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**multi-Risk sciEnce for resilienT commUnities undeR a changiNgclimate**

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## Deliverable title:

# Logical and physical multi-hazard classification of impacts and fallout (impact assessment). Report outlining main consequences and impacts for CIs

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# 1 Technical references

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# 2 ABSTRACT

This deliverable presents a comprehensive assessment of multi-hazard impacts and cascading fallout on critical infrastructures across three domains: **transportation networks**, **industrial facilities**, and **urban civil infrastructure (water systems)**. It addresses both direct physical damages and indirect systemic disruptions (“logical” impacts) caused by natural and anthropogenic hazards occurring in combination. A key motivation is to guide practitioners and decision-makers in identifying potential multi-hazard consequences on infrastructure, thus enabling more rational and resilient asset management. In line with emerging European resilience directives (e.g. EU Directive 2022/2557) that call for improved multi-hazard preparedness, the report develops technical methodologies and decision-support tools for each sector, and distills cross-sector insights for policymakers and urban resilience planners.

In the transportation domain, the focus is on **road and railway tunnels** as critical, high-risk nodes. The report introduces a **performance-based multi-hazard Quantitative Risk Assessment (QRA)** methodology coupled with a **Decision Support System for Tunnels (DS4T)**. This approach fuses real-time data on traffic, weather, and equipment status with probabilistic risk models (using Fault Tree/Event Tree logic and Bayesian networks) to continuously evaluate tunnel safety under multiple concurrent threats. Unlike traditional static safety checks, the DS4T employs a risk-based supervisory control loop that dynamically adjusts ventilation, fire suppression, lighting and other subsystems to keep residual risk “as low as reasonably practicable” (ALARP). Diverse hazard scenarios – from fires and dangerous goods accidents to earthquakes, floods, and technological failures – are integrated into a unified model, allowing the system to capture interactions and cascading failures (e.g. a fire during an electrical blackout or an earthquake-induced tunnel flooding) that conventional single-hazard analyses might miss. This **probabilistic, compound-risk framework** yields quantitative indicators to support evidence-based emergency decisions and real-time operator guidance. Simulated implementation of the DS4T showed significant benefits: by continuously updating risk levels and optimising responses, the system reduced evacuation times in critical tunnel emergencies by ~25% and achieved up to 50% energy savings in routine operation through coordinated control of safety systems. The **three-layer DS4T architecture** (incorporating physical infrastructure, on-site renewable energy, and backup storage) proved effective and **replicable for both road and rail tunnels**, and is designed to absorb emerging threats such as lithium-ion battery fires or cyber-attacks. These results demonstrate a shift toward adaptive, resilience-oriented tunnel management, where multi-hazard QRA is directly linked to real-time decision support, improving both safety and efficiency in the face of complex hazard combinations.

For industrial critical infrastructures – particularly **major hazard industries (MHIs)** such as chemical and energy facilities – the report develops a **GIS-based systemic vulnerability mapping** methodology. This approach provides a territorial multi-hazard vulnerability profile of the area surrounding critical industrial sites, accounting for the two-way interactions between industrial facilities and natural hazards. A multi-scale, indicator-driven framework (adapted from Beltramino et al. 2022) is implemented as a proof-of-concept in an Italian case study. **Sensitivity, pressure, and hazard indicators** (21 in total) related to environmental, socio-economic, and infrastructural factors are computed using spatial analyses and then integrated via a hierarchical weighting scheme (involving stakeholder input) to produce a composite **systemic vulnerability index**. The study’s output is a set of high-resolution vulnerability maps (200×200 m grid) that highlight hotspots of compounded vulnerability in the region – visualized on an intuitive green/yellow/orange/red scale to be easily interpretable by local decision-makers. This GIS tool establishes a **baseline for multi-hazard vulnerability** at municipal scale and can be tailored to specific industrial sites for land-use planning and risk management purposes.

A detailed case study examines a **thermoelectric power plant** (former Seveso site) and its surroundings (≈280 ha) to demonstrate the methodology. The results indicate that roughly two-thirds of the area exhibit **moderate vulnerability**, while the remaining one-third has **high to critical vulnerability** concentrated in and around the industrial facility. In particular, the **"Building, Heritage, and Infrastructure" component** of the index scored highly, reflecting the susceptibility of built assets to multiple hazards in this urban-industrial setting. Notably, the analysis identified **flood hazard** as a significant driver of vulnerability in low-lying parts of the site, and revealed a critical **interdependency between the power plant and nearby industrial installations**. This two-way interaction (the plant's risk to its neighbors and vice versa) raises the potential for **domino effects** – where an incident at one facility (e.g. an explosion or toxic release triggered by an earthquake or flood) could impact adjacent facilities and escalate into a wider accident. Such findings underscore the need to include external territorial factors and **Natech scenarios** (natural-hazard-triggered technological accidents) in industrial risk assessments. In addition, a complementary quantitative risk analysis is performed for an **accidental gas release scenario** (pipeline leak of hydrogen–methane fuel mix) to illustrate the methodology for estimating incident probabilities (fault and event tree analysis) and consequences (empirical models and CFD simulations). This provides insight into the blast/thermal impact ranges for emerging energy carriers (like hydrogen) and informs safety distances and emergency planning for industrial sites handling new fuels. Overall, the industrial section's methods and case insights help broaden stakeholder awareness of multi-hazard vulnerability in industrial areas, offering a spatial decision-support tool that complements traditional probabilistic risk analyses with a **systemic vulnerability perspective**.

The civil infrastructure analysis concentrates on **urban water supply and drainage (wastewater/stormwater) systems**, which are vital lifelines increasingly challenged by compound hazards. The report takes a **compound risk and interdependency modeling** approach, synthesizing state-of-the-art knowledge on how multiple hazards can jointly affect water infrastructure and how failures can propagate across interconnected systems. Modern urban water networks are tightly coupled socio-technical systems (physical pipes and pumps, cyber controls, human operators) that face **compound extreme events** (e.g. droughts coincident with heatwaves, or intense rainfall with storm surge) and **cascading disasters** (e.g. a power grid blackout disabling pumps, leading to water outages and sewer overflows). Evidence from past crises shows that the worst societal impacts often arise from **hazard interactions and cascade chains**, rather than isolated events – for example, an earthquake that not only damages pipelines but also knocks out power and roads can cause disproportionately severe water service failures. Recognizing this, the report employs a comprehensive hazard taxonomy (covering hydrometeorological, geophysical, biological, and technological threats) and reviews multiple modeling frameworks (network flow models, system dynamics, interdependent network simulations, etc.) to capture these **cascading interdependencies**. The analysis is structured by infrastructure type: it first examines **urban water supply systems** (from source waters and treatment through distribution) versus **urban drainage systems** (sewer networks, stormwater facilities, treatment plants), detailing for each the relevant hazards and typical failure modes. This segmented analysis is then followed by a **cross-system synthesis** identifying how failures can escalate between water supply and wastewater systems and into other sectors (for instance, a flood that disrupts transport and power can hinder repair crews and treatment operations). Crucially, it highlights that traditional single-hazard assessments likely **underestimate risk in water infrastructure** – a "univariate" approach might overlook correlated failures like simultaneous pump station outages and flooding, or the compounding of chronic stresses (e.g. aging infrastructure) with acute shocks. The civil infrastructure section thus advocates for **holistic, multi-hazard resilience assessment** for urban water systems, combining hydraulic simulation, water quality and structural fragility modeling, and consideration of inter-sector dependencies (power, communications, transportation) to evaluate worst-case scenarios. This detailed review of hazard impacts and cascade mechanisms culminates in a set of **mitigation and adaptation recommendations** for water utilities, urban planners, and risk analysts. These recommendations emphasize measures such as ensuring backup power and communications for pumps, flood-proofing key facilities, developing emergency protocols for compound events (e.g. “flood + contamination + power loss” scenarios), integrating real-time monitoring/early-warning systems for cascading failures, and strengthening the redundancy of water supply networks (loops and interties) to prevent single-point failures. By implementing these strategies, cities can significantly improve the robustness of water services under multi-hazard conditions, reducing the likelihood of cascading water crises and safeguarding public health and safety.

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# 4 Main consequences and impacts for transportation CIs

## 4.1 Development of multi-hazard risk assessment for road and railway networks

### 4.1.1 Introduction

The assessment of multi-risk scenarios, characterized by the co-occurrence or interaction of multiple hazardous events, plays a central role in contemporary risk analysis. This methodology combines dynamic (i.e., time-dependent) modelling with both phenomenological and probabilistic data, aiming to identify, evaluate, and manage risks that may arise concurrently or in cascade (Kappes et al., 2012; Gill & Malamud, 2014). A multi-risk approach extends beyond the mere enumeration of hazards to include their interdependencies, exposure, vulnerability, and potential impacts on systems and populations.

Natural hazards such as earthquakes, floods, and wildfires, alongside technological threats such as industrial accidents or tunnel fires, are considered within a unified analytical framework (Liu et al., 2021; Komendantova et al., 2014). The core objective is to provide quantitative and comparable risk indicators that support evidence-based decision-making in emergency preparedness, response planning, and long-term mitigation strategies. By anticipating complex risk chains and their systemic effects, this approach contributes to the protection of communities and the resilience of infrastructure networks (Marzocchi et al., 2012).

Among the various infrastructures exposed to such multi-hazard scenarios, **road and railway tunnels** represent particularly critical assets. Their enclosed nature, limited accessibility, and location in strategic transport corridors make them vulnerable to a broad spectrum of threats, including vehicular fires, collisions, landslides, seismic activity, flooding, and technological system failures (PIARC, 2020; Ronchi & Kinsey, 2011). These conditions are further complicated by the interaction between structural elements, safety systems, and human behavior during emergencies.

In this context, a **multi-hazard risk assessment methodology** becomes essential to ensure the safety, operability, and resilience of tunnel infrastructure. The proposed approach integrates diverse hazard scenarios, both independent and interrelated, into a unified analytical model for risk identification, quantification, and mitigation. It also accounts for the dynamic behavior of infrastructure and the cascading effects that may arise under compound stress conditions (Pescaroli & Alexander, 2016).

The methodology described herein draws upon results from **full-scale fire testing**, **advanced numerical simulations**, and the implementation of **Decision Support Systems (DSS)** (Ingason et al., 2015; Li et al., 2022). This combination enables a transition from prescriptive safety models to **performance-based and sustainability-oriented strategies**. It supports both strategic planning, such as investment prioritization and infrastructure upgrades—and operational readiness, including real-time response under evolving risk scenarios.

In this work, the term ***multi-risk*** encompasses both the physical hazard environment (***multi-hazard***) and the associated dimensions of exposure, vulnerability, and consequences. Particular emphasis is placed on **compound hazard scenarios** relevant to tunnel systems, such as:

- Fire events following vehicular collisions under seismic conditions
- Flooding in conjunction with electrical system failure
- Earthquake-induced slope instability leading to tunnel obstruction

- Simultaneous demand on emergency services due to regional hazard escalation

By adopting an integrated, system-level perspective, this multi-risk methodology enhances the capacity to anticipate, prepare for, and respond to complex threats affecting transportation infrastructure.

The term multi-hazard refers to the simultaneous or sequential occurrence of two or more hazardous events that may interact and amplify each other's impacts (Gill & Malamud, 2014; Kappes et al., 2012). In tunnel infrastructure, such compound scenarios may include:

- a fire occurring during a power blackout (technological + fire hazard),
- a landslide blocking a tunnel portal after intense rainfall (geohazard + hydrohazard),
- an earthquake damaging safety-critical systems (seismic + technological hazard), or
- flash flooding leading to cascading ventilation system failures (hydro + technological hazard).

These complex situations frequently exceed the assumptions of conventional single-hazard risk models and underscore the need for integrated approaches capable of capturing the full spectrum of failure mechanisms (Komendantova et al., 2014; Pescaroli & Alexander, 2016). Traditionally, tunnel risk assessments have focused on specific hazards—predominantly fires—yet the growing exposure to both natural and anthropogenic threats calls for a shift towards systemic multi-risk frameworks (Garcia-Aristizabal & Marzocchi, 2013).

Recent regulatory initiatives, such as the European Directive 2022/2557 on critical infrastructure resilience, promote a more holistic perspective on infrastructure safety, encouraging the adoption of dynamic, time-dependent models that integrate probabilistic, physical, and systemic components. Within this paradigm, multi-hazard risk assessment incorporates:

- **Systemic risk analysis**, accounting for cascading effects across interconnected subsystems (e.g., power supply, communication, ventilation) (Pescaroli & Alexander, 2016),
- **Time-dependent vulnerability**, addressing the degradation of materials and components under environmental and operational stressors (Giovinazzi & Laghi, 2020),
- **Dynamic exposure**, reflecting changes in tunnel occupancy, traffic volume, and hazardous goods transit over time (Krausmann et al., 2019),
- **Interdependencies and feedback loops**, highlighting how failure in one subsystem (e.g., electrical) can propagate to others, triggering wider collapse (Linkov et al., 2014).

This integrated approach aligns with the principles of infrastructure resilience, emphasizing robustness, redundancy, adaptability, and rapid recovery in the face of multiple threats (Cimellaro et al., 2016). Tunnel environments, due to their confined space, limited egress routes, and reliance on active safety systems, are particularly vulnerable to hazard amplification. For example, a failure in the ventilation system during a fire may rapidly degrade tenability conditions, increase toxic smoke concentrations, and delay evacuation or rescue operations (Ronchi & Nilsson, 2016).

Furthermore, the closure of tunnel infrastructure due to multi-hazard events can cause substantial socio-economic disruptions, particularly in mountainous regions or densely populated urban areas with few alternative routes (Vogel et al., 2022). Such closures can affect freight flows, emergency services, and regional mobility.

Modern tunnel infrastructure often includes complex embedded systems—such as sensors, surveillance, variable message signs, and emergency lighting, whose performance is critical during emergency scenarios. Multi-hazard events may impair or disable these systems, undermining situational awareness and emergency coordination. Consequently, resilience strategies must integrate both physical upgrades and smart, adaptive technologies that support real-time monitoring and decision-making (Linkov & Trump, 2019).

### 4.1.2 Multi-Hazard in Tunnels

Understanding the concept of multi-hazard risk in road tunnel infrastructure is essential for assessing the interactions, cascading effects, and potential consequences associated with complex hazard scenarios. When applied to critical infrastructure, the multi-hazard framework should not be limited to events occurring simultaneously. Rather, it must encompass a comprehensive assessment of individual hazards, their probability of occurrence, and their interdependencies. In this context, risks should be analyzed both individually and in combination to capture potential amplification or cascading effects (Gill & Malamud, 2014; Komendantova et al., 2014).

Road tunnels represent strategic components of the European transport network, yet they constitute vulnerable nodes due to their confined geometry, high traffic volumes, and reliance on critical systems for ventilation, lighting, and communication. Over the past two decades, substantial progress in tunnel safety has been achieved through the implementation of regulatory frameworks such as Directive 2004/54/EC and the corresponding Italian Legislative Decree 264/2006, as well as through technological advancements in fire detection, ventilation, and emergency management systems (European Commission, 2004).

However, increasing interconnectivity among infrastructure systems, coupled with the intensification of extreme weather events and anthropogenic threats, necessitates a paradigm shift from mono-hazard models, primarily focused on fire safety, to multi-hazard approaches that integrate the interaction between various threats, including hazardous material accidents, flooding, earthquakes, and system malfunctions (Pescaroli & Alexander, 2016; Rehak et al., 2019).

The emerging regulatory landscape, particularly the draft Directive 2022/2557/EC on the resilience of critical entities, reinforces the need for integrated risk assessment. This Directive mandates operators of essential services to prepare resilience reports and action plans, explicitly calling for methods that assess the vulnerability of infrastructure to compound and cascading events (European Commission, 2022).

Despite this regulatory push, methodological gaps persist. Most current models assess hazards in isolation and fail to account for multi-risk interactions. Superimposing single-hazard risk indices does not adequately represent the system's behavior under compound stressors. Instead, an integrated modeling framework is required to reflect the spatiotemporal dynamics of multi-hazard exposures, cascading failures, and system degradation (Aven, 2011; Tilloy et al., 2019). In this regard, the traditional definition of availability, as the probability of a system functioning under specific conditions, may be extended to include the proportion of operational capacity retained during disruptions, thus enabling the application of resilience concepts to complex engineered systems (Bruneau et al., 2003; Panteli & Mancarella, 2015).

The proposed methodology for multi-risk assessment in road tunnels includes four key components (Figure 4.1):

- **Hazard typology and interdependencies:** a qualitative classification of relevant hazards, fires, accidents involving dangerous goods, seismic events, flooding, and technological failures, is conducted. The analysis includes the identification of causal links and potential domino effects, with each scenario characterized by frequency, severity, and propagation dynamics (Kappes et al., 2012).

- **Quantitative risk modeling based on alarp:** a quantitative risk model is implemented to estimate residual risks and verify their acceptability under the "As Low As Reasonably Practicable" (ALARP) principle. The model utilizes real-time data on traffic, environmental conditions, and system status, and incorporates machine learning techniques to dynamically update risk metrics, including F-N curves (Khan & Abbasi, 1998; Ouyang, 2014).
- **Decision Support System (DSS) architecture:** the DSS constitutes the operational core of the framework, integrating safety management, energy optimization, and resilience planning into a unified platform. This system processes ALARP outputs and translates them into adaptive control parameters for ventilation, lighting, water mist systems, and the tunnel's microgrid (Stergiopoulos et al., 2016).
- **Real-Time operational framework:** the final layer involves an operational loop comprising data acquisition, analysis, decision-making, and actuation. This loop ensures minimal latency and synchronizes safety-critical functions (SCADA, PLCs) with energy management strategies, enabling coordinated and traceable responses during emergencies (Moreno et al., 2019).

By integrating multi-hazard risk assessment into tunnel safety management, this methodology enhances situational awareness, strengthens emergency response capabilities, and promotes long-term resilience of critical transport infrastructure.

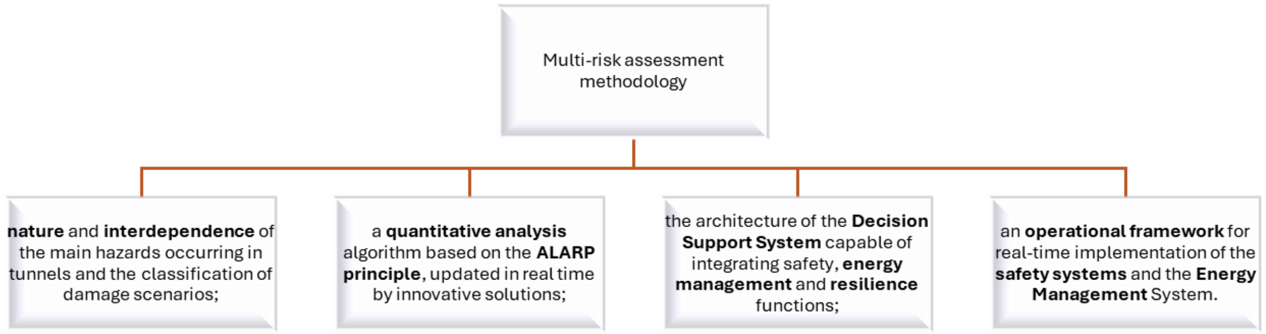


**Figure 4.1:** Multi risk assessment framework

### 4.1.3 Risk Analysis: through a methodology for the assessment of multi-risk scenarios.

Building upon the methodological framework outlined in **Figure 4.1**, this section delineates a comprehensive quantitative risk analysis (QRA) for tunnel infrastructure, starting from the classification of damage scenarios. The approach emphasizes the necessity of precisely defining the mathematical model before its application, particularly in dynamic operating conditions.

Quantitative Risk Assessment (QRA) is a cornerstone of infrastructure safety and resilience analysis. It utilizes probabilistic modelling to evaluate potential accident scenarios, estimate the likelihood of initiating events (IEs), and quantify their associated consequences (Khakzad et al., 2013; D'Andrea et al., 2020). This method provides a structured and reproducible framework for risk-informed decision-making in both design and operational phases of tunnel management.

A key aspect of infrastructure safety management, especially in the context of European regulatory frameworks such as Directive (EU) 2022/2557 on the resilience of critical entities, is the integration of real-time operational data into risk evaluation. Risk-based design must therefore be interpreted as a dynamic and continuous process, rather than a static, design-phase-only activity (European Commission, 2022). In the design stage, risk acceptability is assessed according to predefined thresholds (e.g., ALARP – "As Low As Reasonably Practicable"), while in the operational phase, safety conditions must be re-evaluated in real time based on time-varying system data (Liu et al., 2017). This requires continuous reassessment of residual risk to ensure alignment with evolving safety targets and to support infrastructure resilience in both routine and emergency conditions (Aven & Renn, 2010).

In tunnel environments, this translates into real-time dynamic risk analysis, where the system must be responsive enough to inform operator decisions during critical events such as fires or technological failures. The method must be probabilistic and capable of recognizing early warning signs from environmental and system variables (Gidaris et al., 2017). This includes the fusion of short-term forecasts (e.g., traffic flow, weather conditions) with the assessment of subsystem availability (e.g., ventilation, detection, lighting).

The first analytical step consists of aligning the risk model to the relevant time scale, identifying hazardous events and modelling their evolution using bow-tie logic. This combines fault tree analysis (for cause modelling) with event tree analysis (for consequence modelling), allowing for a detailed mapping of each IE through its possible propagation paths (Pasman et al., 2017). For each scenario, the chain of causality—initiating event, damage mechanisms, exposure, vulnerability, and consequences—is reconstructed to quantify the resulting risk.

In operational verification, the core output is the Individual Risk (IR) indicator, defined as the annual probability of fatality for a person exposed to hazards resulting from IE evolution. This is complemented by the Societal Risk (SR) indicator, which estimates the expected fatalities over a given exposed population. Both indicators are derived from the expected damage value, and IR is normalized over the spatial–temporal exposure levels (Cozzani et al., 2015). In bow-tie diagrams, the IE acts as the central node linking cause and effect domains.

The reliability of the resulting risk indicators depends on several factors: (i) the number and resolution of simulation runs used to construct the event trees, (ii) the completeness of the scenario set for each IE, and (iii) the computational performance of simulators, such as Computational Fluid Dynamics (CFD) engines used for fire spread and smoke movement prediction (Hu et al., 2019).

Where historical data are lacking or incomplete, the analytical workflow incorporates data assimilation and continuous model updating to maintain robustness. Real-time data streams—from, for example, thermal cameras integrated within the SCADA system—contribute to a live representation of current system status, supporting both the assessment of ongoing risk and the diagnostics of safety-system operability (Zhou et al., 2020).

In sum, this dynamic, probabilistic QRA approach provides the foundational infrastructure for both ordinary operation and emergency response, underpinning the resilience of critical tunnel systems exposed to interacting hazards.

#### *4.1.3.1 Decision support system for multi risk management*

Traditional SCADA architectures typically operate safety subsystems—such as ventilation, lighting, and fire suppression—in isolation, following a non-integrated control logic. This siloed configuration leads to two primary inefficiencies: (i) suboptimal emergency response, as each subsystem functions independently without cross-referencing the state or actions of the others, and (ii) unnecessary energy consumption due to redundant or uncoordinated activation of multiple systems.

To address these limitations, the DS4T (Decision Support for Tunnels) system introduces a risk-based supervisory control loop that continuously evaluates residual risk based on the *As Low As Reasonably Practicable* (ALARP) criterion. It dynamically adjusts control setpoints to recommend the lowest-energy operational strategy that maintains risk within the tolerable region. By integrating real-time monitoring with adaptive response logic, DS4T enhances both the efficiency and resilience of tunnel safety infrastructure.

### Three-Layer Interconnected Framework

The DS4T system operates through a multi-layered architecture:

- Physical layer, encompassing core civil infrastructure elements such as longitudinal jet-fan ventilation, low-pressure water-mist fire suppression, and adaptive LED lighting systems.
- Energy-production layer, including on-site renewable energy sources—specifically photovoltaic arrays located at tunnel portals, micro wind turbines integrated into ventilation shafts, and geothermal heat-pump systems.
- Storage layer, comprising lithium iron phosphate (LFP) battery banks engineered to sustain 45 minutes of full-capacity ventilation during a complete electrical blackout.

Sensor data from all layers—together with real-time inputs on traffic density, weather conditions, system integrity, and battery state-of-charge—are processed by the DS4T core. Predictive algorithms dynamically optimize parameters such as jet-fan thrust direction during fire events, ensuring compliance with smoke-control thresholds while minimizing energy expenditure (Li et al., 2021; Carvel & Beard, 2010).

### Architecture and Functionality

The platform architecture is modular and includes the following components:

- Data Collector, responsible for acquisition and preprocessing of real-time sensor streams.
- Risk Engine, implementing probabilistic risk models such as Bayesian networks validated through Chi-square statistical tests to compute the likelihood of initiating events (Cox, 2008; Khakzad et al., 2013).
- Energy Optimiser, integrating predictive models (e.g., CO concentration forecasting) and reinforcement learning algorithms to derive energy-efficient yet safety-compliant ventilation control strategies.
- Human–Machine Interface (HMI), which facilitates coordinated action among operators, infrastructure managers, and emergency response teams through structured scenario-based decision guidance.

During emergency conditions, the optimiser executes smoke-control strategies derived from validated Computational Fluid Dynamics (CFD) simulations. Concurrently, the HMI module provides sequential, context-sensitive instructions to the operator, reducing cognitive load and minimising the risk of human error (Carvel et al., 2001; Beard & Carvel, 2005).

#### *4.1.3.2 Theoretical Model*

The analytical framework adopts a dual-logic approach by coupling Fault Tree Analysis (FTA) with Event Tree Analysis (ETA), thereby enabling propagation modeling of subsystem-level failures. A resilience metric is computed to quantify the system's ability to restore nominal operational status after disruptive events. This closed-loop paradigm establishes a direct link between quantitative risk analysis and real-time decision-making: every control action is traceable to a probabilistic performance benchmark, supporting transparency, repeatability, and regulatory compliance throughout the entire emergency management lifecycle (Hollnagel et al., 2006; Woods, 2005; Aven, 2015).

### 4.1.4 Implementation of Routines for Integration into the Decision Support System Framework – RISK Module

As a part of the architectural framework belonging to the Decision Support System for multi risk management, a model was developed within the macro-area concerning accident analysis for road tunnels, specifically focusing on the definition of probability of initial event and historical data analysis. The model is implemented as an algorithm, capable of performing three fundamental actions required for accident analysis in a tunnel, divided into:

- Chi-square Test ($\chi^2$ Test), which allows for the validation of collected accident data to proceed with the accident analysis;
- Calculation of the Average Daily Traffic (ADT), a key parameter for determining the probability of the initiating event;
- Calculation of the probability of initiating events, which serves as the connection point between the two macro-areas.

The following **Figure 4.2**. describes the flowchart outlining the description of the proposed routines implemented to the DS4T.

Following, three calculation processes related to the entire procedure will be "automated." This approach can be considered a part for the implementation of a decision support system that also extends to post-accident analysis, involving the component of event tree analysis in the preceding chapter.

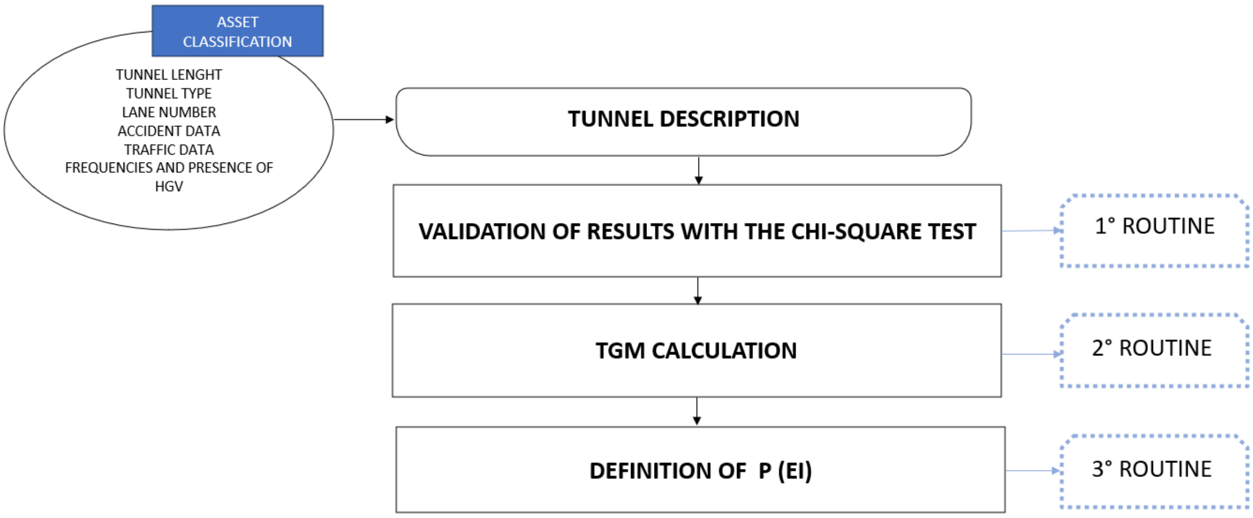


**Figure 4.2:** Description of the architecture of algorithms proposed to implement the DS4T

To build the calculation procedure, it is first necessary to have reliable data on the specific tunnel under study. So, it is important to systemize the following input data:

- Tunnel length;
- Tunnel location along the road section under analysis;
- Tunnel type (single-bore or twin-bore);
- Number of carriageways;
- Accident reports for the road section where the tunnel is located, including differentiation of accident types;
- Accident reports specific to the tunnel, including differentiation of accident types;
- Traffic data for the road section;
- ADR accident event frequencies.

In the first part, the goal is to generate a code that allows subsequent applications to process input data linearly and simply.

Therefore, the idea is to create a default excel sheet containing a label row and one or more rows of values that all three applications can process.

Below in **Figure 4.3**. there is the code related to database preparation:

```
import openpyxl
from math import factorial
from math import e
def importValues(excelFilePath, sheetName):
  workbook = openpyxl.load_workbook(excelFilePath)
  sheet = workbook[sheetName]
  tempLabelList = sheet[1]
  labelList = []
  for label in tempLabelList:
    labelList.append(label.value)
  valueList = []
  j = 0
  while j < len(labelList):
    tempList = []
    i = 2
    while sheet[i][j].value  is not None:
      tempList.append(sheet[i][j].value)
      i += 1
    valueList.append(tempList)
    j += 1
  dataMap = dict(zip(labelList, valueList))
  return dataMap
```

**Figure 4.3:** Data preparation script

After data preparation, the first step summarizing the content of chapter 3, involves the chi – square test procedure. The chi-square test ($\chi^2$) is a statistical technique that can also be applied to accident analysis to evaluate the association between two categorical variables. Specifically, it helps determine whether a relationship exists between certain factors (weather conditions, time of day, type of accident) and the number of recorded incidents.

In the case under examination, the chi-square test measures the discrepancy between observed and expected frequencies under the null hypothesis of independence between the variables. If the chi-square value is sufficiently large, the null hypothesis can be rejected, indicating a significant association between the variables. The final aim of this path is to verify whether the dataset used for the analysis has statistical validity for its use in probability calculations.

The program takes as input:

- x = number of events (accidents) occurring within a given time frame (one week);
- fobs = reference weeks corresponding to the number of analyzed events.

These parameters are translated into the input data for the program designed to perform the chi-square test. Below in **Errore. L'origine riferimento non è stata trovata.** is the source code.

```
def chiSquareOperations(dataMap, excelFilePath, sheetName):
   tempList = []

   for i in range(len(dataMap.get("x"))):
      tempList.append(dataMap.get('x')[i]  * dataMap.get('fo')[i])

   dataMap["fx"] = tempList

   sumFo = sum(dataMap.get("fo"))
   dataMap["sumFo"] = sumFo

   sumFx = sum(dataMap.get("fx"))

   lambdaValue = sumFx / sumFo
   dataMap["lambda"] = lambdaValue

   expLambda  = e ** (-lambdaValue)
   dataMap["expLambda"]  = expLambda

   lambdaPowerXList = [pow(dataMap.get("lambda"),  x) for x in dataMap.get("x")]
   dataMap["lambda^x"] = lambdaPowerXList

   pXList = [(dataMap.get("lambda^x")[i]  * dataMap.get("expLambda"))  / factorial(dataMap.get("x")[i]) for i in
range(len(dataMap.get("x")))]
   dataMap["P(x)"]  = pXList

   feList = [dataMap.get("P(x)")[i]  * dataMap.get("sumFo")  for i in range(len(dataMap.get("x")))]
   dataMap["fe"]  = feList

   x2List = [((dataMap.get("fo")[i]  - dataMap.get("fe")[i])  ** 2) / dataMap.get("fe")[i]  for i in range(len(dataMap.get("x")))]
   dataMap["X2"] = x2List

   sumX2 = sum(dataMap.get("X2"))
   dataMap["sumX2"] = sumX2
   print("The chi-square value is: ", sumX2)

   degreesOfFreedom = input("Enter  the number of degrees of freedom: ")
   workbook = openpyxl.load_workbook(excelFilePath)
   sheet = workbook[sheetName]

   criticalValue = sheet[int(degreesOfFreedom) + 1][1].value
   print("The critical value is: ", criticalValue)

   if sumX2 <= criticalValue:
      print(sumX2,  "is less than or equal to", criticalValue, ", so the Chi-square test is validated")
   else:
      print(sumX2,  "is greater than", criticalValue, ", so the Chi-square test is not validated")

dataMap = importValues("C:/Users/marta/Onedrive/Desktop/DOTTORATO/TESI DOTTORATO/DS4T/ Tunnel  Test. xlsx",
"Foglio2")
chiSquareOperations(dataMap, "C:/Users/marta/Onedrive/Desktop/DOTTORATO/TESI DOTTORATO/DS4T/ Tunnel  Test. ",
"Foglio4")
```

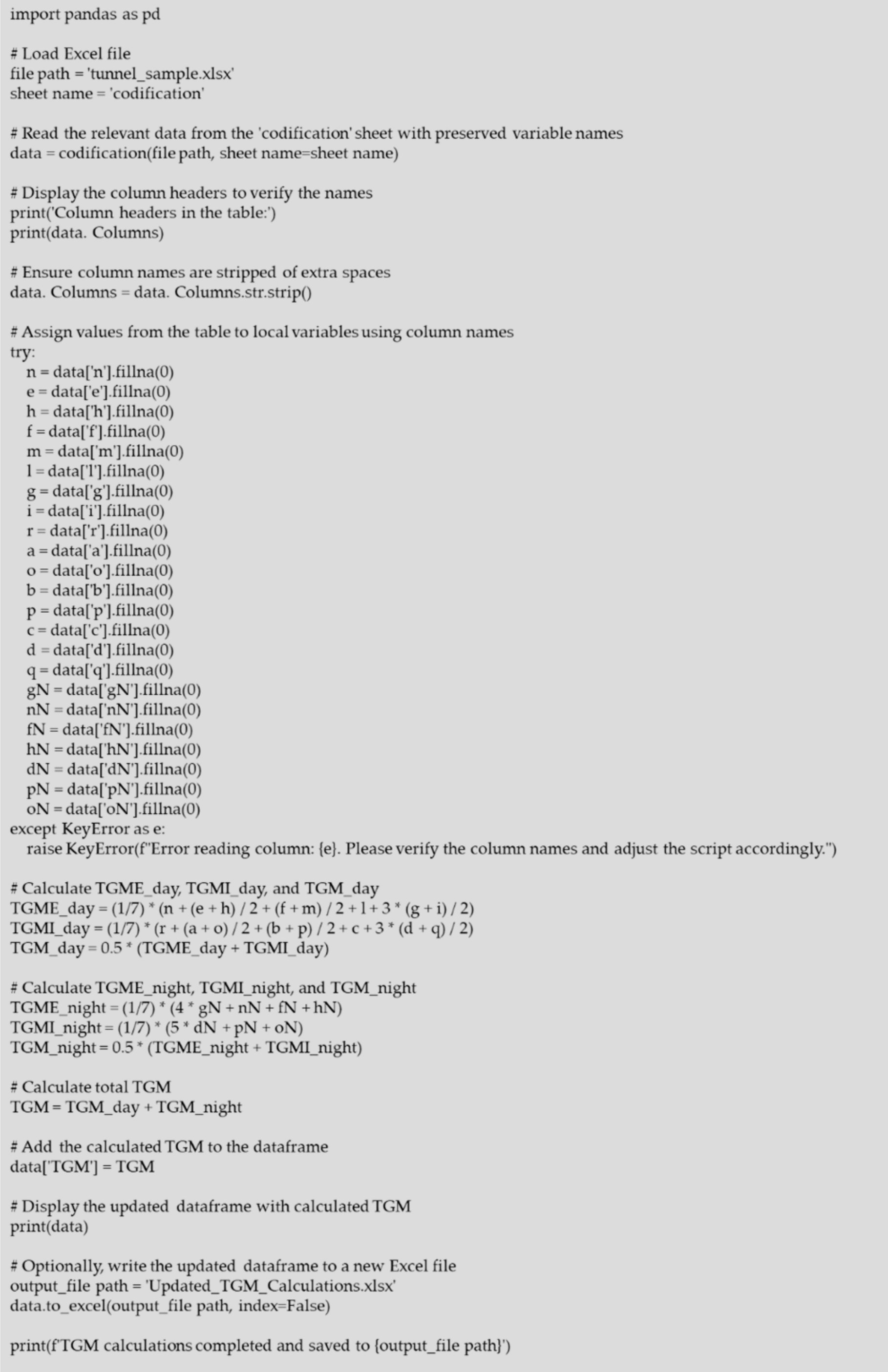
**Figure 4.4:** Chi square test – script

The average daily traffic (ADT), second step of the framework is essential for implementing the methodology, particularly for calculating the initiating event. Traffic data is obtained from the tunnel operator, who provides traffic measurements for light and heavy vehicles at arbitrary intervals (e.g., every hour) for each direction of travel. To proceed with the ADT calculation, the following factors over the years observed must be considered:

- Seasonality: dividing into summertime (April to September) and winter (October to March);
- Time period: split data into daytime (7:00 AM to 7:00 PM) and nighttime (7:00 PM to 7:00 AM);

- Day of the week: for this analysis some representatives day are taken into account. For instance,2 Saturdays, 2 Sundays, 1 Monday, 1 Friday, and 2 weekdays (Tuesday to Thursday) are considered.

The measurements used for the calculations are selected as samples. The developed script, in **Figure 4.5**. allows obtaining the ADT value by entering the data outlined previously. As observed, the categories for light and heavy vehicles have been included, which could be useful for other purposes, such as calculating the percentage of light and heavy vehicles to be used as parameters in the probability calculation of incidental events.



```
import pandas as pd

# Load Excel file
file path = 'tunnel_sample.xlsx'
sheet name = 'codification'

# Read the relevant data from the 'codification' sheet with preserved variable names
data = codification(file path, sheet name=sheet name)

# Display the column headers to verify the names
print('Column headers in the table:')
print(data. Columns)

# Ensure column names are stripped of extra spaces
data. Columns = data. Columns.str.strip()

# Assign values from the table to local variables using column names
try:
   n = data['n'].fillna(0)
   e = data['e'].fillna(0)
   h = data['h'].fillna(0)
   f = data['f'].fillna(0)
   m = data['m'].fillna(0)
   l = data['l'].fillna(0)
   g = data['g'].fillna(0)
   i = data['i'].fillna(0)
   r = data['r'].fillna(0)
   a = data['a'].fillna(0)
   o = data['o'].fillna(0)
   b = data['b'].fillna(0)
   p = data['p'].fillna(0)
   c = data['c'].fillna(0)
   d = data['d'].fillna(0)
   q = data['q'].fillna(0)
   gN = data['gN'].fillna(0)
   nN = data['nN'].fillna(0)
   fN = data['fN'].fillna(0)
   hN = data['hN'].fillna(0)
   dN = data['dN'].fillna(0)
   pN = data['pN'].fillna(0)
   oN = data['oN'].fillna(0)
except KeyError as e:
   raise KeyError(f"Error reading column: {e}. Please verify the column names and adjust the script accordingly.")

# Calculate TGME_day, TGMI_day, and TGM_day
TGME_day = (1/7) * (n + (e + h) / 2 + (f + m) / 2 + l + 3 * (g + i) / 2)
TGMI_day = (1/7) * (r + (a + o) / 2 + (b + p) / 2 + c + 3 * (d + q) / 2)
TGM_day = 0.5 * (TGME_day + TGMI_day)

# Calculate TGME_night, TGMI_night, and TGM_night
TGME_night = (1/7) * (4 * gN + nN + fN + hN)
TGMI_night = (1/7) * (5 * dN + pN + oN)
TGM_night = 0.5 * (TGME_night + TGMI_night)

# Calculate total TGM
TGM = TGM_day + TGM_night

# Add  the calculated TGM to the dataframe
data['TGM'] = TGM

# Display the updated  dataframe with calculated TGM
print(data)

# Optionally, write the updated  dataframe to a new Excel file
output_file path = 'Updated_TGM_Calculations.xlsx'
data.to_excel(output_file path, index=False)

print(f'TGM calculations completed and saved to {output_file path}')
```

**Figure 4.5:** TGM calculation - script

The implemented code follows a structured sequence of operations to process traffic-related data stored in the map dictionary calculating the Average Daily Traffic (ADT). In the code, the TGM means the translation of the italian "traffico medio giornaliero".

The key computational steps are outlined below:

*Removal of null elements*

The code first ensures data integrity by eliminating entries with None values using the .pop(None) method, preventing computational errors in subsequent calculations.

*Computation of period-specific traffic metrics*

- Evening and Night Traffic Extraction: The variables tgmEDay and tgmENight are derived by summing and averaging specific values extracted from map.
- Internal Traffic Metrics: A similar procedure is applied to compute tgmIDay and tgmINight, ensuring a distinction between different sources of data.

*Aggregation of traffic indicators*

- Daytime traffic calculation: tgmDay is obtained by averaging tgmEDay and tgmIDay, providing a representative measure of daytime traffic.
- Nighttime traffic calculation: tgmNight is computed as the average of tgmENight and tgmINight, ensuring a balanced representation of nighttime conditions.

*Final synthesis and output*

Total Average Daily Traffic (ADT) is computed as the sum of tgmDay and tgmNight.

The final computed value is displayed in the console, enabling further analysis or integration into broader traffic studies.

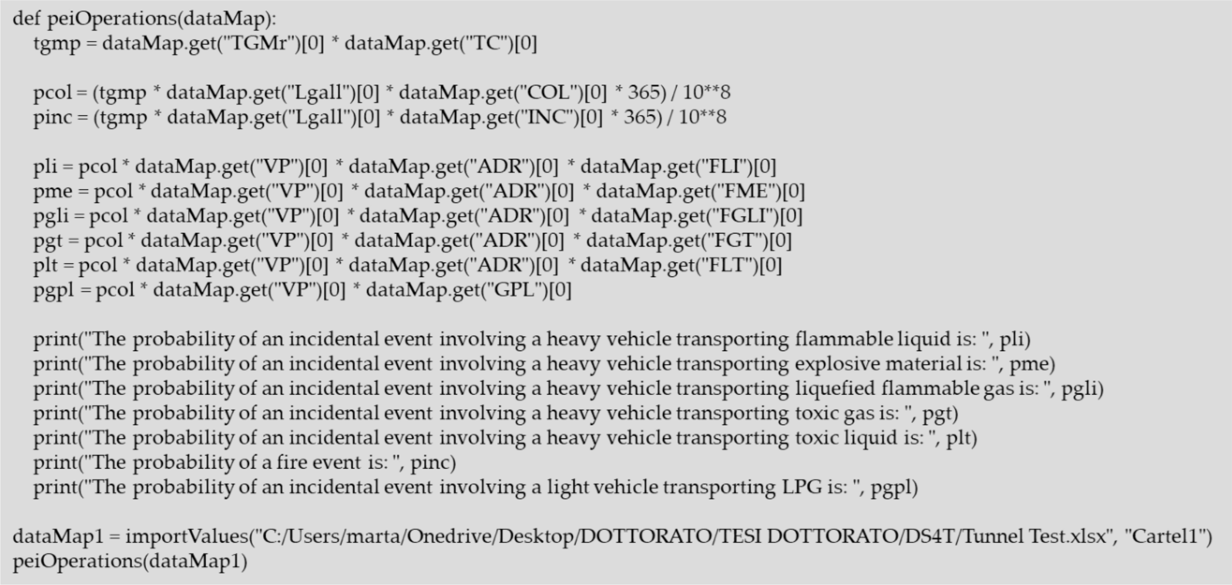
After that, in the third step the calculation of incident event probabilities is structured in two phases: in the first phase, the annual probabilities of collision and fire are determined, while in the second phase, the annual probabilities of each initiating event are calculated based on the input parameters.

The probability depends on some input parameters, listed below:

- TMGr: Recorded Average Daily Traffic;
- Tunnel length;
- Tunnel-specific collision rate, calculated as: Collision Rate = (Number of collision incidents) / (Total number of incidents);
- Tunnel-specific fire rate, calculated as: Fire Rate = (Number of fire incidents) / (Total number of incidents);
- ADR: Proportion of heavy vehicles transporting dangerous goods among heavy vehicles;
- VP: Percentage of heavy vehicles;
- VL: Percentage of light vehicles;
- FLI: Frequency of vehicles transporting flammable liquids;
- FME: Frequency of vehicles transporting explosive materials;
- FGLI: Frequency of vehicles transporting liquefied flammable gas;
- FGT: Frequency of vehicles transporting toxic gas;
- FLT: Frequency of vehicles transporting toxic liquid;

- TC: Growth rate of the Average Daily Traffic;
- GPL: Proportion of LPG-fueled light vehicles among light vehicles.

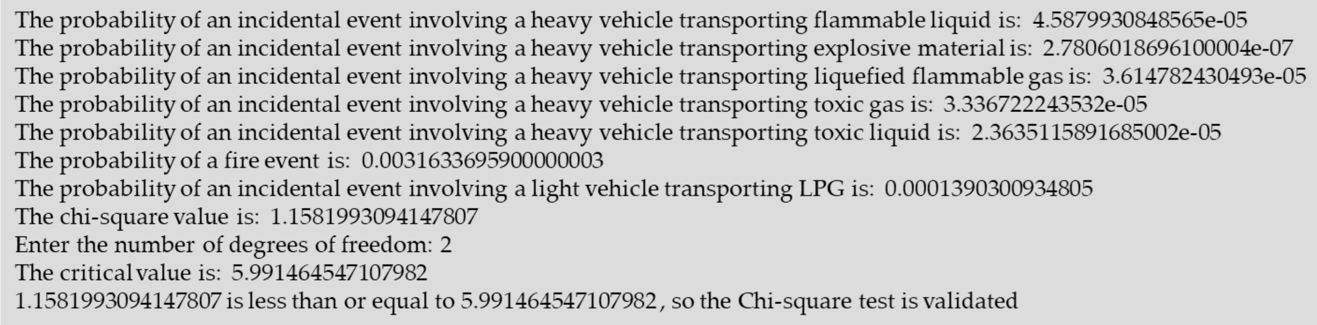
Below in **Figure 4.6**. is the source code for calculating the probabilities of events, following the procedure described above.



```
def peiOperations(dataMap):
    tgmp = dataMap.get("TGMr")[0] * dataMap.get("TC")[0]

    pcol = (tgmp * dataMap.get("Lgall")[0] * dataMap.get("COL")[0] * 365) / 10**8
    pinc = (tgmp * dataMap.get("Lgall")[0] * dataMap.get("INC")[0] * 365) / 10**8

    pli = pcol * dataMap.get("VP")[0] * dataMap.get("ADR")[0] * dataMap.get("FLI")[0]
    pme = pcol * dataMap.get("VP")[0] * dataMap.get("ADR")[0] * dataMap.get("FME")[0]
    pgli = pcol * dataMap.get("VP")[0] * dataMap.get("ADR")[0] * dataMap.get("FGLI")[0]
    pgt = pcol * dataMap.get("VP")[0] * dataMap.get("ADR")[0] * dataMap.get("FGT")[0]
    plt = pcol * dataMap.get("VP")[0] * dataMap.get("ADR")[0] * dataMap.get("FLT")[0]
    pgpl = pcol * dataMap.get("VP")[0] * dataMap.get("GPL")[0]

    print("The probability of an incidental event involving a heavy vehicle transporting flammable liquid is: ", pli)
    print("The probability of an incidental event involving a heavy vehicle transporting explosive material is: ", pme)
    print("The probability of an incidental event involving a heavy vehicle transporting liquefied flammable gas is: ", pgli)
    print("The probability of an incidental event involving a heavy vehicle transporting toxic gas is: ", pgt)
    print("The probability of an incidental event involving a heavy vehicle transporting toxic liquid is: ", plt)
    print("The probability of a fire event is: ", pinc)
    print("The probability of an incidental event involving a light vehicle transporting LPG is: ", pgpl)

dataMap1 = importValues("C:/Users/marta/Onedrive/Desktop/DOTTORATO/TESI DOTTORATO/DS4T/Tunnel Test.xlsx", "Cartel1")
peiOperations(dataMap1)
```

**Figure 4.6:** Example of calculation of probability of initial events

As results, the output that the code generates is illustrated as example in **Figure 4.7**.



```
The probability of an incidental event involving a heavy vehicle transporting flammable liquid is:  4.5879930848565e-05
The probability of an incidental event involving a heavy vehicle transporting explosive material is:  2.7806018696100004e-07
The probability of an incidental event involving a heavy vehicle transporting liquefied flammable gas is:  3.614782430493e-05
The probability of an incidental event involving a heavy vehicle transporting toxic gas is:  3.336722243532e-05
The probability of an incidental event involving a heavy vehicle transporting toxic liquid is:  2.3635115891685002e-05
The probability of a fire event is:  0.0031633695900000003
The probability of an incidental event involving a light vehicle transporting LPG is:  0.0001390300934805
The chi-square value is:  1.1581993094147807
Enter the number of degrees of freedom: 2
The critical value is:  5.991464547107982
1.1581993094147807 is less than or equal to 5.991464547107982, so the Chi-square test is validated
```

**Figure 4.7:** Results output - script example

## 4.2 Consequences on point transport infrastructures

Transport infrastructures are critical systems enabling the continuous movement of people, goods, and services, and are therefore central to economic functionality and societal resilience. Within this domain, bridges serve as essential structural links across natural and artificial obstacles—rivers, valleys, road corridors—and often represent single points of failure in otherwise redundant transport networks. Their structural specificity, combined with their fixed location and exposure to environmental aggressors, makes them particularly vulnerable within the broader infrastructure system.

The global bridge stock—comprising reinforced and prestressed concrete, steel, and masonry structures—includes many assets built over 50 years ago under historical design codes. These codes typically lacked provisions for modern hazard scenarios, such as high-intensity seismic actions, extreme hydrological events, or dynamic effects from heavy freight and high-speed rail traffic. Moreover, older bridges often omitted considerations for multi-hazard conditions or cumulative degradation phenomena.

Bridges located in seismically active regions, flood-prone basins, or landslide-prone slopes face amplified risks due to both their structural aging and environmental context. These vulnerabilities have been clearly demonstrated in recent catastrophic events: the collapse of bridges in Puerto Rico following Hurricane Maria (2017); the widespread failure of road and bridge systems in Sulawesi, Indonesia during the 2018 earthquake; the damage to critical links in Japan during the Tohoku Earthquake and tsunami (2011); and the Tbilisi floods (2015), where bridge restoration accounted for approximately 60% of total recovery costs. In each case, the failure of bridge assets directly disrupted logistics, emergency response, and socio-economic recovery.

Within this context, the present work aims to provide a comprehensive state-of-the-art review on the impacts that both natural and anthropogenic hazards exert on critical transport infrastructures, with a specific focus on road and railway bridges. The analysis addresses not only the direct structural effects—such as physical damage, collapse mechanisms, and degradation processes—but also the indirect impacts, including functional disruptions, accessibility loss, and socio-economic consequences. By examining the typologies of hazards, their modes of interaction with infrastructure, and the propagation of their effects through networked systems, this study contributes to a deeper understanding of systemic vulnerability and supports the development of integrated approaches for resilience and risk-informed infrastructure management.

### 4.2.1 Main Hazards Threatening Bridge Safety

A hazard is defined as “a process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation” [8]. In the field of transport engineering, hazards are understood as external events or conditions capable of compromising the structural integrity or operational functionality of infrastructure systems. Hazards can be broadly categorized into natural and human-induced types [9]. Natural hazards arise from environmental and geophysical processes and are inherently linked to the geographical and climatic characteristics of the area in which the infrastructure is located. This spatial correlation is particularly relevant, as it determines both the probability of occurrence and the potential intensity of hazardous events. Among the most frequent and impactful natural hazards for transport infrastructure are surface flooding, river flooding, coastal flooding, tropical cyclones and earthquakes. These phenomena are not uniformly distributed across the globe; their occurrence is closely tied to the geographical and environmental characteristics of the area. As shown in **Figure 4.8**, each region is typically exposed to one prevailing hazard, highlighting the importance of incorporating spatial variability into the planning and design of transport systems.

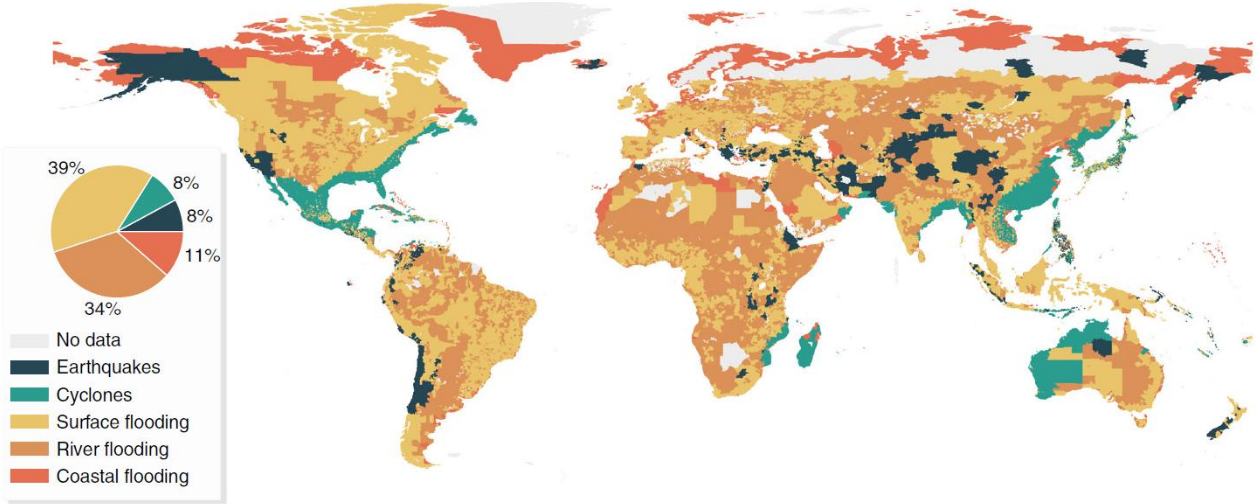


**Figure 4.8:** Dominant hazard per region. This figure presents the hazard causing the highest transport infrastructure exposure in each region

Human-induced hazards, on the other hand, originate from human activities or technical failures. These include accidents, structural malfunctions, fire outbreaks and explosions. Although often less predictable in nature, their impacts can be equally disruptive, especially in densely populated or highly interconnected transport networks.

Both natural and human-induced hazards can compromise transport infrastructure through a combination of direct and indirect effects. Direct consequences involve structural damage to key elements such as bridges, roads, railways, and tunnels. Indirect consequences, while less visible, may be equally significant: extended service interruptions, traffic diversions, increased vulnerability of dependent networks, and broader socio-economic impacts that can persist well beyond the initial event. Understanding the full spectrum of these effects is essential for the design and management of resilient transport systems.

### 4.2.2 Impacts of natural and human-induced hazards on transportation infrastructure

#### *4.2.2.1 Impacts of natural hazards*

A wide range of natural hazards can compromise societal safety and infrastructure resilience, with impacts that vary considerably in terms of spatial extent, frequency, and severity. Based on an extensive literature review, Table 4.1 summarizes 17 primary natural hazards and provides qualitative assessments of their potential consequences on public safety and economic losses, as well as a specification of whether the hazard is significant for bridges. While several hazards - such as drought, snow, and lightning - may cause substantial societal disruptions, their direct relevance to bridge performance remains limited. In contrast, other hazards, including floods, earthquakes, landslides, and strong winds, present significant risks to bridge functionality and safety due to their capacity to induce structural damage, service disruption, and long-term degradation. As such, this classification framework not only supports a broader understanding of hazard typologies but also helps prioritize those that pose the most critical threats to transport infrastructure. In the following sections, the analysis focuses on hazards that have considerable effects on bridges, grouped into three major categories: geological, hydrological, and atmospheric/chemical.

**Table 4.1:** Natural hazards threatening community and social security

| No. | Hazard | Consequence | | Applicability to bridges |
|---|---|---|---|---|
| | | Fatalities | Economy | |
| 1 | Earthquake | Severe | Severe | Yes |
| 2 | Tsunami | Severe | Severe | Yes |
| 3 | Volcanic eruption | Moderate | Severe | No |
| 4 | Landslide | Moderate | Severe | Yes |
| 5 | Snow avalanche | Slight | Slight | No |
| 6 | Flood | Moderate | Moderate | Yes |
| 7 | Drought | Slight | Moderate | No |
| 8 | Regional subsidence and uplift | Slight | Moderate | Yes |
| 9 | Local subsidence and heave | Slight | Moderate | Yes |
| 10 | Ground collapse | Slight | Moderate | Yes |
| 11 | Tropical cyclone | Moderate | Moderate | Yes |
| 12 | Hurricane, wind | Moderate | Moderate | Yes |
| 13 | Hail, snow | Slight | Moderate | No |
| 14 | Lightning, thunderstorm | Slight | Slight | No |
| 15 | Long-term climatic change | Moderate | Severe | No |
| 16 | Short-term climatic change | Moderate | Severe | No |
| 17 | Wildfire | Slight | Severe | No |

#### *4.2.2.2 Geological hazards*

Geological hazards—including earthquakes, liquefaction, landslides, debris flows, rockfalls, erosion, ground deformations, and tsunamis—pose significant risks to transportation infrastructure, often causing abrupt and severe physical damage. Among these, earthquakes represent one of the most destructive threats, primarily due to intense ground shaking that can induce structural failures in bridges, tunnels, and elevated highways. Seismic events may result in misalignment, cracking, or complete collapse of critical structural elements, particularly in assets not designed to withstand high-intensity seismic loads. Liquefaction often accompanies seismic shaking, causing a sudden loss of soil strength in saturated sandy soils. This leads to ground subsidence and undermining of roadbeds and foundations, which can degrade or eliminate load-bearing capacity.

In mountainous or geologically unstable terrain, landslides, debris flows, and rockfalls pose significant hazards to transport infrastructure. Landslides can block or bury road and rail corridors, deform tracks, and damage retaining structures, with their sudden onset limiting effective mitigation and requiring substantial debris removal and structural rebuilding. Debris flows—rapid movements of saturated soil, rock, and organic material triggered by intense rainfall or volcanic activity—can cause severe damage to roads and bridges, especially in steep or volcanic catchments, and may permanently alter terrain, necessitating route realignment. Rockfalls, involving the detachment and downslope movement of rock masses, frequently affect mountainous transport corridors, threatening structural integrity and traffic safety; although mitigation systems such as catch fences and retaining walls are commonly employed, they may prove insufficient during high-magnitude or recurrent events.

Erosion and ground deformation processes pose progressive yet critical threats to transport infrastructure. Erosion, driven by water flow, wind, or anthropogenic factors, gradually degrades road foundations and embankments, leading to pavement subsidence, cracking, or collapse—particularly along riverine and coastal routes. Ground deformations such as subsidence, uplift, and lateral spreading—often resulting from tectonic activity, mining, or soil consolidation—can induce pavement cracking, misalignment of rail tracks, and long-term mechanical strain on bridges and viaducts. In severe cases, these deformations may cause operational disruptions or safety-critical failures in road and rail systems.

Tsunamis, triggered primarily by undersea earthquakes, pose significant risks to coastal transport infrastructure. These large waves can inundate bridges and access routes, causing damage through strong hydrodynamic forces and debris impact. Tsunami-induced flooding often undermines foundations and erodes embankments, leading to structural instability and long-term disruptions that necessitate extensive repairs.

#### *4.2.2.3 Hydrological hazards*

Hydrological hazards—such as flooding, storm surges, and related hydraulic phenomena—pose significant threats to bridge infrastructure due to their capacity to undermine structural components and disrupt functionality. Intense rainfall and flooding events can submerge bridge decks, erode approach embankments, and exert strong hydraulic forces that may compromise foundations through scour, a leading failure mechanism for bridges. Persistent surface runoff further accelerates embankment erosion and may impair drainage systems through sediment and debris clogging. In coastal and estuarine environments, storm surges generated by extreme weather events can produce powerful wave action and rising water levels, exacerbating scour, weakening protective barriers, and contributing to long-term deterioration of critical structural elements.

#### *4.2.2.4 Atmospheric and chemical hazards*

Atmospheric and chemical hazards also present substantial risks to bridge infrastructure, particularly through extreme wind events, intense rainstorms, and corrosive processes. Strong winds—including those associated with hurricanes and cyclonic storms—can exert significant lateral loads on superstructures, damage non-structural components such as lighting and signage, and increase the likelihood of windborne debris striking structural elements or obstructing transport routes. Wind-induced oscillations and vibrations may also compromise the performance of suspension and cable-stayed bridges, while high wind exposure in electrified rail corridors can impair the functionality of overhead lines, leading to service interruptions.

Heavy rainstorms, while often associated with hydrological impacts, also contribute to structural vulnerability through rapid water accumulation, increased surface runoff, and the overloading of drainage systems. These effects can trigger or intensify slope instabilities, especially in hilly or mountainous terrains, indirectly impacting bridge foundations and adjacent earthworks.

Chemical hazards, particularly corrosion, represent a long-term yet critical deterioration mechanism for bridges. Chloride-induced corrosion—accelerated by marine environments, de-icing salts, and atmospheric pollutants—can lead to degradation of reinforced concrete and steel components, compromising structural integrity and increasing maintenance demands. In coastal and estuarine areas, saline intrusion and airborne salt particles exacerbate corrosion rates, particularly when combined with high humidity and temperature fluctuations.

#### *4.2.2.5 Impacts of human-induced hazards*

In addition to natural phenomena, bridges are also exposed to a variety of human-induced hazards, which can compromise structural integrity and operational continuity. As outlined in Table 2, these include events such as explosions, vehicular collisions, fires, and accidental or intentional impacts resulting from human activity. Although their occurrence may be less frequent than that of natural hazards, their consequences can be severe and often immediate, warranting consideration within risk assessment frameworks for transport infrastructure.

**Table 4.2:** Human-induced threatening existing bridges

| No. | Hazard | Consequence | | Applicability to bridges |
|---|---|---|---|---|
| | | Fatalities | Economy | |
| 1 | Vehicle collision | Slight | Moderate | Yes |
| 2 | Vessel collision | Moderate | Severe | Yes |
| 3 | Overload | Slight | Moderate | Yes |
| 4 | Fire | Slight | Moderate | Yes |
| 5 | Explosion | Moderate | Moderate | Yes |

Human-induced hazards, including vehicle and vessel collisions, overload, fire, and explosions, present immediate and often severe threats to the safety and functionality of bridge infrastructure. Vehicle collisions, particularly those involving heavy trucks or high-speed impacts, can compromise structural elements such as piers, parapets, and decks, potentially leading to partial or total closures and necessitating repairs. Similarly, vessel impacts—often affecting bridges located over navigable waterways—pose significant risks to substructures like piers and abutments, especially when caused by large or misdirected ships under poor visibility or strong current conditions. Overloading, whether due to non-compliance with weight regulations or insufficient monitoring, accelerates fatigue and long-term degradation of structural components; a single overloaded vehicle can exert damage equivalent to thousands of compliant ones.

Fires, whether arising from vehicular accidents, wildfires, or industrial sources, can cause thermal degradation of concrete and steel, reduce material strength, and damage expansion joints, electrical systems, and safety installations. In tunnels and underpasses, heat accumulation can lead to rapid deterioration, while visibility-reducing smoke necessitates extended closures for safety. Explosions, accidental or intentional, represent the most destructive hazard, often resulting in immediate structural collapse, fatalities, and long-term service disruptions.

### 4.3.1 Conclusions

This analysis outlines the broad spectrum of natural and anthropogenic hazards that threaten the structural integrity and functionality of critical infrastructure, with particular focus on road and railway bridges (Table 4.3). Furthermore, for each hazard, the associated direct and indirect impacts have been delineated. A thorough understanding of the characteristics of these hazards is essential for robust risk assessment and informed decision-making in infrastructure management. **Figure 4.9** provides a complementary classification by illustrating the spatial and temporal distribution of these hazards, thereby offering a crucial framework for more precise evaluation of their impacts. The inclusion of such spatiotemporal considerations is fundamental to the development of resilience strategies tailored to the specific exposure and vulnerability profiles of critical transport assets.

**Table 4.3:** Natural hazards threatening community and social security

| No. | General category | Subcategory | Hazard | Physical description | Abbreviation |
|---|---|---|---|---|---|
| 1 | Natural Hazard | Geological | Earthquake | Intensive ground motion | EQ |
| 2 | | | Landslide | Enormous sliding soil | LS |
| 3 | | | Tsunami | Huge wave impact | TN |
| 4 | | | Liquefaction | Capacity loss of sandy soil | LF |
| 5 | | | Ground moving | Ground heave or subsidence | GM |
| 6 | | Hydrological | Flood | Continuous water with debris | FL |
| 7 | | | Scour | Soil vanishes near foundation | SC |
| 8 | | | Storm surge (wave) | Rise in water level above the normal tidal level | SS |
| 9 | | Atmospheric | Wind (hurricane) | Natural movement of air | WD |
| 10 | | | Rainstorm | Heavy rainfall with strong wind | RS |
| 11 | | Chemical | Corrosion | Degradation of steel and concrete | CR |
| 12 | Human-induced hazard | Manipulated | Vehicle collision | Vehicles crash with pier or other components | VC[1] |
| 13 | | | Vessel collision | Vessels crash with piers or other components | VC[2] |

---

| | | | | |
|---|---|---|---|---|
| 14 | | Overload | Vehicles load exceeds structural capacity | OL |
| 15 | Subsequent | Fire | Continuous heating process | FR |
| 16 | | Explosion | Instant blast effect | EP |

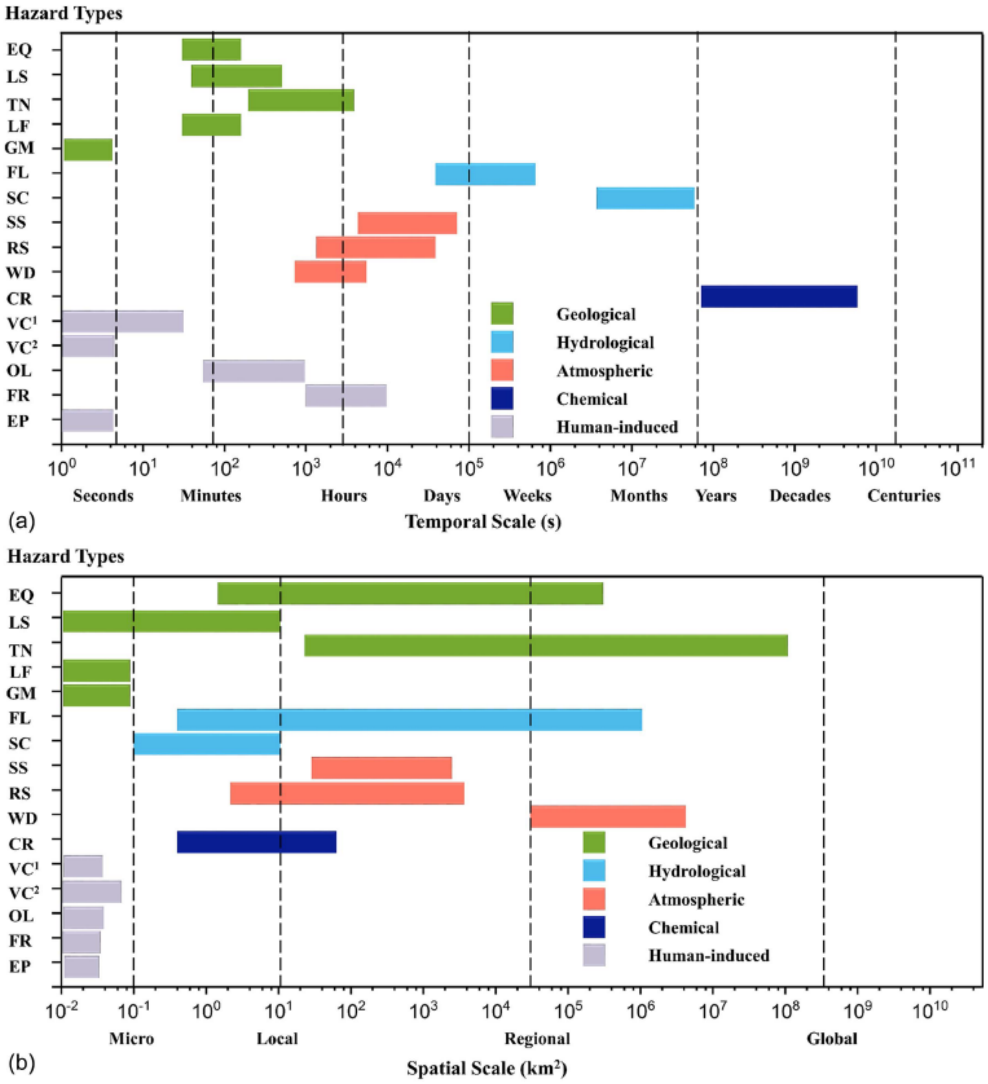


**Figure 4.9:** Temporal-spatial characteristics of different hazards: (a) temporal; and spatial (b).

# 5 Main consequences and impacts for industrial CIs/Tailored Multi-hazard tool to assess the territorial vulnerability

## 5.1 Definition of a baseline for the representation and estimation of mutual impact between anthropic and natural related impact.

As far as the natural hazards are concerned in Italy, each natural risk is managed through separate sectorial plans issued by different authorities, with different scales and methodologies. The contents of these plans are implemented by the City Plans and Municipal Emergency Plans, drafted by the Municipalities, which are responsible for direct land use management. Then, decision-makers are involved in assessing different independent hazards but also their interactions that threat common exposed areas or elements but lack tools and methodologies to analyze these multiple risks systemically (Mesa-Gómez et al., 2020; Pilone and Demichela, 2018). This issue makes it hard for them to understand potential simultaneous threats to their areas. Regarding the multi-risk available methods in urban areas, they focus on risk mitigation without taking into account NaTech risk (Mesa-Gómez et al., 2020). In addition, research has shown that methods used at large or medium scales might be too general to work at a plant scale (Gallina et al., 2016; Pilone et al., 2016).

Therefore, the determination of a baseline at the municipal scale to characterize the susceptibilities of critical infrastructures against external factors inherent to their multi-hazard surrounding territories can be useful to assist the different actors involved in the decision-making process. To achieve this goal, the multi-risk tool proposed by Beltramino et al. (2022) to assess territorial vulnerability in the municipality of Moncalieri was introduced as a proof of concept.

Summing up, this multidisciplinary tool consists of the representation of an index of systemic vulnerability in a territory obtained through a mathematical framework. The calculation includes the integration of multiple predefined indicators clustered into three factors defined as sensitivity (S), pressures (P), and hazards (H), normalized and weighted according to a participatory procedure. It ensures not only the estimation of different stressors and hazards according to impacting sensible elements belonging to the location of interest but also gives the stakeholders the possibility of expressing a coefficient of interest regarding the pressures and hazards. In addition, the mathematical equation for the estimation of systemic vulnerability considers dynamic factors for both the impact of climate change and the temporal character of the pressures. The vulnerability characterization is achieved through the five steps depicted in **Figure 5.1**.

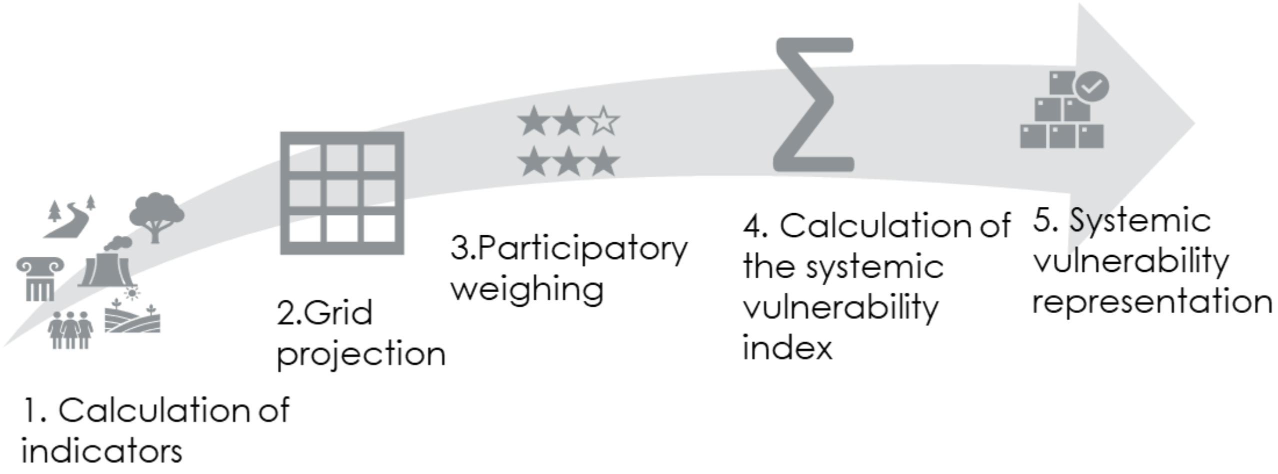


**Figure 5.1:** Steps to characterize the territorial vulnerability at the municipal scale**.**

### 5.1.1 Characterization of territorial vulnerability at local scale.

To characterize territorial vulnerability at local scale it is necessary to explain the steps achieved intercalating the results obtained for the case analyzed.

#### *5.1.1.1 Step1: Selection and calculation of individual indicators*

The cornerstone for this introduced tool is the selection of a set of sensitivity, pressure, and hazard indicators and their calculation using GIS tools. They were selected after a workshop between the territorial stakeholders from the territory of interest and a multi-disciplinary research team, considering the principal spatial government plans and territorial instruments, and highlighting the municipality specificities. It is important to note that this methodology is open to incorporating new indicators that match sensitive elements of interest.

The indicators definition and calculation are the most consistent and time-consuming steps of the tool used. Each of the 21 indicators selected has followed a process of data collection, calculation, and validation in a GIS environment. **Figure 5.2** shows the set of sensitivity indicators grouped into three components (Environment and Landscape-A; Building, Heritage, and Infrastructures-B; Economy and Population-C). The authors Beltramino et al. (2022) understood sensitivity as the physical predisposition of human beings, infrastructure, and the environment to be affected by a dangerous phenomenon.

Regarding the dangerous phenomena, **Figure 5.3** shows the pressure and hazard indicators contextualized to the case study in the municipality of Moncalieri. Pressures were considered as linear and predictable trends that affect the system gradually altering its condition (Intergovernmental Panel on Climate Change, 2023). On the other hand, the concept of multi-hazards was addressed as a combination of two or more threat factors manifested in an isolated, simultaneous, or chain reaction, to produce a trigger event of a disaster, where hazardous events can be one or more natural (Mesa-Gómez et al., 2020). The source of data, the description, and the calculation of each indicator can be consulted in previous research (Beltramino et al., 2022).

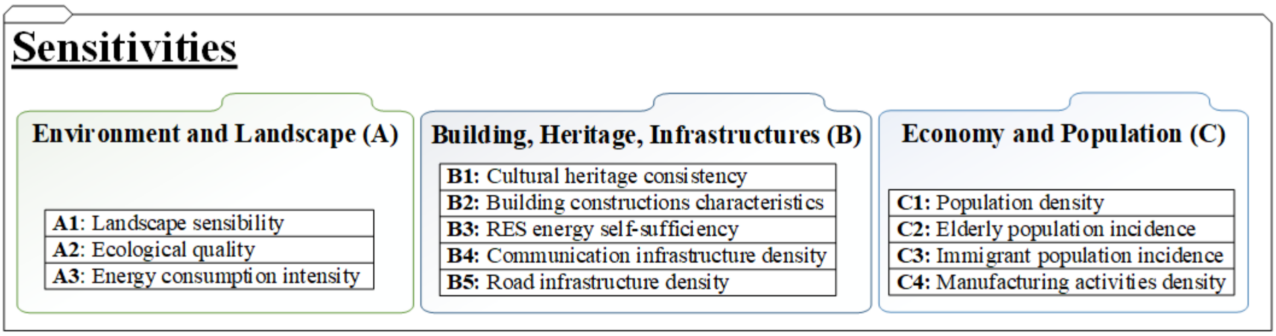


**Figure 5.2:** Set of indicators of sensitivity divided by components to characterize the territorial vulnerability in the municipality of Moncalieri.

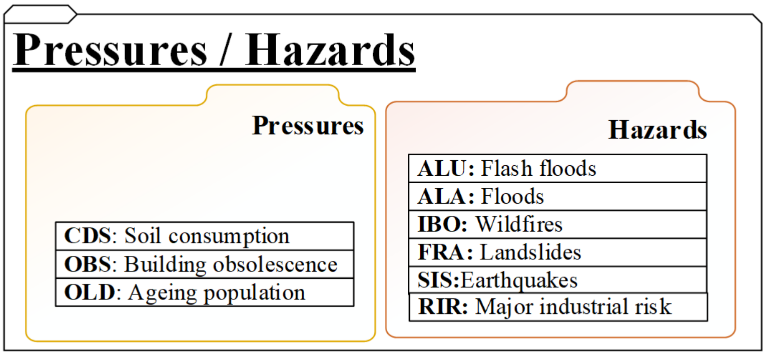


**Figure 5.3:** Set of indicators of pressures and hazards used to characterize the territorial vulnerability in the municipality of Moncalieri.

#### 5.1.1.2 Step2: Indicators grid projection and representation

The individual indicators were projected onto a grid of homogeneous cells (200 x 200 m), which covered the municipality. For their attribution into the grid, spatial join operations through a specific field identifier (FID) were assigned to each cell in the GIS environment, normalizing the values to obtain a standard metric belonging to the [0;1] interval, where 1 represents critical vulnerability.

Depending on the geometry of the input data (point, line, or polygon), the attribution of the values obtained for each indicator to the grid was carried out according to five criteria: (i) point count (Cultural heritage consistency-B1, Floods-ALA), (ii) sum of the point values (Energy consumption intensity-A3, RES energy self-sufficiency-B3, Earthquakes-SIS), (iii) weighted sum of linear (Road infrastructure density-B5) or areal elements (Landscape sensibility-A1, Ecological Quality-A2, Building construction characteristics-B2, Communication infrastructure density-B4, Density of productive activities-C4, Soil consumption-CDS, Building obsolescence-OBS, Wildfires-IBO, Lands slides-FRA), (iv) average value of areas within the cell (Population density-C1, Elderly component-C2, Immigrant Component-C3, Aging population-OLD) and (v) intersection between input polygons and each cell (Flash floods-ALU, Major Industrial Risk-RIR). The values for each indicator and the cells for the territory meet in a table with 2550 rows (FID) and 21 columns (individual indicators). In addition, five charts (B1, B5, C4, SIS, ALU, and SIS) that meet the different criteria for the attribution of values according to the data geometry, are used to exemplify the visualization of the individual layers.

#### 5.1.1.3 Step3: Participatory weighing

The connection between each indicator of sensitivity, pressures, and hazards followed a hierarchical network at three levels. This structure is illustrated in **Figure 5.4**, facilitating the determination of a unique index of systemic vulnerability. This hierarchical relationship was assessed through a weighted crossing matrix involving a participatory approach and the engagement of 13 researchers from the multidisciplinary team. The background of knowledge composition for the research team was: two urbanistic planners, two territorial planners, two energetic planners, one chemical engineer, one industrial engineer, one statistician, one historian of the territory, one risk analyst, one environmental engineer, and one structural and construction engineer.

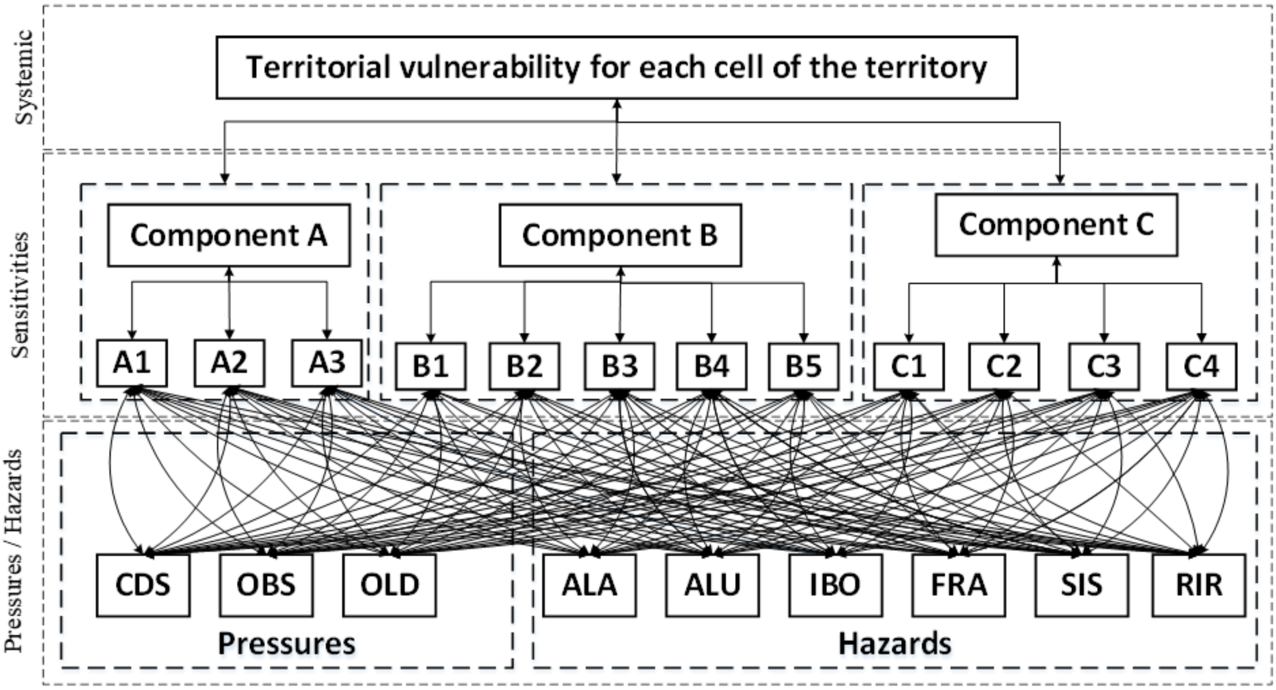


**Figure 5.4:** A hierarchical network of three levels for the territorial systemic vulnerability characterization at the municipal scale

### 5.1.1.4 Step4: Calculation of the Vulnerability Index

The above-described hierarchical network for determining the systemic vulnerability index was operationalized meticulously through the section mathematical framework detailed in Beltramino et al. (2022).

### 5.1.1.5 Step5: Systemic Vulnerability Representation

The principal outputs of this spatial methodology consisted of colored maps, which constitute a municipal baseline of the systemic vulnerability for the set of indicators superposed as layers under the mathematical framework mentioned in Step4. Finally, a detailed breakdown of vulnerability intervals, leveraging GIS natural-brakes categories is offered, putting together a four-category ordinal scale (low-green, moderate-yellow, high-orange, and critical-red) is used to show systemic vulnerability in a way that can be easy to understand for decision-makers.

The principal outputs of the GIS detailed in section 3.3 are shown in **Figure 5.5**. The critical susceptible areas primarily include the historical center, industrial sectors, and densely populated regions in the north-northwest. Other scattered locations imply punctual aspects of the territory. However, as these visualizations rely on spatial data availability and certain assumptions for indicator calculation and spatialization, they may introduce uncertainties into the model. Therefore, meticulous validation of the obtained values against territorial characteristics is crucial. This involves both statistical and spatial verification, drawing on the expertise of planners and stakeholders in the analyzed territory. It is important to remark that the test case in Moncalieri municipality served to obtain a first baseline of the systemic vulnerability at the time that indicators, the procedures for their calculation, and the matrix of weights were obtained. However, in dependence on the interest or the necessities, it is possible to disregard, add, or refine some of them, modifying the matrix of weights according to the place-based characteristics. The subsequent section delves into applying this systemic vulnerability baseline, focusing on an energetic critical infrastructure at an industrial context scale.

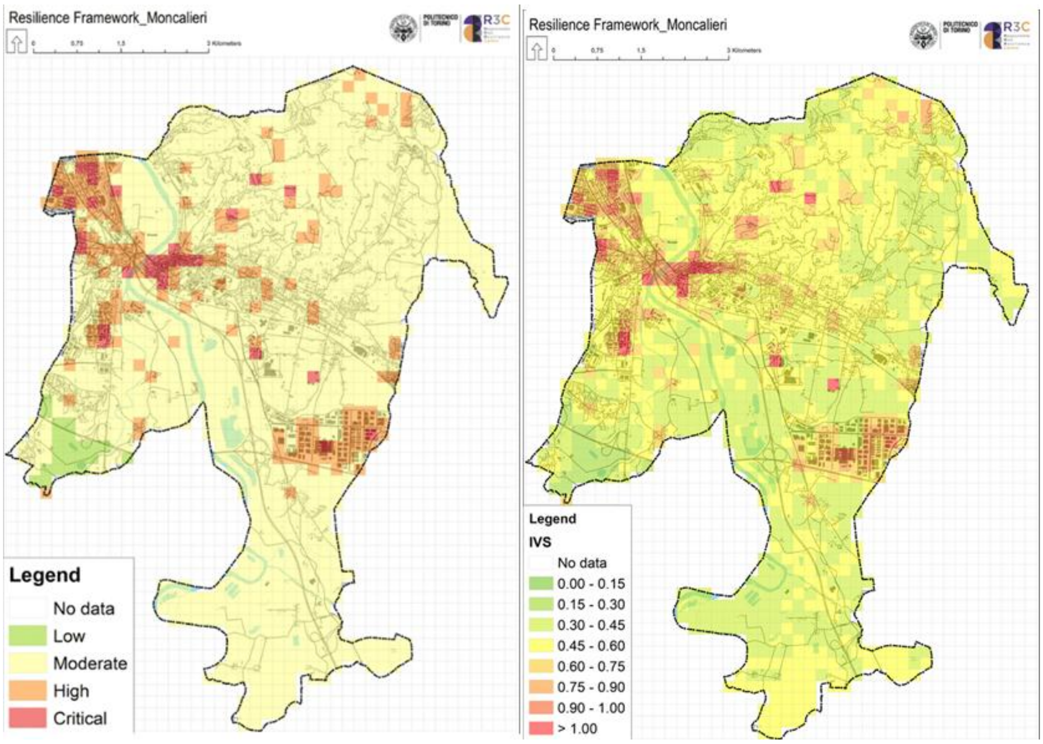


**Figure 5.5:** Final systemic vulnerability map for the municipality of Moncalieri. a) using a categorical simplified scale. b) using numerical intervals scale. Source: (Beltramino et al., 2022).

### 5.1.2 Municipality case study and deployment in the context of an energetic critical infrastructure.

The bidirectional sense of the connections within the hierarchical network of **Figure 5.4** representing the systemic vulnerability baseline at the municipal level, makes it possible to deploy the nested components and indicators. This approach facilitates tailoring assessments to specific territorial sectors of interest at the local scale, encompassing the critical infrastructures of concern and their surroundings. In addition, safety distances projected for potentially damaged areas are here introduced to develop a more comprehensive evaluation of technical and external factors at the local scale.

The industrial plant used as here a case study, corresponded with a thermoelectric plant clustered in the macro-sector “Power production,” according to the categories defined by (Casson Moreno et al., 2018). In addition, according to Directive (EU) 2022/2557 on the resilience of critical entities, the establishment can also be classified as energetic critical infrastructure, since its specific activity is to produce energy from the combustion of hydrocarbons. Even if currently the plant of interest is not anymore under the Legislative Decree 105/15, the high inventory of dense fuel-oil BTZ that it detained in the past, granted it the classification of Seveso establishment. Therefore, for methodological purposes, some elements will be hypothesized to enhance the case analysis. The unitary operations that are carried out in the plant are both chemical and physical. The activities also include auxiliary technical systems necessary for the production plant operation, such as compressed air, treated wastewater, steam production, and warehousing. Within all the processes and functions of the plant, the following items were identified: atmospheric storage tanks, tall structures such as chimneys and process columns and equipment, heat exchangers, complex systems of pipelines, complex electrical networks, water treatment organs, and storage of raw materials (see **Figure 5.6**).

**Figure 5.6:** Satellite view of the critical energy infrastructure used as a case study.

The selected area of interest for the industrial context under analysis comprised approximately 280 hectares and is composed of 70 homogeneous cells (200 x 200 m) mutually exclusive including the industrial plant and its surroundings. These homogeneous cells came from the same grid at the municipal scale introduced previously showing a subset of the systemic vulnerability determined at the municipal scale. To determine to what extent the indicators are responsible for the systemic vulnerability, firstly, the territorial analysis by components of sensitivity according to **Figure 5.2** was carried out. Subsequently, the vulnerability components breakdown by indicators of multiple hazards was done to spatially represent the mutual vulnerability between ICI and its surrounding territory.

Then, **Figure 5.7** represents the industrial context section within the systemic vulnerability map for the municipality of Moncalieri.

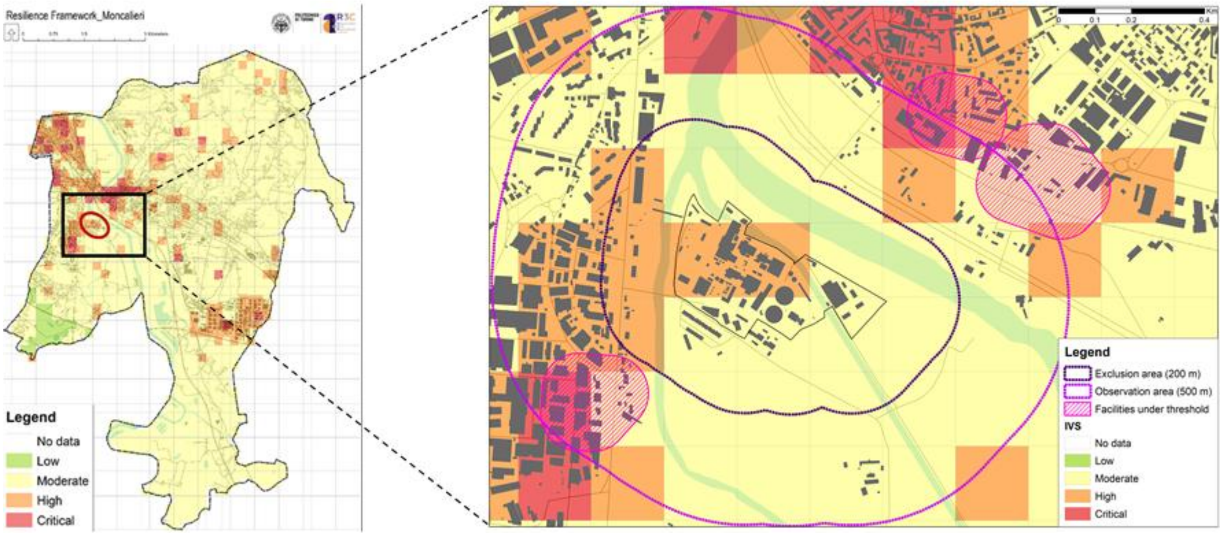
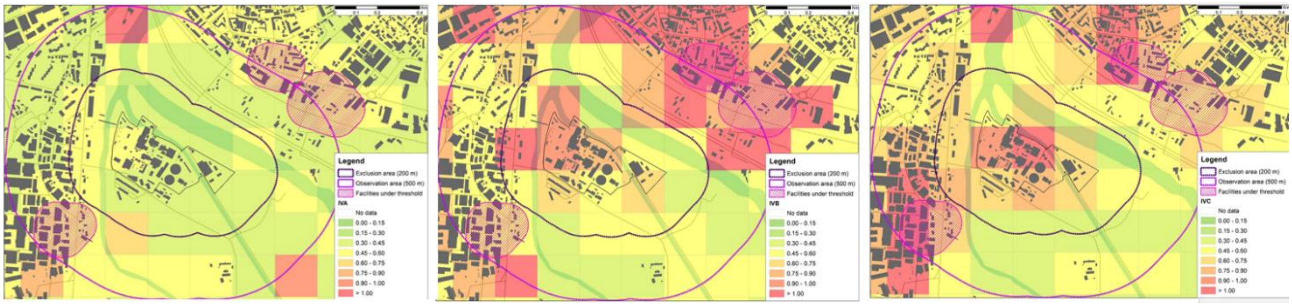


**Figure 5.7:** Systemic vulnerability for the industrial context of interest.

It can be appreciated in both areas, inside and outside the facility fence. Additionally, the lines for the exclusion and observation areas, the representation of neighboring plants, together with urban and geographical elements are also represented.

The visual field analysis of systemic vulnerability identified the following percentages of vulnerable cells: 65% moderate vulnerability (yellow), 26% high vulnerability (orange), and 9% critical vulnerability (red). It is noteworthy to mention that the critical vulnerability cells were observed in external regions that intersected the observation area only partially (over 500 meters away). On the contrary, inside the plant perimeter, over 50% of the occupied space is characterized by a coloration which indicates a high level of vulnerability. Furthermore, the exclusion zone partially intersects three additional orange cells. Overall, the energetic critical infrastructure of concern seems susceptible to the external multi-hazard contexts considering the superposition of the set of indicators nested in the vulnerability baseline.

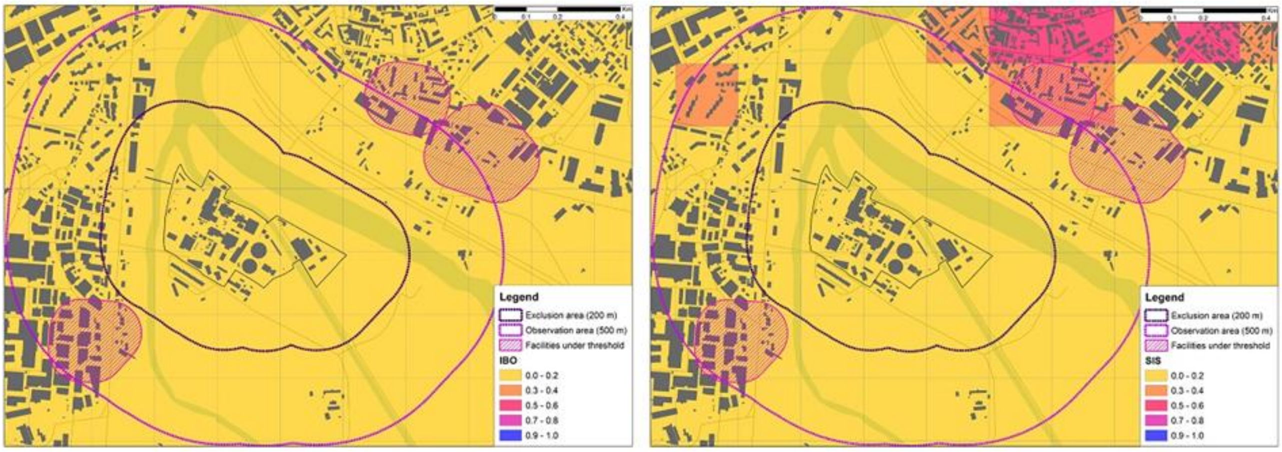
Specifically, since there are zones with high or critical vulnerability the real causes must be deepened to avoid cascading events that could harm the environment, population, and infrastructure. In this regard, **Figure 5.8** shows that component A has almost no susceptible cells in the region of concern for the industrial plant. In contrast, the patterns for components B and C reveal cells with high and critical vulnerability, which are responsible for the observed systemic vulnerability. Even though the study of component C may be valuable for stakeholders, for the scope of this research, the focus will be concentrated on component B, which shows a significant critical status and includes the infrastructural dimension.



a) b) c)

**Figure 5.8:** Territorial vulnerability by components of sensitivity. a) Environment and Landscape; b) Building, Heritage, and Infrastructures; c) Economy and Population.

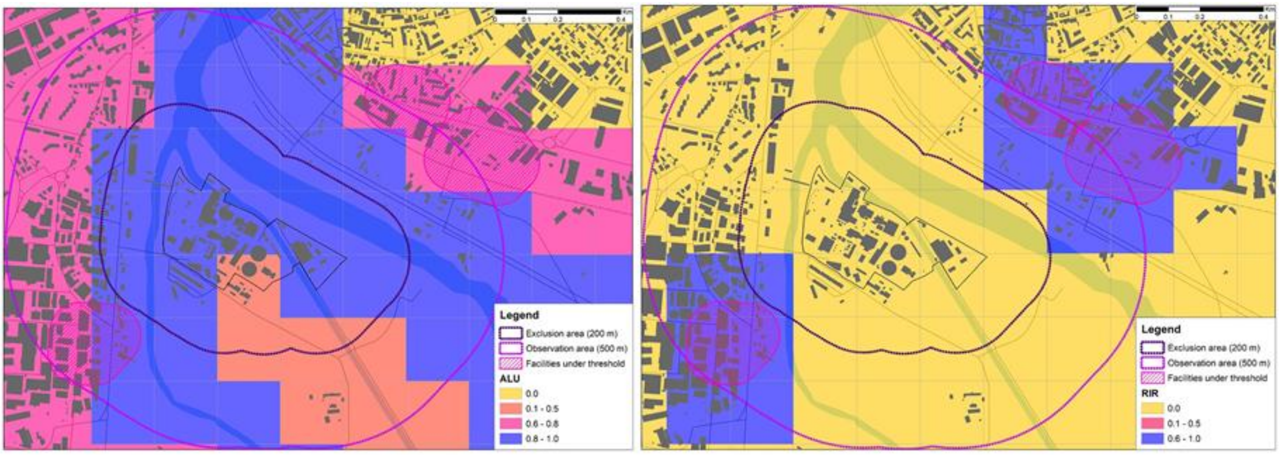
To exemplify the multi-hazard perspective, this part compares the less important and more important hazard indicators during the breakdown of sensitivity component B. Thus, **Figure 5.9** shows a couple of natural hazards that can be disregarded in this specific case, while **Figure 5.10**, illustrates significant hazards.



a) b)

**Figure 5.9:** Vulnerability representation of hazards not significant to the industrial context. a) Wildfires (IBO). b) Seismic (SIS). Source: (Castro Rodriguez et al., 2023b)

From the picture above, even though earthquake and wildfire risks should not be completely ignored, the industrial context presents low vulnerability to these risks. In the case of seismic this visualization is in line with the level of dangerousness corresponding to the seismic zone of concern (Dipartimento della Protezione Civile, 2023)**.**



a) b)

**Figure 5.10** Vulnerability representation of hazards significant to the industrial context. a) Floods (ALU) b) Industrial risk (RIR).

It is simple to recognize in **Figure 5.10** a) how almost all the cells in the cutoff area are very sensitive to flooding (near to 1). This includes cells that are inside the plant boundaries. The rest of the visual field in the industrial context alternates between critical and high vulnerability. Because the plant is close to the bed of a river that splits in two, the effects of this natural danger could be evident. However, this kind of natural hazard may trigger multiple damaged modes to industrial items (Cozzani et al., 2010; Necci and Krausmann, 2022) which should be complemented by modeling techniques for functional factors.

Referring to **Figure 5.10** b), the industrial risk hazards depicted correspond with facilities that fall outside the scope of regulation by Legislative Decree 105/15. However, these facilities having maximum chemical inventories exceeding 20% of the lower-tier Seveso threshold (Sub-threshold Seveso facilities), they must be considered under the current Piedmont regional guidelines for land use planning (Regional Council Resolution No. 17-377, July 26, 2010[1]). When considering major risk hazards (RIR) vulnerability, the two-ways interaction between the damaged areas of the neighboring facilities and the energetic critical infrastructure under concern can be appreciated as the buffer intersections. In cases of accidents, significant implications for subsequent domino effects analysis are posed by the interplay of the non-Seveso facilities not only within the observation area of the power production plant Legislative Decree but also with implications inside the exclusion area and vice versa.

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[1] Regional Council Resolution No. 17-377, July 26, 2010, "Approval of Guidelines for Industrial Risk Assessment in Spatial Planning." Official Bulletin of the Piedmont Region No. 31, 05/08/2010.

## 5.2 Consequence analysis of accidental release of H2 and H2/CH4 mixture)

Consequence analysis of $H_2$ and $H_2/CH_4$ mixtures was performed using both empirical methods and advanced CFD methods. In particular, the first was used to assess consequences in steady-state condition; the second approach was instead used to evaluate atmospheric dispersion at unsteady conditions and to correctly take into account the peculiar fluid flow development and large-scale turbulence dispersion of $H_2$ and $H_2/CH_4$ mixtures. In both the approaches the consequences are evaluate considering the formation of a 50-mm hole on the top of aboveground pipeline (500mm external diameter) operating at 40 atm (Capasso et al, submitted IJHE). In the following paragraph a summation of the results obtained from both approaches are reported.

### 5.2.1 Empirical consequence evaluation

To quantify the LOC of the hazardous substances a Source model was adopted: the specific case of gas release from a hole (Crowl 2002) was considered, where the mass flow rate of gas released ($Q_m$) is described from the following equation:

$$Q_m = C_0 \cdot A \cdot P_0 \sqrt{\frac{2g_c M}{R_g T_0}\frac{\gamma}{\gamma-1}\left[\left(\frac{P}{P_0}\right)^{\frac{2}{\gamma}} - \left(\frac{P}{P_0}\right)^{\frac{\gamma+1}{\gamma}}\right]}$$

Where $C_0$ is a discharge coefficient, A is the hole surface, M is the molecular weight of the gas, $\gamma$ is the heat capacity ratio, $T_0$ is the temperature of the source, $R_g$ is the ideal gas constant, $g_c$ is the gravitational constant. For a conservative study, the maximum value of the mass flow is considered, i.e. when the exit gas velocity reaches the sonic velocity (chocked flow).

For each mixture, a value *of* $C_0 = 1$ e $g_c = 1\frac{m}{s^2}$ for the calculation of the maximum mass flow rate of gas leaving the borehole. The values of $Q_{m,chocked}$ and $P_{chocked}$ calculated are shown in **Table 5.1**.

**Table 5.1:** Chocked mass flow rate and pressure after leak formation

| Mixture | $Q_{m,chocked}$ (kg/s) | $P_{chocked}$ (atm) |
|---|---|---|
| Methane | 13.4 | 21.7 |
| 90% $CH_4$ – 10% $H_2$ | 12.8 | 21.6 |
| 80% $CH_4$ – 20% $H_2$ | 12.2 | 21.6 |
| Hydrogen | 4.7 | 21.0 |

To assess the effects of a certain accident event on human beings, the consequences can be expressed through the number of deaths or injuries. A statistical method useful for evaluating consequences is called the dose-response method, which is generally coupled with a Probit equation (Center for Chemical Process Safety (CCPS) 1999; Crowl 2002):

$$\mathrm{Y} = \mathrm{k}_1 + \mathrm{k}_2 \ln \mathrm{V}$$

Where Y is the probit variable, $\mathrm{k}_1$ and $\mathrm{k}_2$ are parameters and V is the causative variable, a parameter representing the extent of exposure. In **Table 5.2** are shown variables and parameters used in this work.

**Table 5.2:** Variables and parameters used for the evaluation of probit

| Outcome | Damage | Causative variable | $\mathbf{k_1}$ | $\mathbf{k_2}$ | References |
|---|---|---|---|---|---|
| **UVCE** | Deaths from lung haemorrhage | $\mathrm{P}_0$ | -77.1 | 6.91 | (Eisenberg, Lynch, and Breeding 1975) |
| **Jet Fire** | Death due to received heat flux | $\frac{\mathrm{tI}^{\frac{4}{3}}}{10^4}$ | -14.9 | 2.56 | (Eisenberg, Lynch, and Breeding 1975) |

The gas mixture in the pipeline is highly flammable but not toxic, so the only accidents considered were fires and explosions. The positive buoyancy of the gas prevents accumulation at ground level, so two possible outcomes are considered in this analysis: Unconfined Vapour Cloud Explosion (UVCE) and jet fire.

The consequence of a UVCE was modelled using the equivalent TNT method (Center for Chemical Process Safety (CCPS) 1999; Crowl 2002), where a correction factor α takes into account the difference in energy associated with a deflagrative UVCE versus a TNT explosion. To evaluate the flammable mass at steady-state case ($\mathrm{M_e}$), Van Buijtenen model was used. Moreover, using probit equation on death due to pulmonary haemorrhage submitted in **Table 5.2** and considering a death probability of 50% an overpressure equal to $\mathrm{P_0}^* = 145$ kPa is obtained.

In **Table 5.3**, the parameters used and the value of $\mathrm{m_{TNT}}$ ed $\mathrm{R_{e.z.}}$ associated with the possible UVCE in the case of steady-state release, obtained by means of the equivalent TNT method, are given as the composition of the gas released changes.

**Table 5.3:** Values associated with possible UVCE in the case of steady-state release

| Mixture | $\mathbf{M_e}$ (kg) | α (-) | $\mathbf{\Delta H_C}$ (kJ/kg) | $\mathbf{m_{TNT}}$ (kg) | $\mathbf{R_{e.z.}}$ (m) |
|---|---|---|---|---|---|
| $\mathbf{100\%\ CH_4}$ | 615.35 | 0.04 | -50000 | 262.41 | 17.28 |
| $\mathbf{90\%\ CH_4 - 10\%H_2}$ | 702.83 | 0.108 | -50966 | 779.96 | 24.85 |
| $\mathbf{80\%\ CH_4 - 20\%H_2}$ | 756.96 | 0.176 | -52135 | 1481 | 30.78 |
| $\mathbf{100\%\ H_2}$ | 688.67 | 0.72 | -120000 | 12687 | 62.97 |

A jet fire may occur in the case of immediate ignition. The main causative variable of the damage caused by a Jet fire is the thermal radiative flux that can be evaluate with several empirical models (Center for Chemical Process Safety (CCPS) 1999). The point source model (PSM) is the simplest and most widely used method of evaluating radiative heat flux: it assumes that heat flow due to radiation associated with the fire is released from a single point at a height equal to half the total length of the flame. **Figure 5.11** shows the received radiation heat flux as a function of the distance from the point source, calculated with the point source model, for the different compositions of the outlet gas.

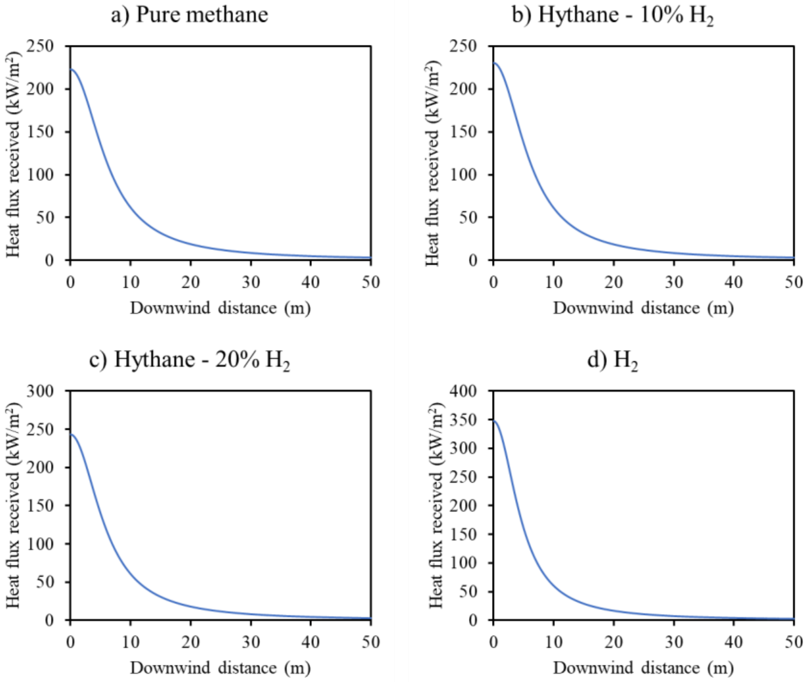

**Figure 5.11:** Radiation heat flux received, varying the composition of the gas released: pure methane (a), 10% $H_2$ (b), 20% $H_2$ (c), pure hydrogen (d).

Applying the probit equation for death due to received heat flux presented in **Table 5.2**, considering exposure times of 1 min and 5 min and a probability of death of 50%, we obtained received radiation heat flux values of $16\,\frac{\mathrm{kW}}{\mathrm{m}^2}$ and $4.8\,\frac{\mathrm{kW}}{\mathrm{m}^2}$ respectively. **Table 5.4** lists the radius $R_{e.z.}$ of the corresponding effect zones as the composition of the released gas changes. As the mole fraction of hydrogen in the released gas increases, there is a decrease in the extent of the effect zone. This is mainly due to the reduction in the outflow mass flow rate.

**Table 5.4:** Extension of effect zones for possible Jet Fire

| Mixture | $R_{e.z.}$(1-min) (m) | $R_{e.z.}$(5-min) (m) |
|---|---|---|
| $100\%\ CH_4$ | 21.7 | 39.8 |
| $90\%\ CH_4 - 10\%H_2$ | 21.5 | 39.4 |
| $80\%\ CH_4 - 20\%H_2$ | 21.3 | 38.9 |
| $100\%\ H_2$ | 20.4 | 37 |

### 5.2.2 CFD-based consequences evaluation

Unsteady simulations were carried out using a CFD model developed by means of the Ansys Fluent software. The Unsteady Reynolds Averaged Navier-Stokes (URANS) approach and the standard k-ε model for turbulence were used. For all CFD simulations, the input parameters shown in **Table 5.5** were kept constant while varying the hydrogen molar fraction released.

**Table 5.5:** Input parameters for CFD simulations

| Input Parameter | |
|---|---|
| **Class stability** | F |
| $u_w\left(\frac{m}{s}\right)$ | 1.5 |
| **RH** (%) | 60 |

The graphical representation of the optimized and validated meshes is shown in **Figure 5.12** and their associated values are given in **Table 5.6**. The centre of the release zone was placed at coordinates (10,50,0) m for all CFD simulations performed. In addition, to better represent the early phase of gas release, local mesh refinement near the release zone was carried out.

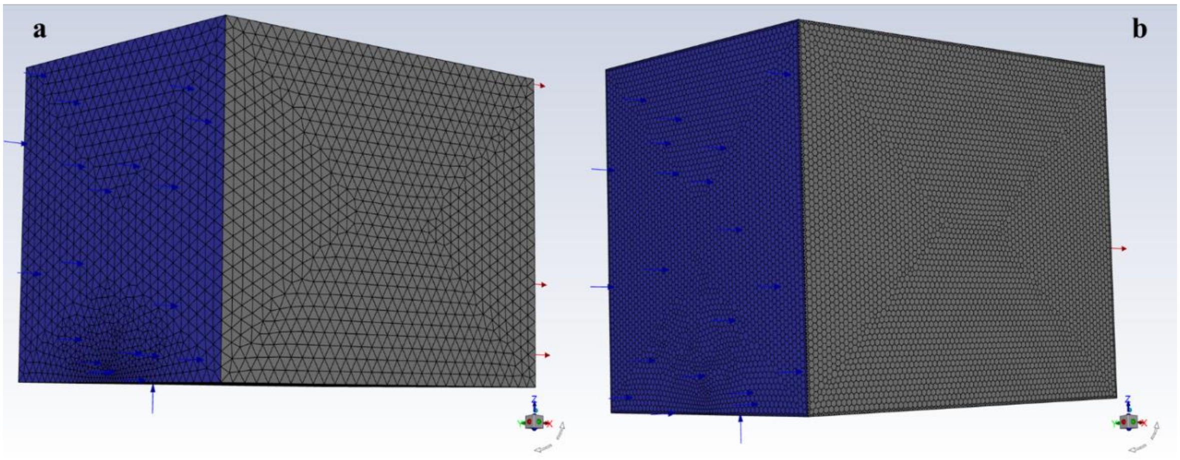

**Figure 5.12:** Meshes used for: (a) methane and Hythane mixtures; (b) hydrogen

**Table 5.6:** Values related to meshes in Figure 5.12

| | a | b |
|---|---|---|
| **Mesh length X (m)** | 130 | 140 |
| **Mesh width Y (m)** | 100 | 100 |
| **Mesh height Z (m)** | 100 | 115 |
| **Element type** | tetrahedra | polyhedra |
| **Number of elements** | 631218 | 882324 |
| **Number of nodes** | 136142 | 4340560 |
| **Number of faces** | 1310712 | 5444758 |
| **Minimum orthogonal quality** | 0.392 | 0.215 |

In **Figure 5.13**, a comparison of molar fraction profiles of the gases released, in the plane z-x at y=50 m, is shown. As can be seen, on increasing the hydrogen content in the methane/hydrogen mixtures, the plume changes both qualitatively (plume shape) and quantitatively (plume length). This behavior can be better explained comparing the time evolution of the velocity fields in time of released hydrogen and methane, shown in **Figure 5.14**. Both for hydrogen and methane, there are two zones above and below the plume where the velocity is about 1 m/s starting from 1 s after the beginning of the release. However, in the case of hydrogen release, parts of these zones separate from the rest during emission and are swept along by the plume, influencing the shape of the plume, forming a spherical shape.

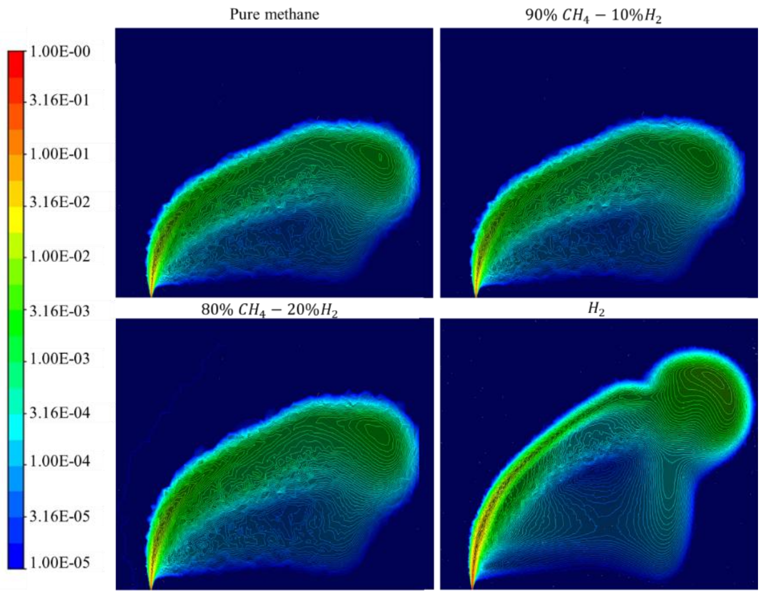

**Figure 5.13:** Molar fraction profile of the gas released in the plane z-x at y=50m

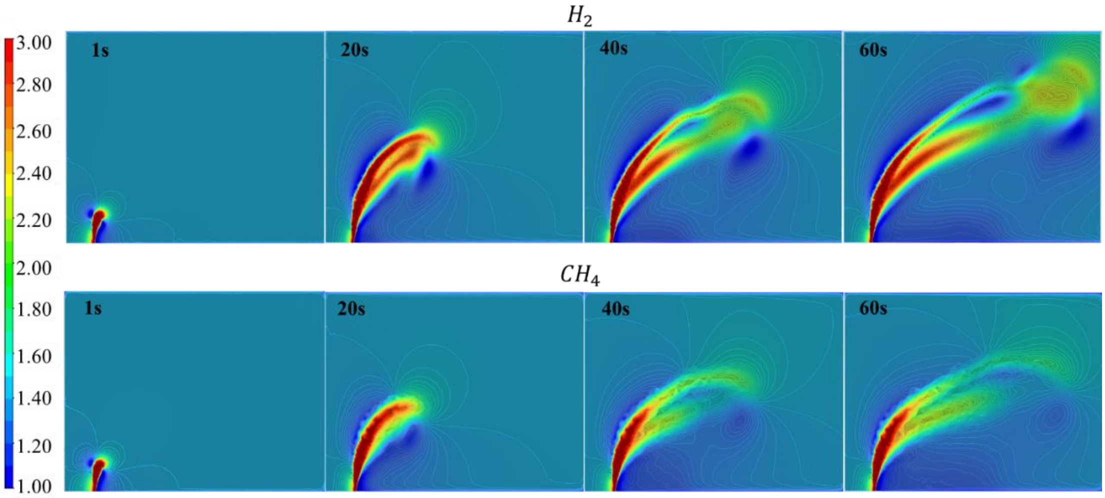

**Figure 5.14:** Velocity fields [1-3 m/s] z-x plane to y=50m over time

**Figure 5.15** shows that the molar fraction profile of the gas released within the flammability limits increases with the increase of hydrogen in the mixture. As can be seen when comparing the contours in **Figure 5.13** and **Figure 5.15**, the mass of the combustible gas is extremely limited compared to the total mass released.

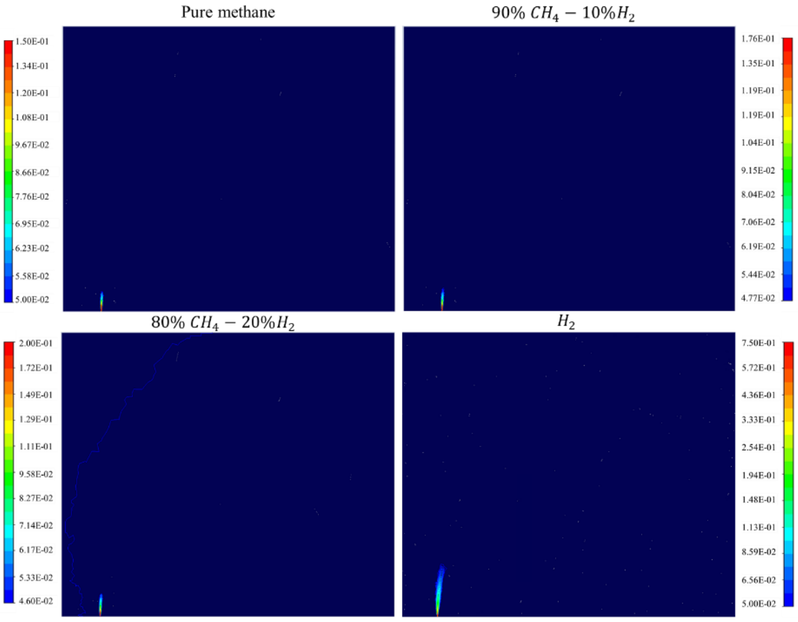

**Figure 5.15:** Molar fraction profile of the gas released within the flammability limits in the plane z-x at y=50m

**Table 5.7** shows the maximum height of the aeriform plume ($H_{max}$), distance at which momentum and buoyancy effects are extinguished ($r_{pd}$), maximum height of the aeriform jet ($H_{j\,max}$) and flammable mass ($M_e$) as computed at different mixture compositions. The maximum height of the plume, the distance at which momentum and buoyancy effects wear off, and the flammable mass increase as the hydrogen content increases. This behaviour can be addressed to the high diffusivity and extremely positive buoyancy of hydrogen. However, the maximum height of the jet does not increase monotonically as the molar fraction of hydrogen in the released gas increases. This can be explained by the fact that the released mass flow rate of pure hydrogen is much lower than that of pure methane and Hythane mixtures. Moreover, the value of $m_{TNT}$, in the case of 1-minute release, obtained by means of the equivalent TNT method, are given as the composition of the gas released changes. In this case, since the masses $M_e$ and $m_{TNT}$ are too small, the probability of the outcome is negligible.

**Table 5.7:** Results obtained from CFD simulations, varying the composition of the released gas

| **Mixture** | **$H_{max}$ (m)** | **$r_{pd}$ (m)** | **$H_{j\,max}$ (m)** | **$M_e$ (kg)** | **$m_{TNT}$ (kg)** |
|---|---|---|---|---|---|
| **100% $CH_4$** | 73 | 71 | 26.5 | 0.158 | $6.74 \cdot 10^{-2}$ |
| **90% $CH_4$- 10%$H_2$** | 73.4 | 70.7 | 27.3 | 0.182 | 0.214 |
| **80% $CH_4$-20%$H_2$** | 75 | 70.3 | 27.5 | 0.207 | 0.405 |
| **100% $H_2$** | 103.6 | 73 | 25.8 | 0.522 | 9.62 |

# 6 Civil Critical Infrastructures

## 6.1 Introduction

Urban water supply and drainage systems are central to modern infrastructure, underpinning public health, economic continuity, fire suppression, environmental quality, and overall livability. These systems operate as tightly coupled socio-technical networks (physical assets, operators, control systems, institutions, and users) that increasingly face *multi-hazard* conditions. Such conditions include **compound extremes** – e.g. droughts concurrent with heatwaves, or heavy rainfall coincident with storm surge – and **cascading disasters**, where one initiating event propagates through interdependent systems (for example, a power outage triggers pumping failures, leading to water service disruptions and sewage overflows). Research has shown that the largest societal impacts often arise not from a single hazard alone, but from **interactions between hazards and underlying vulnerabilities**, and from the propagation of failures through networked infrastructure systems. In other words, a univariate, single-event perspective may **severely underestimate risk**, because combinations of events or cascading sequences frequently lead to disproportionate damages compared to isolated incidents.

Recognizing this, critical infrastructure scholarship has developed multiple modeling and conceptual approaches to represent interdependencies and cascading failures. These include network models, system dynamics models, and economic input-output models, among others. In the urban water context, this means traditional “single-hazard, single-failure” risk analyses can miss correlated failures (e.g. a simultaneous pump outage and flood) and cross-sector dependencies, thereby underestimating high-consequence scenarios. For example, an exclusive focus on flood defense might overlook that a **power outage during a storm** can incapacitate pumps and treatment plants, resulting in widespread service loss even if physical flood barriers hold. To address such gaps, **state-of-the-art assessment frameworks** integrate hydraulic and water-quality simulation with fragility models and recovery dynamics, allowing analysts to simulate post-event system performance and restoration processes. This approach represents a shift toward holistic resilience assessment, combining multiple domains of analysis.

In summary, the emerging paradigm emphasizes that urban water supply and drainage systems must be evaluated under *multi-hazard scenarios* – accounting for compound events, cascading interdependencies, and feedback loops – to fully capture their vulnerability and resilience characteristics. This report synthesizes high-impact literature on: **(a)** hazards and their impacts on water infrastructure and services, **(b)** the targets and receptors impacted, and **(c)** interconnections and cascading effects. The analysis is presented separately for **urban water supply systems** and **urban drainage (wastewater/stormwater) systems**, followed by a synthesis of cross-system cascade pathways. A final section outlines **Mitigation and Adaptation Recommendations** for utility operators, urban planners, and risk analysts to strengthen these systems against multi-hazard risks.

### 6.1.1 Scope, Definitions, and Literature Basis

*Urban water supply systems* are defined here as the end-to-end chain from raw water sources (surface water, groundwater, or desalinated sources) through intake, transmission, potable water treatment, storage, and pressurized distribution to consumers. *Urban drainage systems* are defined as the networks handling stormwater and wastewater collection – including separate or combined sewer networks, pumping stations, regulators and overflow structures, detention basins – and downstream wastewater treatment facilities leading to safe discharge to the environment. Both types of systems are considered **cyber-physical infrastructures**: they rely not only on physical components (pipes, pumps, tanks, etc.) but also on sensors, telemetry, SCADA controls, and automated decision systems that monitor and manage flows. This cyber-physical nature means that information technology failures or cyberattacks can have direct physical consequences on water services, a point we return to under technological hazards.

A comprehensive hazard taxonomy is used to ensure all relevant threats are considered. Major categories include:

- *Hydro-meteorological and climatological hazards:* extreme precipitation (intense rainfall), pluvial flooding (surface water flooding from rain), fluvial flooding (river floods), droughts, heatwaves, cold snaps and freezing events, windstorms, and lightning. These primarily arise from weather and climate processes.
- *Coastal and sea-level-related hazards:* storm surges during coastal storms, chronic sea-level rise, and related issues like rising coastal groundwater and saltwater intrusion into aquifers.
- *Geophysical hazards:* earthquakes, soil liquefaction and permanent ground deformation, landslides, and land subsidence. These stem from earth processes and can cause structural damage to buried infrastructure.
- *Biological and ecological hazards:* pathogen proliferation in source waters (e.g. after contamination or warm conditions), harmful algal blooms (HABs) producing cyanotoxins, and post-wildfire landscape changes (which can alter water quality and erosion patterns).
- *Technological and anthropogenic hazards:* extended power outages, cyberattacks on control systems, telecommunication failures, chemical spills or industrial releases into water bodies or sewers, intentional contamination (sabotage), critical supply-chain disruptions (e.g. shortages of treatment chemicals), and workforce shortages during concurrent crises (such as a pandemic combined with a natural disaster).

This taxonomy guides the report’s structure, ensuring that for both water supply and drainage systems, we cover the full range of hazards from natural to human-induced, and from acute events to chronic trends. Each hazard type can impact infrastructure in distinct ways, but as we will see, *worst-case scenarios often involve overlapping hazards* (e.g. a storm causing both flooding and a power outage, or an earthquake causing simultaneous structural damage and power loss). Table 1 (later in the report) will provide a comparative summary of key hazards and their typical impacts on water supply versus drainage systems.

The contemporary literature on multi-hazard and cascading risk highlights a few key paradigms and tools:

1. **Compound event framing:** This approach emphasizes identifying and modeling *correlated extremes* and shared drivers (e.g. heat and drought co-occurring, or heavy rain plus storm surge). It stems from the recognition that climate risks are often due to multiple factors acting together. For instance, Zscheischler et al. (2018) demonstrate how compound climate events can produce outsized impacts compared to isolated events.
2. **Interdependent infrastructure modeling:** Models that capture how failures propagate across sectors (power, water, transportation, etc.) are crucial. Classic frameworks by Rinaldi et al. (2001) and modern reviews by Ouyang (2014) categorize interdependencies as physical, cyber, geographic, or logical, and provide methods to simulate cascading outages. For water

systems, this means understanding, for example, how an electrical grid failure can knock out pumps (physical dependency), or how a flood might simultaneously affect transportation (delaying repair crews) and communication systems.

3. **Integrated water system resilience tools:** There have been significant advances in simulation tools that integrate hydraulic modeling of water networks with damage and repair dynamics. One example is the **WNTR (Water Network Tool for Resilience)**, which can simulate disruptions (e.g. pipe breaks, power loss) and subsequent service restoration in water distribution systems. Klise et al. (2017) present a software framework combining such simulations with resilience metrics, illustrating that post-event service levels depend not just on hazard intensity but also on the timing and efficiency of repairs. These tools allow scenario analysis for earthquakes, floods, contamination incidents, etc., and help identify how long it takes to restore water supply under different strategies.

4. **Performance and resilience metrics with multi-failure trade-offs:** Recent studies (e.g. Diao et al. 2016) highlight that improving resilience to one failure mode can inadvertently reduce resilience to another. For example, a network reconfiguration that protects against pipe bursts might increase vulnerability to low-pressure events. This has led to the use of **global resilience analysis** – evaluating system performance across many failure scenarios to identify trade-offs. It underscores the importance of not optimizing for a single threat at the expense of others.

5. **Emerging hazard-specific reviews:** The literature is rapidly evolving for certain new or intensifying threats. For instance, Albustami et al. (2025) review **cyber-physical attacks on water networks**, demonstrating how a stealthy cyber intrusion could manipulate sensors and valves to cause hydraulic disruptions. Similarly, Zou et al. (2026) provide a systematic review of how **climate change affects sewer overflow failures**, finding that heavier precipitation and shifting weather patterns will dramatically increase overflow risks and public health impacts. These domain-specific studies feed into the broader multi-hazard perspective by detailing how one class of hazard can cascade within water systems.

The above elements form the scientific basis for this report. We aim to integrate these state-of-the-art insights in the following sections, first examining urban water supply systems, then urban drainage systems, and finally their interconnections. All cited literature is preserved in APA style in-text and in the reference list, to guide readers to detailed sources.

## 6.2 Urban Water Supply Systems

### 6.2.1 Hazards and Impacts on Infrastructure and Services (Water Supply)

Urban water supply systems are vulnerable to a spectrum of hazards. Key dependencies make them sensitive: (i) they require continuous energy (electricity or fuel) for pumping and treatment processes; (ii) they rely on the physical integrity of widespread, often aging, buried pipe networks and storage reservoirs; and (iii) they need stable raw water quantity and quality (meaning a safe yield from sources and treatable source water conditions). A disruption in any of these dependencies – power, infrastructure integrity, or source water – can degrade service. Contemporary resilience frameworks for drinking water utilities explicitly account for many hazard types (earthquakes, floods, droughts, hurricanes, winter storms, wildfires, contamination events, etc.) and integrate hydraulic models with water quality and restoration planning. Below we detail how major hazard classes affect water supply infrastructure and operations.

#### *6.2.1.1 Seismic hazards (earthquakes, liquefaction, land deformation)*

Earthquakes impose sudden mechanical stresses on pipelines and structures. Ground shaking can crack pipes (especially brittle cast iron or older pipes), cause joint failures, and even lead to the collapse of reservoirs or water tanks. In areas of susceptible soils, *liquefaction* (where saturated ground turns fluid-like during shaking) or permanent ground deformation can shear buried pipelines or misalign them. The immediate consequence is often massive **pipe breaks and leaks**, leading to loss of pressurized service. Water distribution systems rely on maintained pressure; when dozens or hundreds of main breaks occur (as in major earthquakes), the network may experience widespread pressure drops or complete outages. The principal service impact is therefore **loss of pressure and loss of delivered volume** over large areas. Recovery can be prolonged – for instance, after the 1994 Northridge earthquake, parts of Los Angeles had boil-water advisories for 12 days until water quality was restored, and it took seven days to restore basic water quantity delivery, even though full infrastructure repair took years. Seismic resilience studies quantify these post-event service shortfalls and emphasize that the speed and strategy of pipe repair crews is a central determinant of how quickly service recovers. For example, Liu et al. (2020) model various pipe repair prioritization strategies after a quake and show large differences in the time to restore water to critical facilities. Aside from the physical disruption, a critical water-quality failure mode with earthquakes is **intrusion contamination**. When a pipe breaks or when pressure drops near zero, there is a risk that dirty water from the surrounding environment (soil, groundwater, or sewer water if near sewer lines) can be sucked into the water pipes through cracks once pressure is re-established. Intrusion requires a combination of factors – a pressure drop, a pathway (crack) in the pipe, and contaminated water outside – which can indeed coincide after earthquakes. Studies have used quantitative microbial risk assessment to estimate infection risks from such intrusion events, underscoring that earthquake-induced low-pressure episodes present a public health hazard if not managed properly. Notably, waterborne disease outbreaks have been documented in the aftermath of earthquakes in areas where water and sewer pipes were damaged together, highlighting the need for boil-water advisories until network integrity is confirmed.

#### *6.2.1.2 Flooding and extreme precipitation*

Floods impact water supply systems via two dominant mechanisms. First, **direct inundation** of critical facilities – if floodwaters submerge wellheads, surface water intakes, pumping stations, treatment plants, or power substations, those facilities can be damaged or forced offline. Many water treatment plants are built near rivers (for source water access) and thus are in floodplains; during extreme river floods or urban flash floods, these plants can be partially submerged, damaging electrical control panels or forcing operators to shut down for safety. Second, floods cause **indirect impacts** by triggering power outages, hindering staff access to sites, and washing large loads of contaminants into source waters. From a service perspective, floods can be a double blow: they degrade raw water quality *at the same time* as they disrupt treatment and distribution operations. For example, heavy rainfall can wash massive sediment loads, nutrients, or pathogens into a reservoir or river (a well-known case is increased turbidity and pathogen spikes in source water after extreme storms), just when the treatment plant is struggling with possible inundation or low manpower. This scenario often forces utilities into issuing **boil-water advisories or mandatory conservation** if water quality standards can't be guaranteed or if capacity is reduced. In compound event terms, an extreme storm may present multiple concurrent stresses: high pathogen and turbidity loads, possible chemical spill runoff, plus physical damage to infrastructure. Zscheischler et al. (2018) specifically cite extreme precipitation coincident with other stressors as a recipe for unexpected failures. An illustrative example is when intense rainfall caused flooding that knocked out a city's substation power (halting pumps) while also causing raw water turbidity to spike; the utility had to resort to emergency water storage and issue a boil advisory for several days. Flood-related contamination of water supplies is also a concern: if floodwaters breach distribution system barriers (through broken pipes or flooded pump stations), they can introduce microbial or chemical contaminants. After major hurricanes (Katrina 2005, Harvey 2017), some water systems were compromised both by physical damage and by contamination from floodwaters carrying sewage and industrial chemicals. Thus, flood resilience for water supply involves not just physical floodproofing of facilities but also backup power and robust source water protection.

#### *6.2.1.3 Drought and heatwaves*

Drought represents a slow-onset but severe hazard for water supply. Extended drought reduces the available raw water in rivers, reservoirs, and aquifers. Utilities may be forced to tap **marginal sources** (e.g. smaller aquifers or older wells, emergency interconnections) that could have quality issues (higher salinity, higher contaminant concentrations) or insufficient quantity. As surface reservoirs shrink, water temperature often rises and water quality can deteriorate – for instance, concentration of pollutants and algae can increase in a smaller volume. Droughts also lead to higher **water age** in distribution networks because utilities impose usage restrictions; water sits in pipes longer, which can reduce chlorine residual and let bacteria regrow. Heatwaves, often accompanying droughts, compound these issues. Heatwaves spur higher water demand (for cooling, irrigation, firefighting), sometimes pushing systems to operate near capacity. High temperatures can also **reduce pipe capacity** by lowering distribution system pressure (due to increased friction losses and lower source elevation head in extreme heat) and can accelerate chemical reactions in water. For example, disinfectant (chlorine) decays faster in warmer water, and biological activity (microbial regrowth in pipes) increases, potentially leading to taste, odor, or bacteria problems. Heat can also stress electrical components (transformers, motors) needed for pumping. Climate change analyses have found that as temperatures rise, utilities face increasing operational "at-risk" situations where water quality or supply may fall below standards. One study showed that a combined drought and heatwave scenario can lead to **lower distribution system pressure** (because of peak demand spikes for cooling) at the same time water quality degrades (because of longer stagnation and higher bacteria growth), creating conditions ripe for **health risks**. Additionally, drought conditions often correlate with increased wildfire risk, which has its own impacts (discussed next). Prolonged droughts have pushed some cities (e.g. Cape Town in 2018) to the brink of running out of water, illustrating that severe supply shortages are a real multi-hazard: part natural (lack of rain) and part socio-technical (demand management and emergency infrastructure). Drought contingency plans now form a core part of water supply resilience, including measures like diversified water sources, demand curtailment, and even desalination plants as backups in arid regions.

#### *6.2.1.4 Wildfire and post-fire runoff*

Wildfires have emerged as a significant hazard to water supply systems in two distinct ways: **watershed effects** and **urban interface effects**. In the *watershed pathway*, a wildfire in the catchment (upstream of a reservoir or river intake) can dramatically alter the water quality and hydrology of that source. High-severity forest fires combust vegetation and create ash and charcoal; afterwards, rainstorms on burned areas can produce **runoff with extremely high turbidity, nutrients, and organic carbon**. For example, studies in Colorado after major wildfires found that subsequent storms washed charred soil and debris into streams, raising turbidity to levels far above treatability and introducing problematic **disinfection by-product precursors** (organic compounds that react with chlorine). Hohner et al. (2016) documented that a treatment plant had to adjust coagulant dosing significantly and still struggled to meet standards due to the influx of post-fire contaminants. These effects can last for several years until vegetation regrows and stabilizes soils. Thus, a wildfire can indirectly cause a **water treatment crisis**, where a plant is pushed beyond its design by the changed source water quality (e.g., sediment, nitrates, dissolved organic carbon, heavy metals mobilized from soils). In extreme cases, water utilities have had to shut down intakes and draw from alternative sources after wildfires due to untreatable water quality. The *urban interface pathway* refers to fires that encroach into communities and damage the distribution network infrastructure itself. When wildfires sweep through neighborhoods (as seen in the 2017 Tubbs Fire and 2018 Camp Fire in California), the extreme heat can cause the melting or chemical breakdown of plastic pipes and gaskets in water systems. In some wildfire disasters, **toxic volatile organic compounds (VOCs) like benzene** were found in drinking water distribution networks post-fire, likely due to a combination of burning of plastic pipes and suction of contaminated air/fluids into the depressurized lines. This resulted in “Do Not Drink” orders that persisted for months while utilities flushed and replaced contaminated pipes. Solomon et al. (2021) report on such cases, calling this an emerging failure mode: the fire doesn’t just destroy houses, it also **contaminates the water system** for the surviving houses. In addition, wildfires often cause extended power outages and loss of communications, complicating the operational response. Therefore, wildfires pose a multi-faceted hazard to water supply: immediate infrastructure damage (e.g. melting pipes, destroyed meters), acute water quality degradation (VOC contamination, ash in source water), and longer-term watershed effects (erosion, algae blooms in reservoirs due to nutrient runoff). Water utilities in fire-prone regions are now developing wildfire response plans, including pre-installing backflow prevention devices (to stop toxic suck-back into mains) and collaborating on forest management to protect source watersheds.

#### *6.2.1.5 Coastal hazards (storm surge, sea-level rise, salinity intrusion)*

Coastal water supply systems face both catastrophic and chronic challenges. An acute coastal storm (hurricane or cyclone) can drive **storm surge** – essentially a temporary rise in sea level – that can inundate low-lying water facilities. Water treatment plants near estuaries or coasts, intake pumping stations at river mouths, or power supply lines in coastal areas can all be flooded by storm surge. As with river floods, **saltwater inundation** can damage electrical components and foul treatment processes (for instance, if saline water enters a freshwater treatment train, it can cause process upsets). Beyond the event itself, **sea-level rise (SLR)** is a creeping hazard that can permanently alter source water conditions. Gradual SLR leads to **saltwater intrusion** into coastal aquifers (the boundary between fresh groundwater and seawater moves inland/upward) and increased salinity in estuaries and deltas where many cities draw water. Over time, previously fresh sources may become too salty or brackish for use without expensive desalination or blending. A systematic review by Ketabchi et al. (2016) confirms that SLR significantly influences coastal aquifer salinization, though local geology and pumping patterns modulate the impact. Furthermore, recent research has identified an under-recognized mechanism: **vertical saltwater intrusion due to storm overwash**. If seawater from a surge floods the surface and infiltrates, it can form a “lens” of saline water that percolates downwards, rapidly salinizing wells that were previously fresh. Cantelon et al. (2022) demonstrated this in a model: even a single seawater flooding event can push saltwater far into an aquifer from above. The implications for water supply include rising **chloride levels** in raw water (harmful for distribution pipes and limiting to reuse on crops), more **corrosive water** (salt accelerates corrosion in pipes and fixtures), and potential health impacts if consumers drink high-sodium water (e.g. contributing to hypertension). Indeed, a recent study linked chronic consumption of slightly saline water to increased blood pressure in coastal communities. On the infrastructure side, coastal utilities must also contend with **groundwater rise** (as sea level pushes water tables up, it can infiltrate into sewer lines or basements, affecting co-located systems). In summary, coastal hazards force water utilities to invest in flood barriers, relocate critical equipment to higher elevations, consider **salinity control measures** (like blending or desalination), and plan for **worst-case scenarios** where a storm could knock out both power and treatment simultaneously. Where sea-level rise threatens long-term source viability, strategies like developing inland wellfields, using surface water or recycled water, or building desalination plants become adaptation measures.

#### *6.2.1.6 Technological hazards: power outages and cyberattacks*

Water supply is heavily **energy-dependent**. Even systems with gravity-fed transmission (e.g. mountain reservoir to city) usually need pumps for distribution boosting, treatment processes (like rapid mixing, filtration backwashing), and maintaining pressure in elevated zones. A broad power outage – whether due to grid failure, storm, or even a deliberate attack – is therefore one of the most common initiators of water service disruptions. In disaster scenarios, power loss often precedes or coincides with water outages (for example, earthquakes and hurricanes routinely cause blackouts, which then cause pumps to stop, leading to loss of water pressure in hours). Without power, **treatment plants may have to shut down** (no treatment = unsafe water), and **pump stations stop**, causing reservoirs to drain and pressures to fall. Many utilities have backup generators, but these cover only essential loads and often fuel supplies are limited. Studies have shown that power outages can trigger **low-pressure events** and "boil water" conditions simply due to loss of chlorination or inability to maintain pressurization. In terms of risk cascades, a power outage is often the first domino: it violates operational rules (e.g. treatment standards, minimum pressure) and sets the stage for intrusion or contamination if not promptly managed. Concurrently, the digitization of water infrastructure introduces **cybersecurity threats** as a novel hazard. Modern water systems use SCADA (Supervisory Control and Data Acquisition), networked sensors, and remote control valves. This creates an attack surface for cyber intrusions. Albustami et al. (2025) demonstrated "stealthy" cyberattacks where false sensor readings were fed to operators, masking the fact that a pump was maliciously turned off. The attack led to abnormal pressure drops without triggering immediate alarms, showing that a hacker could engineer a water outage or contamination event covertly. Real-world incidents have also occurred (e.g. a 2021 attempt in Oldsmar, Florida, to alter chemical dosing via remote access). A successful cyberattack could, for instance, open all hydrants or valves to drain a system, shut down disinfection so that unsafe water is delivered, or alter setpoints to overpressurize and burst pipes. These scenarios highlight that **cyber hazards are operationally plausible stressors, not just IT problems**. Water utilities must now treat cyber-physical security as part of their hazard set. From an impact viewpoint, a well-timed cyberattack could amplify a physical disaster – e.g. during a storm, disable pumps or alter sensor data to mislead operators – thereby worsening the cascade (this will be discussed under cross-system cascades).

### 6.2.2 Infrastructure failure modes and internal hazards

In addition to external hazards, water supply systems also deal with intrinsic failures: aging pipes leak or burst routinely, valves malfunction, storage tanks corrode, etc. These "everyday" failures become more frequent under stress (for instance, pressure fluctuations during a fire flow or after a seismic jolt cause weak pipes to fail). Hazards often *amplify* underlying deterioration – an earthquake might break pipes that were already weak, or a drought-induced pressure increase might cause an old main to burst. Frequent pipe breaks in aging networks are a known issue; for example, some cities experience dozens of main breaks per 100 km of pipe annually even without disasters. Under multi-hazard scenarios, the **failure rates can spike** – cold weather causes many breaks due to thermal contraction, or stormwater infiltration causes pressure transients. Diao et al. (2016) noted that system performance under failure is highly non-linear: a single large main break in a critical location might be worse than 10 small breaks elsewhere. Moreover, their analysis showed that increasing resilience to one failure mode (say, installing seismic-resistant pipe in earthquake zones) might reduce resilience to another if not carefully planned (for instance, a very rigid pipe might be more prone to bursting under pressure surges). Wéber et al. (2020) introduced methods to identify *vulnerable segments* of a network, finding that certain pipe segments can cause disproportionate system outages if they fail, due to network topology This emphasizes that understanding internal network structure (loops, redundancies, or lack thereof) is as important as understanding external hazards. **Operational changes** themselves can be hazards: for instance, switching water sources abruptly can cause corrosion scale to dislodge (as happened in the Flint water crisis), introducing contaminants. Thus, water utilities consider even things like *water age, pressure transients, maintenance neglect,* etc., as part of a holistic risk assessment. In multi-hazard conditions, these internal issues often interact with external triggers – e.g. a hurricane might cause so many simultaneous leaks (from tree root intrusion or impact) that normal leak repair crews and isolation valves are overwhelmed, leading to a systemic pressure collapse.

### 6.2.3 Impacted Targets for Water Supply failures

When water supply services are disrupted or degraded by the hazards above, the impacts radiate to multiple targets or “receptors” in the community and environment. In multi-hazard planning, it is useful to delineate these **impacted targets** because each has different vulnerabilities and criticalities. For urban water supply, key impact domains include **human health and safety**, **environmental ecosystems**, **economic activities and critical services**, and **quality of life/social stability**. We discuss each in turn:

- **Human Health and Public Safety:** This is the most direct and high-stakes impact category. A safe water supply underpins public health; any compromise can expose populations to microbial or chemical hazards. A major risk during water supply failures is **infectious disease** from microbial contamination. As noted earlier, *intrusion of pathogens* into pipes can occur during low or negative pressure events (for example, after an earthquake or during a power outage when pressure drops). For contamination to enter, three conditions must coincide: a pressure deficit, a physical pathway (leak or break), and contaminated water or soil surrounding the pipe. Disasters can create all three – e.g. an earthquake breaks a sewer and a water main in proximity while water pressure is lost. Studies (Besner et al. 2011; Propato 2004) have quantified how such events increase illness risk, often prompting boil-water orders as a preventive measure. Apart from pathogens, **chemical hazards** are also a concern. In wildfire-affected systems, as described, VOCs like benzene can render water acutely toxic. Also, backflow incidents (where chemically contaminated industrial water flows backward into mains due to pressure loss) can happen during certain hazard scenarios. Public safety is also affected in terms of **firefighting**: water supply networks provide fire hydrant flows. If an earthquake or a drought-heatwave reduces water pressure, firefighters may find hydrants ineffective just when fire risk is high. This multiplier effect was tragically observed in some wildfires when water systems lost pressure, hampering firefighting and leading to greater fire spread. Ensuring *fire flow* during multi-hazard events (e.g. backup pumping capacity during earthquakes) is thus a critical public safety need. In summary, water supply failures can directly cause disease (via unsafe water) and indirectly cause harm by failing to support hygiene and fire suppression. Historical analysis of disasters shows spikes in gastrointestinal illness after water outages (if alternate safe water isn't provided) and increased fire damage where water was not available for suppression. Therefore, **human health** considerations drive much of the emergency response in water supply crises – for instance, rapid issuance of boil-water advisories, deployment of water tankers or bottled water to prevent dehydration and allow hygiene, and prioritization of hospitals and shelters for water service restoration.

- **Environment and Ecosystem Services:** Water supply disruptions can impact the environment in several ways, often indirectly. If a city's main water source is compromised (say a reservoir becomes too turbid after a storm), operators might switch to an alternative source or implement emergency measures that affect ecosystems. For example, if a treatment plant is flooded, the utility may need to **bypass normal processes**, perhaps discharging partially treated water or flush water directly, potentially polluting downstream waterways. During flooding or earthquakes, **chemical spills** from treatment plants (like chlorine or fuel from generators) can occur and contaminate soil or water bodies. Also, when water supply is scarce (as in drought), cities may overdraw from rivers or groundwater, reducing flows needed for fish and wetlands. There is also interplay with drainage: if drainage infrastructure fails, sewage could contaminate a raw water intake, forcing changes in operation that might lead to emergency discharges elsewhere. Additionally, long-term changes like climate-driven source water quality shifts (warming, more algae, etc.) can lead to adjustments in water treatment (e.g. using more coagulants, producing more concentrated sludge) which must be disposed of, sometimes affecting the environment if disposal practices change. Wildfires again provide an example: a wildfire upstream leads to **erosion pulses** – large loads of sediment and nutrients flow into reservoirs, which can cause algal blooms. Managing those blooms might involve copper-based algaecides or other chemicals that then outflow in the treatment plant's effluent or sludge, eventually affecting downstream aquatic life. So the environment can be both a victim (fish kills from pollution after a water plant failure) and a contributor (wildfire causing conditions that challenge the water system). It's also worth noting that *ecosystem services* like natural water filtration (forests filtering water) and storage (wetlands attenuating floods) are part of the broader system; when hazards disrupt those, water infrastructure feels the strain. A resilience perspective thus sees maintaining healthy upstream ecosystems as a form of hazard mitigation for water supply. For example, preserving watershed forests reduces post-storm water quality spikes, protecting the water supply.

- **Economic Activities and Critical Services:** Reliable water is essential for nearly all economic sectors in a city. Obvious ones include food service (restaurants cannot operate without water for cooking and cleaning), manufacturing (especially pharmaceuticals, microelectronics, food/beverage processing needing pure water), and construction (water for concrete, dust control). When water outages or boil advisories occur, many businesses must curtail operations, leading to economic losses. A specific subset of customers, often termed **critical services**, suffer outsized consequences from water supply issues. Hospitals and healthcare facilities need water for sanitation, instrument sterilization, patient care, dialysis, etc., and typically have limited water storage on site. Schools and care homes may close if water is not available for restrooms or kitchens, disrupting daily life and incurring costs. Emergency response services (fire departments, as mentioned, but also cooling centers during heatwaves) rely on water. Resilience modeling often includes maintaining service to "sensitive customers" like hospitals at all costs. For instance, after a disaster, utilities will prioritize re-routing water to a hospital zone via emergency pump or tanker. The economy also feels impact in terms of **non-revenue water losses and repair costs**: a hazard that increases pipe burst frequency means the utility loses more treated water into the ground (wasting treatment chemicals and energy) and must spend more on overtime for repair crews. As Wéber et al. (2020) highlighted, if hazard events cause simultaneous bursts, isolating and fixing them becomes more complex, possibly requiring shutting larger sections and thus affecting more customers. There are also long-term economic impacts: if an area's water supply is perceived as unreliable, it can deter investment or lower property values. For example, repeated water shortages or contamination incidents might cause food processing companies to relocate or invest in costly pre-treatment, raising prices. A study following a hypothetical major earthquake in the San Francisco Bay Area estimated billions in business losses due to water service interruption On the flip side, investment in resilience (like seismic upgrades or dual power feeds) can be cost-justified by avoiding these losses. Utilities now often perform **risk and resilience assessments** that compute potential economic losses from hazards to prioritize improvements (mandated, for instance, by the U.S. America's Water Infrastructure Act for large utilities).

- **Quality of Life and Social Stability:** Water is a basic need, and its absence quickly affects daily life. Even short outages (<24 hours) force households to expend significant effort to obtain drinking and cooking water, and longer outages severely disrupt sanitation (toilets, bathing) and convenience (laundry, dishwashing). For vulnerable populations (the elderly, low-income communities, those with disabilities), these burdens are amplified – they may not have means to buy bottled water or transport it, and they may have higher health risks if hygiene suffers. Multi-hazard events often exacerbate inequities: for example, during a flood or hurricane, wealthier residents might evacuate to hotels where water is available, whereas poorer residents in shelters are reliant on emergency water provisions. **Social stability** can be tested if water outages persist; there have been instances of public protests or unrest when communities feel government responses are inadequate (for instance, the frustration in Cape Town during the "Day Zero" drought crisis, or in parts of Christchurch, New Zealand after the 2011 earthquake where some neighborhoods lacked water for weeks). Quality of life also ties into mental health – living with constant boil-water advisories or fearing contamination can cause anxiety and erode trust in institutions. The compound-events literature (like Zscheischler 2018) points out that *social vulnerabilities* interact with physical hazards to produce ultimate outcomes. If a population has coping capacity (e.g. money to buy alternatives, knowledge to boil water, community support networks), the impact on quality of life is mitigated, and vice versa. Planners thus consider how to make water supply systems not just technically robust but also socially equitable under stress. This could involve ensuring distribution of emergency water supplies to all areas, clear risk communication (so people know if water is safe or not), and engaging communities in resilience planning. In summary, quality of life impacts range from inconvenience to severe hardship, and often the **indirect** consequences (schools closed because no water, or needing to spend hours in line for water) can accumulate to significant social and economic costs.

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### 6.2.4 Impacts, Interconnections, and Cascade Effects for Water Supply

Multi-hazard scenarios in water supply systems can typically be characterized by **(i)** an initiating hazard, **(ii)** intermediate infrastructure failures or functional degradations, and **(iii)** secondary impacts that sometimes exceed the primary hazard's direct effects. The scientific literature on interdependent infrastructure (e.g. Ouyang 2014; Rinaldi 2001) emphasizes that **indirect effects often dominate** the overall consequences of disasters. In the context of water supply, a seemingly localized event can cascade into a citywide crisis if critical nodes are affected. Below we outline several cascade archetypes for water supply, drawn from real events and modeling studies:

- **Seismic Cascade:** *Earthquake → widespread pipe breaks → pressure loss → contamination intrusion → public health response.* Here, an earthquake (initiating hazard) damages numerous water mains and perhaps storage tanks. The immediate effect is large leaks draining the system and loss of pressure across neighborhoods. Low pressure then becomes the gateway for contaminants: if there are any sewage line breaks, flooded areas, or soil pathogens, these can intrude into the water pipes at break sites once pressure is restored or fluctuating. As a result, even after the quake shaking passes, the water system continues to suffer – not only is service disrupted (no water flow), but when service resumes it may be unsafe. Public health agencies must intervene with boil-water advisories or distribution of bottled water, and water utilities must undertake widespread **flushing and disinfection** post-repairs to ensure no pathogens remain. This cascade shows how the initial physical damage (pipes breaking) leads to a secondary health risk that can persist for weeks. Importantly, studies like Besner et al. (2011) have quantified infection risks from such intrusion events, providing a science basis to say that yes, an earthquake can indeed cause a drinking water outbreak in worst cases. Seismic resilience studies (e.g. Liu 2020; Klise 2017) also highlight that the *duration* of this cascade – how long people lack safe water – depends heavily on repair resource deployment. If repair crews and materials are limited (maybe roads are damaged, slowing repairs), the outage and contamination risk period lengthens. Therefore, the severity of the cascade is not purely a function of earthquake magnitude, but also of **system preparedness and emergency response capacity**.

- **Hydro-Climatic Cascade:** *Extreme precipitation → source water deterioration + facility flooding → water treatment plant failure/service restrictions.* In this scenario, a very heavy rainfall event (possibly combined with a storm surge or high river flow) hits a region. The **compound nature** is that it simultaneously causes *source water quality problems* (e.g. muddy runoff into a reservoir) and *physical flooding of low-lying infrastructure* (e.g. the raw water intake pumps or parts of the treatment plant). As a result, the water utility faces a situation of "worse water arriving when capacity is reduced." Turbid, pathogen-laden water reaches the intake, straining filtration and disinfection processes, at the same time portions of the treatment plant might be offline due to flooding or power loss. The cascade outcome might be that the plant cannot produce fully treated water at needed volume, forcing the utility to **issue boil-water advisories or cut off supply to maintain pressure for firefighting**. In some cases, utilities perform emergency measures like blending partially treated water with fully treated water to stretch capacity, which carries regulatory risks. Delpla et al. (2009) pointed out that with climate change, such water quality degradation events are expected to increase, meaning utilities will more frequently enter these "at-risk operating conditions". An example: during a 2016 West Virginia extreme storm, a water plant saw raw water turbidity jump to 100 NTU (normal <5), and simultaneously lost grid power. Despite backup generators, filter performance dropped and the utility preemptively issued a boil advisory for 48 hours while rushing in bulk water to hospitals. This cascade demonstrates how an environmental hazard translates to a **public health protection challenge** via water infrastructure. It also underscores the need for *multi-hazard emergency plans*: the utility had contingency to bring in generator fuel and pre-position extra treatment chemicals to handle the poor water quality, actions that mitigated the worst outcomes.

- **Wildfire Cascade:** *Wildfire (watershed burn) + subsequent rainstorm → treatment process stress → distribution contamination risks.* This is a multi-stage cascade where a **geophysical/ecological hazard** (wildfire) is followed by a **meteorological hazard** (rain) that together impact the water system. As described earlier, after a wildfire denudes a watershed, even a moderate rain can wash enormous sediment and organic loads into source water. Hohner et al. (2016) showed that post-wildfire runoff dramatically increased turbidity and organic carbon, forcing the treatment plant to adjust processes and flirting with regulatory limits on disinfection by-products. The cascade can continue: if the plant struggles, some contaminants could pass through to the distribution system, or the plant might have to **operate at reduced capacity**, leading to low pressures in the distribution network. Meanwhile, *in parallel*, if the wildfire also damaged parts of the distribution network or created vacuum conditions as described (urban interface effects), there is a direct chemical contamination risk inside the pipe network. So the water system is hit from two sides – the supply side (source water quality) and the distribution side (infrastructure damage and contamination). Solomon et al. (2021) documented exactly such a dual-pathway cascade in the 2018 Camp Fire aftermath: not only was the source water in the creeks full of ash requiring enhanced treatment, but the surviving parts of the town's distribution system had benzene contamination from burned pipes. The end result was a long-term water outage where even areas whose pipes did not burn couldn't be served because treatment had to be throttled and the distribution risked spreading contamination. This cascade underscores the need for holistic risk assessment: wildfire management isn't just a forest or fire department issue – water utilities need to engage in *pre-fire mitigation* (like creating fuel breaks around critical infrastructure, having emergency filtration measures) and *post-fire response* (like special pipe flushing protocols, rapid reservoir cover deployment to prevent ash influx). Multi-hazard thinking has to consider sequences like **fire → rain → water crisis** which cross the typical boundaries of disciplines.

- **Energy–Water Cyber-Physical Cascade:** *Regional blackout or targeted cyber intrusion → pump/control failure → pressure transients → intrusion risk amplification.* This cascade recognizes the interdependence between the power grid and water systems, as well as the growing cyber dimension

- . Suppose a major blackout occurs (due to a hurricane, heatwave overloading the grid, or even a cyberattack on the grid itself). Immediately, water pumping stations and treatment plants without adequate backup power shut down. Storage tanks start to drain. Within hours, parts of the distribution system experience **low pressure or no water**, especially higher elevations or distal parts of the network. As pumps intermittently come back (maybe some have generators), **pressure transients** – rapid rises and drops – occur in the piping, which can cause weak pipes to crack or existing leaks to suck in contaminants. In parallel, if the initiating cause was a **cyberattack on the water SCADA system**, similar outcomes can be engineered: valves could be maliciously opened or pumps stopped to mimic a physical failure. Albustami et al. (2025) showed that an attack could be subtle enough to evade immediate detection and still produce significant hydraulic disruptions (like emptying a critical tank). The cascading mechanism is that once low or negative pressure happens, the conditions for intrusion (which we've noted as a key health risk) are set. Thus, a power failure or cyber event becomes a *public health event* if contaminants enter and people consume water before warnings go out. One notorious real-world example: the 2003 North America blackout led to loss of water pressure in Cleveland's system; although no outbreak was recorded, it highlighted that water boil advisories could be needed during a power outage – something not everyone anticipates when they think of a blackout (they think of lights and refrigerators, but not tap water safety). In a more dramatic hypothetical, imagine a coordinated cyberattack during a natural disaster: hackers disable the water system's pressure alarms during a flood, leading operators to not realize sewer water has leaked into water mains. The lesson from this cascade is that **water and energy resilience are deeply linked**, and new investments like backup generators, islandable micro-grids for water plants, and robust cybersecurity protocols are vital to prevent one infrastructure's failure from cascading into another's.

- **Coastal Compound Cascade:** *Sea-level rise + storm surge + operational pumping changes → saltwater intrusion → long-term potable supply loss.* This cascade is partly gradual and partly event-driven. With rising sea levels, a coastal city's groundwater wells become increasingly brackish over years. Then a storm surge event strikes, pushing seawater into the aquifer and perhaps also flooding a key freshwater intake with saline water. The immediate effect is a **salinization of the water supply** – chloride levels in distributed water spike above palatable or safe thresholds (causing taste issues and hypertension concerns). In response, the utility might have to shut down those sources and switch to emergency sources (tankers, distant pipelines). But the cascade persists: **corrosion** in the distribution system accelerates if saline water was in the pipes even briefly, potentially causing later pipe breaks or leaching metals like lead from pipes. The community faces a chronic loss of a potable source; in extreme cases, areas might need desalination or relocation of water supply infrastructure. Mueller et al. (2024) have mapped regions where drinking water salinity poses increasing health risks, indicating that without adaptation, some coastal populations may effectively lose their local fresh water by mid-century. Unlike the sudden cascades of earthquakes or storms, this one is insidious: it's a combination of incremental stress (sea-level rise) and episodic shocks (storm surges) that together push the system beyond a tipping point. The socio-economic cascade here could include outmigration (if a town's wells go bad and water must be trucked indefinitely, people may leave) and property value declines. It illustrates the importance of long-term hazard **foresight** in current planning – by the time salt intrusion is obvious, it may be too late to cheaply fix. Some utilities are already mapping future salinity intrusion under SLR scenarios and identifying alternative water supplies decades in advance.

These examples reinforce a few general points about water supply cascades: (1) **Multi-hazard synergy:** often two hazards (or a hazard plus infrastructure fragility) coincide to drive the cascade, (2) **Temporal extension:** impacts can continue long after the initial event (e.g. contamination risk after an earthquake lasts until pipes are repaired and flushed, which might be weeks), and (3) **Cross-sector aspects:** water cascades often involve power, health, or environmental sectors, meaning inter-agency coordination is needed in response.

The above scenarios are not exhaustive but represent common patterns identified in the literature and past disasters. We will see analogues in the drainage system context, and later, how supply and drainage failures can interconnect.

## 6.3 Urban Drainage Systems

These systems serve dual critical functions: **flood protection** (keeping urban areas from flooding by conveying or storing runoff) and **public/environmental health protection** (conveying wastewater and stormwater pollutants to treatment instead of letting them foul streets or waterways). Their failure modes typically manifest as either hydraulic exceedance (water not contained – leading to flooding) or water quality failures (untreated sewage overflows to the environment). Climate change and urbanization are placing increased stress on drainage systems, with recent reviews (e.g. Zou et al. 2026) indicating that overflow failures are expected to intensify in many regions. We explore hazard impacts on drainage infrastructure and services as follows:

### 6.3.1 Hazards and Impacts on Infrastructure and Services

#### *6.3.1.1 Extreme precipitation and pluvial flooding*

Intense, short-duration rainfall can overwhelm the capacity of urban drainage networks. Even a well-designed storm sewer has some design storm (e.g. a 5-year or 10-year event) beyond which its inlets and pipes cannot carry all the water. During cloudbursts or tropical downpours, **surface flooding** occurs when rainfall rates exceed what storm drains can ingest. This leads to water ponding in streets, flowing into low-lying areas, and often flooding basements if it backs up through building sewer connections. In combined sewer systems (where stormwater and sewage share pipes), heavy rain causes **combined sewer overflows (CSOs)** – excess mixed wastewater is discharged directly to rivers or coasts to relieve pressure, as the system's capacity is exceeded. These overflows carry pathogens (from sewage) and various pollutants into receiving waters, posing immediate health risks at recreation areas and to downstream water supplies. A recent modeling study (Hauser et al. 2025) projected that with continued urban growth (more impervious surfaces causing more runoff) and heavier rainfall trends, many cities will see significantly more frequent and larger CSO events. This stresses compliance with water quality regulations and elevates public health threats. Additionally, **flash flooding** in urban areas can cause direct damage: road flooding, erosion of stream channels or green infrastructure, and infiltration of floodwaters into wastewater treatment plants (if floodwaters enter through manholes or facility gates). For drainage infrastructure, extreme precipitation tests the integrity of every component: inlets can get clogged by debris (leaves, trash) quickly, pipes under surcharge can crack or dislodge at joints due to extreme internal pressures, and pump stations for stormwater can get overwhelmed or shorted out. Intense rainfall also often highlights *small-scale vulnerabilities* – for instance, one neighborhood's undersized culvert becomes the bottleneck that floods the whole area. It's been noted that urban expansion often outpaces drainage upgrades, leading to gradually increasing pluvial flood risk unless mitigated.

#### *6.3.1.2 Fluvial (river) flooding and tailwater effects*

When major rivers flood, urban drainage systems that outlet into those rivers can back up. A river in flood creates high **tailwater levels** at the storm sewer or combined sewer outfalls, meaning water cannot discharge and instead backs up into the system. This *backwater effect* raises hydraulic grade lines in sewers far upstream, potentially causing overflows and basement flooding well away from the river. If a river's level exceeds the elevation of inland drains, water can actually reverse flow into the city through the drainage system. Many cities have experienced such issues – e.g. riverine floods that cause sewage to erupt from manholes because the river water pushes in. These effects get worse if the river flood *coincides* with local heavy rainfall (a compound event): the drainage system is trying to handle intense local runoff but finds the outlets blocked by high river levels. Zscheischler et al. (2018) pointed out that concurrent drivers (in this case, a rainstorm + high river stage) lead to impacts beyond either alone. Infrastructure impacted includes flap gates or check valves at outfalls (which can fail or get stuck, allowing backflow) and low-lying interceptor sewers that might be completely submerged. Prolonged high tailwater can also cause **inflow/infiltration** – river water leaking into sewer pipes through cracks – adding to treatment plant flow volume once the flood recedes (this can overwhelm treatment after the flood). Cities like London and Paris, which have tidal rivers, manage tailwater with massive gates and pumping stations to avoid such backflows. However, extreme events can exceed design; for example, during a severe river flood in the U.S. Midwest, some city sewers surcharged despite floodwalls, because groundwater and sewer interconnections provided pathways. The takeaway is that urban drainage must be considered in context of watershed-scale processes, not just local rainfall.

#### *6.3.1.3 Sea-level rise and coastal storm surge (for wastewater systems)*

Coastal wastewater infrastructure is very vulnerable, as treatment plants and pumping stations are often at low elevation near the shore (since historically it was convenient to discharge effluent to the ocean or estuary). Storm surges can directly flood treatment plants (knocking out equipment, as happened to some New York City wastewater plants during Hurricane Sandy 2012) and flood large stretches of sewer network. Even if a plant is protected by a levee or berm, **pump stations** that lift sewage from neighborhoods to the plant may not be, and if they fail, sewage will back up and overflow into streets or backup into homes. Additionally, **outfalls** for both stormwater and treated effluent face higher tailwater with rising sea levels, similar to the river case but on a chronic basis. Hummel et al. (2018) provided a coastal-scale assessment showing that sea-level rise and surge threaten not only treatment facilities but also the basic ability of gravity systems to discharge. Essentially, pipes that used to drain freely at low tide may become submerged even at normal tide in the future, requiring expensive pumping or forcing overflows inland. The analysis by Hummel et al. found that populations at risk of losing wastewater services due to SLR are *many times* those at risk of direct flooding. Specifically, they estimated about 10.4 million coastal U.S. residents could lose wastewater service with 3 feet of SLR, whereas only about 2.0 million of those would have their homes directly flooded – illustrating a fivefold amplification due to system cascades. This highlights that even moderate sea-level rise (a chronic stress) greatly expands the footprint of impact via infrastructure networks. Impacts on infrastructure include saltwater corrosion (saltwater intruding into sewers or plants can corrode concrete and metal), reduced plant treatment effectiveness (if high salinity or dilution from floodwaters upsets biological treatment processes), and the need for new infrastructure like **sewer pumps or storage tunnels** to cope with tides. Coastal cities are increasingly planning large investments such as levee-protecting treatment plants, raising pump station electrical gear, installing tidal gates on outfalls, and even relocating facilities inland. Nevertheless, as storms intensify, the risk of multi-day wastewater service outages after coastal floods remains high.

#### *6.3.1.4 Seismic hazards (earthquakes) in drainage systems*

Though often less discussed than water supply, sewer and drainage networks are equally or more susceptible to earthquakes. Buried gravity pipelines (especially older clay or concrete sewers) can crack or offset at joints when the ground shakes or shifts. Manholes and pump stations can tilt or sink if the ground liquefies. In Christchurch 2011, for example, large portions of the sewer system were damaged by liquefaction, leading to sewage flowing in streets and requiring months of emergency restoration (chemical toilets were deployed citywide). Unlike pressurized water pipes which *force* water out when broken, sewer pipes are gravity – breaks cause leakage *out* or *in* depending on groundwater levels, and loss of conveyance capacity. A major concern is that if treatment plants are damaged (concrete tanks cracked, clarifiers knocked out of alignment), sewage may have to be bypassed to the environment for some time. Hou et al. (2026) extended seismic resilience modeling to include not just water distribution but wastewater systems, acknowledging that both need evaluation in quake-prone cities. They stress that the same ground motion that breaks water mains will also break sewers, but the consequences are different: water main breaks cause service loss, sewer breaks cause **environmental contamination and potential disease risk** (from sewage spills). Another failure mode: earthquakes can cause **misalignment or reverse slopes** in sewers – the pipe might not break, but if the ground shifts, a gravity sewer can end up sagging or with an uphill section that impedes flow, creating chronic choke points. Post-earthquake, inspections need to find and fix those to restore capacity. Also, where wastewater relies on large interceptor tunnels, seismic shaking can cause those tunnels to crack or joints to leak, which can be very expensive to repair (often requiring trenchless relining). So, impacts include immediate overflows, and long-term reduction in capacity until repairs. If a wastewater system fails, it becomes a *cross-sector health hazard* as well – sewage overflows can contaminate drinking water sources or streets, leading to boil-water advisories and beach closures. Therefore, seismic resilience for a city must tackle *both* water and wastewater in tandem. Some mitigation measures like using flexible pipe joints, back-up generators at pump stations (so they don't overflow when power fails during a quake), and predetermined sewer bypass setups can help.

### *6.3.1.5 Power outages and operational failures in drainage systems*

Drainage and wastewater systems depend on power for many critical functions: sewage lift stations (which pump sewage from low areas to higher interceptors or treatment plants), stormwater pumping stations (common in flat or below-sea-level cities like New Orleans or parts of the Netherlands), and treatment plant processes (aeration blowers, return pumps, etc.). A power outage can therefore force a wastewater system into **emergency modes** quickly. Typically, gravity can carry sewage only so far – lift stations might be needed to avoid overflows at low points. If power is lost and backup generators fail or are absent, sewage will start backing up and eventually **overflow (sanitary sewer overflows, SSOs)** at manholes or within homes. Treatment plants usually have some detention capacity, but without power, they might divert incoming sewage to an emergency retention basin or simply bypass to the receiving water after minimal screening. For example, during Hurricane Sandy, several large treatment plants lost power for days and had to discharge untreated sewage, leading to major environmental contamination. Even in less dire situations, a short outage can cause partial treatment (e.g. lack of aeration leads to poor treatment quality) and a release of high-pollution effluent. Telemetry loss often accompanies power loss (unless there are battery backups), meaning operators might not even know where overflows are happening until reported by the public. Sea-level rise analysis, as cited earlier, explicitly identifies pump station disruption as a key failure mode – even if the plant is safe behind a levee, if the network's pumps can't run (due to power or inundation), sewage won't reach the plant. Another aspect is **operational process upsets**: for instance, a sudden heavy rain may dilute sewage so much that treatment biology (microbes) is upset, or toxic wastewater from an industrial spill could "poison" the treatment microbes, causing a plant failure. These are more chemical than physical hazards, but their effect is similar to a power outage – the plant cannot effectively treat, leading to bypasses or violations. In sum, drainage systems require robust **power reliability** (generators, redundant feeds) and strong operational monitoring to handle shocks. When those fail, the result is often immediate uncontrolled discharges or flooding.

### *6.3.1.6 Thermal extremes and biological process performance*

Wastewater treatment is essentially a controlled biological ecosystem (for secondary treatment). Temperature plays a critical role in microbial metabolism. In cold climates, *cold snaps* or extended freezing periods can slow down microbial activity in treatment plants (and cause physical issues like frozen sludge in clarifiers). Conversely, *heatwaves* can warm the sewage, increasing microbial activity but also perhaps stressing aeration systems (since warmer water holds less dissolved oxygen, the plant must work harder to aerate). Wanner et al. (2005) studied wastewater heat recovery – intentionally cooling sewage to recover heat – and found that even small temperature reductions in influent caused notable drops in nitrification efficiency. This underscores that nitrifying bacteria (which remove ammonia) are sensitive to temperature; below about 15°C their activity slows, possibly leading to ammonia breakthroughs. On the flip side, in very hot weather, some plants see increased biochemical oxygen demand (BOD) removal rates, but also an increase in filamentous organisms that can cause foaming or bulking in aeration tanks. Extreme heat could also coincide with low oxygen levels in receiving waters, making any effluent impact more severe (less dilution oxygen). Additionally, *indirect thermal hazards* include **snowmelt timing shifts** – warmer winters might cause mid-winter melts that send pulses of water (and salt from road de-icing) into sewers, challenging plants. Climate change is expected to alter not only rainfall but temperature regimes, which in turn affect wastewater processes and the **energy demand** of treatment (for heating digesters, etc.). If a plant is already near capacity, a heat-induced efficiency loss could push it into non-compliance or force an expansion. During compound events like a heatwave plus a power grid strain, operators might face decisions like reducing aeration to save power, which could reduce treatment effectiveness – a difficult trade-off. Thus, thermal hazards mainly affect the **treatment performance** aspect of drainage systems, but poor performance can cascade into environmental hazards (e.g. higher effluent ammonia can cause fish kills downstream). Incorporating temperature projections into wastewater design (e.g. ensuring nitrification can be maintained in warmer conditions or providing cooling if needed) is a growing area of resilience planning.

### 6.3.2 Impacted Targets (Drainage/Wastewater)

Failures in urban drainage and wastewater systems primarily impact two broad domains: **flood exposure** (when drainage fails and causes flooding) and **pollution exposure** (when wastewater escapes the system). These translate to impacts on *human health*, *environmental health*, *economic activity/urban functionality*, and *social equity/quality of life*. We break these down:

- **Human Health:** Urban drainage failures can directly affect human health in at least three ways. First, **floodwaters** in urban areas often carry pathogens, chemicals, and debris; people caught in flash floods can be injured or contract infections from contact with contaminated water (wound infections, diarrheal disease, etc.). There have been cases of leptospirosis outbreaks following urban floods due to rat urine in floodwater. Second, **sewer overflows contaminating water sources** pose a serious health risk. A notable epidemiological study by Jagai et al. (2015) found that after extreme precipitation events, areas with combined sewer systems had statistically significant increases in gastrointestinal illness ER visits. The mechanism is that CSOs polluted the source of some communities' drinking water, leading to waterborne illness spikes a few days later. This provides direct evidence that what might seem like an environmental issue (sewer overflow) can become a *public health outbreak* if the water supply is affected. Third, **indoor health hazards**: basement sewage backups are a common result of drainage failures. When sewage comes up in homes, it exposes occupants to pathogens and mold growth if not cleaned properly, potentially causing illness or long-term health effects for residents (especially children or those with weak immune systems). Additionally, loss of sanitation (if toilets can't drain) can force unsanitary conditions like outdoor defecation or sewage backup within homes, again raising disease risk. During large disasters, such as Hurricanes or earthquakes, if the wastewater system is down, relief camps or shelters must manage sanitation carefully to prevent cholera, norovirus, etc. Thus, drainage infrastructure is indeed a *health protection system*: its failure can manifest as anything from mild illness upticks to major disease outbreaks. This has shifted how public health agencies view flood response – now recognizing the need to test and possibly chlorinate drinking water sources after big storms, and to warn the public to avoid floodwaters.

- **Environment and Receiving Waters:** When drainage systems fail by overflowing, the environment is the immediate receptacle of the excess. CSOs and SSOs (sanitary sewer overflows) discharge **pathogens, nutrients, organic matter, and various pollutants** into rivers, lakes, or coastal waters. The environmental impacts can be acute (fish kills from oxygen depletion, algal blooms from nutrient spikes, beach contamination leading to shellfish bed closures) and chronic (build-up of contaminants in sediments). Climate change-induced increases in these overflows threaten to roll back gains made in water pollution control over past decades. For instance, a city might have been meeting water quality standards for bacteria most years, but with heavier rains causing more frequent overflows, it could start violating those standards, leading to regulatory penalties and degraded urban waterways. Beyond overflows, if a wastewater treatment plant is compromised (say a power outage causes it to bypass treatment), **partially treated sewage** entering a waterway can cause eutrophication or toxin accumulation that affects aquatic life and even drinking water downstream. For example, excess nitrogen in effluent can contribute to dead zones in estuaries. Another environmental impact is on **groundwater**: if sewers crack and exfiltrate, in areas with high groundwater usage that could lead to groundwater contamination (though usually surface impacts are of greater concern). There is also a feedback loop: environmental changes like sea-level rise and larger storms are making overflows more common, which in turn harm the environment, a cycle that must be broken by infrastructure adaptation. Notably, Zou et al. (2026) frame overflow control as an increasingly central *climate adaptation* challenge – essentially, improving drainage infrastructure is needed to adapt to a wetter climate to protect environmental and public health. In summary, rivers, streams, and coastal waters around cities are key targets of drainage failures, and the impacts range from nuisance (floating sewage debris) to severe (toxic algae, loss of aquatic life, unsafe beaches).

- **Economic Activity and Urban Functionality:** Flooded streets and backed-up sewers directly disrupt urban life and commerce. In the immediate sense, **flooded roads** halt transportation – people can't get to work, deliveries are delayed, emergency vehicles get detoured. Even a few hours of inundation in a downtown can mean millions in lost productivity. If critical facilities (airports, ports, transit systems) flood due to drainage failure, the economic ripple is large. For businesses, **property damage** from floods (ruined inventory, mold remediation in buildings) can be significant; many small businesses never fully recover from major flood hits. Sewer backups in commercial or industrial buildings can force temporary closures and expensive cleanup. Additionally, cities often incur costs after overflow events: cleanup of contaminated mud and debris, repairing damaged infrastructure (e.g. washed-out roads or eroded culverts), and potential **fines or legal costs** if environmental regulations were violated by the overflows. There are also **long-term economic constraints** imposed by chronic drainage issues. For instance, coastal cities facing sea-level rise might need to install expensive pump stations or sea walls to keep their sewer systems functional; failing to do so could constrain new development (because insurance or regulations won't allow expanding population in areas with inadequate wastewater service). Hummel et al. (2018) noted that if wastewater systems can't adapt to rising seas, cities could see increasing operational costs (like continuous pumping, infiltration management) and perhaps limits on growth in flood-prone zones. Another economic aspect is *public infrastructure damage*: floodwaters can damage power stations, telecom, etc., causing multi-sector losses. Each flood or overflow event also chips away at infrastructure life – pipes may be undermined by erosion or vehicles on flooded roads cause accelerated pavement deterioration – leading to higher maintenance costs. In coastal tourist economies, sewage overflows that pollute beaches can result in lost tourism revenue and harm a city's reputation (nobody wants to swim at a beach known for sewage contamination). Therefore, effective drainage is part and parcel of a functioning economy; conversely, drainage failures create both direct losses and opportunity costs for a city.

- **Quality of Life and Social Equity:** Sewer and drainage failures often disproportionately impact certain communities. Low-lying, often lower-income neighborhoods can become **chronic flood zones**, experiencing recurrent basement flooding or street flooding with every heavy rain. This leads to repetitive loss of personal property (furniture, cars) and high stress. The **mental health toll** of living with frequent flooding or sewage backups is well documented – residents report anxiety whenever rain is forecast, and frustration or distrust if the city doesn't address the issue. Social equity issues arise because wealthier areas sometimes have newer or upgraded drainage, whereas marginalized communities might have undersized or poorly maintained infrastructure. Additionally, those with fewer resources find it harder to recover from floods (no spare funds for repairs, maybe no flood insurance). As compound hazards increase (e.g. a neighborhood could be hit with a power outage and flood simultaneously), these communities may experience cascading hardships: property damage, health risks from mold or contamination, displacement if housing is ruined. Repeated failures can also **erode social trust** – people lose confidence in local government or utilities, potentially affecting community cohesion and willingness to cooperate with future emergency measures. At a city scale, if particular districts keep flooding, it can influence migration patterns (those who can afford may move out, leaving behind those who can't). This has implications for urban blight and economic disparity. High-impact compound events literature emphasizes these interactions: it's often the combination of physical hazard and social vulnerability that produces disaster. For example, two neighborhoods might flood with the same depth of water, but the one with older housing and no resources will suffer far more in terms of long-term consequences (health issues, inability to rebuild, etc.). In terms of overall quality of life, effective drainage is something urban residents often take for granted – until it fails. Losing that security (knowing that a rainstorm could mean sewage in your basement) detracts from well-being and can reduce property values, investment in homes, etc., perpetuating cycles of disinvestment. Therefore, addressing drainage issues is not just a technical engineering task but also a critical part of *ensuring equitable, livable cities*. Efforts like green infrastructure in low-income areas or targeted sewer rehab aim to alleviate these chronic burdens and improve quality of life resilience.

### 6.3.3 Impacts, Interconnections, and Cascade Effects on Drainage

Drainage and wastewater system failures often follow a chain pattern like: **"extreme load (rain or inflow) → infrastructure failure or bypass → pollution release → health/environmental impact."** Importantly, these cascades can be amplified by interdependencies (like power loss making things worse) and feedback loops with the water supply system. We outline key cascade scenarios for urban drainage:

- **Rainfall-Induced Overflow Cascade:** *Extreme rainfall → combined sewer overflow (CSO) → waterborne disease risk.* In cities with combined sewers, a heavy rain quickly exceeds the capacity of sewer pipes and treatment plants, triggering CSO discharges into local water bodies. The immediate impact is that pathogens and pollutants enter rivers or coastal waters. If those waters are used downstream for drinking water or recreation, people can be exposed. Jagai et al. (2015) provides clear evidence: they observed that after extreme rain, gastrointestinal illness ER visits increased significantly in Massachusetts communities with CSOs impacting their drinking water sources. This shows a cascade where the rainfall (hazard) causes an engineered system overflow (infrastructure impact), leading to an environmental contamination, which then manifests as a **public health event** (illness outbreak). Prior to such research, CSOs were often viewed narrowly as a water pollution compliance issue for ecosystems. Now it's recognized that they can have **direct human health outcomes**. The public health burden (more ER visits, potential hospitalizations) can actually outweigh the immediate flood damage in cost, especially if vulnerable populations get sick. This cascade underscores why reducing CSOs (through green infrastructure, storage tunnels, etc.) is often justified not just by environmental benefits but by health protection. It also demonstrates a cross-system interaction: the failure of the drainage system created a problem for the water *supply* system (contaminating source water). In multi-hazard terms, that rain event was not isolated to one infrastructure's impact but bridged to another.

- **Coastal Surge Cascade:** *Coastal storm surge + sea-level rise → pump station failure & outfall submergence → urban sewer backups & overflow.* This scenario is drawn from coastal vulnerability studies like Hummel et al. (2018). A storm (hurricane) pushes a high surge into a coastal city. Wastewater pump stations located near sea level get flooded or lose power, halting sewage conveyance. At the same time, the elevated water level at outfalls means even gravity drains can't empty (water might actually be flowing backward). The result: sewage starts backing up in the network, causing overflows from manholes and backing into basements. Essentially, an initial coastal flood hazard transforms into a **widespread urban sanitation failure**. This is a classic cascade: the coastal boundary change (surge+SLR) creates an infrastructure functional bottleneck (pumps can't work, pipes can't drain) which then leads to secondary impacts (urban flooding with sewage, environmental contamination). Hummel's work showed that many more people could lose wastewater service from such a scenario than those directly flooded by the surge. The consequences include not only the water damage from flooding but the added public health risk of sewage contamination and the difficulty of cleanup (as floodwaters recede, they leave sewage contamination in homes and streets). This cascade also can hamper recovery: a city can pump out floodwater relatively quickly, but restoring the wastewater system can take longer if electrical and mechanical components were damaged, meaning parts of the city might remain unlivable (no functioning toilets) even after floodwaters are gone. Cities like Miami and New Orleans are facing exactly this challenge: high tides already cause local sewer backups (so-called "nuisance flooding"), a preview of larger failures during major surge events. Mitigation often involves installing **one-way valves** on outfalls and elevating or floodproofing pump stations, but the cascade risk is hard to eliminate entirely without massive infrastructure changes or pumping everything – which has its own limits.

- **Power Outage Cascade:** *Widespread blackout → sewer pumping failure → sewage surcharges/backups → overflows and contamination.* We touched on this in the hazard impacts, but as a cascade: imagine a city loses grid power due to a windstorm. Within an hour, sewage pump stations without generators stop, sewage begins pooling in gravity mains. Lift stations typically serve low neighborhoods – those areas will experience sewer backup first. As wet wastes keep coming from usage (hospitals, people who still flush until water pressure is lost, infiltration), manholes start to overflow or sewage backs up into houses. If heavy rain is also occurring (storms often bring both wind and rain), storm drains might also fail concurrently, mixing stormwater and sewage on the streets. Even if drinking water remains on (some pumps might have backup power), the inability to clear sewage means the water people use ends up spilling out untreated. The public and environmental health implications are significant: pathogens in overflows can cause disease, as discussed, and contamination of standing floodwater becomes a major hazard (rescuer and resident exposure to sewage). Hummel et al. identified pump stations as critical nodes – losing one can cascade failure through large areas of the network. Climate change reviews (Zou et al. 2026) also note that *operational disruptions* like power loss are key amplifiers of overflow risk. This cascade can also complicate other emergency response: for instance, firefighters responding to a concurrent fire have to wade in sewage-fouled water, or emergency shelters must deal with waste if sewer service is out. If the power outage is prolonged (days), cities might have to resort to **emergency sewage disposal**, like pumping sewage from manholes into tank trucks or setting up portable toilets – expensive and challenging at scale. In the 2003 Northeast blackout, some cities indeed had sewage overflows and had to advise people to restrict water usage to reduce sewage generation until power came back. This scenario reinforces the infrastructure interdependence concept: electricity infrastructure failure can propagate to water infrastructure failure, necessitating integrated resilience solutions like ensuring generators at sewage pumps and prioritizing power restoration to water/wastewater facilities in blackouts.

- **Chronic Climate and Urbanization Cascade:** *Urban growth + increased rainfall intensity → system design exceedance → frequent overflows → cumulative pollution and health burden.* This is a slow-motion cascade scenario where no single "disaster" triggers it, but the combined pressure of trends results in a de facto failure state becoming common. As cities densify, more surfaces become impervious, sending more runoff into drains. Climate change brings more frequent heavy downpours. The legacy drainage system, designed perhaps decades ago for smaller storms and smaller populations, is now **undersized for the new reality**. The outcome is a shift from what used to be occasional overflows (maybe a few times a year) to very frequent overflows (dozens of times a year), meaning the system is chronically in a semi-failed state. Each overflow might be minor enough not to cause an immediate crisis, but over time the cumulative effect on water quality and public health is significant (e.g. regularly elevated bacteria counts at a downstream beach leading to permanent swimming advisories, or incremental contributions to nutrient loads fueling algal blooms that degrade a lake's ecosystem). Hauser et al. (2025) and Zou et al. (2026) both point to evidence that **what were once rare events are becoming more frequent** due to these compounding factors. In essence, the baseline likelihood of "failure states" (like an overflow that can cause illness) is rising. This is a cascade in the planning sense: if design standards and infrastructure investment don't keep up, the system's performance degrades gradually until something that would have been considered an extreme event becomes almost routine. The response often involves revising design criteria (e.g. many cities are updating storm sewer design storms to larger ones) and accelerating infrastructure expansion or green infrastructure adoption to handle greater volumes. Until such measures catch up, communities may suffer a **new normal** of frequent minor disasters – a form of creeping risk that can be as damaging in total as a big singular disaster. For example, instead of one catastrophic flood every 30 years, a neighborhood might now get minor flooding every year – the total damage and disruption over 30 years could be comparable. Recognizing this cascade motivates calls for **transformative adaptation**, such as completely redesigning urban stormwater systems (daylighting rivers, building huge tunnels, etc.) rather than incremental fixes, to avoid drifting into an untenable future.

These drainage cascade scenarios highlight how interlinked factors create outcomes that often cross the boundary from simple "infrastructure problem" to broader **public crisis**. Another theme is that drainage failures can feed back into water supply problems – contaminated floodwater can infiltrate water pipes, or environmental pollution can harm water sources – reinforcing the concept that water supply and drainage resilience must be tackled together.

## 6.4 Cross-System Cascades and Systemic Interdependencies

Urban water supply and drainage systems do not operate in isolation; they share the urban environment and are often physically and operationally interconnected. Some of the **most consequential multi-hazard scenarios involve cascades that jump between water supply and wastewater systems** (and sometimes beyond to other infrastructures). Understanding these cross-system cascades is crucial for holistic resilience. We examine a few key interdependency scenarios:

- **Water–Wastewater Contamination Feedback Loop:** *Sewer overflow or leak → contamination near water pipes → water distribution intrusion during low pressure.* This is a direct coupling of drainage failure increasing water supply hazard. As mentioned, if a sewer line breaks or overflows in the vicinity of a water main (especially an old, leaky one), it creates a hazardous condition: the soil around the water main becomes contaminated with pathogens. Normally, water mains are pressurized to prevent anything infiltrating. But if a concurrent event causes **low pressure** in that water main (e.g. a pump failure or another main break), that loss of positive pressure can suck in the contaminated water from the soil through any leaks. The result is pathogens entering the drinking water distribution system – a potentially invisible but serious public health threat. This loop essentially connects a drainage system failure (e.g. sewer overflow during heavy rain) with a water supply failure (microbial intrusion) through the medium of the environment and a pressure failure. Besner et al. (2011) and Propato (2004) explicitly modeled how *vulnerable points* in water networks (like corroded pipe sections) are at risk if low pressure coincides with external contamination. In practical terms, after any major flood or combined sewer overflow, water utilities often boost chlorination and monitor for bacterial indicators in nearby water mains, precisely because of this concern. This cross-system cascade is inherently multi-hazard: it might require a flood to cause the overflow and a power outage to cause the pressure drop, for example. The presence of one without the other might not cause a big issue, but together they do. Breaking this loop might involve things like **backflow prevention valves** on service lines, more **sewer exfiltration testing** (to fix leaks so sewage doesn't get out near water lines), and ensuring water pressure is maintained or quickly restored during concurrent events.

- **"Blackout-Initiated Dual Failure" Scenario:** *Initiating hazard (e.g. earthquake or storm) knocks out power grid → simultaneous water supply and wastewater failures.* This scenario was alluded to in earlier sections and was specifically requested as an archetype: for instance, an earthquake causes a regional blackout; as a result, drinking water pumping halts *and* wastewater pumping/treatment halts. You now have a city experiencing a **dual water crisis** – loss of potable water pressure and overflow of sewage. Even if each alone might be manageable, together they create a compounded disaster. Rinaldi's framework on interdependencies describes how shared dependencies (like power) can lead to *correlated failures*: multiple infrastructures fail at the same time because they depend on a common service. The consequences are non-linear: losing either water or wastewater alone is bad, but losing both multiplies public health risks (people might resort to using alternate water sources and also have no sanitation, greatly increasing disease spread potential). In our example, with power out, many treatment processes might bypass, so sewage could contaminate areas where people are also lacking clean water, a worst-case public health scenario. Also, firefighting capability is hit doubly: no water supply pressure and maybe no water to even flush hydrants of sewage. The "loss-of-service + pollution + health risk" combination is exactly what multi-hazard planning tries to avoid. The lesson is that emergency power provision is crucial for both sides of the water infrastructure. It's not enough to keep the drinking water flowing; if sewage isn't moving, it will back up into the same homes that are struggling to get water, thus fouling whatever water is left. In fact, modern disaster management often prioritizes restoring *power* to water and wastewater facilities quickly for this reason. And where backup generators are installed, ensuring fuel supply during wide-area disasters is equally key (during a prolonged event, fuel for generators might run out, causing this cascade even if it was initially averted). In summary, this cascade emphasizes **multi-infrastructure coordination**: utilities, power companies, and city emergency managers need to collaborate so that a single initiating event doesn't cause parallel infrastructure collapses.

- **Compound Coastal Scenario:** *Storm surge + heavy rainfall + elevated base sea level → drainage system failure → secondary water supply impacts.* In coastal cities, hazards often cluster – a tropical cyclone brings both torrential rain and a coastal surge, and if it happens in a future scenario with higher baseline sea level, the impact is magnified. The drainage system cascade is: surge floods outfalls and pump stations, rain overwhelms capacity, leading to widespread sewage overflows as described. But now consider the cross-system extension: the floodwaters mixed with sewage may contaminate surface waters that include drinking water intake locations (for cities that draw from nearby rivers or bays). Alternatively, if floodwaters inundate areas around water distribution mains (especially if any water main breaks occurred due to undermining or pipe floatation in saturated soil), the risk of contamination in the potable network rises. Essentially, a **drainage infrastructure failure can compromise water supply infrastructure either by contaminating its source or by directly contaminating distribution**. Empirical and modeling literature supports this: Hummel et al. (2018) noted pump station failures leading to backups, and Zscheischler et al. (2018) stressed that multi-hazard combinations (like concurrent inland and coastal flooding) drive high-impact outcomes. The expected cascade outcome is that the water utility might have to **shut down water intakes** to avoid drawing in contaminated water (which itself can cause water shortages), or issue region-wide boil advisories if intrusion is suspected. Meanwhile, the environmental damage needs addressing (fish kills from pollution, etc.), diverting resources. Essentially, the **boundary between drainage and water supply blurs** during big coastal events: normally, drainage takes waste *away* and water supply brings clean *in*; a disaster can flip this where drainage failure brings waste *into* areas it shouldn't be, affecting the clean water. For mitigation, coastal cities are looking at integrated water management: for example, constructing storm surge barriers that protect both water and wastewater plants simultaneously, or relocating intakes further offshore or upstream to avoid worst contamination zones. There's also interest in **real-time sensors** in water distribution that can detect intrusion early (some utilities have started installing pressure and quality sensors that might catch a contamination early, allowing faster isolation). All these efforts acknowledge that when the perfect storm hits – literally – it hits the whole urban water cycle, not just one half of it.

- **Cyber-Physical Threats as Cascade Multipliers:** *Cyberattack timed with physical hazard → confusion and delayed response → prolonged water quality and service issues.* This is more of a compound threat scenario: say a major storm is occurring and at the same time, a bad actor launches a cyberattack on the water utility's SCADA system, perhaps to exploit the chaos. The combined effect can be **far worse** than the natural hazard alone. For instance, during the storm, operators rely on sensors to know which areas are flooding or which pumps are down. A cyberattack could feed false data (saying a pump is on when it's actually off, or vice versa), leading to misallocation of repair crews or failure to open an emergency valve. Albustami et al. (2025) demonstrate that stealthy attacks can indeed create *real* hydraulic impacts without immediate detection. Under multi-hazard conditions, the operators may attribute weird readings to the storm rather than an attack, thus not realizing they need to counter a cyber threat. This can **impair situational awareness**, meaning decisions are delayed or wrong. For example, if a pressure sensor is spoofed to show normal pressure, they might not issue a boil-water advisory even though intrusion might have occurred. Or if valve controls are unresponsive due to a hack, they might not be able to shut off a contaminated zone. Cyber disruption becomes a "force multiplier" by making the physical cascade worse and recovery slower. One could imagine the aftermath of a hurricane where days later they discover that a deliberate attack kept a critical pump offline longer than necessary, leading to preventable sewage spills. Or during a wildfire response, a cyber incident might disable communication between field crews and control centers. The 2015 cyberattack on Ukraine's power grid shows how during conflict, infrastructure is attacked to amplify chaos; similar could happen with water systems. While actual cases in water are few so far, water sector is identified as a target by security agencies. Therefore, building **cyber resilience** (backup manual controls, network segmentation, intrusion detection systems) is now part of multi-hazard planning. Importantly, operators are being trained to consider that some anomalies during disasters might not be accidents but attacks, and to have protocols to "fight through" a cyber incident while handling the physical emergency. In terms of cascade, a cyber-physical multi-hazard event might result in pressure problems persisting longer (because SCADA wasn't available to quickly reroute flow) or water quality issues not being recognized (if monitoring equipment was compromised). The literature suggests treating cyber scenarios as *legitimate stress tests* for water systems – meaning, for example, to simulate a hacker shutting your pumps during a peak demand and see if the system can cope. We include this here to emphasize that multi-hazard isn't just multiple natural hazards; it can be a natural and man-made hazard combined, which infrastructure must be prepared for.

In sum, cross-system cascades reveal that **risk does not respect infrastructure sector boundaries**. A failure in one system often propagates to another. The examples above illustrate water supply and drainage interdependence, but also their joint dependency on power and information systems. The modern approach to resilience is therefore **system-of-systems thinking** – evaluating the entire urban water cycle and its links to energy, environment, and public health as an integrated whole. The next section will discuss needs and research gaps to better address these complex cascades, before we move on to practical recommendations for mitigation and adaptation.

Before that, we provide **Table 6-1** as a comparative summary of how key hazards impact water supply vs. drainage systems, to highlight similarities and differences and aid integrated planning.

**Table 6.1:** Summary of various hazards and their typical impacts on urban water supply vs. urban drainage systems. Note that many hazards (extreme weather, power loss, etc.) can trigger simultaneous issues in both systems, compounding overall impact

| **Hazard** | **Impacts on Water Supply System** | **Impacts on Drainage/Wastewater System** |
|---|---|---|
| **Extreme Rainfall** (cloudburst, heavy storm) | – Inundation of water treatment plants and pump stations, causing service outages.<br/> – Raw water quality degradation (high turbidity, pathogens) challenging treatment.<br/> – Need for boil-water advisories if treatment compromised. | – Stormwater volumes exceed pipe capacity → urban flash flooding (streets, basements).<br/> – Combined sewer overflows (CSOs) releasing sewage to rivers.<br/> – Wastewater plant influent dilution or overload, potential bypass of treatment. |
| **River Flooding** (fluvial) | – Source intakes potentially flooded or needing closure due to high debris/sediment.<br/> – Treatment plants near rivers inundated unless protected.<br/> – Potential contamination of distribution if river water intrudes at pipe breaks. | – High river levels back up into drainage outlets → sewers surcharge and overflow inland.<br/> – Pump stations at river outfalls may be submerged, stopping drainage.<br/> – Wastewater plant outfall submerged, reducing discharge capacity and causing upstream backups. |
| **Drought & Heatwave** | – Water shortages; reservoirs low, forcing usage of poorer-quality sources.<br/> – Higher water age in pipes → chlorine residual loss, microbial regrowth.<br/> – Peak demand spikes (e.g. for cooling) strain | – Low flows in sewers (during drought) can cause solids deposition and odor issues.<br/> – In combined systems, dry weather can lead to blockages that cause localized backups when flow returns.<br/> – Treatment plant |

| Hazard | Impacts on Water Supply System | Impacts on Drainage/Wastewater System |
|---|---|---|
| | capacity and pressure.<br/> – Heat accelerates chemical decay; potential taste/odor issues. | biological processes stressed by extreme temperatures (e.g. nitrification drops in cold, swings in heat).<br/> – Potential sewer line cracking from soil movement in desiccated clay soils. |
| **Earthquake** | – Many water mains break, causing widespread pressure loss.<br/> – Storage tanks or reservoirs damaged (sloshing, structural failure).<br/> – Pump stations lose power or structure; SCADA communications disrupted.<br/> – Risk of contamination intrusion at break sites leading to boil advisories. | – Sewer pipes fracture or collapse, leading to inflow of soil and exfiltration of sewage.<br/> – Loss of sewer continuity causes immediate overflows of sewage in streets or rivers.<br/> – Treatment plant structures (clarifiers, digesters) crack; plants may be partially inoperable.<br/> – Pump stations misaligned or lose power, halting sewage conveyance. |
| **Wildfire** (and post-fire effects) | – If wildfire near urban interface: distribution network may incur heat damage, causing chemical contamination (VOCs like benzene).<br/> – Loss of power and personnel during fire affects operations.<br/> – Post-fire rainfall washes ash into source water, causing turbidity and organic spikes beyond treatment design.<br/> – Watershed erosion fills reservoirs with sediment, reducing capacity. | – Wildfire damage to remote pump station or infrastructure (less common, but possible e.g. damage to aeration equipment at lagoons).<br/> – Post-fire heavy rains produce debris flows that can clog stormwater channels and culverts, causing flash floods.<br/> – Increased runoff due to lack of vegetation can overwhelm existing drainage (higher peak flows).<br/> – If fire hits structures, lots of fire-fighting water enters storm drains with debris and contaminants (firefighting runoff carrying chemicals). |
| **Coastal Storm Surge** | – Saltwater inundation of wells, intakes, or low-lying treatment facilities.<br/> – Corrosion and fouling of equipment by saltwater; potential need to flush entire system if saltwater entered pipes.<br/> – Source water may become brackish, requiring emergency blending or cessation of supply. | – Surge floods wastewater treatment plants (unless protected), causing total loss of treatment and raw sewage releases.<br/> – Low areas of collection system flood, with saltwater entering and diluting sewage (and killing microbes in biological treatment).<br/> – Pump stations offline from flooding → widespread sewer backups inland.<br/> – Outfalls submerged by surge, no gravity discharge → extensive urban flooding with sewage. |
| **Sea-Level Rise (chronic)** | – Gradual salinization of coastal aquifers, forcing abandonment or expensive desalination for water supply.<br/> – Higher groundwater | – Higher base sea level means gravity outfalls increasingly underwater; storm sewers drain slower or require pumping.<br/> – Groundwater rise |

| Hazard | Impacts on Water Supply System | Impacts on Drainage/Wastewater System |
|---|---|---|
| | can cause infiltration of saline water into water pipes (especially if depressurized), causing corrosion issues.<br/> – Some low-lying wellfields might be lost, reducing supply capacity.<br/> – More frequent tidal flooding of streets can intermittently disrupt water distribution operations (access, pipe corrosion). | infiltrates sewer pipes (significantly increasing treatment volumes with saltwater intrusion, which can inhibit biological treatment).<br/> – Low-lying communities may experience septic system failures (where used) or constant sump pump running.<br/> – Long-term, portions of sewer network may need redesign (one-way valves, new pump stations) to prevent everyday high-tide backups. |
| **Power Outage** (grid failure) | – Pumps stop; water supply pressure drops if backup power is insufficient.<br/> – Treatment stops unless generators are present; water quality may degrade (no disinfection dosing, etc.).<br/> – If prolonged, water outages occur for most customers; boil advisories issued once power back (due to potential stagnation).<br/> – Firefighting capability severely reduced during outage (hydrants may have no pressure). | – Sewage lift stations stop, causing immediate surcharges and potential overflows at low points.<br/> – Wastewater treatment plants go offline unless generators supply full process power (rare); many will bypass or partially treat sewage.<br/> – Within hours, sewage can back up into streets or homes, especially in flat areas.<br/> – Combined systems during storms: without pumps, no flood control – exacerbating flood damage. |
| **Cyberattack** (on water systems) | – Potential manipulation of treatment chemical dosing (risking public health with under- or over-dosing, e.g. caustic incident).<br/> – Pump controls could be overridden, causing intentional pressure loss or overflow of reservoirs.<br/> – False sensor readings could mislead operators (e.g. showing safe water quality when contaminated).<br/> – In worst case, distributed contamination or prolonged outage engineered by attacker. | – Attack on wastewater SCADA could disable pump stations or valves, leading to uncontrolled sewage releases.<br/> – False data might hide an ongoing overflow or prevent alarm of critical equipment failure, delaying response.<br/> – Treatment plant controls could be manipulated: e.g. stop aeration (killing microbes and causing plant failure) or disable automated CSO gates (causing avoidable spills).<br/> – Coordinated with physical event (e.g. during heavy rain) to maximize damage and chaos in the drainage system. |

This comparative view reinforces that while water supply and drainage systems experience some hazards differently (drought is a bigger direct issue for supply; extreme rain obviously for drainage), **many hazards (e.g. earthquakes, power outages, storm surges) threaten both**, and failures in one can propagate to the other. Thus, resilience planning should evaluate these systems together to ensure that improvements in one domain don't inadvertently worsen another (and preferably, find co-beneficial solutions).

## 6.5 State-of-the-Art Needs and Research Gaps

The literature synthesis above, covering many high-impact studies, points to several recurring *gaps and needs* in current knowledge and practice for multi-hazard urban water resilience. Addressing these gaps is critical to advance our ability to predict, mitigate, and respond to complex hazard scenarios:

1. **Integrated Multi-Hazard Modeling of Water Systems:** There is a noted **lack of tools and studies that jointly simulate hydraulic performance, water quality, and infrastructure recovery under multi-hazard scenarios**. While we have robust models for single hazards (e.g. earthquake damage to pipes, or flood hydraulics in sewers), the integration of multiple hazard drivers in one modeling framework remains limited. For example, few models can handle a scenario like "earthquake damages pipes and then a rainstorm two days later floods the system during repairs" in a unified way. Resilience tool frameworks like WNTR are progressing, but more work is needed to incorporate compound events (like correlated weather extremes) and cross-sector impacts (like power loss) into routine water system risk analysis. The gap is partly methodological – combining stochastic hazard models with network hydraulic solvers and recovery algorithms is complex – and partly data-driven (needing interdisciplinary data sets). **Research need:** development of simulation platforms or standardized methodologies to evaluate water infrastructure under scenarios of *multiple simultaneous or sequential hazards*, which would help utilities identify hidden vulnerabilities (e.g. a pump station that is fine under a flood or a blackout separately, but not if both happen).

2. **Quantification of Trade-offs and Interactions Among Failure Modes:** Many studies call out that improving resilience to one type of failure might reduce resilience to another. For instance, isolating a zone quickly after a contamination may conflict with maintaining supply pressure; adding backup pumps improves reliability but could encourage development in risky zones (exposure). Diao et al. (2016) observed non-intuitive trade-offs, meaning traditional single-metric optimization (e.g. minimize expected outage) might be misguided if it inadvertently amplifies another risk. However, **quantitative methods to evaluate these trade-offs across multiple hazards are still in early stages**. We lack easy-to-use multi-objective optimization tools tailored for water infrastructure resilience. **Research need:** frameworks for evaluating *resilience metrics across hazard types simultaneously*. This could involve combining performance metrics for pressure restoration, water quality, overflow volumes, etc., into a multi-criteria decision analysis. By quantifying trade-offs (e.g. how much does raising flood walls at a treatment plant reduce flood risk vs. increase earthquake vulnerability due to heavier structure?), decision-makers can better justify holistic investments. Essentially, an extension of risk assessment that doesn't produce a single number but a Pareto front of resilience outcomes for different investments – enabling informed choices about, say, whether to prioritize seismic retrofits or flood control or backup power, or find sweet spots that improve all moderately.

3. **Incorporating Compound-Event Risk into Planning and Design:** The planning and engineering design standards for water infrastructure are often based on historical data and single-event return periods. For example, a storm sewer might be designed for a "10-year storm" and a water main for a certain earthquake PGA threshold. However, as Zscheischler et al. (2018) and others argue, *future risk is increasingly about interacting extremes*. A big gap is that **design and planning guidelines have not yet fully integrated compound event analysis**. This means that infrastructure built today might perform as expected for one hazard

at a time, but fail under realistic multi-hazard scenarios. **Research and practice need:** climate change models and hazard analyses need to provide scenarios of compound events (e.g. heat + drought frequency, or hurricane + river flooding joint probability) to engineers, and standards bodies should begin to include safety factors or scenario-based checks for such combinations. Additionally, *scenario planning* should be embedded in utility risk assessments: rather than planning separately for a “flood scenario” and an “earthquake scenario,” plan for an *earthquake-followed-by-flood* scenario, however rare, if consequences are extreme. Tools like scenario ensembles and stress tests (running thousands of combinations of events through models) could help reveal which combinations are most dangerous. The literature (e.g. Zou 2026 review) suggests that many extreme impacts observed have been due to such combinations, implying our conventional risk assessments (which might underplay joint probabilities) are underestimating real risk. Bridging this gap will likely require collaboration between climate scientists, statisticians, and water engineers to create accessible design frameworks that include compound risk.

4. **Holistic Resilience Metrics and Lifecycle Approaches:** Another gap is in metrics – how to measure if a system is resilient to multi-hazards. Single metrics like “days of outage” or “volume of overflow” capture pieces but not the whole picture. Some researchers propose composite metrics (e.g. combining extent, duration, and severity of service loss into an index). But consensus is lacking. And many metrics don’t directly account for the quality aspect (e.g. water may be delivered but not potable due to contamination, or sewage may flow but partially treated). **Need:** development of **resilience metrics that cover both quantity and quality dimensions of performance**, and that account for recovery time explicitly. Additionally, incorporating economic and social factors (like number of people affected weighted by vulnerability) into metrics can help prioritize equity – a gap often noted. On lifecycle, current designs assume stationarity to some degree – a pipe is put in ground expecting the same hazard frequency for 50 years. With climate change, that’s not true; hazard frequencies are changing within infrastructure lifespans. So a gap is how to incorporate *adaptive design* – for instance, build drainage that can be upgraded as rainfall intensifies, or water systems that can adjust treatment as quality shifts. This is more of a forward-looking gap, needing strategies for flexible, modular, or over-designed systems that can accommodate a range of futures. Very few utility capital plans currently do that in a rigorous way.

5. **Data and Monitoring for Multi-Hazard Early Warning:** The literature implies a gap in **real-time monitoring across systems**. We have SCADA for water, separate SCADA for wastewater, often separate again for stormwater (if any). An integrated view (maybe a control center that sees the whole water cycle and related energy feeds) is uncommon. Also, data on near-misses or past multi-hazard incidents are not systematically collected – making research harder. Improved sensor networks (e.g. pressure sensors in low-lying sewers to detect backflow, or water quality sensors in distribution) could serve as early warnings for cascades – but deploying and maintaining those is challenging. Additionally, using non-traditional data (social media reports of flooding or water outages) might fill gaps.

6. **Human and Institutional Factors:** Lastly, beyond engineering, there’s a gap in understanding human decision-making in these events. How do operators prioritize actions under multi-hazard duress? How do communication and coordination protocols (between water supply and sewer departments, or with emergency services) influence outcomes? The best hardware might fail if institutional response is siloed. Case studies of past events (the ones that went well vs. poorly) can yield lessons on training, mutual aid, and contingency planning. This is noted in some reviews but not deeply studied; it might be more in the emergency management literature, which should be cross-pollinated with technical studies.

In summary, the cutting edge needs revolve around **better integration** – of hazards in models, of objectives in planning, of systems in operations, and of sectors in governance. Addressing these gaps will help transform our water infrastructure from being reactive (recovering from the last disaster) to proactive (withstand and adapt to the next, whatever form it takes). The final section of this report translates these insights into actionable recommendations for practitioners: utility operators, urban planners, and infrastructure risk analysts.

## 6.6 Mitigation and Adaptation Recommendations

Building resilience against multi-hazard and cascading failures in urban water systems requires coordinated actions spanning engineering, operations, planning, and policy. Below, we provide recommendations tailored to key stakeholders – **water utility operators**, **urban planners/engineers**, and **infrastructure risk analysts** – while recognizing overlap among these roles. The focus is on practical, actionable measures that can mitigate risks or improve adaptive capacity in face of the complex scenarios described above.

### 6.6.1 For Water Utility Operators (Drinking Water and Wastewater Utilities)

- **Implement Redundant Power and Control Systems:** Ensure all critical facilities (pump stations, treatment plants, control centers) have reliable backup power (generators or battery UPS) sized to handle extended outages. Regularly test these backups under load. Consider dual feed electrical supplies or on-site cogeneration (e.g. using biogas at wastewater plants) to reduce dependency on the grid. Equally important, establish backup communications and SCADA control methods (like radio or satellite links, and manual control procedures) in case primary networks or PLCs are compromised. These measures address the common-mode failure of power loss and ensure continuity of operation or at least graceful degradation (controlled shutdowns instead of uncontrolled failures).

- **Enhance Physical Protection of Facilities:** Flood-proof water and wastewater infrastructure located in hazard-prone zones. For flood and surge threats, use barriers, berms or elevation to protect treatment plants and pump stations (as many coastal utilities are now doing by relocating electrical components above design flood elevations). Install backflow prevention valves on key outfalls and interconnections to prevent reverse flows during floods. In seismic zones, prioritize seismic retrofits of critical pipelines (especially large transmission mains and river crossings) and anchor or flexibly joint them to withstand ground movement. Use earthquake-resistant pipe materials in new projects or when replacing old mains (e.g. ductile iron with restrained joints, HDPE for smaller diameters). Similarly, reinforce or seismically isolate tank bases, pump motors, and other equipment so they don't topple or break in quakes. Utility operators should maintain up-to-date **hazard mitigation plans** that identify facility vulnerabilities and track implementation of protective measures (often tied to FEMA or local funding for risk reduction projects).

- **Develop Emergency Response Plans for Multi-Hazard Scenarios:** Utilities typically have emergency plans for singular events; these should be expanded to cover combined scenarios. For example, create specific response protocols for *"earthquake + boil water + sewer overflow"* or *"flood + power outage"* situations. Conduct drills or tabletop exercises simulating compound events – e.g., an exercise where a hurricane causes flooding and simultaneously hackers attack the SCADA. These drills should involve both water supply and wastewater staff (and ideally power utilities and public health officials) to practice coordination. Plan for alternate water supply methods (like mobile treatment units or bottled water distribution) under scenarios where normal treatment is compromised. Likewise, plan for emergency sewage management (portable pumps, tankers, even temporary latrine facilities) if the sewer system fails widely. Identifying and practicing these contingencies in advance greatly improves response when real events strike.

- **Invest in Monitoring and Early Warning**: Deploy enhanced monitoring that can detect the onset of cascading issues. For water supply, install more pressure loggers in the distribution network (especially at extremities and low-pressure risk zones) and online water quality sensors (for chlorine residual, turbidity) that might signal intrusion. Pair these with alarms that alert operators to possible contamination immediately (some utilities use automated pattern recognition to catch anomalies). For drainage, use level sensors in manholes or smart manhole covers that alert when water is surcharging towards the surface – giving crews possibly an extra hour to respond with pumps or sandbags in intense rains. Integrate weather and power grid forecasts into operations – if a major storm or heatwave is forecast, ramp up staff and chemical stocks, and fuel for generators. Some cutting-edge utilities have **predictive models** that simulate impact given a forecast (for example, predicting which sewers will overflow for a given rainfall event); using these can guide pre-storm actions like lowering storage ponds or pre-deploying pumps. Early warning extends to public notification systems: ensure you have a reliable way (text alerts, radio announcements) to tell the public quickly if water becomes unsafe or if they should reduce usage to help the system.

- **Source and Network Diversification:** Increase the redundancy in both water supply sources and distribution pathways. For water supply: develop or maintain multiple independent source options (e.g., reservoir + groundwater + emergency intertie to neighboring utility) so that if one source is compromised by hazard (e.g. a wildfire contaminates the reservoir), others can cover. Some utilities invest in emergency desalination units or keep old wells in serviceable condition as backups. Within the distribution network, create more interconnections and looped circuits so that if one trunk main fails (earthquake or otherwise), areas can still be fed from another direction. Install additional isolation valves to section off damaged zones more precisely – this minimizes the area that loses water or gets contaminated in an intrusion event. For drainage/wastewater: provide dual feed power where possible and consider **distributed treatment or storage**. For example, satellite wastewater holding tanks in sub-basins can hold sewage during an emergency if the main plant or pumps fail. Green infrastructure (rain gardens, retention basins) while primarily for routine benefits, also adds resilience by taking load off pipes during extreme rain, thus reducing overflow cascade risk. Essentially, a system with multiple pathways and buffers is much less likely to see catastrophic failure propagation than a tightly bottlenecked system.

- **Protect and Prioritize Critical Users:** As part of emergency planning, identify critical customers (hospitals, emergency shelters, key government operations, industries that must not spill chemicals, etc.) and ensure strategies to maintain at least minimal service to them. This might include dedicated backup generators at hospitals for water boosting, or supplying them with tankers if distribution fails. Fire departments should be engaged to coordinate on hydrant backup plans (e.g. drafting water from ponds or pools if hydrants are dry, or prioritizing which areas to support first when water is scarce). Coordinate with public health to potentially set up **temporary potable water stations** in areas with vulnerable populations during prolonged outages (so people don't resort to unsafe sources). For wastewater, coordinate with public health on setting up emergency sanitation (like portable toilets) at shelters or neighborhoods if needed to prevent disease spread. These measures ensure that, even if the system as a whole is compromised, life safety and key societal functions are preserved as much as possible.

- **Continued Training and Mutual Aid:** Train operational staff for improvisation – sometimes in multi-hazard events, field crews must do things outside normal procedures (like jury-rigging a pump bypass, or manually opening a stuck valve) under pressure. Cross-train some staff across water supply and wastewater divisions so they can assist each other; this was found valuable in some utilities where, for example, distribution operators helped at the wastewater plant during a flood when drinking water demand was low, maximizing skilled hands where needed. Participate in networks like WARN (Water/Wastewater Agency Response Network) which facilitate **mutual aid** – if your utility is hit by a disaster, others can send crews or equipment. This greatly helps for cascades covering large areas; e.g., after a big quake, neighboring utilities not as affected can lend repair teams to speed up pipe fixes. Mutual aid pacts should explicitly consider multi-hazard stress: ensure that backup generators, spare pipes, water tankers, etc., can be shared quickly. Essentially, no utility should plan to face these scenarios entirely alone.

**For Urban Planners and Engineers (City Planning, Infrastructure Design, Regulators)**

- **Integrate Multi-Hazard Risk Assessment into Urban Planning:** City planners should incorporate multi-hazard maps and scenarios into land use and infrastructure planning. This means going beyond floodplain maps or seismic zones in isolation, and considering overlaps (e.g. identify areas that could flood and have high liquefaction risk and are vital for water infrastructure). Use this information to **steer critical facilities away from high compound-risk zones**. For instance, do not site new water treatment plants or pumping stations in locations that are both low-lying (flood-prone) and near a fault line if alternatives exist. If relocation isn't feasible, invest more in protective measures for those that are in multi-risk hotspots. When approving new developments, require assessment of whether existing water and sewer services can handle not just average conditions but extreme combined loads (like heavy rain + existing flows). If not, developers should contribute to capacity upgrades or green infrastructure to offset their impact. Essentially, hazard risk (and particularly multi-hazard risk) should become a factor in zoning and capital improvement prioritization. Some leading cities are updating their comprehensive plans to mandate considering climate projections (for flood, heat) – this should extend to combining those with seismic or other local hazards.

- **Adopt Adaptive and Resilient Design Standards:** Engineering design standards for water infrastructure should be revised to account for non-stationary and compound risks. This could include higher safety factors or design events. For example, design storm sewers for a future 100-year storm rather than historical 50-year, acknowledging heavier downpours expected, and add checks for tailwater conditions (assuming high river or surge simultaneously). For combined sewers, consider designing for *concurrent events* like a high tide during heavy rain (some cities are installing tidal gates and pumping specifically for that scenario). For water supply pipes in seismic areas, consider the interaction of quake + subsequent fire: design the network with enough sectionalizing valves and loops so that even with some breaks, enough hydrants will have water for firefighting. Introduce **dual-purpose infrastructure** where possible: e.g., a big stormwater detention basin that also serves as an emergency water supply reservoir for firefighting during droughts – creative synergies can improve resilience to multiple hazards. Planners and engineers should also champion **green infrastructure** and nature-based solutions as they often address multiple hazards: e.g., restored wetlands reduce flood peaks (flood resilience) and provide water quality filtration (reducing pollution load, helping water supply quality). Regulatory agencies should update codes to require utilities to assess **interdependencies** – for instance, as part of a treatment plant design, require analysis of how power loss would be handled and how that could affect both water and wastewater continuity.

- **Promote Decentralization and Backup Systems in Design:** Encourage (or mandate where appropriate) distributed infrastructure that can act as backup. For water supply, this could mean neighborhood-scale emergency wells or cisterns (especially in earthquake-prone regions, having community wells or water ATMs that run on generator can ensure some water if main system fails). Rainwater harvesting systems in buildings can serve non-potable needs during restrictions, easing pressure on main system in droughts or after disasters. For drainage, sustainable urban drainage systems (SUDS) like bioswales, permeable pavements, green roofs absorb some rain at the source, lessening the burden on central sewers during extreme events. In combined systems, strategically placed **storage tunnels or tanks** in each sub-catchment can isolate and contain overflows, preventing a citywide water quality crisis. Planners should incorporate such decentralized elements in new developments (e.g., require large campuses to manage their 100-year storm on site, not just the 10-year as usual, to handle extreme compound storm scenarios). Also, consider **dual systems**: separate critical infrastructure lines for potable vs. firefighting water, or redundant sewer lines for critical facilities, etc., though expensive, can be justified for critical zones (like downtown areas, hospitals cluster). Decentralization also applies to power: promoting microgrids or solar + storage at water facilities means they might ride through a grid outage (planners can work with energy providers to prioritize water sector in resilience grants).

- **Plan for Climate Change and Future Scenarios Explicitly:** Urban and infrastructure planning documents should explicitly factor in climate projections (intensity of rainfall, sea level by mid/late century, drought frequency, heat extremes) and **plan upgrades accordingly now**. This often means building bigger capacity or higher protection than current conditions warrant. It may also mean building *modularly*: e.g., designing a stormwater tunnel that can be extended or supplemented easily if rainfall exceeds predictions. For water supply, planners may need to identify and secure new water sources ahead of need (like considering potable reuse or desalination with trigger points based on reservoir trends). Also, incorporate **sea-level rise buffers**: for instance, if constructing a new coastal pump station, situate it with space for future elevation of walls or addition of pumps as tailwater rises. Doing this at design stage is cheaper than retrofitting hurriedly after failures. Engaging with climate scientists to downscale relevant data for local water planning is advisable. Scenarios should also consider socio-economic changes: e.g., population growth could increase water demand at the same time hazards worsen – those compound stresses should inform master plans. Planners should use scenario analyses (including worst-case and what-if multi-hazard scenarios) to stress-test infrastructure plans and identify which investments yield resilience across multiple futures (so-called *robust decision making* in planning).

- **Strengthen Building Codes and Site-scale Requirements:** On the private side, update building codes to reduce damage and health risks from water system failures. For example, require backflow prevention valves on sewer laterals for buildings in flood-prone or low areas – so if sewers back up, they don’t flow into homes. Mandate that critical buildings (hospitals, high-rises) have sufficient on-site water storage (tanks) to last 24-72 hours of outage, and on-site power to run at least minimal plumbing. Plumbing codes could consider dual piping in high-rise buildings: one system for reclaimed water (for toilet flushing etc.) that can be shut off in emergency, preserving potable water for critical use. Ensure that materials used in construction won’t leach contaminants into water if heated (the wildfire experience suggests reviewing materials for distribution pipes in high-risk WUI areas – maybe require metal pipes in those areas rather than plastic to avoid VOC contamination). Require sealing of sewer manholes in flood zones and using backwater valves in drains – small details that prevent floodwaters from overwhelming sewers. All these micro-level rules, aggregated across a city, can significantly reduce cascade initiation (e.g., if every basement has a backflow preventer, a combined sewer flood won't fill thousands of basements with sewage, preventing a public health disaster).

- **Coordinate Infrastructure Upgrades Across Sectors:** Urban planners and engineers should promote projects that tackle multiple systems together. If a city street is being reconstructed (open trench), coordinate water, sewer, and storm drain improvements at the same time ("dig once" principle). This way, for instance, you can ensure that the new sewer line is watertight so it won't contaminate the parallel water line – perhaps even separate them vertically more or add a protective sleeve to the water main in that section (cheap to do during reconstruction). When building new roads or transit lines, integrate flood mitigation (drainage capacity) and consider using those corridors for additional water system redundancy (e.g. space for an extra water main or emergency conduit). Similarly, coastal defense projects (like levees or surge barriers) should be planned with water infrastructure in mind: maybe incorporate an intertidal wetland that not only buffers surges but also filters runoff (improving water quality) and provides groundwater recharge (supporting water supply). These cross-sector synergies often unlock funding from multiple sources and yield more robust outcomes. On policy level, planners can convene **resilience task forces** that include water, wastewater, power, transportation departments to ensure interdependency issues are routinely addressed in infrastructure design and emergency planning (some cities now have Chief Resilience Officers aiming for this holistic approach).

### 6.6.2 For Infrastructure Risk Analysts and Resilience Planners

- **Develop and Use Advanced Modeling Tools:** Risk analysts should leverage and further develop models that can simulate **cascading failures and interdependencies** specific to water systems. This might involve coupling hydraulic models with network interdependency models. For example, use one of the interdependent network models (like those reviewed by Ouyang 2014) to link a water network model with a power grid model to see how an outage spreads in one and impacts the other. Analysts can work with utilities to create **digital twins** of their systems and then stress test them: e.g., input a scenario of earthquake plus storm plus cyberattack, and see what breaks where, how service levels drop, and how different interventions (valve shutoffs, mutual aid arrival) change outcomes. These analyses can identify critical nodes that might not be obvious – maybe a particular neighborhood pump station turns out to be the linchpin in many scenarios. Highlight those for targeted mitigation. Risk models should also quantify *uncertainty*: help decision-makers understand confidence levels around various scenarios, so they can apply precaution where needed. In presenting results, show **worst-case cascades** as well as probabilities, because waiting for statistical certainty might be imprudent if worst-case is catastrophic. Analysts should integrate climate model outputs for future hazard parameters (this is a job for specialists who can translate climate data into inputs for engineering models).

- **Economic and Health Impact Analysis:** Analysts need to extend traditional risk assessments (which often focus on asset damage) to include **economic downtime costs and public health outcomes**. For example, use historical data or models to estimate how many illnesses a certain water contamination event might cause, or how much GDP loss a week-long water outage would incur, and include those in risk calculations. This holistic impact view can elevate water projects in priority compared to, say, more visible infrastructure, by showing the true stakes (e.g., a sewer overflow scenario might cost the city economy X million in tourism loss, or a long water outage might cause a certain mortality among vulnerable populations). Incorporating these broader impacts helps justify resilience investments to policymakers and the public by translating them into human and economic terms (not just engineering terms). Tools like probabilistic risk analysis, Monte Carlo simulation, and value of statistical life (for health impacts) can be employed to monetize these factors, supporting cost-benefit analyses for mitigation projects.

- **Resilience Metrics and Indices:** Work on creating or refining **resilience indices** that can be tracked over time for water systems. For instance, an index that combines "risk of water outage" + "risk of boil-water advisory" + "risk of sewer overflow" could be developed, weighted by severity. This could feed into city-wide resilience scorecards. Having measurable indicators (like "able to meet at least 80% of water demand within 3 days of disaster" or "no more than 50 gallons per capita of sewage overflow in 100-year storm") gives targets to aim for and measure progress. Risk analysts should also help utilities develop **trigger criteria** for adaptation actions – e.g., if climate data shows 5-year moving average of intense storms increasing by X%, trigger an upgrade of drainage capacity. These kind of foresight metrics ensure adaptation isn't reactive but timely.

- **Scenario Planning and Adaptive Pathways:** Employ scenario planning techniques to map out multiple plausible futures (e.g., optimistic, moderate, pessimistic climate scenarios combined with different socio-economic developments) and test how water systems perform in each. Develop **adaptive pathways**: sequences of actions with decision points depending on how the future unfolds. For example, a pathway might be: improve pumps now, if by 2030 overflow events haven't reduced (due to even heavier rain than expected), then build storage tunnel; if they have reduced, next invest in green infra instead. By presenting flexible roadmaps, analysts help avoid both under- and over-investment and keep options open. This approach is being used in progressive water agencies especially for climate adaptation.

- **Stakeholder Engagement and Communication:** Risk analysts often are the bridge between technical findings and policy decisions. They should communicate multi-hazard risks in clear, compelling ways to stakeholders (city officials, public, industries). Use visualization tools – e.g., maps showing areas at risk under multiple scenarios, or flow diagrams of a cascade (like how an earthquake leads to water outage leads to hospital impact) – to tell the story. Sometimes a simple **infographic or impact chain diagram** resonates with decision-makers more than dense reports. Emphasize the co-benefits of resilience actions (like "this project will reduce flooding *and* safeguard drinking water quality") to garner broader support. Engage communities in scenario discussions – for instance, host workshops where residents explore how a combined power-water outage would affect them and what they would need – this grounds risk analysis in real-world concerns and can spur community preparedness initiatives alongside infrastructure fixes.

- **Policy and Funding Strategy:** Finally, risk analysts should feed their work into policy and funding strategy. Identify which resilience measures give the biggest risk reduction per dollar (the proverbial "low-hanging fruit"), and which are essential for mitigating worst-case scenarios even if unlikely (the high-impact low-probability events). This can guide grant applications and budget allocations. Also, use analysis to inform updates to regulations (e.g., suggest changes to design standards or emergency planning requirements based on identified gaps). Often funding for multi-hazard projects can come from multiple sources – for example, a tunnel that prevents CSOs and also prevents water supply contamination might tap both clean water funding and hazard mitigation grants. Analysts can help package these multi-benefit cases. They should also consider equity: ensure that resilience investments protect vulnerable communities (using metrics like social vulnerability indices overlaid with hazard risk) so that funding is prioritized not just by economic cost-benefit but also by community need and justice – a direction many cities are now committed to.

By implementing the above recommendations, **water utility operators** can drastically improve their emergency preparedness and system robustness, **urban planners and engineers** can create infrastructure and urban layouts that inherently resist and adapt to multi-hazard stresses, and **risk analysts** can provide the insights and metrics to drive informed, forward-looking decisions. The challenges of multi-hazard resilience in urban water systems are significant, especially under climate change and urban growth pressures, but with proactive and coordinated efforts across these domains, cities can greatly reduce the likelihood of cascading water crises and ensure reliable, safe water services under even the most adverse conditions.

# 7 Conclusions

This conclusion chapter synthesizes the key findings from the multi-hazard risk assessment of transportation, industrial, and civil (urban water) critical infrastructures, and outlines recommendations for policy and planning. The analyses across these domains demonstrate that understanding and managing cascading risks in a **multi-hazard** context is essential for resilient infrastructure systems. Below, we summarize the primary insights for each sector, followed by technically grounded recommendations for national and regional stakeholders.

## 7.1 Transportation Infrastructure: Multi-Hazard Risk Insights

Transportation assets – exemplified by road and railway **tunnels and bridges** – were found to benefit greatly from advanced multi-hazard risk analysis and decision-support integration. A dynamic, probabilistic risk management approach was developed, shifting away from static safety checks toward **real-time, data-driven evaluation**. In particular, tunnel safety management now integrates live traffic, weather, and equipment status data into **Fault-Tree/Event-Tree models enhanced with Bayesian networks**, enabling continuous risk updates. This approach allows operators to constantly reassess threats (e.g. fire, hazardous material spills, flooding, equipment failure) and update the **residual risk** in line with the ALARP ("As Low As Reasonably Practicable") principle. By aligning operational decisions with ALARP thresholds, uncertainties in complex cascade scenarios were sharply reduced.

Critically, this multi-hazard methodology yielded tangible improvements in both safety and efficiency. Simulations and field trials showed that **energy-optimised control algorithms** (for ventilation, lighting, etc.) could maintain safety while cutting normal operating energy use by up to 50%. Likewise, refined emergency response protocols (informed by real-time risk models) decreased evacuation times in critical tunnel incidents by about 25% without requiring major civil works. The study also pioneered a three-layer resilience framework – combining physical upgrades, on-site renewable energy, and battery storage – to keep transportation tunnels functional during external disruptions. This framework was **replicable for both road and rail networks**, proving robust against emerging threats like Li-ion battery fires and cyber-attacks. In summary, the transportation infrastructure assessment underscored the value of **integrated Decision Support Systems (DSS)** for multi-risk management. The results demonstrate that adaptive, probabilistic safety models can significantly enhance the resilience of transport tunnels and bridges, especially in confined or high-risk environments. These innovations lay the groundwork for "federated" digital twins and predictive monitoring platforms to proactively manage transportation infrastructure risk in real time.

## 7.2 Industrial Infrastructure: Systemic Vulnerability and Domino Effects

In the industrial domain, a **systemic vulnerability tool** based on GIS mapping and a hierarchical network of indicators was applied to assess multi-hazard exposure at both the municipal and facility scales. This quantitative tool (adapted from Beltramino et al., 2022) integrates diverse indicators across three levels – overall systemic vulnerability, contributing sector sensitivities, and individual hazard factors – providing a **comprehensive vulnerability map** for decision-makers. Applied to a proof-of-concept case (an ~280 ha industrial area that includes an energy production plant), the method revealed a patchwork of vulnerability: roughly two-thirds of the area showed **moderate**

**vulnerability**, while the remaining portions exhibited **high to critical vulnerability** under multiple hazards. The hierarchical breakdown identified which components and sub-areas drive this risk. Notably, certain **infrastructure and building assets** (including heritage structures) were highlighted as highly susceptible due to the concurrence of hazards in the model. This indicates that even in an industrial zone, vulnerabilities can be elevated not just by single threats but by their combinations – for example, seismic risk compounded by flood exposure in the same structures.

A key insight from the industrial analysis is the importance of **hazard interactions and domino effects**. The case study detected a significant two-way interaction between neighboring industrial facilities and the adjacent power plant, meaning each could serve as a hazard source for the other. For instance, flooding emerged as a critical initiating hazard that might both impact the power station and be exacerbated by it (e.g. if flood-induced failures at one site trigger accidents at the other). Such a **"double-sense" interdependence** has serious implications: it elevates the risk of **Natech** scenarios (natural hazards triggering technological accidents) and cascade events that spread across facility boundaries. The analysis underlines that traditional siloed risk assessments may overlook these cross-facility linkages. By using a spatial, indicator-based vulnerability model, planners can pinpoint these hotspots of **systemic risk** and prioritize interventions (e.g. flood defenses or safety system upgrades) for clusters of industrial infrastructure rather than isolated sites. In summary, the industrial CI findings show that a territorial multi-hazard approach – combining **land-use planning insights with engineering risk analysis** – is essential to capture how one facility's risk can affect another. This approach supports more informed municipal planning, such as zoning decisions and emergency response plans that account for **domino effects** beyond single-facility scenarios.

## 7.3 Civil Infrastructure (Urban Water Systems): Compound Hazards and Cascading Failures

The assessment of **civil infrastructures** focused on urban water supply and wastewater systems, which are tightly interlinked with each other and with other sectors (power, transportation, communications). This study confirms that analyzing these systems under **compound hazard scenarios** reveals serious resilience gaps that would remain hidden under single-hazard analysis. In urban water networks, the **worst impacts often occur when hazards coincide or cascade**: for example, an earthquake can damage pipelines while simultaneously causing a power outage that disables pumps, leading to a widespread water outage and sanitation breakdown. Indeed, research and real-world cases show that the largest societal disruptions arise not from one hazard in isolation, but from **interactions between hazards and the propagation of failures through interconnected systems**. A univariate, single-event perspective **severely underestimates risk**, as combined events lead to disproportionate damage compared to isolated incidents. In the water infrastructure context, this means that a **single trigger can snowball**: for instance, a storm not only floods neighborhoods but also causes a power blackout, which in turn knocks out drinking water treatment and sewer lift stations – a scenario that yields far greater service loss and damage than each hazard alone.

Specific compound scenarios analyzed include **"earthquake + boil water order + sewer overflow"** events (e.g. earthquake damages pipes, contaminates water, and disables wastewater pumping) and **"flood + power outage"** events (storm flooding coinciding with grid failure). These scenarios illustrated how an extreme natural event can quickly deteriorate into a multi-system crisis. For example, a widespread blackout will almost immediately halt water distribution pumps and sewage pumps lacking backup power, causing loss of water pressure and **raw sewage overflows** into streets and buildings. Even a few hours of concurrent power loss and heavy rainfall can force sewage onto streets (when lift stations fail) and allow contaminants to infiltrate water pipes, creating a **public**

**health emergency** on top of physical flood damage. Such cascades can render parts of a city uninhabitable (no potable water or functioning sanitation) even after the initial hazard passes. This underscores that **cross-system dependencies** (like electricity supply for water utilities) are potential single points of failure: an outage in one infrastructure can propagate into others, greatly amplifying the overall impact.

Moreover, the civil infrastructure review highlighted that focusing narrowly on one threat can create **resilience trade-offs**. For instance, improving flood defenses without securing backup power means a storm's **secondary effects** (power loss) could still cripple water services. It became clear that **resilience gaps** often lie at the interfaces between systems – gaps such as insufficient emergency power at water facilities, or lack of protocol for coordinated response when multiple networks fail at once. A comparative analysis of water supply vs. drainage system hazards reinforced that many threats (earthquakes, power failures, cyber-attacks, etc.) **threaten both systems simultaneously**, and failures in one will cascade to the other. Therefore, true resilience for civil infrastructures demands **holistic, joint evaluation of water, wastewater, and power systems**, rather than siloed planning. The study points to the need for integrated modeling tools (e.g. WNTR-based simulations) that can capture multi-hazard impacts and **cross-sector interdependencies**, in order to identify hidden vulnerabilities (such as a sewer pump station that is safe against either a flood or a blackout alone, but not both together). Overall, the civil infrastructure findings stress that **urban water systems must be strengthened against concurrent and cascading events**, with strategies that ensure one utility's failure does not spiral into a city-wide crisis. This entails bridging the traditional gaps between utilities, and adopting resilience measures that address compound failure scenarios (from emergency plans and backup systems to diversified supplies and enhanced design standards).

## 7.4 Policy and Planning Recommendations

Based on the above insights, we propose the following recommendations for national and regional stakeholders to enhance critical infrastructure resilience through multi-hazard approaches. These recommendations are technically grounded in the findings and aim to integrate improved risk analysis into practice, bolster early warning and response, define resilience targets, and foster cross-sector collaboration:

- **Integrate Multi-Hazard Risk Assessment into Planning and Design:** Infrastructure regulators and planners should incorporate **multi-hazard scenarios and cascading risk analysis** as a standard part of project development and asset management. This means moving beyond single-hazard safety margins and requiring analyses of credible compound events (e.g. sequential natural hazards, or natural-technological combinations) for major projects. Planning guidelines should be updated so that **design standards and land-use zoning** account for domino effects – for example, ensuring an industrial facility's siting considers flood and earthquake risks *together* with potential Natech accident propagation to neighboring sites. Quantitative risk criteria like ALARP can be adopted at the policy level to decide when risk mitigation measures are "as low as reasonably practicable" for complex hazard combinations. Ultimately, **regulatory frameworks** should encourage the use of advanced modeling tools (e.g. Bayesian network risk models, system dynamics simulations, coupled infrastructure stress tests) during the approval and periodic review of critical infrastructure, to capture interdependencies and avoid underestimating risk. By institutionalizing multi-hazard risk assessments, authorities can promote investments in designs that are robust against **multiple failure modes** rather than optimized for one threat at the expense of others.

- **Implement Early Warning Systems and Real-Time Monitoring:** Deploy and integrate **early warning systems** that monitor emerging hazards across sectors and provide timely alerts to infrastructure operators and emergency agencies. This includes enhancing sensor networks and predictive analytics: for instance, installing smart monitoring in tunnels, bridges, and utility networks to detect stressors (rising water levels, vibration, smoke, pressure loss, cyber-intrusions) and forecast cascading failures. Coupling weather forecasts, seismic alerts, and power grid status into a unified **Decision Support System** allows operators to anticipate compound events – such as preemptively lowering reservoir levels if a storm and power failure are forecast together. National policy should support the development of **interconnected warning platforms** that automatically share risk indicators between infrastructure sectors (e.g. a flood warning triggers alerts for transportation departments and utilities to prepare). Real-time dashboards or even **digital twin** models of critical assets can be used to simulate the progression of an incident, enabling proactive control actions (like traffic closures, system isolations, load shedding) to prevent minor incidents from cascading. Furthermore, early warning extends to the public: authorities must ensure there are robust communication channels (SMS alerts, sirens, broadcast messages) to warn communities of infrastructure service disruptions or safety actions (such as boil-water notices or evacuation routes) during multi-hazard crises. Strengthening early warning and monitoring not only helps manage imminent events but also serves as a feedback loop to continuously improve risk models with real incident data.
- **Adopt Resilience Metrics and Performance Targets:** Governments and infrastructure agencies should develop and use **resilience metrics** to quantify how systems perform under stress and how quickly they recover. Traditional reliability metrics (uptime, single-point failure rates) are insufficient for cascading scenarios; instead, metrics like **service downtime after an event, recovery time to x% functionality, or the robustness of alternative service routes** should be tracked. For example, water utilities might set a target that even under a simultaneous power outage and pipe break, at least 80% of customers have minimal service within 24 hours. Similarly, transportation agencies could measure the **time to restore connectivity** after a multi-hazard event (landslide + flood) as a resilience indicator. Adopting such metrics encourages a culture of continuous improvement in multi-hazard preparedness. National infrastructure strategies can require periodic **resilience audits** where critical infrastructure operators report on their performance in drills or past incidents using standardized metrics (e.g. the resilience "triangle" area quantifying loss and recovery). These metrics should also be integrated into investment decisions: cost-benefit analyses for upgrades should include the value of improved resilience (e.g. avoided economic losses due to faster recovery). Over time, establishing clear resilience goals (like a maximum allowable outage time for critical services under worst-case scenarios) will drive coordinated enhancements across different networks. Importantly, metrics must be **multi-criteria** – capturing trade-offs – to avoid optimizing one aspect of resilience at the expense of another. For instance, plans should be evaluated on a combination of criteria such as safety, service continuity, environmental impact, and societal costs under multi-hazard stress. By making resilience measurable and transparent, stakeholders at all levels can better prioritize actions and resources to strengthen weak links revealed by those metrics.
- **Strengthen Cross-Sector Coordination and Communication:** The complex interdependencies highlighted in this study call for much tighter **coordination among infrastructure sectors**. It is recommended to establish formal mechanisms – such as regional **Resilience Task Forces or Inter-Agency Working Groups** – that bring together transportation, energy, water, and communication infrastructure operators along with civil protection authorities. These groups should meet regularly to share risk assessments, develop joint emergency response plans, and conduct **multi-sector exercises**. As demonstrated, a compound crisis will often involve power utilities, water companies,

transport agencies, and more simultaneously; coordinated planning ensures that, for example, the power utility prioritizes restoring electricity to water treatment plants and tunnel ventilation systems after an event. Joint emergency drills or tabletop exercises are particularly useful for identifying gaps in communication and resource allocation. National guidelines could mandate annual **compound scenario drills** (e.g. simulating a major earthquake that affects roads, bridges, pipelines, and grid power at once) involving all relevant operators and emergency services. During real events, cross-sector communication protocols (potentially via a unified command center or incident management system) should be in place so that one sector's situational data (like flood extent maps or power outage regions) are instantly shared with others. Another aspect of coordination is **mutual aid and resource sharing**: regional agreements can allow, for instance, transportation departments to lend pumps or generators to water utilities during floods, or water utilities to assist fire departments with tanker trucks when hydrants are down. Such cooperative arrangements greatly increase adaptive capacity when cascading failures strain individual sectors. At the policy level, governments can facilitate this by creating multi-agency emergency funds and communication infrastructure (common radio frequencies, joint operations centers) dedicated to multi-hazard response. In summary, breaking down the silos between infrastructure sectors and **institutionalizing collaborative resilience planning** is crucial to ensure that improvements in one domain do not inadvertently undermine another, and that during crises, all players act in a synchronized manner to mitigate cascading impacts.

By implementing these measures – embedding multi-hazard analysis in planning, deploying early warning systems, using resilience metrics, and enhancing cross-sector coordination – national and regional stakeholders can substantially **improve the resilience of critical infrastructures**. The findings of the RETURN project's multi-hazard risk assessment make clear that a siloed approach is no longer sufficient. Instead, an integrated strategy that recognizes **the interconnected nature of transportation, industrial, and civil infrastructures** is required to reduce cascading disaster risks. Proactive policy actions and investments guided by the above recommendations will help transform the study's insights into practice, leading to infrastructure networks that can withstand and rapidly recover from the complex hazard scenarios of the future.

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