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2. Abstract

In recent years, the rising frequency and severity of NaTech incidents — industrial accidents triggered by natural events such as earthquakes, floods, and storms — has raised growing concern among researchers and risk management authorities. These complex events require the development of specific prevention and management strategies. This study proposes an analysis of 1,300 NaTech incidents over the past 70 years, aiming to identify trends, geographical distribution, and material damages.

The analysis highlights the need for a systematic approach to data collection and organization, as fragmentation and lack of standardization across databases limit the sharing of information. The study also examines NaTech risk assessment methodologies, divided into quantitative and qualitative approaches for natural events such as earthquakes, floods, and storms. The review of these methodologies emphasizes the importance of an integrated approach to risk assessment, helping to improve preparedness and response to future NaTech incidents.

To further illustrate the risks and complexities of NaTech events, the study presents an in-depth analysis of the fire at the TUPRAS refinery during the 17 August 1999 Kocaeli earthquake. This case study highlights the sequence of events, the severe environmental and economic consequences, and the lessons learned from the incident. By examining the structural weaknesses that contributed to the disaster and the subsequent measures taken to enhance safety, the analysis provides actionable insights for improving industrial resilience to natural hazards.

The results underscore the importance of accurately identifying natural hazards, assessing their potential impact on industrial facilities, and developing effective mitigation strategies. Despite advancements in the field, greater efforts toward standardization and international collaboration are essential to improving global readiness and response to NaTech events, ultimately optimizing risk management and environmental safety.

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4.1. NaTech accidents

NaTech accidents, a term coined by Showalter and Myers in 1994, refer to technological incidents triggered by natural hazards such as earthquakes, floods, and storms, leading to events like fires, explosions, or hazardous substance releases in industrial settings (Cruz and Suarez-Paba (2019)). These incidents pose significant risks to public safety, the environment, and industrial activities, often resulting in severe economic losses. NaTech events are categorized into meteorological, hydrological, climatic, and geological hazards.

Despite an increase in their frequency and severity since the 1970s (Cruz et al. 2004), regulations addressing NaTech risks have been slow to develop, with the European Union only incorporating NaTech considerations in safety reports for sites handling hazardous chemicals in 2012 (Directive 2012/18/EU; European Commission (2024)). The study aims to build a database of NaTech incidents (eNatech (2021)) and explore methodologies for analyzing and managing them.

A key case study focuses on the TUPRAS refinery fire during the 1999 Kocaeli earthquake, highlighting the challenges and lessons learned in preventing and managing such accidents.

4.2. Evolution in NaTech research

NaTech research has evolved significantly over time, with a major focus on understanding technological accidents triggered by natural events. A 2019 systematic review of literature (Suarez-Paba et al. (2019)) identified key trends in NaTech risk management, revealing a shift from earthquake-related research to a broader focus on hydrometeorological hazards and a growing interest in multi-hazard, interdisciplinary approaches.

The development of both quantitative and qualitative risk management methodologies has opened opportunities for innovative semi-quantitative tools. The importance of risk reduction, communication, and community involvement in NaTech management is increasingly recognized, alongside growing attention to long-term health and environmental effects.

Various global databases, such as eNatech, ARIA, and eMARS, have been created to document NaTech events, but challenges such as data fragmentation, lack of standardization, and limited geographical coverage hinder their full potential. These databases provide valuable insights into trends, risks, and consequences, aiding in the improvement of risk management strategies, although their effectiveness could be enhanced through international collaboration and standardization efforts.

4.3. Development of the database

The development of a NaTech database aimed at tracking industrial accidents caused by natural events began by analyzing data from two primary sources: eMARS (Major Accident Reporting System) and eNATECH (Natural hazard-triggered technological accident database). These databases were selected due to their ease of access and user-friendly interfaces, allowing researchers to efficiently collect relevant data. The eMARS database provided 1198 records, with only 29 identified as NaTech-related (2.42%), while eNATECH offered 79 records, with 40 being NaTech-related (50.63%).

To further refine the database, additional information from other sources such as MHIDAS, TAD IChemE, ARIA, NRC, and CONCAWE could be considered, offering comprehensive details on industrial incidents and hazardous substance spills (Ricci et al. (2021)). Data retrieval focused on various factors like incident date, geographical location, industrial activity, involved substances, and incident descriptions, ensuring a targeted collection. Over 1277 records were processed, and after filtering, the final database included detailed information on the natural hazard, the affected industrial site, the incident type, and the specific substances involved.

Table 1. Number of NaTech events collected from various consulted databases. Reported are the total number of records in the database, the number of selected records, and the % of NaTech events present in each database

Database	Total number of records	Selected records	% reliable Natech events
eMARS	1198	29	2,42 %
eNATECH	79	40	50,63 %

The database structure is organized into categories such as 'DATE,' 'LOCATION,' 'NATURAL HAZARD,' 'INDUSTRIAL ACTIVITY,' 'LOCAL UNITS,' 'RELEASE TYPE,' 'INVOLVED SUBSTANCES,' and 'EVENT DESCRIPTION.' This structure allows for comprehensive tracking and analysis of NaTech incidents across different industries, with a focus on the risks posed by natural hazards. Notably, the eMARS database does not provide company-specific or location details to protect privacy, while eNATECH allows users to contribute and access information under three status levels: Draft, Final, and Published.

Table 2. Database Structure

Date	Location	Natural hazard	Industrial activity	Local units	Release type	Involved substances	Event description

The analysis of the data revealed key trends in the occurrence of NaTech events. The distribution of incidents showed that the highest frequency was in industrialized regions, such as North America, Europe, and Asia, reflecting the correlation between industrial density and the likelihood of NaTech incidents. While industrialized countries have a higher absolute number of recorded incidents, this is more a reflection of industrial activity rather than a predisposition to accidents.

Figure 1. Location of accidents NaTech

In terms of the natural hazards involved, the data indicated that meteorological (e.g., lightning, hurricanes) and hydrological (e.g., heavy rainfall, floods) events were the most common triggers for technological accidents. The petrochemical and refinery industries were the most impacted sectors, followed by general chemical production and biogas plants. Accidents were often linked to storage tanks (34.78% of incidents), pipelines (10.14%), and other plant units (27.54%).

Table 3. Category 'Natural Hazard'. It reports: the types of natural hazards, the number of different events, and the % of events based on the category of natural hazard

NATURAL HAZARD	Number of events	% natural hazard
Lightning	16	23.19
Strong wind (+3 as a secondary event)	8	11.59
Hurricane	5	7.25
Earthquake	7	10.14
Heavy rainfall	16	23.19
Landslide	5	7.25
Flood	4	5.80
Storm	2	2.90
Tsunami	2	2.90
Low temperature	7	10.14

Table 4. Category 'Industrial Activities'. It reports types of natural hazards, the number of events, and the percentage of events based on the category of industrial activity

INDUSTRIAL ACTIVITIES	Number of events	% Industrial activities
Petrochemical/refineries	27	37.68
Pipelines and gas pipelines	5	7.25
Mining activities	3	4.35
Wastewater injection plant	1	1.45
General chemical production	16	23.19
Plastic and rubber production	3	4.35
Metal processing	2	2.90
Pharmaceutical product manufacturing	1	1.45
Energy and desalination plant	1	1.45
Pesticide, biocide, fungicide production and storage	1	1.45
Biogas plant	6	8.70
Food and beverage production	1	1.45
Natural gas storage plant	2	2.90
Wholesale and retail storage and distribution	1	1.45

Table 5. Category 'Local Units'. It reports types of involved units, the number of events, and the percentage of events based on the category of involved units

LOCAL UNITS	Number of events	% local units
Storage tanks	24	34.78
Pipeline	7	10.14
Settling basin	3	4.35
Material or waste storage depot	3	4.35
Pipelines	5	7.25
Rainwater collection tank	4	5.80
Heat exchangers	2	2.90
Steam cracking units	2	2.90
Other plant units	19	27.54

The types of releases reported varied, with the majority being gas, vapor, or smoke releases (43.48%), followed by liquid releases on the ground (28.99%) and liquid releases in water (20.29%). These hazardous releases were often linked to substances such as hydrocarbons and their mixtures, which are prevalent in the petrochemical and chemical industries. These substances pose significant environmental and health risks, including water contamination, explosions, and ecosystem damage.

Table 6. Category 'Release Type'. It reports types of release, the number of different events, and the percentage of events based on the category of release type

RELEASE TYPE	Number of events	% release type
Solid release on the ground	1	1.45
Liquid release on the ground	20	28.99
Liquid release in water	14	20.29
Gas, vapor, mist, or smoke release in the air	30	43.48
No information	5	7.25

The database also highlighted that NaTech incidents often involve substances like methane, natural gas, and chlorine compounds, which can lead to severe environmental consequences and safety hazards. This comprehensive analysis underscores the need for robust safety measures, particularly in industries such as petrochemicals and chemical production, where the risk of catastrophic incidents triggered by natural events remains high.

Table 7. Category 'Involved Substances'. It reports substances involved, the number of events, and the percentage of events based on the category of involved substances

INVOLVED SUBSTANCES	Number of events	% involved substances
Methane	5	7.25
Hydrocarbons and hydrocarbon mixtures	36	52.17
Natural gas (and derivatives)	7	10.14
Nitrogen compounds	3	4.35
Other substances	10	14.49
Chlorine and chlorine compounds	5	7.25
Cyanide and derivatives	3	4.35

In conclusion, the database provides a valuable tool for understanding the link between natural hazards and technological accidents in industrial settings. It offers critical insights into the types of hazards, the industries most at risk, and the substances involved, serving as a foundation for improving safety standards and risk management strategies.

4.4. Risk Assessment methodologies

National and international regulations, such as the Seveso III Directive (2012/18/EU), require industrial facilities to be properly designed, assess risks to surrounding areas and develop emergency plans for public protection. These regulations require that natural disasters be included in risk analyses, as they can trigger industrial accidents by releasing dangerous substances, increasing risks to public health and the environment.

The interaction between natural disasters and industrial facilities has led to the development of specific procedures for the assessment and management of NaTech (natural-technological) risks. NaTech scenarios involve the combination of natural hazards and industrial events, such as equipment failures or damage, that can cause accidents such as explosions, fires or toxic spills. Risk analysis evaluates two key parameters: probability and magnitude of such accidents.

Risk analysis methods can be qualitative, semi-quantitative or quantitative, depending on the data and resources available. Quantitative methods, such as Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) (Al-Shanini et al. (2014); Misuri et al. (2023); Necci et al. (2014)), are commonly used to estimate the probability and consequences of accidents, such as environmental damage, economic loss or injury to people. Quantitative methods are the most accurate but are time-consuming and resource intensive.

For more simplified assessments, qualitative methods are used. These involve preliminary assessments of potential risks, using fewer variables and expert judgement to assign risk classifications. The results are typically presented in a risk matrix, identifying acceptable, tolerable or unacceptable risks. If necessary, quantitative analysis follows to refine the risk assessment.

Storms, earthquakes and floods are the main natural events responsible for triggering industrial accidents and most of the NaTech risk analysis research has focused on these phenomena.

4.4.1. Earthquake Related Risk Assessment Methodologies - Quantitative Methodologies

Quantitative methods for earthquake risk assessment, such as those by Antonioni et al. (2007), use historical data to determine earthquake frequencies and severity. The severity is measured by Peak Ground Acceleration (PGA), and damage to equipment is evaluated using fragility curves. Hazardous substance release is estimated based on expected damage, and a software tool is developed to assess individual and societal risks. Similar methods have been proposed by Fabbrocino et al. (2005) and Campedel et al. (2008).

4.4.2. Earthquake Related Risk Assessment Methodologies - Qualitative Methodologies

Qualitative methodologies, like the one by Giannelli et al. (2020), use indices to assess seismic risk and equipment vulnerability, ultimately forming a risk matrix. Novelli et al. (2024) developed a more complex approach, ranking equipment by risk. Busini et al. (2011) proposed a methodology for storage equipment, using key hazard indicators (KHIs) to assess risk, leading to a global risk index for the plant.

4.4.3. Flood Related Risk Assessment Methodologies - Quantitative Methodologies

Flood risk is assessed by parameters like water level and flow rate (Landucci et al. (2014); Marzo et al. (2012)). In flood-related NaTech scenarios, models predict the probability of containment loss based on flood severity. This approach integrates the tank vulnerability model with quantitative risk assessment.

4.4.4. Flood Related Risk Assessment Methodologies - Qualitative Methodologies

Krausmann and Mushtaq (2008) proposed a qualitative method for assessing flood risk in chemical plants, using a damage scale linked to flood severity. Marzo et al. (2012) developed a similar approach, employing performance indices based on the analytical hierarchy process (AHP) for flood risk evaluation (Busini et al. (2011); Marzo et al. (2012)).

4.4.5. Storm Related Risk Assessment Methodologies

Storm-related risks, particularly lightning, are less studied but significant for NaTech events. Necci et al. (2013) and Misuri et al. (2020) and Yang et al. (2018) proposed quantitative methods for assessing lightning-related damage and domino effects. Other studies focus on specific targets, such as gas transmission stations (Wang et al. (2024)) or floating roof tanks (Wei et al. (2018)), in assessing lightning risk.

For heavy rainfalls, flood risk methods can be applied since the risks to industrial plants are similar to those posed by flooding.

4.4.6. Summary of Methodologies

The methodologies, summarized in Table 8, are grouped by natural events (earthquakes, floods, storms) and categorized by their type (qualitative or quantitative), equipment studied, and whether domino effects are considered. These methods generally include:

1. characterizing the natural event;
2. identifying target equipment;
3. correlating event intensity to equipment failure probability;
4. assessing domino effects (if applicable); and
5. evaluating the consequences of hazardous material release.

Table 8. Sum up of the methodologies presented, grouped by natural hazard

Paper	Natural hazard	Quantitative / Qualitative	Focus (target equipment)	Domino effect	Application to a case study	Validation
Antonioni et al. (2007)	Earthquake	Quantitative	Atmospheric storage tank Pressurized vessel	no	yes	Yes
Busini et al. (2011)	Earthquake	Qualitative	Atmospheric storage tank Pressurized vessel	yes	yes	yes
Campedel et al. (2008)	Earthquake	Quantitative	Atmospheric storage tank Pressurized vessel Pressurized reactors Pumps	no	yes	no
Fabbrocino et al. (2005)	Earthquake	Quantitative	Atmospheric storage tank Pumps Buildings Pipework	yes (only for tanks located in the same basin)	yes	no
Giannelli et al. (2020)	Earthquake	Qualitative	Atmospheric storage tank Pressurized vessel slender structures (e.g., columns) Pipes	no	no	no
Novelli et al. (2024)	Earthquake	Qualitative	Atmospheric storage tank Pressurized vessel Buildings Process equipments	yes	yes	no
Krausmann and Mushtaq (2008)	Flooding	Qualitative	Atmospheric storage tank Pressurized vessel Buildings Pipework	no	no	no
Landucci et al. (2012)	Flooding	Quantitative	Atmospheric storage tank	no	yes	yes
Landucci et al. (2014)	Flooding	Quantitative	Atmospheric storage tank	no	yes	yes
Marzo et al. (2012)	Flooding	Qualitative	Atmospheric storage tank Pressurized vessel	no	yes	yes
Misuri et al. (2020)	Storm (Lightning)	Quantitative	Atmospheric storage tank Pressurized vessel	yes	yes	no
Necci et al. (2013)	Storm (Lightning)	Quantitative	Atmospheric storage tank Pressurized vessel	no	yes	yes
Santamato and Busini (2024)	Storm (wind)	Qualitative	Atmospheric storage tank Pressurized vessel	yes	yes	no
Wang et al. (2024)	Storm (Lightning)	Quantitative	Gas transmission station equipments (e.g., pipelines, buildings, tanks)	yes	yes	yes
Wei et al. (2018)	Storm (Lightning)	Quantitative	Atmospheric storage tank	no	yes	no
Yang et al. (2018)	Storm (Lightning)	Quantitative	Atmospheric storage tank	yes	yes	no
Castro Rodriguez et al. (2023)	Multi (Earthquake, flooding and storm)	Qualitative	Atmospheric storage tank Pressurized vessel, Tall structures (e.g., flares, columns) Pipelines Reactors	no	no	no
Cruz and Okada (2008)	Multi (Earthquake and flooding)	Qualitative	Atmospheric storage tank	yes	yes	Yes (only for earthquake)

Wang and Weng (2023)	Multi (flooding, wind and hail)	Qualitative	Atmospheric storage tank	no	yes	no

4.5. A NaTech case study

NaTech events have gained attention only recently, despite their potential to cause significant damage to industrial sites. Major disasters such as Hurricane Katrina (2005) and the Great East Japan Earthquake (2011), which triggered the Fukushima nuclear accident, underscored the vulnerability of industrial facilities to extreme natural events (Kamiya et al. (2022); Tokyo Electric Power Company Inc. (2012)). These events have highlighted the need for improving safety measures to prevent such accidents in the future. The 1999 Kocaeli earthquake, one of the most industrialized regions of Turkey, stands out as a key NaTech event due to its severe impact on industrial infrastructure.

4.5.1. Sequence of Events

The earthquake struck at 03:02 local time on 17 August 1999, with a magnitude of 7.4, causing 17,500 deaths and 44,000 injuries. It affected 15 million people and resulted in over $15 billion in property damage. The earthquake led to significant destruction of infrastructure, including industrial facilities, triggering several NaTech events, notably a major fire at the TUPRAS Izmit refinery.

TUPRAS, the largest refinery in Turkey, suffered considerable damage. The fire began with the collapse of a chemical warehouse, leading to the ignition of chemicals. The second fire occurred at the crude oil processing plant, where a collapsed heater stack ruptured 63 pipes, spilling flammable liquids (Girgin (2011); Johnson et al. (2000)). The third and most destructive fire took place at the tank farm, where sloshing liquids damaged floating roof tanks, igniting fires that spread across multiple tanks, burning for five days (Scawthorn and Johnson (2000)).

4.5.2. Aftermath

There were no fatalities or injuries during the firefighting, but the economic and operational consequences were severe. Six tanks were destroyed and 30 of the 45 floating roof tanks were damaged. Approximately 350,000 m^3 of crude oil and products were exposed, resulting in a loss of processing capacity of 4.6 million tonnes, equivalent to six months of production. Environmental damage included oil pollution, with large quantities of naphtha and other products being burned, and oil spilled into Izmit Bay from broken pipes and the firefighting (Johnson et al. (2000)).

Material and cleanup costs were estimated at over US$57 million (eNatech (2021)).

4.5.3. Lessons Learned

TUPRAS was criticized for insufficient preparedness for such a NaTech event, despite having been previously affected by the 1967 Mudurnu Valley earthquake. Although the refinery had an emergency response plan, it proved inadequate as it did not accurately estimate the earthquake's intensity and duration (Danış and Gorgun (2005)). The response was hindered by the loss of utilities such as water, power, and communication, and the inability to use the full firefighting capacity due to infrastructure damage (Scawthorn and Johnson (2000)).

The refinery was also criticized for lacking foaming systems, inadequate diesel pumps, and insufficient fire protection measures (eNatech (2021)). The fire could not be fully controlled due to design flaws, such as the inability to shut off a leaking naphtha line (Scawthorn and Johnson (2000)). The risk of domino effects, such as explosions from nearby LPG vessels, was not properly assessed, leading to the construction of a barrier to prevent further escalation (Girgin (2011)).

Despite significant damage, restoration was rapid, with most units back in operation within three months (eNatech (2021)). Based on the lessons learned, TUPRAS revised its emergency response plan in 2000, enhancing active protection measures, such as increasing water capacity for firefighting, installing new sprinkler and foaming systems, and deploying additional safety measures like gas and flame sensors. A 3 km oil barrier was also placed to prevent future oil spills into the sea (eNatech (2021)).

5. Conclusions

An extensive review of databases collecting NaTech events highlighted challenges such as fragmentation, limited geographical coverage, and lack of standardization. Different databases categorize natural events differently, with some distinguishing between lightning, wind, and rain, while others use generic terms like "storm." The need for a standardized approach to data collection and sharing between databases is evident.

The review of risk analysis methods showed a lack of uniform attention to various natural phenomena. Most research focused on earthquakes, with minimal attention given to the impact of strong winds or the interaction of lightning with industrial facilities. Existing risk analysis methods have limited applicability, mainly to atmospheric storage tanks and pressurized vessels, which are considered higher-risk due to the large quantities of hazardous materials they store. Future efforts should expand the analysis to other types of equipment and develop fragility curves for them.

Additionally, the long-term effects of NaTech events, such as the release of toxic or radioactive materials, have had significant social, environmental, and economic impacts. These consequences are often underestimated. NaTech accidents exacerbate the burden on populations already coping with the immediate aftermath of natural disasters.

Examples of NaTech events include:

- Hurricanes Katrina and Rita (2005): These caused severe damage to Gulf of Mexico oil and gas infrastructure, leading to the release of hazardous materials, environmental pollution, and concerns about long-term soil contamination (Krausmann and Mushtaq (2008)).
- Arkema Plant Explosion (2017): Caused by Hurricane Harvey, it led to the decomposition of organic peroxides and the release of contaminants into nearby homes due to flooding (U.S. Chemical Safety and Hazard Investigation Board (CSB) (2018)).
- Fukushima Nuclear Disaster (2011): A tsunami triggered by a 9.0 earthquake caused the loss of utilities, leading to a nuclear meltdown and the release of radioactive materials (Tokyo Electric Power Company Inc. (2012)).

In these events, the long-term effects, such as contamination and ecological damage, have often extended beyond industrial sites and affected entire communities. Research has been conducted on the long-term risks in some cases, such as the contamination in New Orleans after Hurricane Katrina and the radiation effects following Fukushima (Kamiya et al. 2022; Lu et al. (2021)). However, there is still limited attention to the long-term impacts of NaTech events on the process industry, which requires further investigation.

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ABSTRACT

In this study, a risk assessment to tornado event was conducted for an atmospheric storage tank.
Given the scope of the study, only the vulnerability analysis of the tank was performed, thus excluding the consequences analysis. The study was carried out following the methodology presented in Santamato and Busini (2025).
The first step of the analysis is the historical review of the tornado events occurred in the area where the tank under investigation is located. This territorial screening was carried out by extracting and classifying tornado events according with the Enhanced Fujita (EF) Scale, using the European Severe Weather Database (ESWD). The analysis revealed that during the survey period, and in the survey area, 9 events were recorded as EF1, 5 events as EF2, and 2 events as EF3. No events categorized as EF4 or EF5 were reported. For each i-th degree of EF scale, a frequency of occurrence $Fr_{(EF_i)}$ was estimated considering the number of recorded events, the survey period, the survey area, and the plant surface, according to eq. (1).
The potential damage for the tank was evaluated with respect to three failure mechanisms: overturning, buckling, and debris impact ("puncturing damage").
As a result of the assessment, no potential for overturning nor buckling was identified regardless of the tornado intensity, mainly due to the fill level and the tank design. Conversely, from the vulnerability analysis to debris impact, an increasing probability of damage was found with the intensity of the natural event, ranging from 9% for EF1 to nearly 50% for EF5 tornadoes.
Finally a frequency of occurrence was assigned to the top event, i.e., LOC from the storage tank under analysis due to tornado impact, conservatively assuming certain the loss of containment following tank damage. Since the damage can occur as a result of any of the three mechanisms investigated, and due to tornadoes classified with any of the category of the Enhanced Fujita scale, the total damage probability can be calculated by multiplying, for each degree of intensity, the frequency of occurrence of the event by the probability of tank damage, and then summing the three contributions from the three damage mechanisms.

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4.First Section

4.1 Natech risk assessment for tornado events - atmospheric storage tank containing tetrahydrofuran (THF) located in Sassuolo (MO)

Tornado event characterization

The first step of the analysis is the territorial characterization, thus an historical overview of the tornadoes that have affected the territory where the investigated industrial plants is located, was performed. This was carried by extracting the tornado events from the European Severe Weather Database (ESWD) and by classified them according with the Enhanced Fujita (EF) Scale, which estimates the intensity of the tornado based on a series of damage indicators, classifying it in 6 categories, from EF0 to EF5 (Dotzek, 2009; Edwards et al., 2010).
Among the various physical parameters that characterize the phenomenon, surely the wind speed appears to be the most indicative and most suitable for risk analysis context: the upper limit of the wind speed range for each category of the EF scale will be taken as a reference, starting with events classified as EF1, since wind gusts up to 137 km/h are not considered capable of causing significant damage to industrial assets (Lara Carvajal et al., 2022). For category EF5, for which no indication of maximum speed is given, reference was made to that indicated in the same degree of intensity but in the version of the scale before 2007, i.e., tornado F5 - maximum wind speed 512 km/h.
The criteria set for the historic analysis in the ESWD are reported in Table 1.

Table 1: Criteria set for Historic Analysis (ESWD)

Survey period	50 years (from 01/01/1975 to 21/07/2025)
Survey area	8,904 km^2 (from 44° to 45° N and from 10° to 11° E)
Atmospheric event	Tornado
Place of occurrence	Occurring over land and water
Reliability level of the report	QC1, QC2

For each i-th degree of EF scale, a frequency of occurrence was estimated by the ratio of the number of recorded events to the survey period. Then a normalized frequency of each i-th category of tornado was computed by multiplying the frequency of occurrence with the statistically derived values of surfaces affected by tornadoes (mean paths values are taken from Elsner et al. (2014)) and dividing it by the survey area, as shown in equation (1). The results are reported in
Table **2**.

$$Fr_{EFi} = \frac{number\ of\ events_{EFi}}{investigation\ period} \cdot \frac{affected\ surface_{EF_i}}{survey\ area} \quad (1)$$

Table 2: Results of the historical analysis.

Classification	Affected surface	Number of recordered events	Fr_{EFi}
[-]	[km^2]	[-]	[ev/yr]
EF1	1.16	9	2.18E-05
EF2	4.92	5	5.11E-05

EF3	15.96	2	6.64E-05
EF4	52.4	0	0.00E+00
EF5	117.70	0	0.00E+00

Vulnerability Analysis

The assessment of the vulnerability of the storage tank exposed to strong gusts was carried out considering three possible damage mode:

- overturning,
- buckling, and
- debris impact.

For each, it is possible to pinpoint relations that assign specific wind speed values to specific damage probabilities. Note that the term "*damage*" was used without referring to equipment "*failure*": this means that the structure of the tank itself is damaged because of the impact of the wind, but without specifying whether this damage is followed by an effective loss of functionality of the tank and a consequent loss of containment (LOC) of the stored material. Conservatively, in this study, the failure following the damage will be considered certain.
The main features of the tank under analysis are reported in Table 3.

Table 3: Characteristics of the atmospheric storage tank

	Parameter	Value	Unit
-	Substance	Tetrahydrofuran (THF)	-
ρ_s	Substance density (@ 20°C)	887.6	kg/m^3
P_V	Substance vapour tension (@ 20°C)	17.6	kPa
-	Anchor	yes	-
C	Capacity	1590	m^3
D	Diameter	15	m
H	Height	9	m
t^*	Shell Thickness	4.8	mm
t_R^{**}	Roof Thickness	5	mm
t_B^{**}	Base Thickness	6	mm
DL	Shell and base mass	24292	kg
DLR	Roof mass	6933	kg
FL	Filling level	80	$\%$
-	Shell material	Stainless steel AISI 302	-
σ_D	Ultimate Tensile strength σ_D	620	MPa
ρ_{ss}	Steel density	7850	kg/m^3
E	Young Module	193	GPa
υ	Poisson's ratio	0.231	-

Since no information about the plate thickness are available in the open literature, reference was made to the API standards (API 620, 2002; API 650, 2012): * The API 620 standard states a minimum nominal shell thickness which varies according to the tank diameter (Table 5.6). ** The API 650 standard states that all roof plates and bottom plates shall have a minimum nominal thickness of 5 mm (paragraph 5.10.2.2) and 6 mm (paragraph J.3.2.1) respectively.

Overturing analysis

Key factors in determining the overturing vulnerability of storage tanks to strong wind gusts are the filling level, the presence of anchorages and the maintenance status of the structure (Lara Carvajal et al., 2022). According to previous work, overturing is one of the least likely types of damage to occur, more typical for small tanks (ASCE, 2011), and when it occurs the storage tank must be empty or partially empty (Olivar et al., 2020). This is not the case of the storage tank under consideration; as its filling level is 80%, however, the analysis is still carried out, in accordance with the guidelines stated in the API 650 standard (API 650, 2012), which establishes that, in order for the tank not to overturn, both of the following stability criteria must be satisfied:

$$0.6\, M_w + M_{pi} < \frac{M_{DL}}{1.5} \tag{2}$$

$$M_w + F_p(M_{pi}) < \frac{(M_{DL} + M_F)}{2} + M_{DLR} \tag{3}$$

Where both in equations (2) and (3) and in Figure 1, M_w is the overturning moment about the shell-to-bottom joint from horizontal plus vertical wind pressure (w), M_{pi} is the overturning moment about the shell-to-bottom joint from design internal pressure (pi), M_{DL} is the stabilizing moment about the shell-to-bottom joint from the nominal weight of the shell and roof structural supported by the shell that is not attached to roof plate (DL), F_p is the pressure combination factor (see appendix L.3.1. of the standard. Use 0.4 when not specified), M_F is the stabilizing moment of the shell-to-bottom joint from liquid weight (F), and M_{DLR} is the stabilizing moment of the shell-to-bottom joint from the nominal weight of the roof plate plus any attached structural (DLR). The calculation of wind pressures is also reported in section 5.2.1 of the standard.

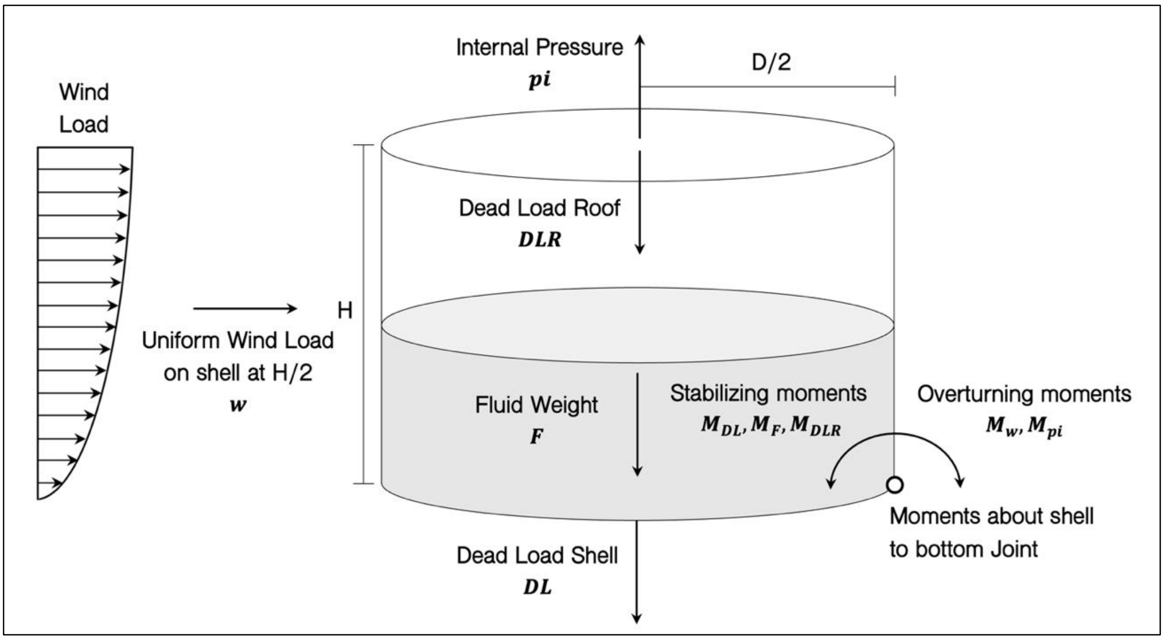

Figure 1: Overturning check for unanchored tanks according to API 650 (API 650, 2012).

The relations (2) and (3) are applied to un-anchored vertical storage tanks subjected to strong winds. However, the application of such criteria to tanks used for the storage of very volatile liquids (i.e., liquids characterized by high vapour pressure), such as in the case of the storage under analysis, often results in the first requirement not being met, since the M_{pi} term assumes high values. For this type of storage, anchorages are required. The design load for the anchorage (U) is also provided by the API 650 standard (API 650, 2012) in section 5.12, both considering the design internal pressure and the wind load.

For anchored tanks, the overturning analysis is carried out by comparing the overturning moments due to internal pressure and wind load, and the stabilizing moments due to the nominal weight of the tank, the weight of the stored liquid and the force exerted by the anchorages. By means of a classical mechanical balance it can be established that, in order for the tank not to overturn, the relation (4) must be satisfied.

$$f_S\,(M_w + M_{pi}) < M_{DL} + M_{DLR} + M_F + M_U \tag{4}$$

Where f_S is a safety factor (a value of 1.2 is recommended). The analysis is conducted taking as reference the five wind speed corresponding to the upper limit for each EF category of tornado intensity, thus assigning to each category a probability for tank k to overturn equal to zero (i.e., $OP_{EF_i} = 0$) when the relation is satisfied,

and equal to one (i.e., $OP_{EF_i} = 1$) when it is not.
The results are shown in
Table **4.** Overturing can occur only in the case of EF5 event and for a maximum of 30% filling level. Lower tornado intensity or higher filling rate will result in no vulnerability to overturning.

Table 4: Overturning analysis result. In case overturing requirement (3) is met (YES) overturing cannot happen, when it is not satisfied (FALSE) overturing can occur.

Fill rate	EVENT INTENSITY				
	EF1	EF2	EF3	EF4	EF5
10%	YES	YES	YES	YES	FALSE
20%	YES	YES	YES	YES	FALSE
30%	YES	YES	YES	YES	FALSE
40%	YES	YES	YES	YES	YES
50%	YES	YES	YES	YES	YES
60%	YES	YES	YES	YES	YES
70%	YES	YES	YES	YES	YES
80%	**YES**	**YES**	**YES**	**YES**	**YES**
90%	YES	YES	YES	YES	YES
100%	YES	YES	YES	YES	YES

Buckling Analysis

The term "*buckling*" refers to the deformation, or the sudden change of shape, of a structural component, typically metal shell, subjected to load. Thus, it is a typical damage mode involved during natural events that can bring on the structure a sudden load, such as storms, hurricanes and floods (Godoy, 2016).
The main parameters capable of influencing the vulnerability to buckling of atmospheric vertical storage tanks are (Godoy, 2016) (Wang and Weng, 2023): tank design (i.e., height, diameter, and shell thickness), structural material properties (Young's modulus and Poisson's ratio), distribution (i.e., spacing, relative position and pattern) of tank groups and topographic effects (i.e., hills, containment dikes).
However, as well as for overturning, also for buckling the most critical factor in determining the damage probability of the tank appears to be his filling level (Zuluaga Mayorga et al., 2019), since when a vessel is empty, the structure is at its lowest strength against buckling and it is vulnerable to either wind or water pressure (Necci et al., 2018).
Several standards, such as the API 620 (API 620, 2002) and the API 650 (API 650, 2012), provide guidelines for the design of atmospheric storage tanks against external wind loads. Shell buckling occurs when the pressure exerted by the wind load P_w at any point along the tank shell exceeds the tank resistance pressure P_r, which is the sum of the tank critical pressure P_{cr}, i.e., the maximum resistance pressure of the tank shell material, and the fluid pressure P_f exerted by the fluid stored in the tank.
For cylindrical shell structures which are subject to the action of uniform external lateral pressure, the critical pressure P_{cr} can be estimated using the elastic shell theory reported in Timoshenko and Gere (Timoshenko and Gere, 1963), on the basis of the geometrical characteristics of the tank and the mechanical properties of the shell material:

$$P_{cr} = \frac{2Et}{D}\left(\frac{1}{(n^2-1)\left(1+\left(\frac{2nH}{\pi D}\right)^2\right)} + \frac{t^2}{3D^2(1-\nu^2)}\left(n^2-1+\frac{2n^2-1-\nu}{1+\left(\frac{2nH}{\pi D}\right)^2}\right)\right) \quad (5)$$

Where E is the elasticity module (Young's module) (Pa), t is the thickness of the shell (m), D is the diameter of the tank (m), n is the number of waves involved in the buckling, H is the height of the tank (m) and is ν

the Poisson's coefficient ($\nu = \frac{E}{2G} - 1$, where G is the shear modulus). Since the number of waves n involved in the buckling is difficult to determine, it can be seen as a parameter included to minimize the critical pressure (Landucci et al., 2012; Olivar et al., 2020; Timoshenko and Gere, 1963). There are also in literature simplified equation both for long and short cylinders often used to calculate critical pressure (Iturgaiz Elso et al., 2012; Khakzad and Van Gelder, 2017; Timoshenko and Gere, 1963; Wang and Weng, 2023).
Besides, the fluid pressure P_f is a function of the density of the stored fluid ρ_f, the gravity constant g, and the height of the stored substances h_f, which depends on the filling level:

$$P_f = \rho_f \, g \, h_f \quad (6)$$

Once the critical pressure and the fluid pressure are defined, they are compared with the pressure exerted by the wind, for the calculation of which it is possible to refer again to the API standard, to the Eurocode (EN 1991-1-4, 2005) or to other sources (Olivar et al., 2020; Pan and Liang, 2020; Xu et al., 2023). If the relation (7) is not satisfied, buckling will occur.

$$f_S \, (P_w) < P_{cr} + P_f \quad (7)$$

Where f_S is a safety factor (a value of 1.2 is recommended). The analysis is conducted taking as reference the five wind speed corresponding to the upper limit for each EF category of tornado intensity, thus assigning to each category a probability for tank k to suffer buckling equal to zero (i.e., $BP_{EF_i} = 0$) when the relation is satisfied, and equal to one (i.e., $BP_{EF_i} = 1$) when it is not.
The results are shown in Table 5. Buckling can occur only in the case of EF3, EF4 and EF5 event and for a maximum of 10% filling level. Lower tornado intensity or higher filling rate will result in no vulnerability to overturning.

Table 5: Buckling analysis results. In case wind load does not exceed (FALSE) the sum of critical pressure and fluid pressure buckling cannot happen, when it does exceed (TRUE) the sum of critical pressure and fluid pressure buckling can occur.

Fill rate	EVENT INTENSITY				
	EF1	EF2	EF3	EF4	EF5
	Wind pressure load [kN/m^2]				
	2122	3212	4932	7191	18648
0%	FALSE	FALSE	TRUE	TRUE	TRUE
3%	FALSE	FALSE	TRUE	TRUE	TRUE
4%	FALSE	FALSE	TRUE	TRUE	TRUE
5%	FALSE	FALSE	FALSE	TRUE	TRUE
6%	FALSE	FALSE	FALSE	TRUE	TRUE
8%	FALSE	FALSE	FALSE	TRUE	TRUE
10%	FALSE	FALSE	FALSE	FALSE	TRUE
20%	FALSE	FALSE	FALSE	FALSE	FALSE
30%	FALSE	FALSE	FALSE	FALSE	FALSE
40%	FALSE	FALSE	FALSE	FALSE	FALSE
50%	FALSE	FALSE	FALSE	FALSE	FALSE
60%	FALSE	FALSE	FALSE	FALSE	FALSE
70%	FALSE	FALSE	FALSE	FALSE	FALSE
80%	**FALSE**	**FALSE**	**FALSE**	**FALSE**	**FALSE**
90%	FALSE	FALSE	FALSE	FALSE	FALSE
100%	FALSE	FALSE	FALSE	FALSE	FALSE

Debris Impact analysis

One common feature of a tornado is wind-generated debris, caused by wind speeds exceeding the threshold for lifting various elements into the air (Stevenson et al., 2023). Such wind-borne debris may have the potential to damage storage tanks, in a phenomenon also referred to as "puncturing damage" (Necci and Krausmann, 2022). This is a very critical damage mode among those analyzed, because, while overturning and buckling can occur only at very high wind speeds and under specific filling conditions, serious damage of this type can already be observed in tornadoes ranked as EF1 intensity.

The vulnerability analysis to debris impact is carried out following the methodology proposed in Talay (Talay, 1975). The aerodynamic force on a static debris object in a wind field can be expressed as:

$$F = \frac{1}{2}\,\rho_a\,U^2\,A_d\,C_l\,I \qquad (8)$$

Where, ρ_a a is the density of air; U is the wind speed; A_d is the reference debris area and C_l is an aerodynamic force coefficient. A further distinction can be drawn between particles at rest, i.e., lying on the ground; and attached particles (like roof tiles). To take into account that for the latter the wind load is also required to break them loose, in Wills et al. (Wills et al., 2002) a fixed strength integrity parameter I has been introduced, equal to the value of force required to dislodge the objects, expressed as a multiple of their weight (Holmes, 2001). In this work, as a precaution, only non-fixed objects will be considered, thus assuming I equal to one, and minimizing the wind speed required for their lifting.

As wind speed increases, the aerodynamic force on the debris increases, until exceeding its gravitational force, $F_P = m\,g$. A wind speed threshold at which a debris starts its flight, becoming an airborne, can be estimated by comparing the aerodynamic force and the gravity force of the debris (Lin, 2005).

$$F = P \quad \rightarrow \quad \frac{1}{2}\,\rho_a\,U^2\,A_d\,C_l\,I = m_d\,g \quad \rightarrow \quad U_{lim} = \sqrt[2]{\frac{2\,m_d\,g}{\rho_a\,A_d\,C_l\,I}} \qquad (9)$$

Similarly, it is also possible to determine the maximum mass of debris of size A_d which can be lifted at a fixed wind speed:

$$m_d = \frac{\rho_a\,U^2\,A_d\,C_l}{2\,g} \qquad (10)$$

Once it has been established whether a debris can lift, it remains to determine what the effect of its impact on a storage tank may be. In this work the methodology proposed by Salzano and Basco (Salzano and Basco, 2015) is adopted. It is based on the computation of the Johnson's number J, a function often adopted in impact engineering, for evaluating the severity of the impact on a continuum loaded impulsively and impinged by the initial velocity pulse. Several authors have generalized and modified Johnson's number to consider the geometrical characteristics of the debris and to cover dynamic plastic failures (e.g., tearing, buckling) (CCPS, 2010; Nurick and Martin, 1989; Zhao, 1998). In this work the formulation provided in Mannan (Mannan, 2005), and reported in other papers (Olivar, 2017; Salzano and Basco, 2015), will be applied:

$$J = \frac{U^2\,m_d}{\sigma_D\,t\,r_d^2} \qquad (11)$$

Where U is the impact speed [m/s], σ_D is the dynamic yield stress (Pa), m_d and r_d are the debris mass [kg] and the radius [m], and t is the shell thickness of the target [m].

A relation between impact speed and wind speed is provided in Lin et al. (2007). According to this study, the ratio of horizontal debris speed to wind gust speed is primarily a function of the horizontal distance travelled by the debris. This ratio tends to increase with the distance, as the debris accelerates toward the wind speed, and it stabilizes in a range between 0.6 and 0.8, after being transported for a variable distance depending on its characteristics (size, density and shape). Conservatively, in this analysis the impact speed was calculated starting from the wind speed and applying a reduction coefficient C_w equal to 0.8.

By combining expressions (10) and (11) it is possible to obtain the following expression of Johnson's number can be written as:

$$J_{EF_i} = \frac{C_w^4 U_{EF_i}^4\,\pi\,\rho_a\,C_l}{2\,\sigma_D\,t\,g\,I} \qquad (12)$$

Where the subscript "EF_i" indicates that the Johnson's number refers to the maximum damage suffered in correspondence of tornado events of a specific EF scale intensity. The range values of Johnson's number and the corresponding regimes, i.e., the kind of deformation exhibited by the impacted material (quasi-static elastic, moderate plastic behavior and extensive plastic deformation) are defined in Nurick and Martin (Nurick

and Martin, 1989). Starting from these values, Salzano and Basco (Salzano and Basco, 2015) performed a probit analysis.
The Probit analysis assumes a nonlinear dose-effect relationship, characterized by almost no response for weak actions, then, as the action increases there is also a proportional increase in the effect, until a certain threshold (i.e., the saturation condition) is reached, thus attributing to the dose-effect curve the characteristic sigmoidal shape. In Probit analysis that curve is assumed to be the normal (or Gaussian) cumulative probability curve. However, for most engineering computations the sigmoidal-shaped dose-response curve does not provide much utility; and an analytical equation is preferred. In particular, a straight line would be ideal since it is amenable to standard curve fit procedures. The probit (probability unit) method provides a scale transformation through a suitable variable, reducing the problem from nonlinear to linear (Aldrich and Nelson, 1984; Barazza et al., 2009; CCPS, 1995; Finney, 1971). This variable, Y, is called the Probit variable and is related to the probability P_f by:

$$P_f = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{Y-5} e^{-\frac{u^2}{2}} du \tag{13}$$

Where:

$$u = \frac{J - \mu}{\sigma} \tag{14}$$

Where $\mu = 5$ and $\sigma = 1$ are the median and the variance of the Gaussian distribution (Finney, 1971). P_f is the target population that will suffer a certain effect if exposed to a given dose (i.e., the percentage of the storage tanks exhibiting failure if exposed to a given impact, characterized by a certain J' value). Probit equations for the probit variable are derived as lines of best fit from experimental data and are based on a causative variable (the dose, J) and at least two constants. To calculate the variable Y, Finney (Finney, 1971) has proposed to use the logarithm of the dose, therefore the following relation can be assumed:

$$Y = K_1 + K_2\, ln(J) \tag{15}$$

Where the values of the parameters $K_1 = 4.5$ and $K_2 = 0.3$ have been determined in Salzano and Basco (Salzano and Basco, 2015) to evaluate the damages to equipment due to fragment projection, eventually correlating all the values of J in the range $10^{-4} \div 10^4$, to a specific probability of failure (P_f), as shown in fig. S2 of the Supplementary materials. For convenience, conversion tables from probit to percent are also available in literature and reported in tab. S1 of the Supplementary materials.
The analysis is conducted taking as reference wind speed the upper limit for each EF category of tornado intensity, thus assigning to each category a probability for tank to fail due to debris impact DIP_{EF_i}.
The results are reported in Table 6.

Table 6: Debris impact probability (DIP) of damage.

Tornado event category	km/h	m/s	J -	Y -	DIP %
EF1	177	49	0.0644	3.6774	9.29
EF2	217	60	0.1462	3.9231	14.08
EF3	266	74	0.3262	4.1639	20.13
EF4	322	89	0.7041	4.3948	27.16
EF5	512	142	4.4802	4.9499	48.00

A summary of the vulnerability analysis is reported in Table 7.

Table 7: Summary of damage probabilities

Tornado event category	km/h	m/s	OP %	BP %	DIP %
EF1	177	49	0	0	9.29

EF2	217	60	0	0	14.08
EF3	266	74	0	0	20.13
EF4	322	89	0	0	27.16
EF5	512	142	0	0	48.00

Risk assessment

In this paragraph a frequency of occurrence is assigned to the top event, i.e. LOC from the storage tank under analysis due to tornado impact. As reported in paragraph 2, loss of containment following tank damage has been considered certain.

Since the damage can occur as a result of any of the three mechanisms investigated, and due to tornadoes classified with any of the category of the Enhanced Fujita scale, the total damage probability can be calculated according to eq. (16).

$$Total\ Damage\ Frequency = \sum_{i=1}^{5} Fr_{EF_i} \cdot \left(OP_{EF_i} + BP_{EF_i} + DIP_{EF_i}\right) \tag{16}$$

Where $OP_{EF_i}, BP_{EF_i}, DIP_{EF_i}$ are the overturning, buckling, and debris impact probability.
The results are reported in Table 8.
A Total Damage Frequency of 2.26E-05 can be expected.

Table 8: Risk Analysis Results

Event category	Fr_{EF_i} [ev/yr]	Overturning Probability [%]	Buckling Probability [%]	Debris Impact Probability [%]	Overturning Frequency [ev/yr]	Buckling Frequency [ev/yr]	Debris Impact Frequency [ev/yr]	Overall Frequency [ev/yr]
EF1	2.18E-05	0.00	0.00	9.29	0.00E+00	0.00E+00	2.02E-06	2.02E-06
EF2	5.11E-05	0.00	0.00	14.08	0.00E+00	0.00E+00	7.20E-06	7.20E-06
EF3	6.64E-06	0.00	0.00	20.13	0.00E+00	0.00E+00	1.34E-05	1.34E-05
EF4	0.00E+00	0.00	0.00	27.16	0.00E+00	0.00E+00	0.00E+00	0.00E+00
EF5	0.00E+00	0.00	0.00	48.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total Damage Frequency [ev/yr]								**2.26E-05**

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USE APA style https://apastyle.apa.org/style-grammar-guidelines/references/examples

SEE Examples below

TEXTUAL WORK

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1.1. Document history – Part 3

Version	Date	Lead contributor	Description
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0.2	27/06/2025	Marco Ravina, Federico Urbinati, Marta Brignone (PoliTo)	First draft
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0.4	17/07/2025	Marco Ravina (PoliTo)	Revision
0.5	18/07/2025	Deborah Panepinto (task coordinator)	Final version

1. Abstract

NaTech events (Natural-Hazard Triggered Technological Accidents) arise from the interplay between natural phenomena and technological incidents involving the release of hazardous substances. Predicting occupational inhalation risks in industrial areas is particularly challenging in the context of NaTech events due to the difficulty in predicting concentration fields, due to the presence of built elements that induce air flow perturbation. In this work, a methodology for the preventive assessment of the risk associated with the accidental inhalation of toxic substances on an industrial site is presented. The methodology is based on NaTech sequence modelling: event and site characterization; simulation of the accidental release and pollutant dispersion; calculation of short-term risk by averaging concentrations and comparing them with the reference values proposed by the main occupational exposure organizations worldwide. The proposed model is applied to a case study corresponding to a chemical company located in central Italy. A NaTech event (vessel failure caused by a flooding) leads to a pool release, evaporation, and dispersion of tetrahydrofuran. A pool evaporation model is applied, and the Lagrangian particle model Parallel Micro-Swift Spray (PMSS) is used for dispersion modelling. The resulting tetrahydrofuran concentration within the industrial area is between 0 and 596 mg m-3 for both stable and unstable atmospheric conditions. The concentration decreases rapidly with the distance from the source. Areas of pollutant accumulation are present near the buildings, caused by recirculation phenomena occurring in the air flow field. The inhalation risk is negligible from around 10 meters distance from the source. However, the threshold limit value for short-term exposure (TLV-STEL) of 100 ppm is exceeded 23 times during the event. The uncertainty on the calculated risk uncertainty arises by considerations on modelling choices, threshold limit values, and the correction method for short-term concentration averaging. On the proposed general methodology, the presented model can be applied with relatively limited resources in terms of calculation resources and practical applicability. The general approach needs to be tested extensively and integrated with analysis of NaTech events dynamics and existing consolidated methodologies for quantitative risk analysis.

2. Table of contents

3.1. List of Tables

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4. Predicting the consequences of a NaTech event: occupational short-term inhalation risk supported by advanced pollutant dispersion modelling

4.1. Introduction

Natural disasters can have profound impacts on industrial infrastructure, often resulting in technological accidents referred to as NaTech events (Natural-Hazard Triggered Technological Accidents). These incidents arise from the interaction between natural phenomena, such as earthquakes, floods, and hurricanes, and technological systems that involve the storage or handling of hazardous substances (Cruz and Suarez-Paba (2019)). The consequences of NaTech events can be severe, including the release of toxic substances into the environment, leading to significant risks to human health and ecological systems.

In Europe, the Seveso-III Directive (Directive 2012/18/EU; European Commission (2024)) provides a robust framework for managing risks associated with dangerous substances, aiming to prevent major industrial accidents and mitigate their consequences. Depending on the volume and nature of hazardous materials on-site, different safety regimes apply. To support these efforts, several databases, including eMARS (eMARS; European Commission (2024b)), eNATECH (eNATECH; European Commission Joint Research Centre (2024)), and others, collect and organize data on past accidents, enabling better risk analysis and the development of preventive measures.

The assessment of risks from NaTech events is complex, largely due to the unpredictable nature of natural hazards and their cascading effects on industrial processes. Natural events can rapidly alter environmental conditions, leading to sudden and uncontrolled releases of hazardous substances. Traditional methods for assessing inhalation risks, especially during acute scenarios, often fail to provide the precision required to protect workers and plan emergency responses effectively (Krausmann et al. (2017), Dou et al. (2022)).

Recent advancements in computational modeling have significantly improved the ability to predict the dispersion of pollutants under complex conditions. High-resolution models, such as Computational Fluid Dynamics (CFD) and Lagrangian particle dispersion models, incorporate factors like wind speed, temperature, topography, and building structures to simulate pollutant behavior accurately. Despite these advancements, challenges remain in addressing uncertainties in model inputs, such as emission rates and meteorological data, as well as integrating dispersion modeling with short-term risk assessments.

Several innovative approaches to inhalation risk modeling have been proposed. These include integrating dispersion models with risk analysis techniques, often on local or regional scales. Studies employing models like AERMOD, CAREA, CALPUFF, and DiMIZA have demonstrated the ability to predict pollutant dispersion and assess health risks, such as cancer and non-cancer outcomes (Malakan et al. (2024); Hassan Bhat et al. (2021); Teggi et al. (2018); Reichwaldt et al. (2016); Karaca et al. (2021); Jones et al. (2023)). However, challenges persist in adapting these models to account for the intricate and variable dynamics of real-world scenarios, particularly in areas with complex industrial and environmental interactions.

This study introduces an integrated methodology to assess inhalation risks for workers on industrial sites during NaTech events. The approach begins with characterizing the event and the industrial site, including built structures, hazardous substances, and meteorological conditions. It proceeds with modeling potential accidental releases and simulating the dispersion of toxic substances in and around the source area. The estimated pollutant concentrations are then compared with reference levels from international occupational safety organizations to assess health risks.

The proposed methodology is designed to provide timely and accurate risk assessments, enhancing emergency response strategies and protecting worker health. By integrating predictive modeling with spatial mapping, it aims to support proactive and responsible risk management, particularly in the context of increasing climate-related challenges.

4.2. Methodology

The proposed methodology consists of a structured four-phase workflow designed to assess inhalation risks during NaTech events.

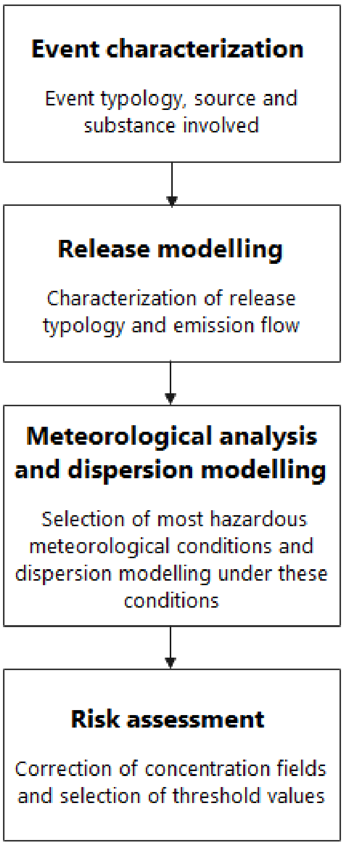

Figure 1. Methodology workflow

The first phase focuses on event characterization, where the type of event, the source, and the hazardous substances involved are identified. This step establishes a detailed understanding of the materials and conditions leading to the accidental release, including critical factors such as the physical state, temperature, and pressure of the hazardous substance.

In the second phase, the accidental release is simulated by defining the source term. This involves characterizing the quantity and nature of the emitted material, the release mechanism, and its physical properties (Fabbri and Wood (2019)). The release process is modeled based on factors such as vessel rupture or leakage, and the subsequent flow dynamics are simulated to capture the behavior of the substance under real-world conditions.

The third phase addresses the dispersion of hazardous substances. Advanced dispersion models, such as Gaussian plume models, Lagrangian particle models, and computational fluid dynamics (CFD), are employed to simulate the spread of pollutants around the source and the affected site. These simulations consider meteorological and atmospheric conditions, terrain features, and obstacles like buildings, providing a detailed understanding of the dispersion patterns. Meteorological data and atmospheric stability, often characterized by the Monin-Obukhov length (Monin and Obukhov (1954)), are integral to this phase.

In the final phase, the exposure levels derived from dispersion simulations are combined with toxicological data to estimate health risks. This is achieved by calculating hazard quotients (HQ), which compare exposure concentrations with reference concentrations (RfC) for specific durations (Ravina et al. (2020b)).

The methodology also adapts hourly average concentrations to shorter intervals using techniques like peak-to-mean ratios or power law functions to reflect acute exposure scenarios.

A case study demonstrates the application of this methodology by analyzing a hypothetical NaTech event. In this scenario, a flood triggers the release of tetrahydrofuran from a chemical manufacturing site. The release and dispersion are modeled under critical meteorological conditions, accounting for site-specific characteristics like wind direction and topography. This case study illustrates the practical utility of the approach in predicting pollutant behavior and assessing the associated health risks.

Overall, the methodology integrates advanced modeling tools, comprehensive data sources, and precise risk assessment techniques. This ensures robust evaluations of inhalation risks, supporting effective emergency planning and worker safety in the dynamic and complex contexts typical of NaTech events.

4.1.1. Case study

The case study explores a hypothetical NaTech event at a chemical production facility in central Italy to assess potential accident dynamics and associated risks. The industrial site spans approximately 145,000 m² on flat terrain 20 km from the sea. The facility houses various production units and solvent storage tanks with differing hazard levels. Using data from the eMARS (Major Accident Reporting System) database (European Commission (2024b)) database, the study is based on a flooding incident that occurred on August 15, 2002, which damaged an ethylbenzene storage tank. For the study, ethylbenzene was replaced with tetrahydrofuran, a volatile and toxic solvent, to model the consequences of its release.

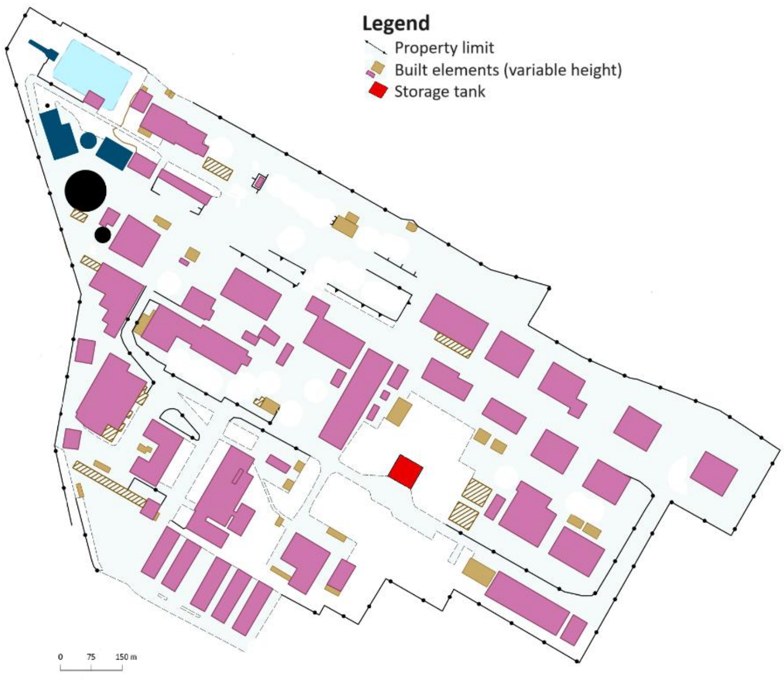

Figure 2. Plan view of the industrial settlement

The damaged tank in the simulation has a cylindrical geometry (15 m diameter, 9 m height) and is positioned within a square containment basin (2 m high, 30 m sides). The tank was assumed to be 80% filled with tetrahydrofuran, a polar aprotic solvent widely used in polymer production. Tetrahydrofuran is a volatile, water-soluble liquid with significant health risks upon inhalation, including symptoms like throat irritation, dizziness, nausea, and potential loss of consciousness (Dannan (2015)).

This case study highlights the use of the eMARS database to model NaTech scenarios and demonstrates preventive risk assessments for chemical facilities exposed to natural disasters. It emphasizes the importance of robust safety measures, including ventilation systems and personal protective equipment, to mitigate health risks associated with hazardous substance releases.

Table 1. Properties of tetrahydrofuran (Dannan, 2015)

Formula	C_4H_8O
Molecular weight (g/mol)	72.1057
CAS number	109-99-9
Density at 25°C (g/ml)	0.881
Henry's law constant for solubility in water at 25°C (mol/(kg*bar))	14
TLV-STEL (ppm)	100
NIOSH REL (ppm)	250

4.2.1.1. Release model and evaporation model

The case study simulated the release and evaporation of tetrahydrofuran (THF) from a damaged storage tank (van den Bosch (2005)). The solvent spilled through a 100 mm pipe rupture at the tank's base, spreading into a containment basin where it formed a pool that evaporated and dispersed into the atmosphere. The hydraulic pressure governed the mass flow rate of the discharge, modeled iteratively using Matlab® (Mathworks Inc. (2024)). Bernoulli's equation determined the discharge rate, while liquid volume and height changes were updated at each time step until the tank emptied.

Simultaneously, evaporation dynamics were modeled, with the evaporation rate dependent on the mass transfer coefficient and vapor concentration. The pool's replenishment and evaporation were iteratively calculated, using the Kawamura and Mackay model for mass transfer and the Antoine equation for vapor pressure.

4.2.1.2. Dispersion modelling

To simulate pollutant dispersion, the PMSS system was employed, utilizing meteorological data from 2021 due to unavailability from 2002. The dispersion model considered a spatial domain of 560x450 m with fine resolution (2 m cells). PSwift accounted for atmospheric and building-induced flow disturbances, while Spray simulated Lagrangian particle dispersion. Critical meteorological conditions, including low temperatures and stable/unstable atmospheres, were analyzed.

4.2.1.3. Short-term risk calculation

Short-term inhalation risks were evaluated by mapping ground-level concentration fields against TLV-STEL thresholds (American Conference of Governmental Industrial Hygienists (2024)). Concentration adjustments for 15-minute exposures were calculated using a factor derived from meteorological data. The findings informed the risk of hazardous substance exposure to workers, emphasizing the importance of atmospheric conditions and structural dynamics in dispersion modeling.

4.3. Results

The simulation of the accidental release of tetrahydrofuran (THF) provided detailed insights into the dynamics of the event and the associated environmental and health risks. The incident began with the rupture of a storage tank, causing THF to spill into a containment basin, where it formed a pool. Initially, the rate of liquid release from the tank exceeded the rate of evaporation, leading to an increase in the pool volume. Following the complete emptying of the tank, evaporation continued independently until the pool fully evaporated within approximately 24 hours. Variations in evaporation rates were influenced by environmental factors, including wind speed and temperature, with these parameters playing a critical role in determining the speed and extent of THF dispersion.

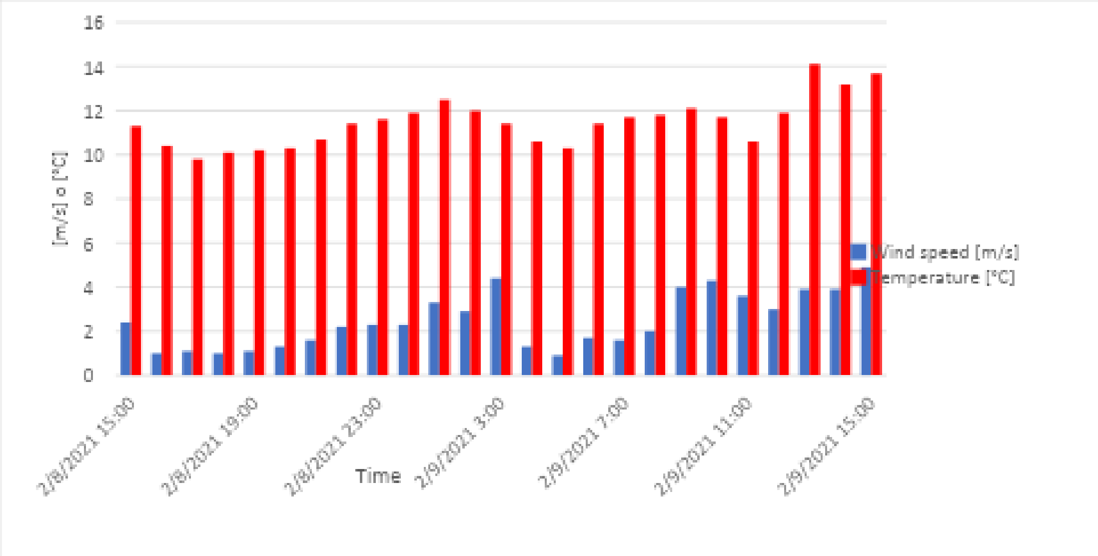

Figure 3. Ambient temperature and wind speed during release and evaporation period

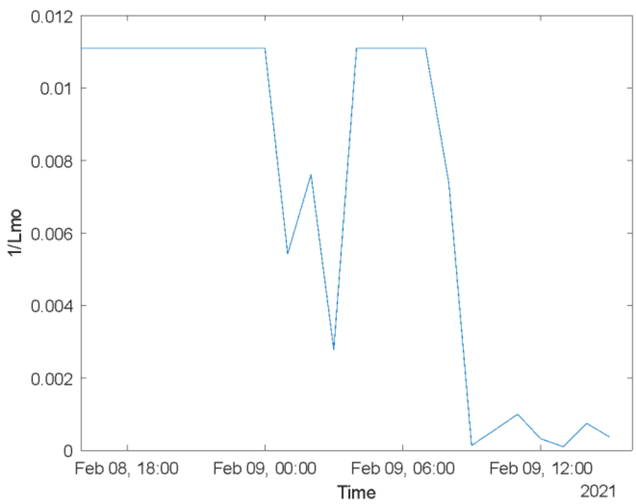

Figure 4. Inverse of the Monin-Obukhov length during the release and evaporation period

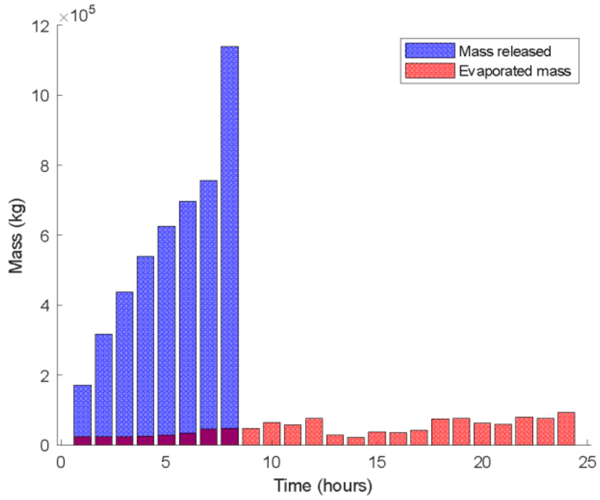

Figure 5. Mass released from the vessel and evaporated during the event

Table 2. Mass spilled, mass evaporated and weather conditions during the event

Time [hours]	Liquid level [m]	Mass released [kg]	Temperature [°C]	Wind speed [m/s]	Evaporated mass [kg]
0	7.24	0	11.3	2.4	0.00
1	6.16	171024.94	10.4	1	22847.38
2	5.23	315866.69	9.8	1.1	23889.72
3	4.46	437580.40	10.1	1	22510.69
4	3.81	539517.04	10.2	1.1	24368.35
5	3.27	624729.92	10.3	1.3	27897.48
6	2.82	695929.63	10.7	1.6	33456.57
7	2.44	755469.32	11.4	2.2	44391.61
8	0.00	1139200	11.6	2.3	46410.08
9	0.00	0	11.9	2.3	47095.45
10	0.00	0	12.5	3.3	64262.48
11	0.00	0	12	2.9	56704.87
12	0.00	0	11.4	4.4	76226.20
13	0.00	0	10.6	1.3	28314.03

14	0.00	0	10.3	0.9	20941.04
15	0.00	0	11.4	1.7	36304.58
16	0.00	0	11.7	1.6	35140.03
17	0.00	0	11.8	2	42025.63
18	0.00	0	12.1	4	73227.40
19	0.00	0	11.7	4.3	75979.07
20	0.00	0	10.6	3.6	62667.42
21	0.00	0	11.9	3	57940.98
22	0.00	0	14.1	3.9	79079.73
23	0.00	0	13.2	3.9	75729.71
24	0.00	0	13.7	4.9	92693.67

Meteorological modeling, conducted using the PSWIFT and SURFPRO tools, provided high-resolution wind field and turbulence data, accounting for the effects of built structures in the area. Under stable atmospheric conditions, characterized by low wind speeds and limited turbulence, THF concentrations remained high near the source due to stagnation and reduced dispersion. In contrast, under unstable atmospheric conditions with higher wind speeds, the pollutant dispersed more effectively, although localized accumulations were observed near buildings due to wake effects and recirculation zones caused by airflow disruptions.

Concentration maps revealed that THF levels decreased rapidly with distance from the source. Maximum concentrations, reaching up to 596 mg m^{-3}, were observed during the first hour of the event within the containment area. For risk assessment, 15-minute corrected concentrations were analyzed and compared to the TLV-STEL (Threshold Limit Value - Short Term Exposure Limit) of 100 ppm (American Conference of Governmental Industrial Hygienists (2024)). The TLV-STEL represents the maximum concentration tolerable for short durations without adverse effects.

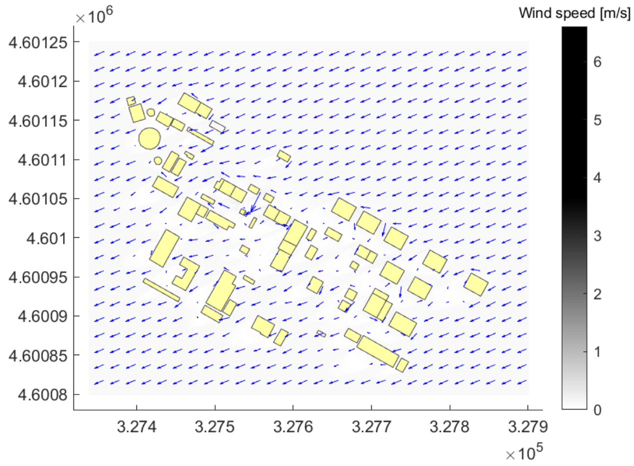

Figure 6. Representation of the wind field during stable atmospheric conditions

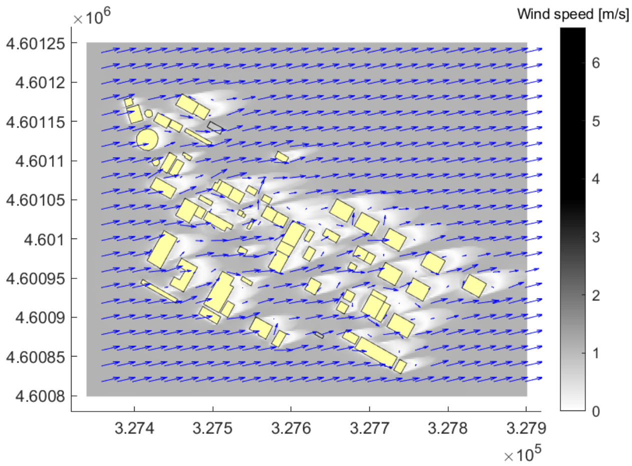

Figure 7. Representation of the wind field during unstable atmospheric conditions

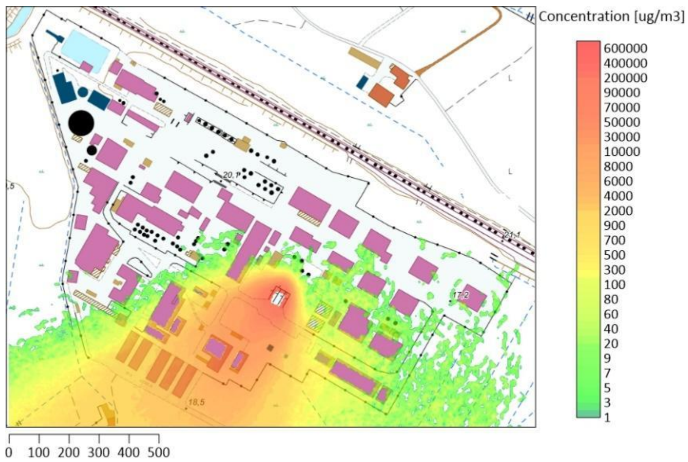

Figure 8. 15-minutes mean tetrahydrofuran corrected concentration during stable atmospheric conditions

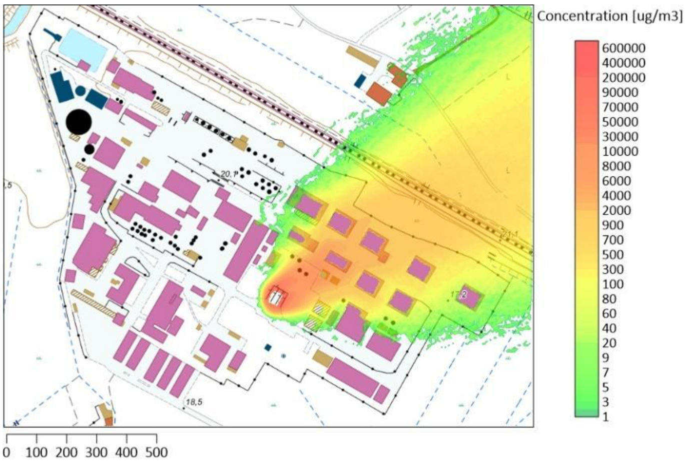

Figure 9. 15-minutes mean tetrahydrofuran corrected concentration during unstable atmospheric conditions

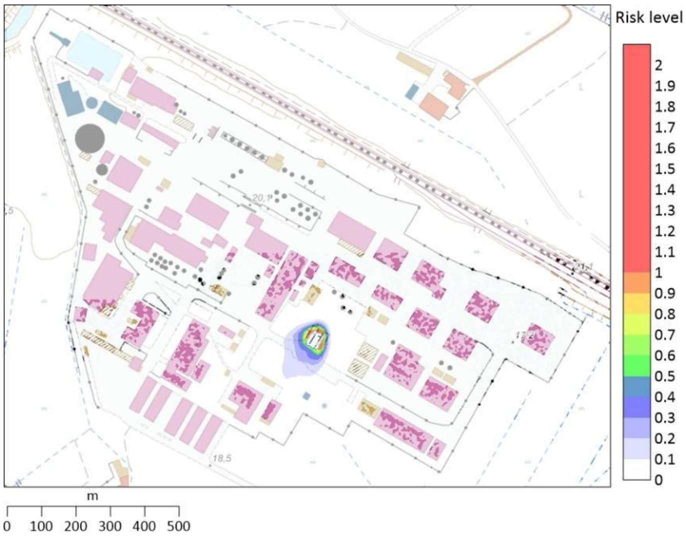

Figure 10. Short-term inhalation risk map in stable atmospheric conditions

Figure 11. Short-term inhalation risk map in unstable atmospheric conditions

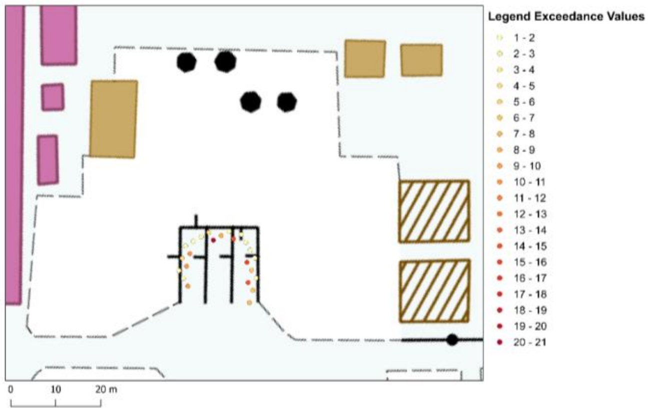

Figure 12. Position and frequency of exceedances of the threshold limit value during the even

The results demonstrated that significant short-term inhalation risks were confined to within 10 meters of the source, where HQ (Hazard Quotient) values frequently exceeded 1, indicating unacceptable risk levels. A total of 23 exceedances of the TLV-STEL were recorded, all within the industrial site's boundaries. These exceedances were most pronounced during the early stages of the release when concentrations were highest. Beyond the immediate vicinity of the source, THF concentrations dropped rapidly, and the associated risks became negligible.

The findings underscore the importance of accounting for both atmospheric and structural factors in evaluating the dispersion of hazardous substances. They also highlight the need for robust containment and emergency response measures to mitigate risks in industrial sites handling volatile and toxic chemicals like THF. Additionally, the study emphasizes the critical role of real-time monitoring and predictive modeling in managing NaTech events and protecting both human health and the environment.

5. Conclusions

The case study demonstrates that, despite occasional exceedances of the TLV-STEL in the vicinity of the release source, the accidental event triggered by a NaTech (Natural Hazard Triggering Technological Disasters) scenario does not pose a significant inhalation risk for tetrahydrofuran (THF). The study primarily highlights the broader applicability of the general methodology used, emphasizing its adaptability across different scenarios. However, it also underscores the complexity and variability of the factors influencing risk, such as the physical and chemical properties of the released substance, environmental conditions, and the geometric and topographical characteristics of the site.

Substance volatility plays a pivotal role in determining evaporation dynamics and, consequently, the dispersion and risk profiles. For instance, less volatile substances like methyl ethyl ketone or ethylbenzene would have significantly longer evaporation durations under similar conditions, potentially allowing for intervention before evaporation is complete. This demonstrates the necessity of tailoring risk assessment models to account for substance-specific properties and site configurations.

The study also reflects methodological considerations. Variability in reference databases for exposure limits, such as the discrepancy between stricter (100 ppm) and less restrictive (250 ppm) TLV-STEL values, can significantly affect risk evaluations. Similarly, debates continue regarding the optimal approach for correcting average concentration values over short periods, with an emphasis on balancing simplicity and rigor in the methodologies applied.

In terms of broader applications, the proposed methodology requires refinement to improve its generalizability while minimizing uncertainties at every operational step. While current large-scale models, such as the Accident Damage Assessment Module (ADAM) (European Commission. Joint Research Centre (2017)) and BenMap-CE (Malakan et al. (2024)), are well-established for major accidents, the study highlights the need for further development of methodologies suited to micro-scale accidents, such as those in industrial environments. Integrating these models into QRA (Quantitative Risk Analysis) processes, especially for both Seveso and non-Seveso facilities, is essential to enhance preparedness for NaTech events.

In conclusion, the proposed methodology offers a valuable tool for emergency management in industrial settings, combining rapid and high-resolution inhalation risk assessments with practical applicability. It enables effective scenario planning, training, and response strategies for potential NaTech events, improving worker safety and operational preparedness. By incorporating a Lagrangian particle model that simulates building effects on pollutant dispersion, the methodology achieves a detailed analysis of dispersion pathways under varying meteorological conditions with reduced computational effort compared to traditional computational fluid dynamics models.

To advance this work, extensive testing and integration with existing risk analysis frameworks are necessary. Addressing the challenges of NaTech events in the context of climate change and evolving industrial practices requires continued research, interdisciplinary collaboration, and technological innovation. Future efforts should focus on reducing model uncertainties, enhancing scalability, and adapting the methodology to diverse industrial sectors and geographic regions. With these advancements, the proposed approach could become a critical tool for protecting health and safety in industrial environments.

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