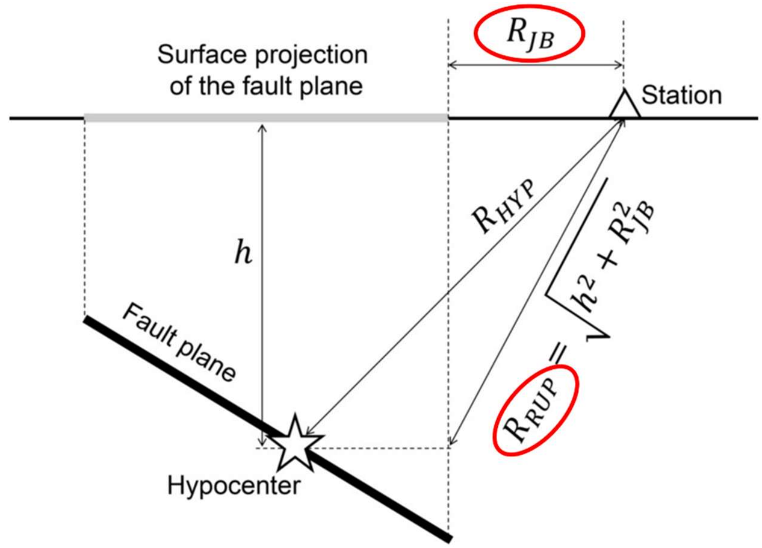

Figure 11: Metrics to evaluate PGA and PGV at the location of a Station – image from (Weatherill and Burton, 2010)

Buried pipeline vulnerability models to earthquakes. These models and guidance for their usage have been obtained from the Hazus Earthquake Model Technical Manual (FEMA, 2024). The Hazus Earthquake Loss Estimation Methodology is implemented in a GIS-based software, provided by FEMA, for estimating potential losses from earthquake events. The entire software has not been integrated in our architecture because our needs are solely to obtain examples of fragility curve models for the infrastructure components considered in RETURN. In the future, these functions may be replaced with more accurate models, if they become available.

The recommended functions relate pipeline damage with seismic parameters, such as PGV or PGD, where the last has been associated with the liquefaction phenomenon. Pipeline damage is generally expressed as a linear pipe repair density (RR), which, for wave propagation, is computed as:

$$\mathrm{RR[rep/km]} \cong \mathrm{K} * 0.0001 * (\mathrm{PGV})^{2.25}$$

where K=1 for brittle pipelines, and K=0.3 for ductile pipelines (steel, ductile iron, and PVC). That is, ductile pipelines have 30% of the vulnerability of brittle pipelines.

A similar equation model allows to estimate the damage from the PGD for ground failure.

$$\mathrm{RR[rep/km]} \cong \mathrm{K} * 7.821 * (\mathrm{PGD})^{0.56}$$

It should be noted that these models differ only based on the pipe materials. A subsequent model (ALA, 2001a,b) assigns different values in the range [0,1] to the coefficient K, considering the soil (corrosive or non-corrosive) and the diameter of the pipe (small or large).

These models assume that damage due to wave propagation will consist of 80% leaks and 20% breaks, while damage due to ground failure will consist of 20% leaks and 80% breaks.

From the RR, one can compute the estimate number of damages over increasing km thresholds of pipelines covering the surface of the city. Furthermore, HAZUS suggests the serviceability index defined by a conjugate lognormal function (i.e., 1 - lognormal function) modelling the damage function. This damage function has a median of 0.1 repairs/km and a beta of 0.85. Hence, it is possible to estimate the probability of service breaks above some average rate, by using this lognormal distribution of damage.

2.2.4.3 Use case implementation

A python application has been developed to implement the earthquake scenario generation and estimation of impacts on repair rates of water pipelines of the Parma network. The software is generic, allowing it to be reused for various infrastructures by retrieving as much information as possible from the knowledge graph.

The application implements the following workflow:

1. Earthquake scenario configuration.
2. Evaluation of the influence of the earthquake event on the system environment.
3. Assessment of damage to the water pipelines.

Earthquake scenario configuration. The application receives as input a message of type EarthquakeEvent with the detail of the event: epicenter, magnitude, depth and fault-line. A Scenario instance is created specifying the Drinking Water System as a target critical infrastructure.

Evaluation of the influence of the earthquake event on the system environment. The ontology pattern in Figure 12 of the knowledge graph can be used to retrieve the GroundSystem from the SystemEnvironment that is directly affected by the EarthquakeEvent, and the GroundMotionModel as the mathematical model to evaluate the EarthquakeInfluence on the WPipe instances.

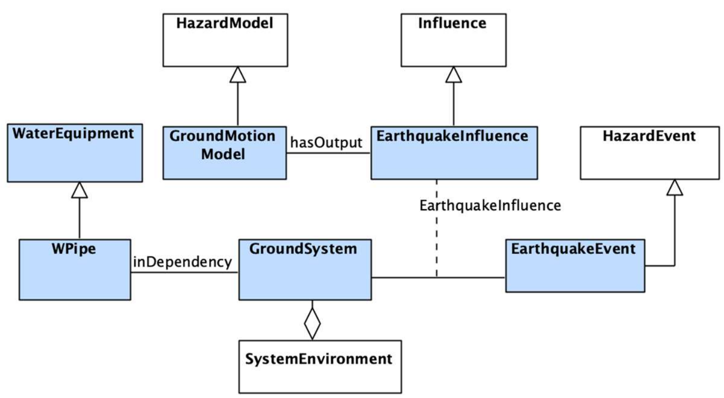

Figure 12: Ontology extension for earthquake assessment on the water pipes of the drinking water system

The implementation of the GroundMotionModel is in a python class that computes the PGV and/or PGD values for each water pipeline of the network, if known.

Assessment of damage to the water pipelines. Similarly, the FragilityFunction model instance for the WPipes is retrieved following the ontology pattern in Figure 7. This model, implemented in python, computes the repair rates of the pipes by using the properties required (material if HAZUS fragility function model is used). The output is a list of type [Pipe -> (type of damage, probability of damage)], that can be delivered in json format.

2.3 Workflow

The workflow diagram shown in Figure 13 summarizes the structured approach for assessing the impact of various natural hazards on critical infrastructure through scenario-based simulations. This approach integrates a knowledge graph and a simulation manager that interfaces with commercial domain-specific simulators. The scenarios are identified by WP3 or the Vertical Spokes, while the knowledge graph and enhanced domain-specific simulators are introduced in Sections 2.3 and 2.2, respectively.

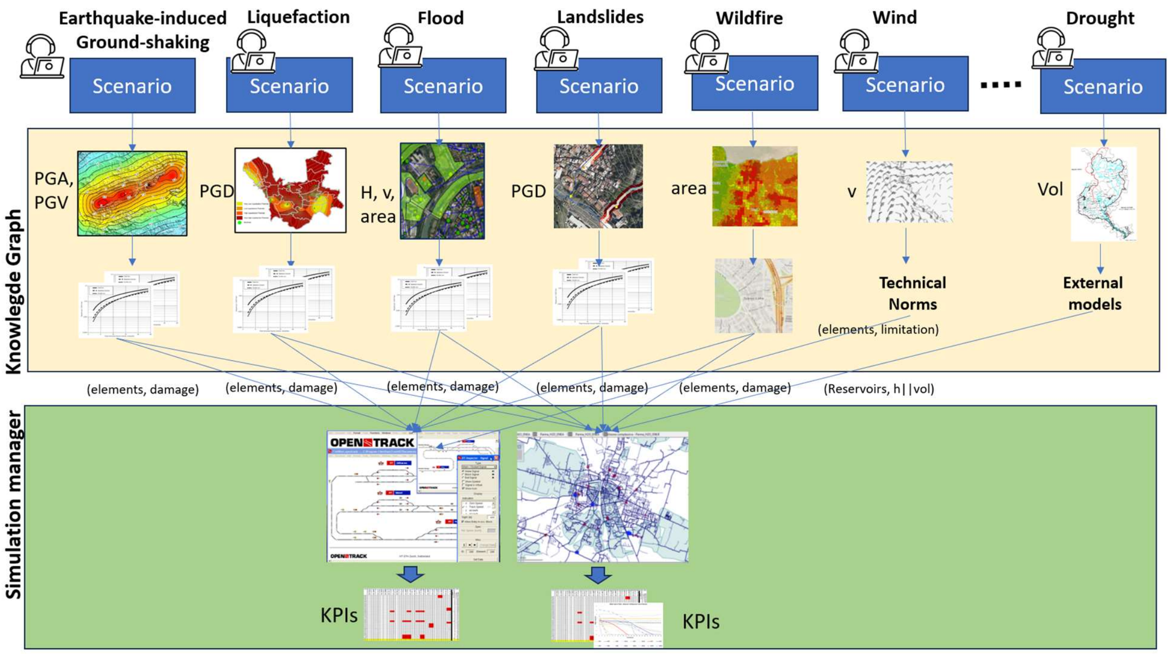

Figure 13: Workflow of the information processing in the simulation environment

At the top level, different **natural hazard scenarios** are considered, including: earthquake-induced ground-shaking, liquefaction (typically a consequence of other natural events), floods, landslides (potentially triggered by natural events), wildfires, wind hazards, drought, and potentially other hazards.

Each scenario provides specific hazard-related parameters to the system, such as:

- PGA (Peak Ground Acceleration) and PGV (Peak Ground Velocity) for earthquakes
- PGD (Permanent Ground Displacement) for liquefaction and landslides
- H (Water Height), V (Velocity), and Area for floods
- Area affected for wildfires
- V (Wind Speed) for wind hazards
- Vol (Volume of Water, in Mm^3) for droughts

The **Knowledge Graph** serves as an intermediate processing layer, integrating:

- **Hazard Data Inputs:** Maps, technical data, and hazard-specific metrics
- **Fragility Curves:** Linking hazard intensity to the probability of damage for different infrastructure elements, representing the vulnerability of each component under specific conditions
- **Technical Norms:** Defining constraints and performance limitations for infrastructure
- **External Models:** Supporting complex scenarios like droughts, where hydrological models are required

The output from the Knowledge Graph includes:

- **(Elements, Damage):** Mapping infrastructure components to their corresponding damage levels under various scenarios

- **(Elements, Limitations):** Constraints on infrastructure performance, such as maximum train speeds based on wind conditions
- **(Reservoirs, h|vol):** Data on reservoir conditions, including water levels (h) and volumes (vol)

The **Simulation Manager** integrates damage data into operational domain simulators, such as OpenTrack for railways, InfoWorks WS Pro for water systems, and other simulators for infrastructures like energy networks. Its functions include:

- **Operational Simulations:** Modelling the performance of damaged infrastructure under different conditions, accounting for cascading failures both internal (e.g., loss of power affecting water pumps) and external (e.g., train delays causing further disruptions)
- **Scenario Evolution:** Dynamically adjusting simulations to reflect the evolving impact of cascading failures across interdependent networks
- **KPI Generation:** Producing Key Performance Indicators (KPIs) that evaluate system performance under each scenario, including metrics related to service availability, recovery times, performance degradation, and overall resilience

2.4 Final remarks

For decades, risk assessments have been conducted in isolation, focusing on singular hazards without accounting for the complex interplay between different threats. However, as extreme weather events increasingly overlap – such as wildfires followed by flash floods – a **multi-risk approach** has become essential for enhancing the resilience of critical infrastructure. The framework presented in this report integrates multi-hazard risk scenarios with domain-specific simulators, allowing for comprehensive analyses that reflect real-world complexities.

This framework could leverage the interdisciplinary contributions of experts across diverse fields, including **geologists, geotechnical engineers, structural engineers, architects, economists, meteorologists, wind engineers, civil engineers, hydrologists, social scientists, emergency planners, GIS specialists, and policymakers**. This collaborative approach ensures that various perspectives and areas of expertise inform the resilience assessment process.

At the core of the framework are the enhanced domain-specific simulators and the Knowledge Graph, which together effectively bridge hazard data with technical standards and vulnerability models. This integration enables dynamic management of cascading effects within the simulation environment, capturing how failures in one system can propagate and impact others. The use of Key Performance Indicators (KPIs) further strengthens this approach by providing quantitative insights that support resilience assessment and strategic planning.

The framework's modular architecture ensures that improvements at any level are automatically propagated throughout the system. For example, while fragility curves – either empirical or derived from three-dimensional nonlinear finite element models – are currently used, advanced modelling techniques incorporating artificial intelligence (AI) and machine learning (ML) could also be integrated, given the great potential they have shown (Rahbaralam et al., 2020; Asadi, 2024). These techniques enhance predictive capabilities by forecasting infrastructure failures based on factors such as age, material composition, soil conditions, and pressure fluctuations, thereby offering significant opportunities to improve the framework's accuracy and effectiveness.

Moreover, predictive models and simulation tools play a crucial role in disaster preparedness. Accurate forecasting and scenario analysis are foundational to anticipating failures, coordinating effective responses, and ultimately strengthening the resilience of critical infrastructure systems in an era of increasing climate-related risks. They enable utilities, governments, and disaster response teams to adopt risk-based approaches that improve their ability to protect, detect, respond to, and recover from all hazards – before disasters strike.

3. Drinking Water Distribution Network

This section details the features of the simulation environment for the drinking water distribution network. However, it is important to note that wastewater and gas networks share similar characteristics, including some fragility curves. Additionally, the referenced sources provide insights into electric infrastructure, wastewater networks, and oil and gas systems, extending the applicability of the concepts discussed here beyond drinking water distribution.

Section 3.1 highlights the most relevant aspects in modelling the physical infrastructure in our proof-of-concept study and integrating the effects of natural hazards. Section 3.2 then examines the relevant natural hazards for water infrastructure and explains how their effects are quantified and incorporated into the model.

3.1 Modelling the Infrastructure

The drinking water distribution network of Parma is briefly described in DV6.2.1 Section 4.1.1, providing an overview of its general functioning and key assets. The network serves approximately 197.191 inhabitants, distributing around 22 million cubic meters of water per year, with an average flow rate of 700 l/s. Water is sourced from wells, while storage tanks ensure sufficient reserves to accommodate peak consumption, primarily in the morning and evening. Wells are commonly used as a primary or supplementary water supply source in many cities. The Parma aqueduct's supply, distribution, and service networks span approximately 756 km.

As previously mentioned, the hydraulic simulation model was developed using InfoWorks WS Pro, a commercial simulator for pressurized water networks already in use at IREN. A preliminary digitized model of Parma's aqueduct had been created in InfoWorks at IREN's as part of previous studies dating back to 2018. This existing model was shared to expedite the modelling process, with a primary focus on integrating the effects of natural events. The shared InfoWorks project includes **24.254 nodes, 18.707 pipes, 28 wells, 44 pumping stations, 93.568 users across 8 categories, 2.138 hydrants, and multiple valves**. It also contains geographical information for all network elements and geometric data for most of them.

Figure 14 provides a visual representation of the model within the InfoWorks simulator. However, as the infrastructure details are confidential and this deliverable is publicly available, the figure is intended solely to illustrate the network layout (which largely follows Parma's streets). To protect sensitive information, the locations of tanks, wells, pumps, and other critical components have been concealed. The Infoworks simulation environment has been removed too in order to conceil model's history and comments.

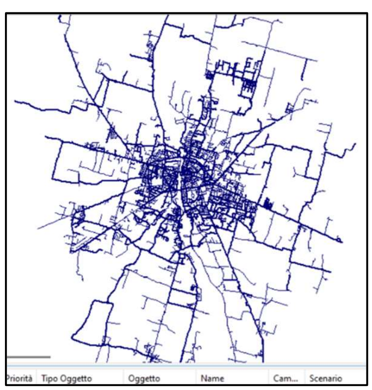

Figure 14: Parma's acqueduct model in Infoworks WS Pro User Interface

3.1.1 Dealing with the quality of data

The use of physical simulators requires the presence of all parameters involved in hydraulic equations. Commercial simulators typically provide common default values or minimum required values. To run a simulation, InfoWorks WS Pro requires three essential data sets:

1. A validated physical network
2. A control set
3. A demand diagram

It is important to note that validation check does not guarantee that the modelled network will yield results matching real-world measurements. Instead, it confirms that the provided data is sufficiently complete and reasonable to attempt solving the hydraulic equations. If the input data lacks coherence, the system of equations may not have a solution, therefore making a successful simulation is the next mandatory step. Furthermore, hydraulic equations may yield mathematically valid solutions that are physically or operationally unrealistic, such as negative pressures, negative velocities, or extremely low pressures. These conditions can stem from trivial errors, such as incorrect pipe orientations, or significant misconfigurations in the network model or control settings, requiring further investigation by the modeler.

The imported InfoWorks project included a physical network but failed the validation check. Discussions with IREN revealed that the model was an outdated draft, and they had no available personnel to improve or support its enhancement. Consequently, several assumptions were made to achieve a validated network, guided by InfoWorks error messages.

Despite being an additional challenge, this process has led to two key benefits:

- **enhanced scalability:** Most of the required information is likely available to any water operator, even though fully calibrated digital models remain uncommon. This suggests that the proof of concept applies to the majority of Italian operators, who typically possess shapefiles and basic network data but may lack advanced hydraulic models. This is even more relevant considering the SINFI initiative (see Section 2.1.2), which mandates that operators acquire and store critical infrastructure data – particularly related to upgrades and expansion works – in a centralized repository. While access is restricted to operators for privacy and competitive reasons, this repository includes detailed information on pipelines (including not only geographical positioning, which generally follows streets, but also diameter, material, and technical construction details), as well as valves, tanks, and pumps which can seamlessly integrate into the model. Lastly, an effort was initially planned to model Genoa's drinking water distribution system to assess the feasibility of applying this methodology in a setting with only shapefiles and no hydraulic model. However, the work conducted in the Parma case study allowed us to develop a step-by-step methodology, reducing the need for additional proof-of-concept work.
- **methodological value and data confidentiality:** While the results obtained may not be fully accurate or entirely reflective of real-world conditions, they remain realistic and sufficient for the project's scope. At the same time, this approach ensures data confidentiality, allowing for the development (and description) of a general methodology that can be adopted by other operators and researchers without exposing sensitive infrastructure information. Any limitations due to modelling assumptions will be explicitly stated where relevant to ensure transparency regarding the network's behaviour.

Checking "Geometry"

That being said, the following is a list of the steps and assumptions made to correct errors and achieve a network that successfully passed the automatic InfoWorks validation check. All modifications have been properly flagged, ensuring full traceability between the original data and the adjustments made.

- First of all, a small disconnected subnetwork was removed, as attempting to infer its connections would not provide any added value. Additionally, a pipeline with identical starting and ending nodes was deleted. As a best practice, it is strongly recommended to prune the network representation into a connected, clean graph as a first step in creating a validated model.

- 98 pipelines were missing the friction coefficient (CW-k), which was defaulted to 0, an unacceptable value. In most cases, the pipeline material was also missing. If the material was available, the friction coefficient was assigned based on the values of other pipes made from the same material. If the material was missing, it was inferred from adjacent pipes, and the CW-k value was set accordingly. While this assumption may not always hold – newer pipes might use more modern materials – it was impossible to determine whether missing data indicated a recent or older installation. If any of these pipes are identified as critical in the risk assessment, further investigation or physical inspection may be warranted.
- 13 measurement components were missing the friction coefficient (CW-k), which was defaulted to 0, an unacceptable value. To ensure consistency, their CW-k values were set to 0.01, matching the values assigned to all other similar components.
- 2 measurement components were missing diameter values. To ensure consistency, their diameters were assigned based on the diameter of the adjacent pipes, in alignment with the approach used for other similar cases.
- 26 valves were missing diameter values. To maintain consistency, their diameters were assigned based on the diameter of adjacent pipes, following the same approach applied to other similar cases.
- the majority of wells generated errors due to incorrect configurations, such as pipelines entering instead of exiting, pumps incorrectly set as inflowing rather than outflowing, or missing associated pumps. These issues were corrected by ensuring proper flow direction and selecting a pump – where necessary – from those already available in the model. While the exact pump model and corresponding data sheet are not strictly mandatory for an initial modelling attempt, as long as the pump provides sufficient head to distribute water effectively, obtaining this information is relatively straightforward if further refinements are needed.
- the majority of uploaded pumps had missing or incorrect parameters. If the issue was due to an incorrect order in the curve description (head vs. rotation, flow vs. rotation), reordering the existing data resolved the problem. If head or flow data were missing, values were copied from similar pumps. Speed parameters (minimum, maximum, nominal speed) were set to the default values suggested by InfoWorks. While the exact pump model and data sheet are not strictly necessary for an initial modeling attempt – as long as the pump provides sufficient head to distribute water properly – this information is relatively easy to obtain for future refinements.
- some hydrants were missing diameter values, which were set equal to the diameter of the connected pipe. Additionally, some hydrants had missing valve diameters, which were assigned as 2/3 of the hydrant diameter, following the same approach used for other similar cases.
- a significant issue was that all storage tank data was missing, including maximum level, depth volume, and minimum depth. Initially, approximate values were assigned to enable model validation. However, upon further consideration, it was decided to exclude storage tanks from the analysis (see below). As a result, these estimated values are not reported.

The model successfully passed the Infoworks validation check and a brief review with IREN confirmed that modification and assumptions made were reasonable.

As a final note, the dataset included three-dimensional coordinates (longitude, latitude, and elevation above sea level) for each network element. If this information is unavailable in another network, InfoWorks allows the integration of a Digital Elevation Model (DEM) to automatically assign elevation values, provided that typical pipeline burial depths are specified. It is also possible to overlap a street map of the city, and then adjust coordinates. Manual modifications are always possible.

Moreover, the dataset contained material data for most pipelines. In cases where such information is missing, an inventory of common construction practices can serve as a starting point. Subsequent refinements can then focus on critical network elements, if sensitivity analyses – by testing different material assumptions within the model – confirm their impact on overall resilience.

Running the hydraulic equations

The provided demand diagram accounted for 8 user categories, including residential, non-residential, agricultural and large consumers. However, no hourly, daily or monthly coefficients were provided. While statistical data exists for these variations – and it is acknowledged that the impact of a failure differs depending on the time of day, day of the week, or season – as the present analysis focuses on evaluating the effects of natural events which typically span multiple days, all the coefficient were set to 1, assuming constant network behaviour and reducing the number of required simulations for each scenario. Although this assumption is sufficient for the current scope, it can be easily refined using statistical data, if available, or by consulting the network operator, who definitely has this information.

The shared Infoworks project included a control set file, but it was empty. Despite this, it was still sufficient to initiate the simulation.

A test simulation was run for a few hours on a random day, and the hydraulic equations successfully converged, confirming that the geometric configuration of the model was correctly set. However, the resulting hydraulic parameters were operationally unacceptable, with only a minimal amount of water circulating in the network. A quick review revealed that the empty control file had set all pumps to OFF and all valves to OPEN, meaning that only the water in the storage tanks was circulating, limited by elevation constraints (z-parameter) relative to user connections. Upon contacting IREN to obtain the correct control file, it was confirmed that no such file was available.

"Calibrating" the model in normal conditions

The next step is to configure the control file to ensure that all hydraulic parameters under normal conditions are operationally acceptable.

More specifically, the goal is to maintain positive pressures and velocities, ensure that all nodes are connected and served, and guarantee that each node with demand has a head at least 30 meters above its elevation (z). These parameters have been verified with InfoWorks support team. While additional operational constraints exist – such as optimizing pump energy consumption, managing water withdrawals, and balancing pressure to adequately serve users while minimizing losses – these aspects are beyond the scope of this study. They are more closely tied to business considerations rather than operational feasibility and would require extensive collaboration with the specific network operator. Additionally, maintaining a constant demand simplifies the process by reducing computational time, as the control settings would otherwise need to be checked and fine-tuned for each hour of the year.

To ensure proper water distribution, the first step was to set all pumps to operate at a medium level and prevent them from switching off. Although this may not reflect the exact real-world behaviour, it is a common practice. Except in cases where storage reservoirs are positioned at significantly higher elevations than the service area, water distribution typically requires at least some pumping. In most networks, water is pumped at a relatively constant rate, with any excess flow being stored in elevated tanks.

Additionally, the water level in wells was set to remain constant at 10 meters below the lowest elevation point (32m). While the exact water level is not a critical parameter – except for determining the minimum pump head, which is typically well-dimensioned – the assumption of a constant water level is more significant. In reality, water levels fluctuate, often compensated by storage tanks, and could be significantly affected during prolonged droughts. However, setting wells as "always full" facilitates making the model operational in the absence of real-world control data. A sensitivity analysis on water level variations will be conducted in Task 6.2.4 to assess potential impacts of drought.

A key assumption in the model is the exclusion of storage tanks by setting them as empty and closing all valves connecting them to the network. This decision followed extensive discussions. The available information on storage tanks was extremely limited, with only their geographical locations known. Further attempts to locate them via satellite imagery on Google Maps and Google Earth were unsuccessful, likely due to their placement within buildings. Although estimating their volume was a possibility, storage tanks play a strategic role in network operations. Since water is pumped at a relatively constant rate, excess flow is stored in elevated tanks, which also serve as reserves for fire flow and emergency supply in case of power failure or pump outages. Any assumption regarding their characteristics would significantly alter network behaviour and resilience. Additionally, while storage tanks are vulnerable to various natural hazards (see Section 3.2.2), their actual vulnerability depends heavily on construction parameters that remain unknown. Finally, obtaining accurate volume and geometric data for storage tanks should be relatively straightforward. For these reasons, it was deemed more appropriate to exclude storage tanks from the model and analyse network behaviour without mitigation measures rather than introduce potentially misleading assumptions about tank robustness or vulnerability.

With these control settings and a series of fine-tuning iterations, the simulation achieved the desired behaviour, ensuring that all users remained connected, pressure levels were adequate, and demand was fully satisfied.

Final remarks

When speaking with operators, it is common to hear that they do not have precise information about the pipes in their network. This often occurs when a utility takes over a system previously installed by another entity or when documentation for certain network sections has been lost.

In such cases, after removing all disconnected sections and, if possible, dividing the network into districts, the next step should be to collect flow and pressure measurements at all district boundaries, in addition to the standard data regularly acquired (such as water volume supplied, consumption levels, and pressure readings).

The following step is to run a batch simulation that systematically varies pipe diameters (considering that diameters are discrete) until the simulated parameters align with the measured values. However, it is important to note that friction parameters depend not only on pipe material but also on age and soil-induced corrosion. Therefore, some discrepancies between the model and real measurements should be expected, especially in the initial calibration attempts.

Due to time constraints, this procedure was not tested during the RETURN project for modelling Genoa's water distribution network. However, these insights may serve as a valuable reference for future studies.

3.1.2 Interfacing InfoWorks WS Pro

As anticipated in Section 2.1.3, InfoWorks WS Pro allows users to automate repetitive tasks, customize workflows, and extend the software's capabilities beyond standard features through scripts written with Ruby programming language. By leveraging Ruby scripting, users can manipulate network data, perform complex calculations, and create customized analyses tailored to specific project needs. The main limitation is that scripts are meant to be launched from within the InfoWorks user interface, aligning with the software's current business model. However, until 2020, API access was available for purchase, allowing external applications to interface with InfoWorks through a command called Exchange. While the Exchange command still exists, it is no longer wrapped within an official API. Despite some differences between internal Ruby commands and those executed externally – particularly in referencing the correct network – it remains possible to develop scripts that control network data (both geometric and operational parameters) and extract key simulation results from the output tables.

The Simulation Manager (see Figure 13) is implemented in Java. For each analysis, it calls InfoWorks with a script and its parameters, processes the results, determines the next set of simulation parameters, and relaunches the simulation as needed. Additionally, the Simulation Manager calculates the KPIs, ensuring a structured evaluation of system performance.

This approach enables InfoWorks WS Pro to be used as a trusted solver for hydraulic equations, leveraging its computational accuracy while maintaining full traceability. Furthermore, all simulations remain stored within the InfoWorks folder, allowing operators to manually review and analyse them when necessary.

3.1.3 Adding damages

Commercial hydraulic simulators are designed to model undamaged systems. However, by enabling automated control over network data, it becomes possible to adjust parameters or introduce additional elements to account for faults caused by natural events.

Some water system components, such as pumps, simply go out of service, a condition that is already supported in most commercial simulators. Similarly, valves can be easily set to open or closed, depending on the desired simulation scenario. The knowledge graph (see Section 2.2) can efficiently identify impacted components and instruct the simulation manager to adjust their status accordingly.

Pipeline damage, on the other hand, requires a more complex modelling approach. Pipeline failures can be categorized as either leaks or breaks (see Section 3.2.2). A **break** refers to the complete separation of a pipeline, preventing any flow between the two adjacent sections of the broken pipe. A **leak** is a smaller failure, such as a pinhole, crack, or minor joint separation, where water continues to flow through the pipeline but with reduced pressure and some water loss (ALA, 2001a). In both cases, water is discharged through the damaged section, and the extent of the leakage determines whether the pipeline can still function.

To simulate leaks, scripts were used to insert a hydrant at the midpoint of every pipe. When the hydrant is closed, the network operates as if no damage is present. To simulate a leak, the hydrant is opened, and the simulator applies the appropriate equations – based on pressure and opening diameter – to calculate the volume of water lost into the surrounding soil. If necessary, this parameter can be fed back into the knowledge graph to activate liquefaction modules where relevant. Simulations can be conducted with different hydrant diameters to account for various types of leaks and their respective probabilities.

Simulating breaks requires a different approach, as hydrants allow water flow to continue, albeit at reduced pressure. Even when fully open, hydrants discharge only about 60% of the total flow. To accurately model complete breaks, Infoworks WS Pro provides a rupture mechanism, which cannot be embedded directly into the network model but can be activated through scripting when needed. The rupture function accurately represents pipe breaks by preventing water flow between two adjacent sections, causing pressure loss and node isolation. It is important to note that these features may not be available in other commercial simulators. For instance, they were not supported in PSS Sincal, a commercial hydraulic simulator we used in a previous project (Lavalle et al., 2020). In cases where such functionality is missing, a workaround involves introducing a fictitious load with zero demand under normal conditions, which can be adjusted accordingly in the event of damage.

Finally, although storage tanks are not included in our network model, it is worth mentioning that modelling tank failures presents additional challenges due to the variety of potential failure modes. For instance, a closed pipe and a fictitious load may need to be added to account for cracks, whereas a tank that completely loses its contents could be modelled as isolated. While this may suffice from a hydraulic modelling perspective, the additional consequences of tank failure – including the water lost in the surrounding soil – should be further analysed using the knowledge graph.

3.2 Modelling the effects of Natural Hazards

3.2.1 Relevant hazards

Climate change is one of the greatest challenges to global water security. It intensifies the frequency and severity of natural hazards, placing increasing stress on water infrastructure.

On one hand, climate change introduces new hazards that alter water availability and quality. Rising temperatures contribute to glacial and snowpack melting, reducing freshwater supplies for downstream communities, while rising sea levels increase the risk of saltwater intrusion into coastal aquifers. Changes in precipitation patterns lead to more frequent droughts in some regions and extreme rainfall in others, disrupting water distribution. The intensification of extreme weather events, including floods, and wildfires, further threatens water infrastructure by increasing exposure to damage and operational disruptions.

On the other hand, hazards that already existed, such as landslides and liquefaction, are exacerbated by climate change. For example, floods can trigger landslides, while liquefaction risks increase when the ground remains saturated with water for extended periods, typically due to persistent heavy rainfall or flooding, weakening soil stability and increasing the likelihood of failure. Even hazards that are independent of climate change, such as earthquakes, can interact with climate-driven factors, leading to compounded impacts. For instance, earthquake-induced landslides can be worsened by wildfires that weaken soil stability.

Some infrastructure damages are relatively straightforward. Earthquakes can rupture pipelines, including large transmission pipelines that transport drinking water from treatment plants to consumers, causing network-wide disruptions. Liquefaction poses a significant risk to underground pipelines, as seen during the 2011 Christchurch earthquake in New Zealand, where widespread liquefaction damaged water pipelines and disrupted supply (Cubrinovski et al., 2014). Droughts reduce reservoir levels, causing supply shortages and leading to water restrictions.

Other damages are less direct but equally critical. Flooding can submerge pump stations and damage buildings housing control centers, delaying system restoration. Wildfires can damage pipelines and contaminate water supplies with ash and debris. During the 2018 Camp Fire (Proctor et al., 2020) in California, extreme heat caused the thermal degradation of plastic pipes, leading to the leaching of volatile organic compounds (VOCs) into the water system. Additionally, the loss of water pressure during the fire allowed contaminants, including ash and smoke, to enter the network.

Beyond these direct impacts, cascading effects must also be considered. Flooding, for example, can disable parts of the electrical grid, shutting down pumping stations and complicating system restoration. Earthquakes can rupture gas pipelines, potentially igniting fires, while also damaging water pipelines, which can hinder firefighting efforts by disrupting hydrant supply. These interactions create complex, system-wide vulnerabilities.

This document focuses exclusively on physical and functional damages to water distribution networks. Water quality issues are not considered, as treatment plants are addressed by another research group (see DV6.2.2 and WP4). If needed, the simulation environment could account for water quality failures by deactivating wells or reservoirs linked to a damaged treatment plant. However, boil-water advisories alone would not be modelled, as they do not directly impact hydraulic equations.

Similarly, this document does not present models for debris flows, rockfalls, or avalanches, as they rarely affect buried water distribution infrastructure. If a specific water system component, for example a storage tank, is found to be vulnerable to these types of landslides, the HAZUS methodology recommends developing a site-specific hazard model.

Finally, we recognize that extreme weather events increasingly overlap and interact in unpredictable ways. While risks to water systems have traditionally been assessed in isolation, a multi-risk perspective is essential for resilience. Our approach explicitly accounts for these interdependencies: the knowledge graph facilitates this integration by combining the effects of multiple hazards, including secondary impacts such as landslides and liquefaction triggered by damage to the water network.

For clarity, however, the following subsections will examine each hazard separately. The approach remains general: the system is configured for all hazards, and the relevant functionalities are activated as needed.

3.2.2 Hazard-induced damages

This section briefly summarizes how the most relevant natural hazards impact key infrastructure components, including pipelines, pumping stations, storage tanks, and valves, highlighting how different materials, structural features, and environmental conditions influence damage severity.

A more detailed review can be found in the results of the Syner-G project (Pitilakis et al., 2013; Maria et al., 2010; Kakderi and Argyroudis, 2014), which conducted a comprehensive analysis of seismic vulnerability assessment methodologies. The project validated these methodologies using damage data from recent European earthquakes and identified the most suitable approaches for European infrastructure. Although the project dates back to 2014, the 2024 update of the HAZUS methodology (FEMA, 2024) has largely confirmed its findings, further reinforcing the validity of its approaches and conclusions.

Section 3.2.3 will outline how these damages are incorporated into the simulation.

Earthquake

In general, water systems can experience significant damage during earthquakes, leading to disruptions in potable water supply and emergency response activities such as fire suppression. This has been observed in nearly all past major earthquakes. Even under moderate shaking, water infrastructure is highly susceptible to damage, affecting key components such as supply, storage, transmission, and distribution networks.

Pipelines are the most affected elements, followed by pumping stations, tanks, and treatment plants. Facilities such as water treatment plants, wells, pumping stations, and storage tanks are particularly vulnerable to peak ground acceleration (PGA) and, in some cases, permanent ground deformation (PGD) if located in liquefiable or landslide-prone areas. As a result, damage states for these components are defined in relation to PGA and PGD. Pipelines, however, are more sensitive to peak ground velocity (PGV) and PGD, as their structural integrity is compromised by permanent ground displacement. Factors such as pipe material, joint type, age, corrosion, and burial depth influence the seismic response of water system elements.

Before detailing damage mechanisms, it is important to acknowledge that fire is a common consequence of large earthquakes in urban and industrial areas. Fire suppression systems play a crucial role in crisis management, yet they can be severely impacted by water network failures. The ability to fight fires may be hindered by disruptions in water or roadway networks following major earthquakes. The simulation environment accounts for isolated or non-operational hydrants to support emergency planning for different scenarios.

Pipelines

Pipelines vary based on several characteristics, including location (buried or elevated), material (e.g., ductile iron, steel, PVC, polyethylene, cast iron, concrete, clay), geometry (diameter and wall thickness), coating and lining type, depth, joint type, continuity (segmented or continuous), corrosion (age and soil conditions), and operating pressure. Material selection and pipe sizing depend on factors such as carrying capacity, material availability, durability, and cost.

Brittle materials, such as cast iron or asbestos cement, are significantly more vulnerable to seismic damage compared to ductile materials like steel or ductile iron. A detailed mechanical assessment of material properties is required for an accurate failure analysis; however, in the absence of such data, simplified assessments based on pipeline material can still be informative. Corrosion exacerbates damage, particularly in segmented steel, threaded steel, and cast iron pipes. Older pipes tend to have higher failure rates due to progressive corrosion, which is further influenced by soil conditions. Experience has also shown that deformation is concentrated at bends, elbows, and local eccentricities, particularly under permanent ground deformation. Pressure fluctuations during an earthquake can exacerbate structural weaknesses in potable water pipes. At the same time, potable water pipes are designed to remain pressurized to prevent contamination by keeping external pollutants from entering the system.

It is important to note that state-of-the-art fragility curves do not account for all these parameters, mainly due to the frequent unavailability of detailed data.

Buried pipeline damage is typically quantified as a repair rate per unit length of pipe (e.g., breaks per 1,000 feet), based on ground shaking intensity (PGV) or ground failure severity (PGD). These fragility curves estimate pipe failures owned by water agencies, including street mains, lateral pipes branching to fire hydrants, and service connections up to the meter. They are largely based on empirical observations, supplemented with engineering judgment and analytical formulations.

Two primary damage states are considered for pipelines: **leaks** and **breaks**. As anticipated in Section 3.1.3, small leaks allow continued system operation and have a lower repair priority, whereas major failures necessitate system shutdowns and prevent water flow, requiring immediate attention. For hydraulic network analysis, differentiating between a minor leak and a major failure is crucial. Generally, pipeline failures due to PGD are more likely to be breaks, whereas those due to PGV tend to involve joint pull-out or crushing at the bell, leading to leaks. Breaks are also common where pipes connect to tanks or buildings. In the HAZUS methodology, damage from seismic waves is assumed to consist of 80% leaks and 20% breaks, while damage from ground failure is assumed to be 20% leaks and 80% breaks.

Pumping stations

Pumping stations play a critical role in maintaining water pressure in both transmission and distribution systems. These facilities typically include buildings, intake structures, pumps and motors, pipes, valves, and associated electrical and control equipment. Key vulnerability factors include station size, anchorage of components, equipment design, and availability of backup power. Being complex sub-systems consisting of different sub-components, their vulnerability assessment is based on the fragilities of the sub-components.

Storage Tanks

Storage tanks are located at various points within a water transmission or distribution system and serve functions such as storing water, providing surge relief, and allowing sufficient detention times for disinfection. Their vulnerability depends on typological features including material (concrete, steel, wood), capacity, volume, wall thickness, anchorage, position (at-grade or elevated), roof type, seismic design, foundation type, and construction technique. The height-to-radius ratio also influences seismic response. Operational status is relevant too: empirical studies suggest that tanks filled beyond 50% capacity are particularly susceptible to earthquake-induced damage (Salzano et al., 2003). According to ASCE (1987), the main failure modes for storage tanks include shell buckling, roof damage, anchorage failure, foundation damage, support system collapse, hydrodynamic pressure failure, pipe connection failure, and manhole failure.

Valves

Historically, in-line valves have not been particularly vulnerable to earthquake damage unless the pipelines they are connected to also experience failures. Their seismic performance is typically tied to the integrity of the overall pipeline network.

The following sections will further explore how these damage mechanisms are modeled within the simulation environment and how the results contribute to risk assessment and mitigation planning.

Fault Crossing

Localized permanent ground deformations occur in areas affected by surface fault ruptures. Segmented pipes, such as cast iron pipes with caulked bell-and-spigot joints, are particularly vulnerable to severe damage when crossing surface rupture faults. In contrast, butt-welded continuous steel pipes may, in some cases, accommodate fault displacements of up to a few feet.

The extent of fault-induced displacement is measured as permanent ground displacement (PGD).

According to ALA (2001a, b), pipe breaks are also commonly observed in areas with differential vertical settlements, particularly at transition zones between fill and more stable soil. Additionally, alluvial soils prone to localized liquefaction further increase the risk of pipe failure due to shifting ground conditions.

Liquefaction

Liquefaction is a phenomenon that occurs in loose, saturated granular soils when subjected to strong, prolonged ground shaking. Under these conditions, silts and sands tend to compact and settle, displacing pore water upward. This increase in pore water pressure leads to two primary effects. First, it temporarily reduces the bearing capacity of the soil, weakening structural support. Second, if the pressure becomes high enough, material can be ejected, forming sand boils on the surface and further contributing to ground settlement.

A common consequence of liquefaction is lateral spreading, which occurs when liquefiable soil layers are present beneath the surface, particularly on sloped terrain or near an open cut (such as a stream or roadbed). In such cases, the surficial soils may flow downslope or toward the cut, significantly disrupting buried pipelines and supported structures.

Liquefaction-induced permanent ground deformation (PGD) is measured in terms of vertical settlement, lateral spread, or a combination of both. Areas experiencing lateral spreading often suffer heavy concentrations of pipeline breaks, with damage severity influenced by the orientation of the pipe relative to ground movement. Assessing liquefaction hazards along a pipeline or canal corridor ideally requires site-specific liquefaction analyses. However, a simplified approach can be useful for regional evaluations, though it may not provide sufficient accuracy for detailed site assessments. A thorough liquefaction analysis should estimate both the probability of liquefaction and the expected magnitude of PGD at a given site.

Landslides

Landslides cause permanent soil deformations, leading to severe localized damage to buried pipelines. The risk of landslides increases when earthquakes occur during the rainy season, as saturated soils are more prone to movement. While some landslides may result in minor displacements, others can shift massive amounts of soil (75.000 m^3 or more) over significant distances, damaging entire pipeline networks. The extent of landslide movement is measured in terms of permanent ground displacement (PGD).

Landslides encompass various types, including deep-seated rotational and translational landslides, debris flows, and rockfalls/avalanches. Each of these hazards affects water system components differently:

- Deep-seated rotational and translational landslides pose a major threat to buried pipelines, valves, and vaults. Most previous assessments of landslide-induced damage to water pipelines have focused on this type of movement.
- Debris flows and avalanches are generally not considered significant threats to buried structures but can damage exposed infrastructure such as storage tanks if they occur at high velocities.
- Rockfalls and avalanches can impact above-ground water storage tanks, particularly when large debris strikes the structure at high speed.

Pipelines

Landslides create localized severe damage to buried pipelines. Welded pipelines with bends and local eccentricities are especially vulnerable, as they tend to deform at these points under compression strains. Segmented pipes with rigid caulking are highly susceptible to leakage when subjected to movement. Pipeline damage tends to concentrate at discontinuities such as pipe elbows, tees, in-line valves, reaction blocks and service connections. Locally high stresses can also occur at pipeline connections to adjacent structures (e.g., tanks, buildings and bridges). Age and corrosion will accentuate damage, especially in segmented steel, threaded steel and cast iron pipes.

While empirical fragility curves for pipeline-landslide interactions remain unavailable due to limited field data, numerical modelling approaches have been developed to assess pipeline performance in landslide-prone areas. Advanced three-dimensional continuum-based numerical methods have been used to analyse pipeline response under transverse PGD conditions (Ni et al., 2018).

Storage Tanks

Landslides also pose a substantial risk to at-grade water storage tanks. Even a few inches of settlement can distort a tank's structure, leading to failure, particularly for concrete tanks. Debris flows can cause additional damage if they strike a tank at high velocity. In some cases, rockfalls or avalanches may impact above-ground structures with sufficient force to cause significant structural damage.

Drought

Although household water conservation efforts have led to a decline in average consumption, they remain insufficient to mitigate the effects of sustained drought, particularly as growing populations and increasing demand place further strain on water resources. In addition to assessing how water supply may change due to climate variability and identifying viable adaptation options, **a major concern is the indirect impact of higher temperatures**. Water purification and distribution systems are highly dependent on electricity, and prolonged drought conditions can stress both sectors. An increase in dry days and higher temperatures will accelerate evaporation, decrease water availability, reduce electricity transmission capacity, and increase cooling demands, compounding the challenges for critical infrastructure.

Also, reduced water availability can disrupt multiple sectors due to **cross-sector dependencies**.

- data centres and critical IT infrastructure rely on water for cooling: they use high-capacity heating, ventilation, and air conditioning (HVAC) systems that require potable water to prevent overheating. A sustained loss of water to a communications facility could result in equipment failures, causing service disruptions ranging from minutes to hours while operations are rerouted.
- drought conditions and record-high temperatures have exacerbated the frequency and severity of wildfires, increasing risks to both infrastructure and public safety. Reduced freshwater availability further complicates firefighting efforts, particularly in urban and suburban areas where conventional suppression tactics, such as chemical retardants or controlled burns, may not be feasible. Fire suppression systems, including some hydrants, require minimum water pressure to function effectively, which may not be met if drought depletes local water supplies.
- another critical consideration is the interdependence between fire suppression systems and electricity supply. Municipal water systems rely on electric pumps to maintain pressure in hydrant networks. If wildfires damage power transmission lines, causing outages in urban areas, insufficient power may prevent hydrants from supplying adequate water pressure, hindering structural firefighting efforts. In such cases, emergency responders may have to rely on tanker fire trucks, which are less efficient in large-scale urban fires.
- fire damage to electric transmission and distribution infrastructure can lead to failures in communication networks.
- under extreme drought conditions, where local water sources are depleted, essential services such as hospitals may be severely impacted even if hospitals are a top priority for water restoration following disruptions. Healthcare facilities, including hospitals, clinics, and nursing homes, rely on water for heating, cooling, and ventilation systems, sterilization and sanitation of medical equipment, patient treatments that require water-based procedures, fire suppression and hazardous material decontamination.

To summarize, drought presents a multifaceted risk to water, energy, transportation, communications, and healthcare infrastructure, with cascading effects that extend beyond immediate water scarcity.

3.2.3 Integrating fragility curves into simulation environment

A fundamental requirement for assessing the performance of water infrastructure under natural hazards is the ability to quantify potential component damage as a function of hazard intensity. This chapter outlines the information integrated into the simulation environment, primarily using fragility curves, which represent the most widely accepted approach in risk assessment. Given that we are not specialists in this field, we leveraged results from European and American research projects to incorporate validated methodologies.

A fragility curve is a mathematical expression that defines the probability of reaching or exceeding a specific damage state given a certain level of natural hazard. These curves are a key component of risk assessment, linking hazard intensity measures (e.g., peak ground acceleration, velocity, displacement, wind, etc.) to different levels of structural damage (minor, moderate, extensive, or collapse).

The mathematical expression of the fragility is given as:

$$\mathrm{P}[\mathrm{DS}|x] = \boldsymbol{\Phi}[\frac{1}{\beta} ln \frac{x}{A}]$$

where P[DS|x] is the probability of being in or exceeding damage state DS given a intensity measure of x, A is the median value of the intensity measure for which the component reaches the threshold for damage state DS (i.e., the intensity measure value when 50% of probability value is reached for being in or exceeding damage state DS), β is the standard deviation of the natural logarithm of intensity measure for damage state DS, and Φ is the standard normal cumulative distribution function (ALA, 2001a).

For water infrastructure components – including tanks, pumping stations, and pipelines – fragility curves are derived through empirical data, numerical modelling, or expert judgment. The SYNER-G project (Pitilakis et al., 2013; Maria et al., 2010; Kakderi and Argyroudis, 2014) conducted a comprehensive review of vulnerability assessment methodologies for water system elements in order to identify and validate the most appropriate fragility functions for European infrastructure. Its proposed vulnerability functions provide key parameters, including component classification, damage scale definitions, intensity indices used and fragility curve parameters for each damage state and infrastructure typology.

For each infrastructure component, damage states definitions are related to the functionality of the components, their serviceability in terms of usage (nominal use, reduced use or not usable) and repair capability (usable without repairs, requiring repairs, or irreparable damage). Damage states can also be related to restoration costs (as a percentage of replacement cost), but these costs are beyond the scope of this study.

The following section presents the fragility curves selected by the SYNER-G project. It is important to emphasize, however, that – as previously mentioned in Section 2.3 – **fragility curves can be replaced if more advanced damage prediction models become available**. For example, analytical fragility curves, which rely on simulated structural responses under increasing earthquake loads, offer reduced bias and greater reliability compared to expert judgment alone. Due to advancements in computational efficiency and data generation techniques, these models are becoming increasingly attractive for seismic vulnerability assessments. Additionally, non-linear finite element models and AI-driven approaches can further enhance failure predictions by incorporating key factors such as material composition, infrastructure age, soil conditions, and pressure fluctuations.

Pipelines

Based on a validation study conducted for the 1999 Düzce and 2003 Lefkas earthquakes, for pipelines the SYNER-G team recommends the empirical fragility curves developed by O'Rourke and Ayala (1993) for wave propagation effects and by Honneger and Eguchi (1992) for permanent ground deformation.

For wave propagation, the O'Rourke and Ayala (1993) model estimates the repair rate (RR, in repairs per km) as a function of peak ground velocity (PGV, in cm/s).

$$RR = K * (0.0001 * PGV^{2.25})$$

For permanent ground deformation (PGD, in meters), the Honegger and Eguchi (1992) model provides the corresponding repair rate.

$$RR = K * (7.821 * PGD^{0.56})$$

The primary factor influencing pipeline vulnerability to seismic shaking or ground deformation is pipe material. A corrective factor (K) is applied to both models, where brittle pipes (e.g., cast iron, asbestos cement, reinforced concrete cylinder) have K = 1, while ductile pipes (e.g., ductile iron, steel, polyvinyl chloride) have K = 0.3, indicating that ductile pipes have 30% of the vulnerability of brittle ones. Older distribution networks, which typically feature rigid, brittle materials with low flexibility, are more vulnerable. In contrast, modern or upgraded networks primarily use ductile materials. Welded steel pipes are categorized based on their joint type: arc-welded joints classify the pipe as ductile, while gas-welded joints classify it as brittle. If specific data on welding types is unavailable, the year of installation may be used as a proxy—pre-1935 steel pipes are assumed to be brittle.

It is assumed that damage due to wave propagation will consist of 80% leaks and 20% breaks, while damage due to ground failure will consist of 20% leaks and 80% breaks.

Notably, both models do not explicitly account for pipe diameter, nor additional factors such as joint type and soil conditions which influence vulnerability.

As an alternative, for general applications, the ALA (2001a, b) relations are recommended if more information about pipelines is available. These models estimate repair rates based on PGV (cm/s) for ground shaking and PGD (cm) for ground failure, incorporating corrective factors:

- K_1, which adjusts the fragility based on backbone curve parameters, including material, connection type, soil type, and pipe diameter (see Figure 15).
- K_2, which depends on pipe material and connection type (see Figure 16).

according to the following equations:

$$RR = K_1 * 0.002416 * PGV$$

and

$$RR = K_2 * 2.5829 * PGD^{0.319}$$

Pipe material	Joint type	Soils	Diameter	K_1
Unknown	Unknown	Unknown	Unknown	1.00
Cast iron	Cement	All	Small	1.00
			Large	0.50
		Corrosive	Small	1.40
			Large	0.70
		Non corrosive	Small	0.70
			Large	0.35
	Rubber gasket	All	Small	0.80
			Large	0.40
Welded steel	Lap – Arc welded	All	Small	0.60
		Corrosive		0.90
		Non corrosive		0.30
		All	Large	0.15
	Screwed	All	Small	0.70
	Rubber gasket			1.30
	Riveted			1.30
Asbestos cement	Rubber gasket	All	Small	0.50
	Cement			1.00
Concrete w/Stl Cyl.	Lap – Arc welded	All	Large	0.70
	Cement			1.00
	Rubber gasket			0.80
PVC	Rubber gasket	All	Small	0.50
Ductile iron	Rubber gasket	All	Small	0.50
			Large	0.25

Figure 15: K1 parameters in ALA (2001a,b) for transient ground motion, for pipes

Pipe diameters are typically greater than 4 inches and in general small diameter means 4 to 12 inches (around 100 to 300 mm) while large diameter mean 16 inches and more (> 400 mm).

Pipe material	Joint type	K_2
Unknown	Unknown	1.00
Cast iron	Cement	1.00
	Rubber gasket	0.80
	Mechanical restrained	0.70
Welded steel	Arc welded, lap welds (large diameter, non corrosive)	0.15
	Rubber gasket	0.70
Asbestos cement	Rubber gasket	0.80
	Cement	1.00
Concrete w/Stl Cyl.	Welded	0.60
	Cement	1.00
	Rubber gasket	0.70
PVC	Rubber gasket	0.80
Ductile iron	Rubber gasket	0.50

Figure 16: K_2 parameter in ALA (2001a,b) relation for ground failure, for pipes

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Pumping stations

For pumping stations, the fragility curves selected by SYNER-G are shown in Figure 17.

Although there are no specific guidelines in the anchorage of the subcomponents in Europe for pumping stations, anchorage is a common practice. It is also assumed that there is no back-up power in case of loss of electric power (worst case scenario). The description of damage states for pumping station is provided in Table 1 while the parameters of the corresponding fragility curves are given in Table 2.

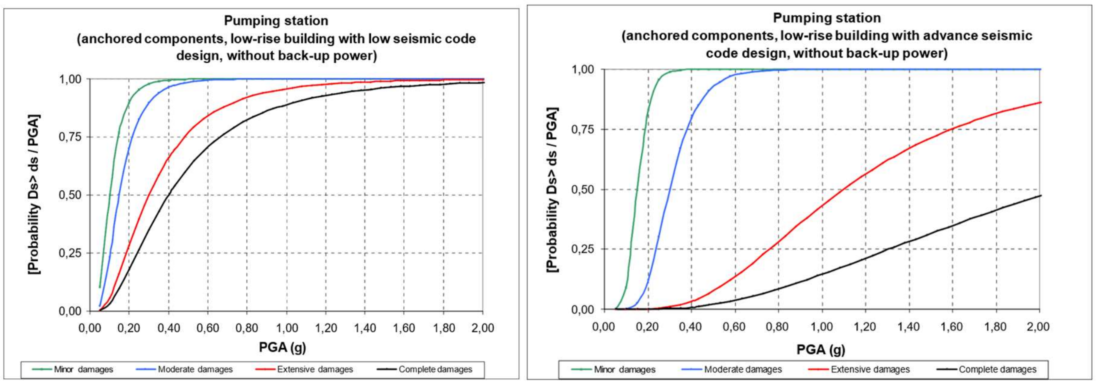

Figure 17: Fragility curves for pumping stations, with anchored components and low-rise R/C building with low (left) and high (right) level of seismic design.

Table 1 - Description of damage states for Pumping Station subjected to ground shaking

Damage state	Description	Serviceability	
Minor	Malfunction of plant for a short time (< 3 days) due to loss of electric power or slight damage to buildings	Normal flow and water pressure	Operational after limited repairs
Moderate	The loss of electric power for about a week, considerable damage to mechanical and electrical equipment, or moderate damage to buildings.	Reduced flow and water pressure	Operational after repairs
Extensive	The building being extensively damaged or the pumps being badly damaged beyond repair		Partially operational after extensive repairs
Complete	The building collapsing	Not water available	Not repairable

When implementing these damage states in the simulation environment, the pumping station remains unaffected in the minor damage state, operates at reduced speed in the moderate and extensive damage states, and is taken out of service in the complete damage state.

Table 2 – Parameters of fragility curves for pumping station

Description	Damage state	Peak Ground Acceleration (PGA)	
		Median (A)	β log-standard deviation
Anchored components (low-rise R/C building with low seismic code design)	Minor	0.10	0.55
	Moderate	0.15	0.55
	Extensive	0.30	0.70
	Complete	0.40	0.75
Anchored components (low-rise R/C building with advanced seismic code design)	Minor	0.15	0.30
	Moderate	0.30	0.35
	Extensive	1.1	0.55
	Complete	2.1	0.70

Wells

Wells are used in many cities as a primary or supplementary source of water supply. Wells include a shaft from the surface down to the aquifer, a pump to bring the water up to the surface, equipment used to treat the water, and sometimes a building, which encloses the well and equipment.

For water sources, the fragility curves selected by SYNER-G are shown in Figure 18. Although there are no specific guidelines in the anchorage of the subcomponents in Europe, anchorage is a common practice. The description of damage states for pumping station is provided in Table 3 while the parameters of the corresponding fragility curves are given in Table 4.

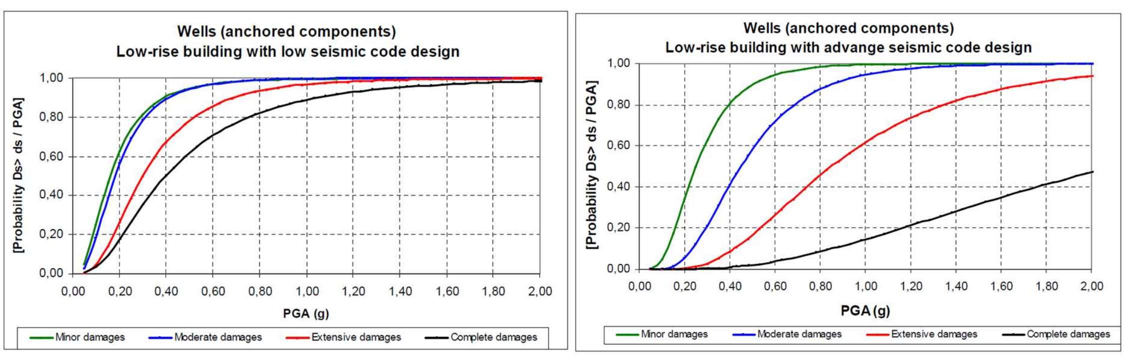

Figure 18: Fragility curves for wells with anchored components and low-rise R/C building with low (left) and high (right) level of seismic design.

Table 3 - Description of damage states for wells subjected to ground shaking

<table>
<tr><th>Damage state</th><th>Description</th><th colspan="2">Serviceability</th></tr>
<tr><td>Minor</td><td>Malfunction of well pump and motor for a short time (less than three days) due to loss of electric power and backup power if any, or light damage to buildings</td><td>Normal flow and water pressure</td><td>Operational after limited repairs</td></tr>
<tr><td>Moderate</td><td>Malfunction of well pump and motor for about a week due to loss of electric power and backup power if any, considerable damage to mechanical and electrical equipment, or moderate damage to buildings</td><td rowspan="2">Reduced flow and water pressure</td><td>Operational after repairs</td></tr>
<tr><td>Extensive</td><td>The building being extensively damaged or the well pump and vertical shaft being badly distorted and non-functional</td><td>Partially operational after extensive repairs</td></tr>
<tr><td>Complete</td><td>The building collapsing</td><td>Not water available</td><td>Not repairable</td></tr>
</table>

When implementing these damage states in the simulation environment, the well remains unaffected in the minor damage state, operates at reduced volume and with pump at reduced speed in the moderate and extensive damage states, and is taken out of service in the complete damage state.

Table 4 – Parameters of fragility curves for wells subjected to ground shaking

<table>
<tr><th rowspan="2">Description</th><th rowspan="2">Damage state</th><th colspan="2">Peak Ground Acceleration (PGA)</th></tr>
<tr><th>Median (A)</th><th>β
log-standard deviation</th></tr>
<tr><td rowspan="4">Anchored components (low-rise R/C building with low seismic code design)</td><td>Minor</td><td>0.16</td><td>0.70</td></tr>
<tr><td>Moderate</td><td>0.18</td><td>0.65</td></tr>
<tr><td>Extensive</td><td>0.30</td><td>0.65</td></tr>
<tr><td>Complete</td><td>0.40</td><td>0.75</td></tr>
<tr><td rowspan="4">Anchored components (low-rise R/C building with advanced seismic code design)</td><td>Minor</td><td>0.25</td><td>0.55</td></tr>
<tr><td>Moderate</td><td>0.45</td><td>0.50</td></tr>
<tr><td>Extensive</td><td>0.85</td><td>0.55</td></tr>
<tr><td>Complete</td><td>2.1</td><td>0.70</td></tr>
</table>

While our case study does not include reservoirs – typically lakes, either natural or man-made, located near and upstream of the water treatment plant – it is important to note that the Hazus loss estimation methodology does not assess the vulnerability of terminal reservoirs and associated dams. Consequently, despite reservoirs being a critical component of potable water systems, water system analyses often assume that the flow into treatment plants remains unchanged immediately after an earthquake.

Storage Tanks

In Europe, the most common type of water tanks are reinforced concrete (R/C) tanks without anchorage; however, no dedicated studies are available for assessing their fragility. For vulnerability assessment under ground shaking or ground failure, the empirical fragility curves proposed by ALA (2001a,b) are recommended, as they are based on a large dataset of empirical observations and are considered the most comprehensive.

Due to the lack of alternative studies, the fragility curves provided by HAZUS for steel and wood tanks are also suggested. These curves, derived from a combination of empirical data and engineering judgment, provide a reasonable approximation for common applications.

The mentioned fragility curves for R/C tanks are shown in Figure 19. The related description of damage states and the parameters of the corresponding fragility curves are provided in Table 5 and in Table 6, with respect to PGA and PGD respectively.

It should be noted that the HAZUS fragility curves apply specifically to water tanks that are at least 80% full at the time of an earthquake.

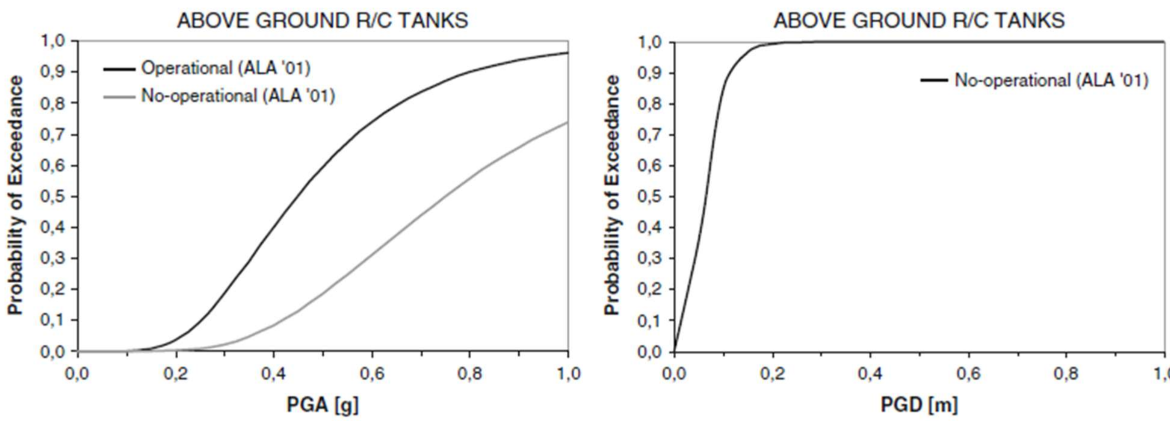

Figure 19: Fragility curves for above ground R/C tanks subject to wave propagation (left) and permanent ground deformations (right). (ALA 2001a,b)

Table 5 – Fragility curves for unanchored R/C at grade tanks (wave propagation). ALA (2001a,b)

Failure	Serviceability		Peak Ground Acceleration (PGA) Median (A)	β log-standard deviation
Cracking or shearing of tank wall	Loss of context	No operational	1.05	0.45
Roof damage	No loss of context	Operational	2.60	0.45
Uplift of wall – crush concrete	Small leak		2.00	0.45
Sliding	Small leak		0.25	0.45
Hoop overstress	Loss of context	No operational	0.75	0.55
	Small leak	Operational	0.45	0.50

Table 6 – Fragility curves for unanchored R/C at grade tanks (permanent deformations). ALA (2001a,b)

Typology		Serviceability	Permanent Ground Displacement (PGD)	
			Median (A)	β log-standard deviation
R/C	Anchored	No Operational	0.06	0.50
	Un-anchored			
Steel	At columns		0.06	0.50
	At grade		0.09	
Wooden		No Operational	0.25	0.55
Without roof		Operational	0.45	0.50

When implementing these damage states in the simulation environment, the tank remains operational if marked as operable and is taken out of service if deemed non-operational. Cracks can be simulated by reducing the water level. While this approach is sufficient from a hydraulic perspective, the volume of water discharged into the environment must be considered for potential cascading effects.

4. Railway

This section provides an overview of the simulation environment for the railway network, though the work is still in progress due to delays in defining the exact terms and scope of the required Non-Disclosure Agreement. However, the process closely follows the methodology already described for the water distribution network, reinforcing that the concepts discussed in Section 3 can be applied beyond drinking water systems. Furthermore, as highlighted in DV6.2.1, the railway and road networks share several critical elements, such as bridges and tunnels, meaning that some findings from the railway network analysis can also be extended to road infrastructure.

As in Section 3, Section 4.1 outlines the key aspects of modelling the physical infrastructure in our proof-of-concept study and integrating the effects of natural hazards. Section 4.2 then examines the relevant natural hazards for railways, detailing how their impacts are quantified and incorporated into the model.

4.1 Modelling the Infrastructure

The railway network in Italy is primarily managed by RFI SpA – Rete Ferroviaria Italiana, a partner of the project, which serves as the public Infrastructure Manager responsible for overseeing railway operations, ensuring traffic safety, and maintaining the national network, including tracks, stations, and related installations. The network – briefly described in DV6.2.1 Section 5.1.1, which provides an overview of its general functioning and key assets – consists of 16,800 km of railway lines, including 1,097 km of high-speed tracks, totalling 24,636 km of tracks and approximately 2,200 railway stations. Around 1,500 km of railway lines managed by RFI are located in tunnels, while 23,300 structures are classified as bridges, viaducts, overpasses, and underpasses, covering a total of about 1,900 km.

Figure 20: Italian railway network

Figure 20 provides a visual representation of the railway network, highlighting its high-speed (green), conventional (blue), complementary (light blue, mainly for local transport), and connection (orange) lines.

The section of the network selected for analysis, due to its representative nature and hydrogeological risk, is the Napoli–Reggio Calabria corridor. This segment, identified for its potential for integrating multidisciplinary expertise in the RETURN project to quantify natural hazards, **spans 750 km of double-track railway, 160 km of single-track railway, and includes 85 medium-sized stations, 9 large stations, and approximately 940 trains**.

As outlined in requirement RL-RR1 (see DV6.2.1), the objective of the model is to identify critical transportation network segments and quantitatively assess the impact of service disruption scenarios. As previously noted for the drinking water distribution network, the results of this analysis will be presented in D6.2.4 and D2.6.2.

4.1.1 Data

As discussed in Section 2.1.1, railway traffic analysis will be conducted using OpenTrack, a commercial simulator that models train movements based on constraints imposed by the signalling system and timetable. OpenTrack employs differential equations to accurately simulate train speed and distance, providing a comprehensive assessment of railway operations and potential disruptions.

To model the railway network in OpenTrack, the following information is required:

- Railway line dossiers
- Station layout
- Planned timetable

The railway line dossier contains essential details about the railway infrastructure, including mileage, braking characteristics, speed limits, signalling, power supply, emergency devices, and other operational information used by train personnel and infrastructure staff. This document is publicly available, and a comparison with similar dossiers from other railway companies operating in Italy and abroad confirms that it follows a standardized structure.

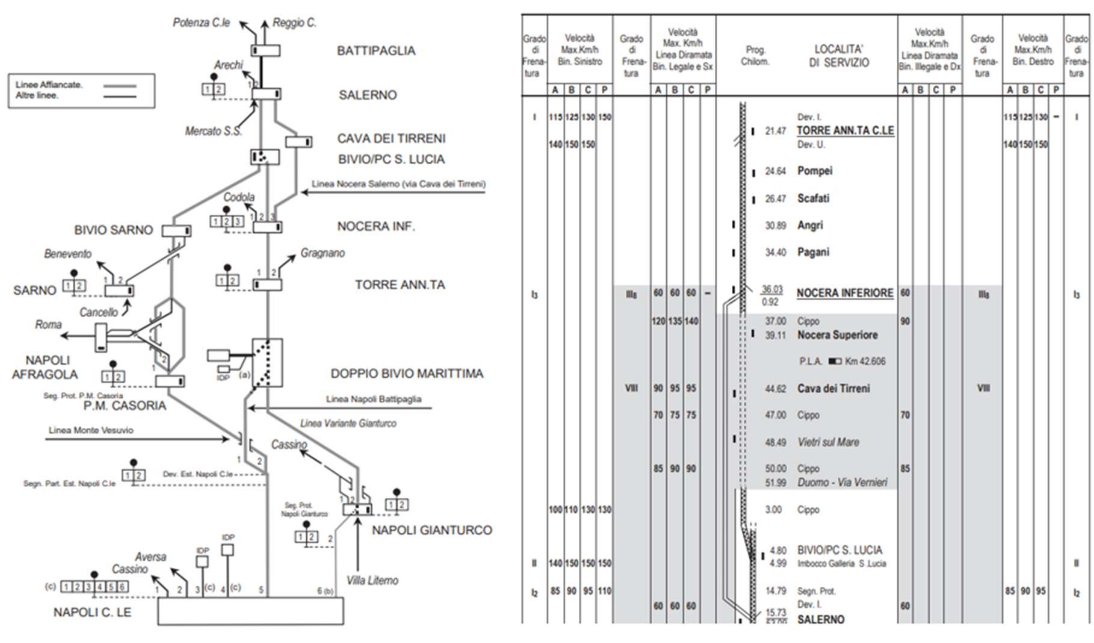

Figure 21: Snapshot of information included in the Railway line dossier, useful to modelling in OpenTrack

Figure 21 provides an overview of some of the information included in the railway line dossier, which is crucial for modelling the railway network in OpenTrack. Figure 22 illustrates a portion of a station layout, which is described in greater detail in the station layout document. This document focuses on individual stations and includes information on manoeuvre actuators, power supply connections, and signalling systems. However, the station layout is confidential, and access to this information requires an NDA agreement.

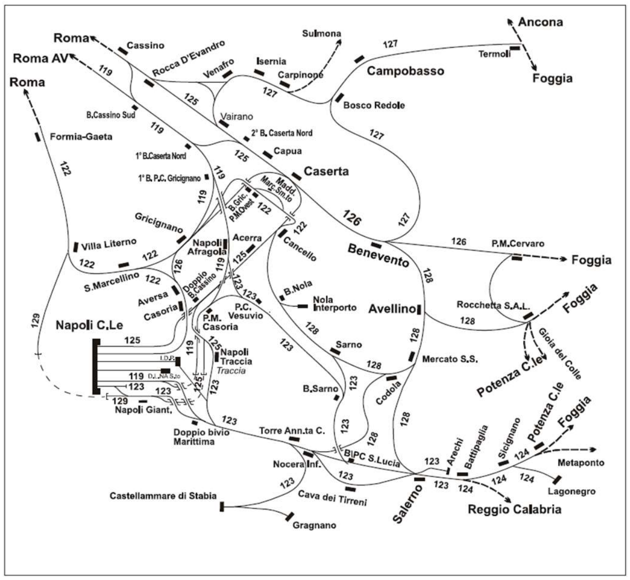

Figure 22: Overview of some connections departing from Naples

It is worth noting that in the RETURN project, assessing the impact of service interruptions on the Napoli–Reggio Calabria corridor – such as delayed trains, total delay minutes, and the number of affected trains, including cascading effects – requires modelling not only the main railway line (including High Speed and Conventional lines) but also the connections to the first station on all branch lines.

Regarding the timetable, all trains operating on the line, including those coming from connected routes, must be included in the model. Given the proof-of-concept nature of the project and to manage modelling effort efficiently, it was decided to simulate train operations based on a single weekday timetable during the winter season. Additionally, since freight trains are managed by a separate division, only passenger trains will be modelled.

4.1.2 Interfacing OpenTrack

OpenTrack enables communication with third-party tools via its API, allowing external systems to interface with and operate the simulation. Communication occurs through the SOAP protocol over HTTP. Figure 23 illustrates an asynchronous API message exchange between OpenTrack and an external tool. The external tool (e.g., our simulation manager) sends commands to control simulation parameters, such as starting, pausing, or stepping the simulation. In response, OpenTrack provides status updates and reports, including train positions and operational data.

The API offers a range of detailed commands for various functionalities:

- Simulation Control: Configuring simulation start, pause, and end times, as well as adjusting simulation speed.
- Train Management: Adding, removing, activating, and deactivating trains, along with controlling speed, engine operations, and performance parameters.
- Timetable and Routing: Managing timetable entries, route reservations, and location-based speed restrictions to optimize operations and prevent conflicts.

- Position Reporting and Departure Commands: Defining how trains report their positions and how departure commands regulate station dwell times.

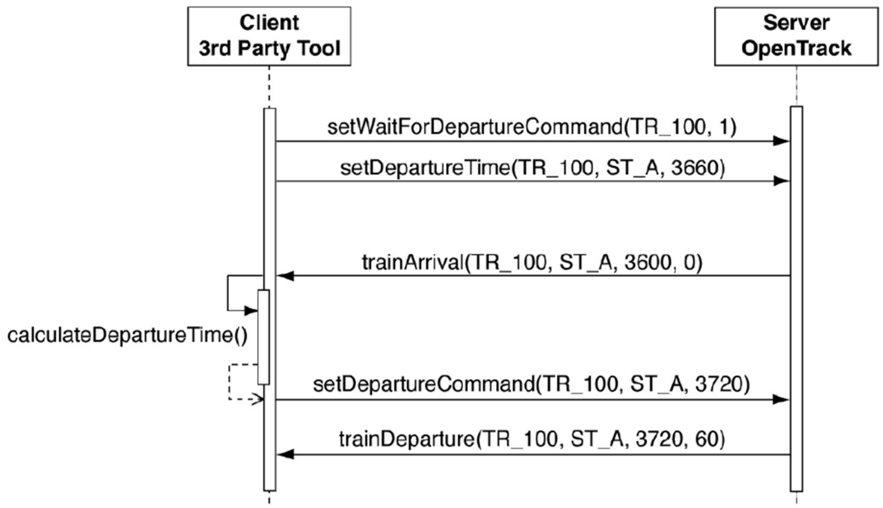

Figure 23: Sequence diagram for the "Departure" command.

4.1.3 Adding damages

Like other commercial domain-specific simulators, as mentioned multiple times, OpenTrack is designed to model undamaged systems. However, by enabling automated control over network data, it becomes possible to adjust parameters or introduce additional elements to account for faults caused by natural events.

Since OpenTrack focuses on train circulation, infrastructure damage or warnings are considered only if they impact train operations. The following scenarios can occur:

- Train circulation is stopped on one or more segments of the line. This may happen due to safety criteria not being met as a result of infrastructure damage, protection devices blocking circulation (e.g., if peak ground acceleration exceeds 0.04g or 40 cm/s²), power supply failure, or loss of telecommunications connectivity. In Italy RFI suspends train operation for PGA ≥ 0.10 g and reduce speed for 0.10 g > PGA ≥ 0.05 g
- Speed is reduced on a segment of the line to meet safety criteria, such as in the presence of strong winds.
- The train is rerouted onto another track, as in cases where a high-speed train is diverted onto a conventional track.

The first two cases can be simulated by adjusting speed settings on the affected segment and configuring the signalling system accordingly. The third case requires the creation of a new train and timetable to accommodate the rerouting.

4.2 Modelling the effects of Natural Hazards

4.2.1 Relevant hazards

Railway infrastructure is exposed to a wide range of natural hazards that can potentially impact its safety, reliability, and service continuity.

Emerging threats – including floods, extreme temperatures, windstorms, wildfires, and drought – have become increasingly severe due to climate change, which has intensified both their frequency and magnitude. Rising global temperatures contribute to more frequent and intense heatwaves, leading to rail buckling and accelerated material degradation. Similarly, increased precipitation variability results in severe flooding, erosion, and soil instability, posing heightened risks to track foundations and embankments. Stronger storms, driven by warming ocean temperatures, exert higher wind loads on railway infrastructure, increasing the likelihood of track obstructions, power failures, and damage to signalling systems. While prolonged drought conditions do not cause immediate operational disruptions, they can lead to soil shrinkage, destabilizing track foundations, increasing embankment failures, and compromising railway substructures.

Even traditional hazards such as earthquakes, liquefaction, and landslides, which have long been recognized for their destructive impact on railway infrastructure and extensively studied in railway engineering and disaster management, are now worsened by climate change (as discussed in Section 3.2.1). These hazards, once primarily driven by geophysical processes, are now increasingly influenced by climatic shifts, exacerbating infrastructure vulnerabilities.

As a result, railway infrastructure is now subject to prolonged exposure to fluctuating environmental conditions, potentially leading to increased material fatigue, progressive degradation of track components, and accelerated aging of supporting structures. This continuous deterioration can impact the long-term efficiency of railway networks, contributing to greater operational unpredictability and higher maintenance demands.

Beyond direct hazard impacts, cascading effects must also be considered. For example, disruptions to external power supplies – caused by floods or wildfires – can severely impact railway electrification, signalling, and communication system, although safety of railway operation is still granted in case of loss of power supply. Likewise, telecommunications failures disrupt train dispatching, real-time monitoring, and emergency response coordination, leading to delays and operational inefficiencies.

Given this broader risk landscape, the activities of Task 2.3, as reported in this document, focus on modelling functional disruptions to railway distribution networks caused by hazards addressed in the RETURN project, while the analysis of physical damage is covered in WP4. Consequently, drought and heatwaves related to rail buckling – although documented in studies from France's 2003 heatwave – are not included in this study. The next section will just provide a brief overview of the primary physical damages to railway infrastructure for reference before outlining the specific disruptions relevant to the RETURN framework, which will be quantified in Section 4.2.3.

The model, however, is designed to be flexible and expandable, allowing for the integration of additional hazards in the future if needed.

4.2.2 Hazard-induced disruptions

Natural hazards cause structural failures in railway infrastructure through various mechanisms.

Earthquake

Earthquakes pose significant risks to railway infrastructure, impacting tracks, bridges, tunnels, stations, and associated facilities. One of the primary consequences is differential settlement in track foundations, leading to increase in the distance between the two rails of a track, track misalignment, and embankment instability. These effects can severely disrupt railway operations, rendering tracks unsafe for use. Tracks built on soft soil, fill material, or near fault ruptures are particularly vulnerable to failure and loss of functionality. Trains and locomotives are highly susceptible to derailments when track integrity is compromised.

Seismic shaking can cause structural cracking, rockfalls, or groundwater ingress in tunnels, while earthquake-induced landslides may block tunnel portals, restricting access. Bridges and viaducts are also at risk from seismic forces, which can result in partial collapses or operational speed restrictions. Given their crucial role in railway connectivity, bridge failures often lead to significant disruptions across the transportation network. Similarly, railway tunnels, which frequently lack redundancy, can cause major operational setbacks if rendered non-functional.

Stations, maintenance depots, fuel facilities, and dispatch centres are sensitive to both ground shaking and ground failure, increasing the likelihood of operational disruptions.

Liquefaction

Often a significant secondary effect of earthquakes, liquefaction also represent a critical threat to railway infrastructure, particularly in areas with loose, water-saturated soils. During seismic events, liquefaction can cause the ground to lose its bearing capacity, leading to severe structural instability. Railway tracks built on liquefiable soils may experience differential settlement, resulting in track misalignment and localized subsidence, all of which compromise operational safety. Track bed deformation can also displace ballast, weakening rail foundations and increasing the risk of derailments. Bridges and viaducts are especially vulnerable, as liquefaction can undermine bridge piers, causing tilting, foundation settlement, or even structural collapse. Additionally, embankments supporting railway lines may suffer lateral spreading, shifting, or collapsing under the influence of liquefied soil movement, further exacerbating service disruptions.

Flooding

Flooding can have catastrophic effects on railway networks, causing structural failures, operational disruptions, and significant repair costs across tracks, bridges, embankments, signalling systems, and trains. The primary mechanisms of flood-induced damage include ballast washout, hydrodynamic scour, foundation erosion, inundation, and debris impact. These effects can significantly compromise railway safety, disrupt operations, and necessitate costly repairs.

Railway tracks and foundations are particularly susceptible to flood-induced erosion. Heavy rainfall and river overflows can wash away ballast, the crushed stone layer that stabilizes tracks, leading to track deformation, misalignment, and instability. The loss of ballast compromises the load-bearing capacity of the track, increasing the risk of derailments and operational disruptions. Floodwaters flowing at high velocity also cause scour and erosion, undermining track foundations, embankments, and bridge piers. This phenomenon has been well-documented in cases such as the 2009 Cockermouth Floods in the UK, where sediment displacement led to structural collapse.

Bridges and viaducts, which are critical for railway connectivity, are highly vulnerable to flood-induced scouring. When floodwaters erode the soil around bridge piers, the structural integrity of the bridge is compromised, increasing the likelihood of partial collapses or severe speed restrictions. Scouring becomes even more dangerous when combined with high debris loads, as lodged debris can increase hydraulic pressure on bridge structures, accelerating erosion and foundation weakening.

Flooding can also damage railway infrastructure through inundation, where water submerges railway components, leading to short circuits, corrosion, and system failures. Prolonged exposure to water can corrode tracks and electrical systems, including signalling and communication networks, resulting in major operational delays.

In extreme flooding events, high-velocity water can carry debris such as trees, rocks, and other materials, which may collide with railway structures, block drainage systems, or exert additional hydraulic pressure on infrastructure. These effects exacerbate existing vulnerabilities, leading to track obstructions, equipment failures, and increased strain on bridges and embankments.

Trains and locomotives are highly sensitive to flood-damaged tracks. If track stability is compromised due to washed-out ballast, foundation erosion, or debris accumulation, the risk of derailments increases significantly. Train operations may also be disrupted if floodwaters damage onboard electrical systems or compromise braking performance due to water infiltration.

Landslide

Landslides and rockfalls can severely impact railway operations, particularly in mountainous or geologically unstable regions. These events can cause critical track obstructions, derailments, and structural damage to tunnels and embankments, leading to operational disruptions and safety risks.

Landslides are often triggered by heavy rainfall, seismic activity, or soil instability. Railway lines traversing steep slopes or weak geological formations are especially vulnerable to slope failures, which can deposit large volumes of debris onto tracks, blocking train routes and compromising rail stability. Rockfalls, in particular, present a sudden and unpredictable hazard, further complicating railway safety and operations.

Tracks and their supporting foundations are especially vulnerable to landslide-related damage. Debris or soil displacement can result in rail deformation, track misalignment, and ballast erosion, rendering tracks unsafe for operation. Embankments supporting railway lines may experience partial or complete collapse, further threatening track integrity and increasing maintenance demands.

Railway tunnels are also at risk when landslides obstruct tunnel portals, preventing access or causing structural instability, which can severely disrupt transportation networks.

Wind

Windstorms pose significant risks to railway infrastructure, affecting train stability, power supply systems, signaling equipment, and operational efficiency. The interoperability regulations for trains traveling within the European Union have highlighted the hazard of train overturning due to crosswinds, prompting scientific research to better understand the issue, identify vulnerabilities, and develop mitigation strategies.

The aerodynamic forces acting on railway vehicles increase proportionally to the square of the relative wind-train speed. This means that at a given wind intensity, these forces grow exponentially with train speed, making high-speed trains particularly vulnerable. Additionally, modern train design trends favor lightweight structures to improve energy efficiency, reducing the stabilizing effect of the train's weight, which would otherwise help counteract the lifting forces generated by strong winds.

Beyond overturning risks, windstorms can topple overhead line equipment, signaling systems, and catenary wires, leading to power outages and widespread service disruptions. The 2022 Storm Eunice in the UK demonstrated the extent of wind-related railway damage, as strong winds brought down power lines, obstructed tracks with debris, and caused severe operational delays.

Windstorms also require operational adjustments, such as speed reductions for safety reasons, even when no direct damage occurs. These reductions impact train scheduling and efficiency, leading to cascading effects across the rail network. Additionally, signaling and communication systems are at risk, as high winds, along with flooding and wildfires, can damage power supplies, control centers, and fiber optic cables, causing significant delays and impairing network coordination.

Wildfires

Wildfires present both direct and indirect risks to railway operations, threatening tracks, power supply infrastructure, signalling systems, and overall service continuity. In regions prone to wildfires, railway infrastructure is particularly vulnerable to extreme heat, fire damage, and smoke-related disruptions.

The 2019 Australian Bushfires exemplified the severity of these impacts, as multiple railway lines were shut down when extreme heat weakened track components and compromised electrical infrastructure. Fires can damage power transmission lines, signalling systems, and supporting steel railway structures, leading to widespread service disruptions affecting both passenger and freight operations.

Beyond physical damage, wildfires indirectly impact railway operations through reduced visibility from smoke and extreme temperatures affecting mechanical components. In many cases, railway operators must implement speed restrictions or temporarily close affected sections to ensure passenger and crew safety.

Signalling and communication systems are also at risk, as wildfires, along with flooding and high winds, can damage power supplies, control centres, and fiber optic cables, resulting in significant operational delays and impaired network coordination.

Section 4.2.3 will outline how these damages are incorporated into the simulation, taking into account that we are interested not in damages but in service reduction, which usually comes long before major damages.

4.2.3 Integrating fragility curves into simulation environment

In Section 3.2.3, we previously discussed fragility curves and their integration into the simulation environment to assess the impact of extreme natural events on overall system functionality.

Both the Hazus methodology (FEMA, 2024) and the SYNER-G project have compiled fragility functions for various railway elements, including bridges, tunnels, fuel and dispatch facilities, and urban stations. In general, methodologies and analysis results developed for roadway elements are also applicable to railway infrastructure. Within the SYNER-G project, fragility curves have been proposed for tracks on slopes and tracks subjected to permanent ground deformations (PGD) due to ground failure. Additionally, several researchers involved in the RETURN project – particularly within the framework of WP4 of Spoke 6 – are actively developing their own fragility curves, with a primary focus on bridges.

For the scope of our task, a key insight is that five standardized damage states – No Damage, Minor, Moderate, Extensive, and Complete – have been widely accepted and are represented in fragility curves. For each of these states, the corresponding impact on service is defined. Figure 24 presents an example of a fragility curve for railway tracks in relation to peak ground deformation, while Table 7 details the damage state descriptions and their effects on operations. Notably, the mean value for minor damage aligns with the upper alert and intervention threshold for longitudinal track level, as outlined in the European Standards for Track Geometric Quality (EN 13848-1, 2008). The remaining values are based on expert judgment and a review of existing studies.

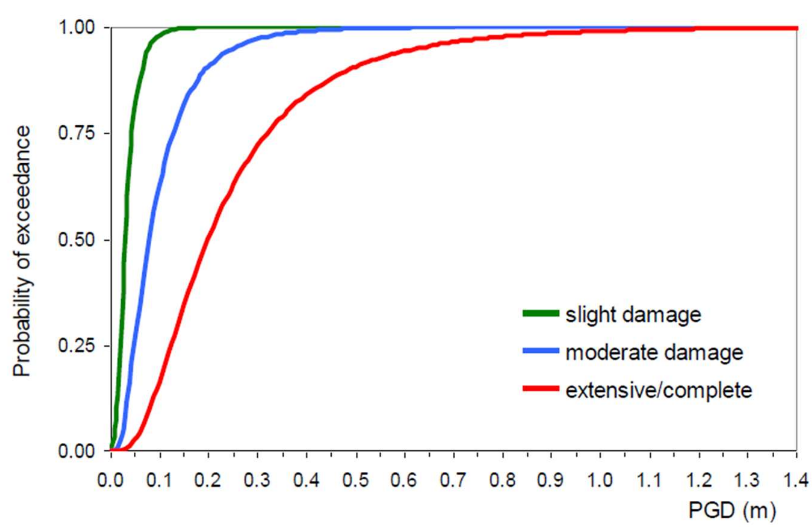

Figure 24: Fragility curves for railway tracks subjected to ground failure (Kaynia et al., 2011)

Table 7 - Description of damage states for railway tracks

Damage state	Description	Serviceability
Minor	Minor (localized) derailment due to slight differential settlement of embankment or offset of the ground.	Operational after inspection or short repairs.
Moderate	Considerable derailment due to differential settlement or offset of the ground.	Closed to traffic. Local repairs or replacement of tracks is required.
Extensive/ Complete	Major differential settlement of the ground resulting in potential derailment over extended length.	Closed to traffic. Replacement of track's segments is required. Duration of closure depends on length of damaged lines.

Similar fragility curves exist for each railway infrastructure component. Table 8 (Kaynia et al., 2011) highlights the operational restrictions corresponding to each damage state, which are implemented in the simulation environment to calculate the selected KPIs (see Section 2.1.4).

Table 8 – Functionality of railway elements (ff: fully functional, sr: speed restriction, c: closed)

Damage state	Bridge	Tunnel	Embankement	Trench	Abutment	Slope	Tracks
No Damage	ff	ff	ff	ff	ff	ff	ff
Minor	sr	sr	sr	sr	sr	sr	sr
Moderate	c	c	c	c	c	c	c
Extensive/ Complete	c	c	c	c	c	c	c

Lastly, even when railway infrastructure remains structurally intact, natural hazards often necessitate operational restrictions to ensure passenger and freight safety:

- **Speed Restrictions** are imposed when meteorological conditions exceed predefined safety thresholds. High winds (80-120 km/h), heavy rainfall (above 50 mm/h), and extreme temperatures trigger precautionary slowdowns to mitigate derailment risks.
- **Signalling Failures and Traffic Delays** occur when flooding, power surges, or wind damage disrupt railway signalling and telecommunications networks.
- **Wildfire and Smoke Disruptions** can force train halts due to visibility and air quality concerns, even when no direct structural damage occurs.

Specific values for operational restrictions will be implemented in the simulation environment in agreement with RFI during the scenario analysis, if relevant.

5. Conclusions

This document presented a rethinking of how infrastructure resilience can be modelled and measured. The key insights can be summarized as follows:

The shift from single-risk to multi-risk thinking is essential

While it is well understood that real-world disasters rarely occur in isolation and research underscores the necessity of multi-risk assessments, existing infrastructure planning tools – originally designed for stable conditions – struggle to address these evolving, interconnected threats. A shift in risk assessment methodologies is essential to explicitly model interdependencies between sectors, rather than assuming them as independent systems.

Commercial simulation tools are not enough – interfacing them is critical

Industry-trusted simulation tools, such as Infoworks WS Pro for water networks and OpenTrack for railways, offer valuable insights but were originally designed for long-term planning rather than real-time emergency response. As a result, they fail to fully capture the system-wide disruptions caused by climate-driven disasters.

Rather than replacing these tools, they can be enhanced through interfacing mechanisms. By developing external layers that dynamically inject failures and control the evolution of cascading events, these simulators can remain trusted by operators while better reflecting real-world complexities. This approach balances reliability and adaptability, allowing infrastructure managers to continue using familiar tools while gaining a more comprehensive understanding of vulnerabilities.

Knowledge graphs as a bridge for interdisciplinary contributions of experts across diverse fields

The introduction of the Knowledge Graph enables a dynamic representation of interdependencies, where failures are not merely pre-defined but evolve in response to external conditions. While conceptually powerful, the Knowledge Graph requires further inputs from expert across diverse fields to ensure it is as robust and reliable as the simulators it interacts with.

The future of infrastructure resilience relies on data—but even partial data is useful

A persistent challenge in risk modelling is data availability and quality, as missing, outdated, or inconsistent data can significantly impact simulation accuracy. However, this research highlights that even partial datasets can be valuable. Rather than waiting for perfect data, domain-specific simulations can extract meaningful insights from existing infrastructure records, fragility curves, and historical failure data, which in turn can encourage further data collection efforts. Moreover, initiatives like SINFI (Italy's Federated National Information System of Infrastructures) reflect a growing movement toward standardized and accessible infrastructure data, which could significantly enhance resilience modelling in the near future.

Modular frameworks ensure future-proofing and integration of emerging technologies

Modularity is the key to continuous improvement. Since the framework is designed with separate but integrated components, advancements in failure predictions, real-time monitoring, and resilience models can be incorporated without disrupting existing workflows. This modularity ensures that the framework does not become obsolete as new technologies emerge.

Quantitative resilience metrics are necessary for decision-making.

KPIs that reflect both system performance and societal impact has been chosen, such as:

- For drinking water networks: Number of isolated users, unserved water flow, areas with inadequate pressure.
- For railway networks: Number of affected trains, total delay time, cancellations, and disruptions to operational schedules.

In the final phase of the RETURN project, this simulation environment will be used to provide insights into effective resilience management

6. References

American Lifelines Alliance (2001a). "Seismic Fragility Formulations for Water Systems. Part 1 – Guideline", ASCE-FEMA, 104 p.

American Lifelines Alliance (2001b). "Seismic Fragility Formulations for Water Systems. Part 2 – Appendices", ASCE-FEMA, 239 p.

Asadi, Y. (2024). Employing machine learning in water infrastructure management: predicting pipeline failures for improved maintenance and sustainable operations. Industrial Artificial Intelligence 2, 8. https://doi.org/10.1007/s44244-024-00022-w

Buttigieg, P.L., Pafilis, E., Lewis, S.E., Schildhauer, M.P., Walls, R.L., and Mungall. C.J. The environment ontology in 2016: bridging domains with increased scope, semantic density, and interoperation. *J Biomed Semant*, 7(1), 57, 2016.

Coletti, A., De Nicola, A., and Villani, M.L.: Building climate change into risk assessments. *Natural Hazards*, 84(2), 1307–1325 (2016).

Cubrinovski, M., Hughes, M., Rourke, T. (2014). Impacts of liquefaction on the potable water system of Christchurch in the 2010-2011 Canterbury (NZ) Earthquakes. Journal of Water Supply: Research and Technology—AQUA. 63. 95-105. 10.2166/aqua.2013.004.

Cybersecurity and Infrastructure Security Agency, U.S. Department of Agriculture, Environmental Protection Agency, National Oceanic and Atmospheric Administration, & Federal Emergency Management Agency, (2021). Drought and Infrastructure – A Planning Guide.

Department of Homeland Security's Office of Cyber and Infrastructure Analysis. (2015). Drought Impacts to Critical Infrastructure. https://www.cisa.gov/sites/default/files/publications/Drought_and_Infrastructure_A_Planning_Guide_508c.pdf

Devanand, A., Karmakar, G., Krdzavac, N., Rigo-Mariani, R., Eddy, Y.S.F., Karimi, I.A., Kraft, M. OntoPowSys: A power system ontology for cross domain interactions in an eco industrial park, *Energy and AI*, Vol 1, 2020, 100008, https://doi.org/10.1016/j.egyai.2020.100008.

Directive (EU) 2022/2557 of the European Parliament and of the council of 14 December 2022 on the resilience of critical entities and repealing Council Directive 2008/114/EC (Text with EEA relevance).

Du, H., Wei, L., Dimitrova, V., Magee, D., Clarke, B., Collins, R., Entwisle, D., Torbaghan, M.E., Curioni, G., Stirling, R., Reeves, H., and Cohn, A.G., City infrastructure ontologies, *Computers, Environment and Urban Systems*, Volume 104, 2023, 101991, ISSN 0198-9715.

Fan, XQ, Zhang, LB, Wang, JK, Ren, YF, & Liu AW (2024). Analysis of faulting destruction and water supply pipeline damage from the first mainshock of the February 6, 2023 Türkiye earthquake doublet. Earthq Sci 37 (1): 78–90. https://doi.org/10.1016/j.eqs.2023.11.004.

FEMA (2024). Hazus 6.1: Hazus Earthquake Model, Technical Manual. Federal Emergency Management Agency, Washington DC. https://www.fema.gov/flood-maps/tools-resources/flood-map-products/hazus/user-technical-manuals

FEMA (2024). Hazus 6.1: Hazus Inventory, Technical Manual. Federal Emergency Management Agency, Washington DC.

FEMA (2024). Hazus 6.1: Hazus Flood Model, Technical Manual. Federal Emergency Management Agency, Washington DC.

Kakderi, K., Argyroudis, S. (2014). Fragility Functions of Water and Waste-Water Systems. SYNER-G: Typology Definition and Fragility Functions for Physical Elements at Seismic Risk, Geotechnical, Geological and Earthquake Engineering 27, DOI 10.1007/978-94-007-7872-6_8, Springer.

Kaynia, A.M., Johansson, J., Argyroudis, S. & Pitilakis, K. (2011). D3.8 - Fragility functions for railway system elements. Deliverable of the project SYNER-G (Systemic Seismic Vulnerability and Risk

Analysis for Buildings, Lifeline Networks and Infrastructures Safety Gain), funded by the European Community's Seventh Framework Programme [FP7/2007-2013] under grant agreement n° 244061, 59 p.

Lanzano G., Luzi L., Pacor F., Felicetta C., Puglia R., Sgobba S., D'Amico M. (2019) A Revised Ground-Motion Prediction Model for Shallow Crustal Earthquakes in Italy. *Bulletin of the Seismological Society of America* 109(2):525-540. DOI: 10.1785/0120180210

Lavalle, L., Patriarca, T., Daulne, B., Hautier, O., Tofani, A., Ciancamerla, E. (2020). Simulation-Based Analysis of a Real Water Distribution Network to Support Emergency Management. IEEE Transactions on Engineering Management, vol. 67, no. 3, pp. 554-567, doi: 10.1109/TEM.2019.2939099

Maria, A., Pitilakis, K., & Souli A. (2010). D3.5 - Fragility functions for water and waste-water system elements. Deliverable of the project SYNER-G (Systemic Seismic Vulnerability and Risk Analysis for Buildings, Lifeline Networks and Infrastructures Safety Gain), funded by the European Community's Seventh Framework Programme [FP7/2007-2013] under grant agreement n° 244061, 129 p

McPhearson, T., Cook, E. M., Berbés-Blázquez, M., Cheng, C., Grimm, N. B., Andersson, E., Barbosa, O., Chandler, D. G., Chang, H., Chester, M. V., Childers, D. L., Elser, S. R., Frantzeskaki, N., Grabowski, Z., Groffman, P., Hale, R. L., Iwaniec, D. M., Kabisch, N., Kennedy, C., Markolf, S. A., Matsler, A. M., McPhillips, L. E., Miller, T. R., Muñoz-Erickson, T. A., Rosi, E., Troxler, T. G. (2022). A social-ecological-technological systems framework for urban ecosystem services. One Earth, vol 5, no. 5, pp. 505-518. https://doi.org/10.1016/j.oneear.2022.04.007

Morbach, J, Wiesner, A., and Marquardt, W. Onto CAPE 2.0 —A (Re-)usable ontology for Computer-Aided Process Engineering, Editor(s): Bertrand Braunschweig, Xavier Joulia, *Computer Aided Chemical Engineering*, Elsevier, Volume 25, 2008, Pages 991-996, ISSN 1570-7946, https://doi.org/10.1016/S1570-7946(08)80171-X.

Ni, P., Mangalathu, S., & Yi,Y. (2018). Fragility analysis of continuous pipelines subjected to transverse permanent ground deformation, Soils and Foundations 58(6), 1400-1413. https://doi.org/10.1016/j.sandf.2018.08.002

O' Rourke, T.D., Toprak, S, Sano, Y. (1998). Factors affecting water supply damage caused by the Northridge earthquake. Proceedings of the Sixth US National Conference on Earthquake Engineering.

Pitilakis, K., Argyroudis, S., Kakderi, K., Gehl, P., Desramaut, N., Khazai, B., Yakut, A., Kaynia, A.M., Johansson, J., Fardis, M., Karantoni, F., Askouni, P., Lyrantzaki, F., Papailia, A., Tsionis, G., Crowley, H., Colombi, M., Bianchi, F., Monteiro, R., Pinto, P., Franchin, P., Lupoi, A., Cavalieri, F., & Vanzi, I. (2013). D8.10 - Guidelines for deriving seismic fragility functions of elements at risk: Buildings, lifelines, transportation networks and critical facilities. Deliverable of the project SYNER-G (Systemic Seismic Vulnerability and Risk Analysis for Buildings, Lifeline Networks and Infrastructures Safety Gain), funded by the European Community's Seventh Framework Programme [FP7/2007-2013] under grant agreement n° 244061, 250 p

Proctor CR, Lee J, Yu D, Shah AD, Whelton AJ. (2020) Wildfire caused widespread drinking water distribution network contamination. *AWWA Wat Sci*. 2020;e1183. https://doi.org/10.1002/aws2.1183

Rahbaralam, M., Modesto, D., Cardús, J., Abdollahi, A. & Cucchietti, F.M. (2020). Predictive Analytics for Water Asset Management: Machine Learning and Survival Analysis. https://doi.org/10.48550/arXiv.2007.03744

Raskin, R.G. and Pan, M.J. Knowledge representation in the semantic web for earth and environmental terminology (SWEET). *Computers & Geosciences*, 31(9), 1119–1125. doi:10.1016/j.cageo.2004.12.004

Rinaldi, S. M., Peerenboom, J. P., and Kelly, T. K.: Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Control Systems Magazine* 21(6), 11-25 (2001).

Sharif, M. N. Haider, H., Farahat, A., Hewage, K. and Sadiq, R. 2019. Water–energy nexus for water distribution systems: a literature review. Environmental Reviews. 27(4): 519-544. https://doi.org/10.1139/er-2018-0106

Weatherill, G. and Burton, P.W., An alternative approach to probabilistic seismic hazard analysis in the Aegean region using Monte Carlo simulation, *Tectonophysics*, Volume 492, Issues 1–4, 2010, Pages 253-278, https://doi.org/10.1016/j.tecto.2010.06.022.

Weeraddana,D., MallawaArachchi,S,, Warnakula,T., Li,Z., Wang, Yang. (2020). Long-Term Pipeline Failure Prediction Using Nonparametric Survival Analysis. https://doi.org/10.48550/arXiv.2011.08671

Xiao, G., Lanti, D., Kontchakov, R., Komla-Ebri, S., Güzel-Kalayci, E., Ding, L., Corman, J., Cogrel, B., Calvanese, D., and Botoeva, E.. The Virtual Knowledge Graph System Ontop. In: International Semantic Web Conference (Resource Track), 2020.