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A COMPREHENSIVE ANALYSIS OF THE OCCURRENCE OF NATECH EVENTS IN THE CHEMICAL AND PROCESS INDUSTRY

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ABSTRACT

Natural events triggering technological scenarios (Natech events) are an increasing concern for regulatory authorities and industry, in particular in areas prone to natural disasters. A comprehensive analysis of the occurrence of Natech scenarios affecting the process industry is presented. A dataset of 9100 past accidents that took place in the last 70 years was compiled and analysed, with the aim of understanding the trend of Natech events, their geographical distribution, the final technological scenarios, and the associated consequences in terms of human losses and asset damages. Meteorological events, such as storms, extreme temperatures and lightning were found to be the main trigger of Natech scenarios (86%). Despite the difficulty in collecting homogeneous data worldwide, an increasing number of Natech events over the time is observed. Moreover, specific increases in the occurrence of Natech events correspond to the occurrence of severe natural disasters as the devastating hurricanes that affected the Gulf of Mexico in recent years. The societal risk curve associated to Natechs was calculated, evidencing the relevance of extremely severe accidents (> 100 deaths). The analysis of the dataset also allowed building quantified event trees for the evolution of Natech scenarios. Specific ignition probability values for Natech events were estimated.

HIGHLIGHTS

- A total of 9100 Natech events were collected and analysed
- Meteorological events were found to be the main trigger of Natech scenarios
- Past accident analysis allowed the quantification of event trees for Natech scenarios
- Ignition probabilities specific for Natech were estimated
- Societal risk curve highlights the relevance of severe accidents

KEYWORDS

Natech; major accident hazard; chemical and process industry; past accident analysis

1 INTRODUCTION

In recent years, the number of meteorological events caused by short-term, medium-scale extreme weather conditions (lasting from minutes to days (Centre for Research on the Epidemiology of Disasters (CRED), 2020)) and climatological events caused by long-term, macro-scale atmospheric processes (ranging from intra-seasonal to multi-decadal climate variability (Centre for Research on the Epidemiology of Disasters (CRED), 2020)) is growing, and such events became of concern for industrial activities (Krausmann et al., 2017). Among the wide number of adverse consequences that severe natural events may have on industrial sites, technological accidents caused by the impact of natural events, defined as Natech scenarios in the literature (Cruz and Krausmann, 2013; Krausmann et al., 2017), are of particular concern, due to the potential escalation of the overall consequences of the impact of the natural event on the population and on the environment caused by such scenarios. Clearly enough, Natech scenarios also have the potential to inflict severe economic losses to industrial activities. On the one hand, these may derive from the direct damages to assets and/or to business interruption. On the other hand, these may be related to the escalation of the technological scenarios, generating major accidents involving hazardous substances similar in consequences to those experiences due to internal failure causes (Andersen et al., 2004; Delvosalle et al., 2006; Krausmann et al., 2017). Furthermore, in some areas of the world, intense natural hazards have expected times of return that are high when compared to those of the expected conventional technological accidents considered for a single facility. As an example, the frequency of a major hurricane in the South Coast of the United States can be estimated of 2·10-2 events/year (Landsea et al., 2004), while reference values for the tolerable frequencies of severe technological accidents are usually lower than 1·10-5 events/year (Uijt de Haag and Ale, 1999). Thus, the frequency of severe Natech scenarios may result higher with respect to that of conventional scenarios when a single production site is considered.

For these reasons, the attention devoted to Natech scenarios has been growing among industry, regulatory authorities and academia. Nonetheless, even if in many countries there is a legal framework for the prevention and mitigation of industrial accidents, only in few cases this extends to address the control of the hazards caused by Natech scenarios: e.g. the European Union required to include Natech scenarios in the safety reports of sites storing or processing relevant quantities of hazardous chemicals only in 2012, issuing the

"Seveso-III" Directive (European Commission, 2012). In the U.S., although several federal programs address the risk management of hazardous materials and the planning of emergency response, none of them requires to consider natural events as a cause of technological accidents. Furthermore, in some cases, regulation addressed Natech scenarios generated only by specific natural events: e.g. in California regulations address only Natechs triggered by earthquakes; similarly, in Japan regulations address only Natechs triggered by earthquakes and tsunamis (Krausmann et al., 2017).

Despite the increasing attention devoted to the topic, there still is no systematic tracking of industrial sites in natural-hazardous zones, and a systematic monitoring of Natech accidents is still missing (Krausmann et al., 2019). In a recent study, Krausmann et al. (Krausmann et al., 2019) highlighted the lack of a harmonized data collection system devoted to Natech, that could be used, among all, as a baseline for comparing risk trends over time.

In this panorama, the present study aims at building an original dataset dedicated to Natech events and to provide a comprehensive analysis of the occurrence of Natech scenarios. More than 9000 Natech events that took place in the last 70 years were collected. The time-trend of Natech scenarios was compared to the corresponding trend of natural events (Centre for Research on the Epidemiology of Disasters (CRED), 2020). The worldwide geographical distribution of Natech events was also analysed. An analysis of the probabilities of occurrence of the scenarios was carried out, by means of even trees derived for categories of hazardous substances involved in the accidents. Correlation between the technological scenarios and the natural events that triggered it were found. Consequences in terms of human and economic losses were analysed, and an estimation of the societal risk associated to Natech events was carried out.

2 METHODOLOGY

2.1 Development of the database

The starting point of this study was the collection of data about industrial accidents caused by natural events, with the objective of building a dedicated data repository. To this aim, several different databases reporting data on industrial accidents, though not specifically on Natech events, have been analysed. The following databases were consulted:

- eMARS (Major Accident Reporting System) database (European Major Accident Hazards Bureau (MAHB), 2019): managed by the European Major Accident Hazards Bureau (MAHB) of the European Commission's Joint Research Centre (JRC), was established after the implementation of the first “Seveso” Directive (82/501/EEC) in 1982, and it is still active. The database includes entries on both accidents and near misses occurred in the European Union, obtained from the mandatory reporting system issues under the Seveso Directives, and event reports provided by regulatory authorities of other countries on a voluntary basis. The records in eMARS provide a detailed description of the accident, including a description of the installation and of the substances involved, the causes, the consequences and the emergency response procedures. This database provided the most detailed data collected within the present study.

- MHIDAS (Major Hazards Incident Data Service) database (Harding, 1997; UK Health and Safety Executive, 2006): managed by AET Technology on behalf of the Health and Safety Executive of United Kingdom, it was dismissed in 2006. It collects accidents that occurred in the process industry, in the transportation and in the storage of hazardous materials that occurred in 95 different countries around the world. MHIDAS records provide an abstract of the accident, specific information about the material and equipment involved, and information on the cause-consequence chain of the events.
- TAD IChemE (The Accident Database, Institution of Chemical Engineers) database (Institution of Chemical Engineers (IChemE), 2000): collects accidents involving dangerous substances that took place worldwide. IChemE 's accident database and contains over 10’500 entries. The database was populated in the period between 1997 and 2000. The records available are detailed and provide a brief description of the accident, including information about causes, consequences and, in few cases, about the equipment and the substances involved.
- ARIA (Analysis, Research and Information on Accidents) database (The French Bureau for Analysis of Industrial Risks and Pollutions (BARPI), 2019): managed by the Bureau for Analysis of Industrial Risks and Pollutions (BARPI), it collects incidents and accidents that affected or have shown a potential damage to health, public safety or environment. Although the database includes events from all over the world, 87% of the records concern accidents that took place in France. The records of ARIA are characterised by a good level of detail. Not all the records are available in English.
- NRC (National Response Centre) database (U.S. Coast Guard, 2019): managed by the U.S. Coast Guard, is part of the American National Response System and since 1990 it collects records about the release of hazardous substances in the environment anywhere in the United States and its territories. The entries are derived from voluntary calls of citizens

witnessing to any type of spill and describing it to the Authorities. For this reason, information reported not always is accurate or verified.

- CONCAWE (Cech et al., 2019): a division of the European Petroleum Refiners Association that annually publishes a report about the performance of European cross-country oil pipelines, in which events resulting in spills are reported. The records of CONCAWE are characterized by a low level of detail, as no description of the event is provided. Nevertheless, information about the service, the type and the part of the pipeline that failed are provided.

Within the various database, Natech events were searched using keywords based on the natural event that could trigger the technological scenario, e.g. "lightning", "earthquake", "flood", etc. The terminology related to natural phenomena used was derived from the EM-DAT glossary (Centre for Research on the Epidemiology of Disasters (CRED), 2020). The keywords were translated also in the language of origin of the database when this was necessary, i.e. for the case of ARIA. The original focus of each database influenced the details available on the Natech events.

Three specific inclusion criteria were defined and used to establish whether to include or not the records found:

1) The event should be classified as an accident, incident or loss of containment event, according to the definitions provided below.
2) The event should be a Natech accident, according to the definition provided below.
3) The event should have occurred in the industrial sectors listed in Table 1.

Concerning the first point, records were retained for the present analysis if they were either incidents, accidents or loss of containment events defined as follows:

- Accident: an event that may cause one or more fatalities or permanent major disabilities, and/or heavy financial loss (Rathnayaka et al., 2011);
- Incident: an event that could cause considerable harm or loss such as a major health effect or injury, localized damage to assets and environment, considerable loss of production and impact to company reputation (Rathnayaka et al., 2011);
- Loss of containment: event resulting in the release of material (Director-general for social affairs and employment (Pays-Bas) and Committee for the prevention of the disasters, 1999).

With respect to the second point, Natech events were considered according to the following definitions available in literature: a “Technological accident involving the release of, or the potential release of, hazardous materials, triggered by a natural event" (European Commission, 2016).

With respect to the third criterion, the records were retained only if occurred in the specific industrial sectors listed and described in Table 1. This last criterion was added to ensure a pool of data relevant for the chemical and process industry. For instance, events that took place in the nuclear industry, or related to agricultural and mining activities were not included due to the different features of safety standards and technological scenarios affecting such systems. The classification into macro-sectors (Casson Moreno et al., 2018) was done starting from the International Standard Industrial Classification of All Economic Activities (United Nations Industrial Development Organization, 2002), where a comprehensive list of productive activities is given and categorised with the purpose of supporting the collection and reporting of statistics according to such activities.

Macro-sector	**Description** (Casson Moreno et al., 2018)
Chemical & Petrochemical	Chemical activities, including pesticides production, pharmaceutical industry, production of basic chemicals. Petrochemical activities, including refineries.
Storage & Warehousing	Sites where chemicals are stored in appointed equipment (i.e. storage tanks) and storage buildings (warehouses/depots).
Power production	Power production plants using hydrocarbons (thermal power stations). Nuclear power plants were not included in the present analysis.
Bioprocesses	Treatment of organic waste and waste fermentation juices; food industry.
Water treatment	Treatment of water for industrial and domestic purposes (excluding bioprocesses-related waters and slurries).
Transportation	Transportation of hazardous materials via road, rail and water.
Pipeline	Oil and gas transportation via pipelines.
Manufacturing	Metal working, textile industry, activities related to automotive sector where hazardous substances are used.

Table 1– List and description of the industrial macro-sectors considered in the data collection.

Since the number of data sources consulted is high and varied, specific attention was dedicated to avoid the inclusion of duplicate records. Specific checks were based on date, geographic location, type of industrial activity, equipment items and substances involved in the event.

During the process of data retrieval, over 35’000 records where processed. Among these, several records were discarded since the event did not comply with the definition of Natech, or did not affect an industrial site, or the industrial activity did not fall within the list reported in Table 1.

The events collected were organized in a database, whose structure is shown in Figure 1. The database contains both free text entries (grey boxes in Figure 1) and itemized lists (coloured boxes in Figure 1). The free entry fields allow collecting data such as the date and the geographic location of the event, the number of injuries and fatalities, the economic damage and the substances involved. The itemized lists were created to standardize the input data regarding the triggering natural event, the final scenario and the category of substance involved.

The final scenarios considered in this study are listed and defined in Table 2. Any combination of them is called “multiple scenarios” in the following.

The hazards related to the chemical substances involved in the technological accidents were classified, according to the Globally Harmonized System (United Nations, 2011), into: Flammable substances, Acutely Toxic substances and substances Hazardous to the aquatic environment, as listed in Figure 1.

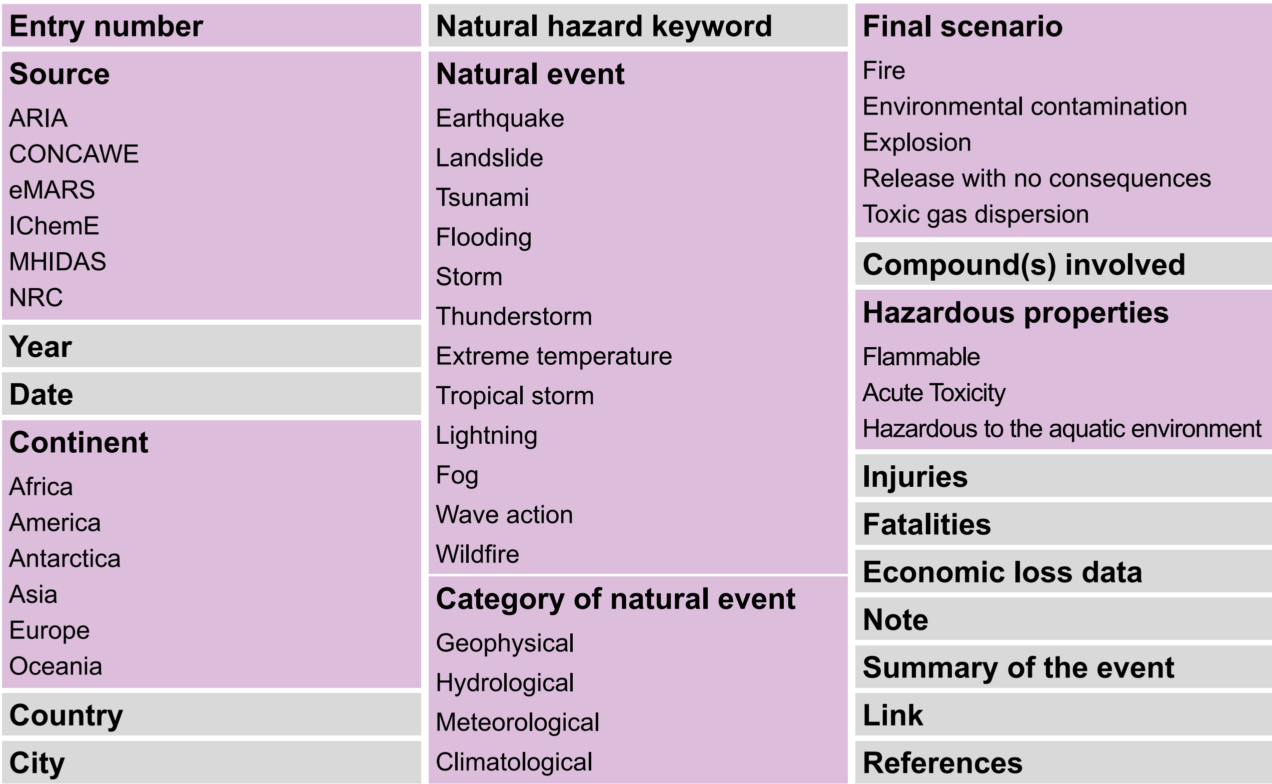

Figure 1 – Structure of the database: coloured boxes represent itemized fields while grey ones represent free text entries. The term "natural event" in the table indicates the natural event that triggered the Natech scenario.

Scenario	Definition
Fire (F)	An uncontrolled combustion process characterized by the emission of heat and smoke. Includes all type of industrial fires, i.e. pool fires, flash fires, jet fires and fireballs (Van den Bosch et al., 1997).
Explosion (E)	A sudden release of energy that causes a blast wave (Van den Bosch et al., 1997). Includes all type of industrial explosions, i.e. unconfined and partially confined gas and vapor explosions (VCE), confined explosions, mechanical explosions (Reniers and Cozzani, 2013)
Toxic gas dispersion (TGD)	The dispersion of a toxic substance in air (Andersen et al., 2004).
Environmental contamination (EC)	Contamination of surface waters (rivers, lakes, seas, ...) or of the aquifer by substances harmful to the aquatic environment (Andersen et al., 2004).
Release with no further consequences (R-NFC)	The release of a liquid or gas from its containment (Van den Bosch et al., 1997), in quantities and concentrations that have no short-term potential consequence for persons and environment.

Table 2 – Definition of final scenarios present in the database.

2.2 Taxonomy of the natural events

Given the variety of the terminology on natural phenomena used to query the original sources (and reported in the box called "Natural Hazard Keyword" in Figure 1, the natural events triggering the technological scenario ("Natural event" in Figure 1) were classified according to the taxonomy provided by the Centre of Research on the Epidemiology of Disasters (Centre for Research on the Epidemiology of Disasters (CRED), 2020) and aggregated into the four macro-categories defined in Table 3. A schematic representation of the categorization of the natural causes into the four macro-categories adopted is reported in Figure 2.

Term	Definitions
Geophysical	A hazard originating from solid earth. This term is used interchangeably with the term geological hazard.
Meteorological	A hazard caused by short-lived, micro- to meso-scale extreme weather and atmospheric conditions that last from minutes to days.

Hydrological	A hazard caused by the occurrence, movement, and distribution of surface and subsurface freshwater and saltwater.
Climatological	A hazard caused by long-lived, meso- to macro-scale atmospheric processes ranging from intra-seasonal to multi-decadal climate variability.

Table 3 – List and definition of the macro-categories of natural events adopted in the present study (adapted from Centre for Research on the Epidemiology of Disasters (CRED), 2020).

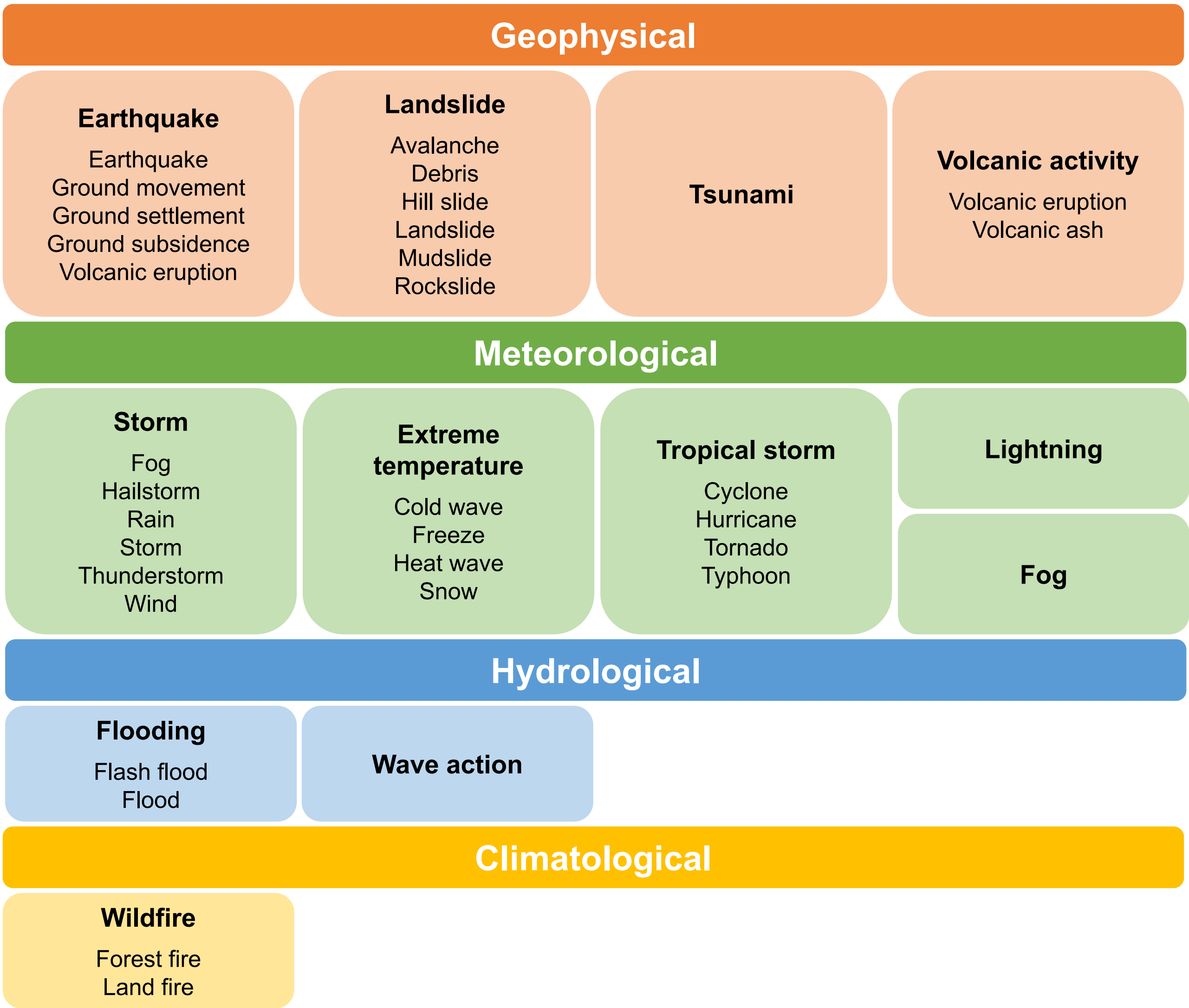

Figure 2 – Taxonomy of the natural events triggering technological scenarios based on the four macro-categories derived from the definitions given by the Centre of Research on the Epidemiology of Disasters reported in Table 3.

2.3 Estimation of representative frequencies and societal risk

On the basis of the records collected, reference relationships between event frequencies and the number of people suffering a specified level of harm expressing the societal risk (Health and Safety Executive (HSE), 2009) was evaluated. The approach used for the estimation of societal risk was derived by that applied in previous studies concerning database analysis (Carol et al., 2002; Fabiano and Currò, 2012). Societal risk is represented by f/N curves, which are plots of the cumulative frequency (*f*) of the accident scenarios causing at least a number (*N*) of casualties associated to the events (Health and Safety Executive (HSE), 2009). The 'casualties' considered in this study are fatalities, as usual when dealing with the societal risk caused by technological scenarios (Health and Safety Executive (HSE), 2009). Since a direct comparison of societal risk due to transportation accidents with accidents occurring in fixed installations is not significant, only societal risk and accidents occurred in fixed installations were considered in the calculation of societal risk.

Since no data are available for the worked hours or chemical and process sites worldwide, proxies for the yearly frequencies of the scenarios ($f_{\bar{n}}$) were obtained dividing the number of records with the same number of fatalities ($\bar{n}$) present in the dataset considered by the worldwide number of industrial sites (s) and by the reference time period of accidents:

$$f_{\bar{n}} = \frac{\bar{n}}{s \cdot t_{ref}} \quad (1)$$

The reference time period, t_{ref}, is the time interval, expressed in years, of the events considered in the analysis, that may correspond to the entire dataset to a subset of data, as discussed in the following.

The worldwide number of industrial sites (s) considered in the present study was derived from the data available in the United Nations Industrial Development Organization website (United Nations, 2020), where the number of sites present in each Country is given per year for the period 2000-2017. These data were considered for the calculation of the trend of Natech events normalized with respect to the yearly active number of industrial sites (as reported in section 3.1), where the yearly value of s in the period 2000-2017 was used. However, the data available in the UN database do not cover the entire time interval of the events included in the database. Therefore, in Eq. (1), in order to obtain at least a representative value of the frequencies of the events to be considered in the assessment of societal risk, the average value obtained considering the entire period for which data are available (1’671’000) was used to estimate the number of sites, *s*.

Clearly enough, Eq. (1) only provides a rough estimation of the actual frequencies of the events, since the number of operating hours per site is not reported in the consulted database, and relevant differences may be present among different sites.

The cumulative frequency (f_N) of the accident scenarios with a number of fatalities equal or higher than (N) is then calculated as:

$$f_N = \sum_{\bar{n}=N}^{N_{max}} f_{\bar{n}} \qquad (2)$$

2.4 Natural disaster data trends

In order to find a possible correlation between the number of Natech events and that of natural disasters or severe natural events, a comparison with a dataset of natural disasters was carried out. The set of data was derived from the International Disaster Database of the Centre of Research on the Epidemiology of Disasters (EM-DAT) (Centre for Research on the Epidemiology of Disasters (CRED), 2020). The definition of “natural disaster” given by the original source (Centre for Research on the Epidemiology of Disasters (CRED), 2020) implies that at least one of the following conditions is verified:

- Fatalities: equal or more than 10.
- Affected individuals: equal or more than 100.
- The state of emergency is declared.
- International assistance is required.

3 RESULTS AND DISCUSSION

3.1 Data sources and distribution over time and space of Natech events

A total of 9100 events were included in the developed database. Table 4 shows the share among the original sources of data: approximately 85% of the records were retrieved from the NRC database, 11% from ARIA, and the remaining 4% from the other databases consulted. It is interesting to notice that the Natech events selected with the above-listed criteria are between 0.9% and 2.4% of the total number of events present in the original source. Overall, the Natech events collected represent the 1% of the total records of all the available records in the databases consulted.

Source	Total number of records in the source (R)	Selected records (r)	% of Natech events (r/R) [%]
NRC	852159	7752	0.9%
ARIA	52598	1028	2.0%
MHIDAS	14000	170	1.2%
TAD IChemE	10500	113	1.1%
eMARS	1015	24	2.4%
CONCAWE	756	13	1.7%
Total	931028	9100	1.0 %

Table 4 – Number of Natech events collected in the different databases consulted. The total number of records and the % of Natech events in each database are also reported.

The time span of the records is of almost 70 years, as shown in Figure 3. The time trend of the Natech events included in the developed database is reported in Figure 3a, where the contribution of the data deriving from NRC database is evident. Population of NRC database was started in 1990 and, from that year on, the number of events related to natural phenomena and fulfilling the above defined inclusion criteria seems almost constant (≈ 250 events/year), four to ten times higher than the events reported in all the other sources analysed. Some peaks visible in the trend of the NRC data included might be related to particularly severe and extended natural events, such as hurricanes, which have the characteristic of impacting vast areas (Misuri et al., 2019).

However, even when looking only at the trend of data deriving from all the other databases, thus excluding NRC data (Figure 3b), still an increasing trend of Natech events is observed, in particular when focusing on the last 50 years (since 1970). Even if the increasing trend may have multiple causes (increase in the number of operating sites, increase in the number of records reported in the original databases, etc.), still it confirms the relevance of Natech hazard.

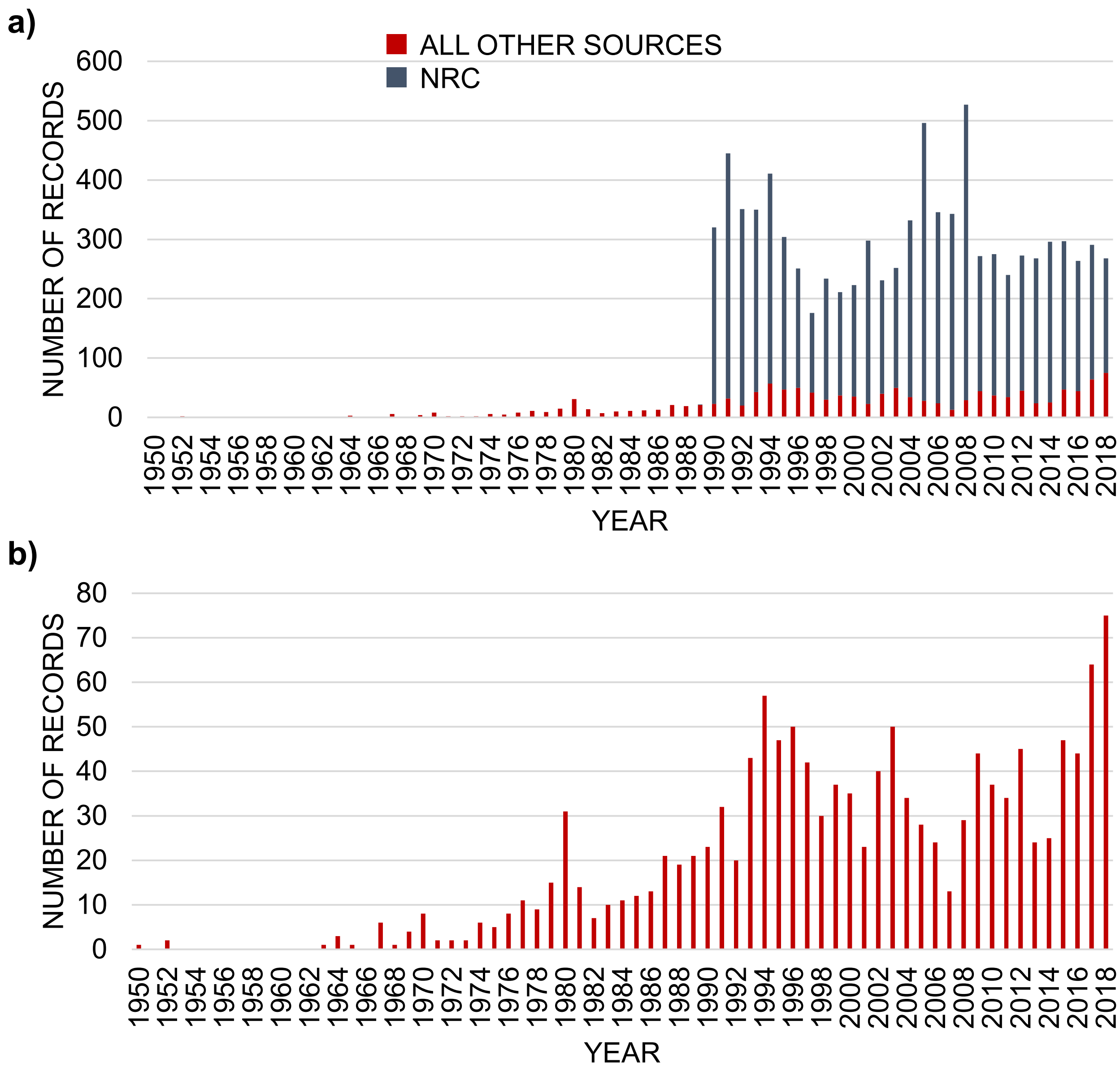

Figure 3 – Overall time trend of Natech events included in the database developed: (a) considering all the records; (b) excluding the records derived from the NRC database.

Figure 4 reports a comparison between the worldwide geographical distribution of Natech events recorded in the developed database (Figure 4a) and that of natural disasters as defined in section 2.4 (Figure 4b). The comparison shows that there is a correlation between the number of Natech events recorded and natural disasters. As shown in Table 5, the most affected geographical area is North America, where the ratio between the number of Natech events recorded and the number of natural disasters is of about 3.5. This can be explained by the fact that the most affected U.S. States are those typically interested by the landfall of

Atlantic hurricanes. During these events, several industrial sites at relevant distances may be affected, thus more than one Natech scenario may be generated by the same natural event.

In Europe, the ratio of Natech to natural events results of 0.5. In this case also, the Atlantic coastal areas seem to be the most affected by Natech events (see Figure 4a).

In all the other geographical areas considered the results are similar, and this can be attributed to underreporting (e.g. in the case of some industrialised countries in Asia) combined with low industrialization (e.g. in Africa).

Geographical Area	**Natural Disasters (N_D)**	**Natech events recorded (N_R)**	**Ratio (N_R/N_D)**
North America	2276	7925	3.5
Europe	1947	897	0.5
Asia	5199	67	0.01
South America	1070	27	0.03
Africa	1735	25	0.01
Oceania	630	22	0.03

Table 5 – Number of natural disasters (N_D) provided by EM-DAT (Centre for Research on the Epidemiology of Disasters (CRED), 2020) and number of Natech events recorded in the developed database (N_R).

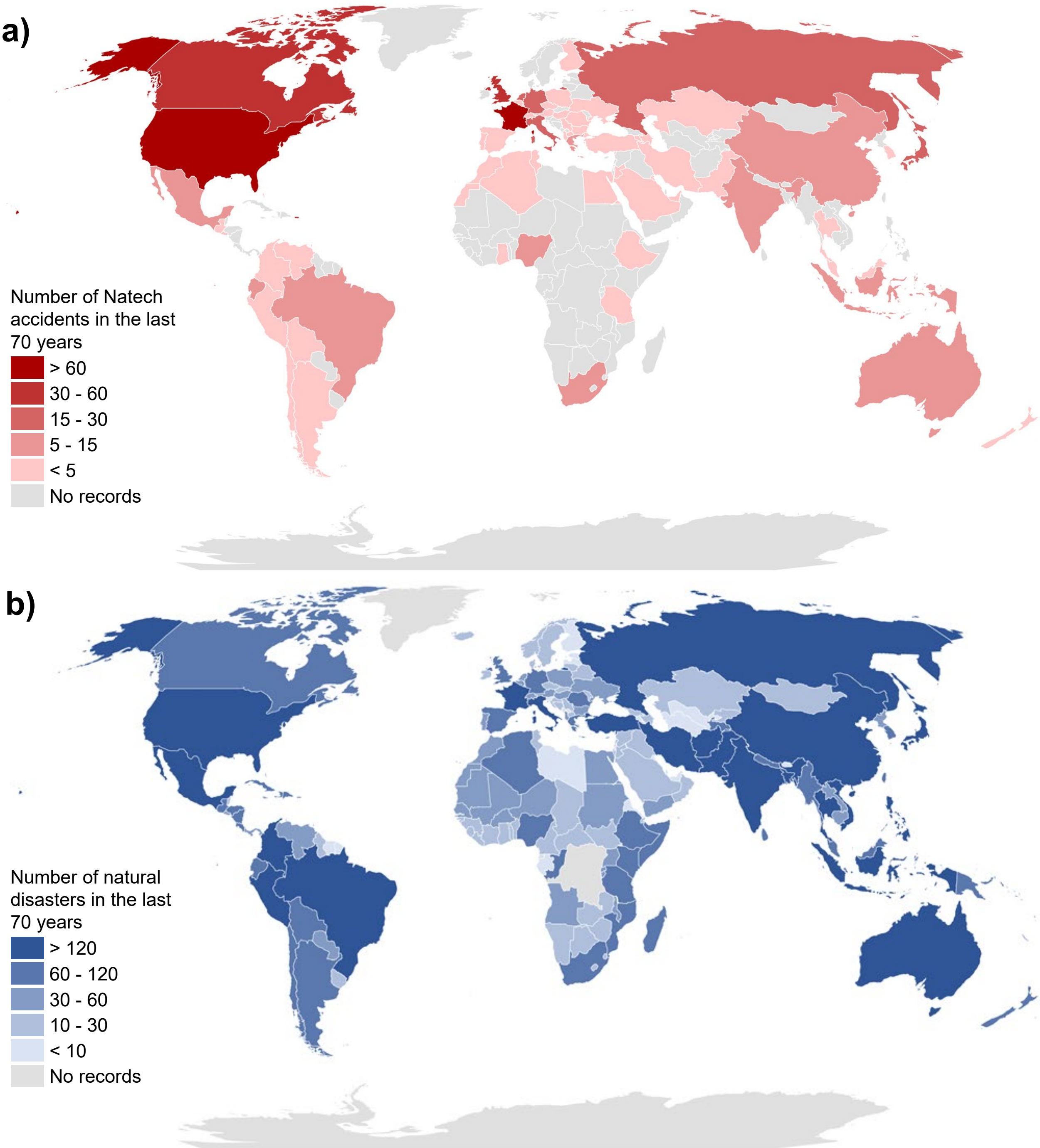

*Figure 4 – Geographical distribution of **(a)** Natechs recorded in the developed database and **(b)** of natural disaster recorded by the Centre of Research on the Epidemiology of Disasters (Centre for Research on the Epidemiology of Disasters (CRED), 2020) in the last 70 years.*

Given the significant number of Natech records related to Europe and US, it is interesting to estimate the trend of Natech events normalized with respect to the number of industrial sites in such geographical areas, dividing the yearly number of Natech events recorded by the number of active industrial sites each year. The latter, as explained in section 2.3, is available for the period 2000-2017. Therefore, the analysis was limited to this time range and records related to "Transportation" activities (see Table 1) were excluded. The results are shown in Figure 5. In the case of Europe (Figure 5a), a slightly increasing trend can be observed, and an average representative value for frequency of Natech events can be estimated of about $3.5 \cdot 10^{-5}$ events/year/site for the reference period. For the case of US (Figure 5b), no trend is identified and peaks are present, that can be associated to specific events, i.e. hurricanes Kathrina and Rita in 2005, Gustav ed Ike in 2008. The average representative value for the frequency of Natech in the US in the period 2000-2017 can be estimated around $2.3 \cdot 10^{-3}$ events/year/site.

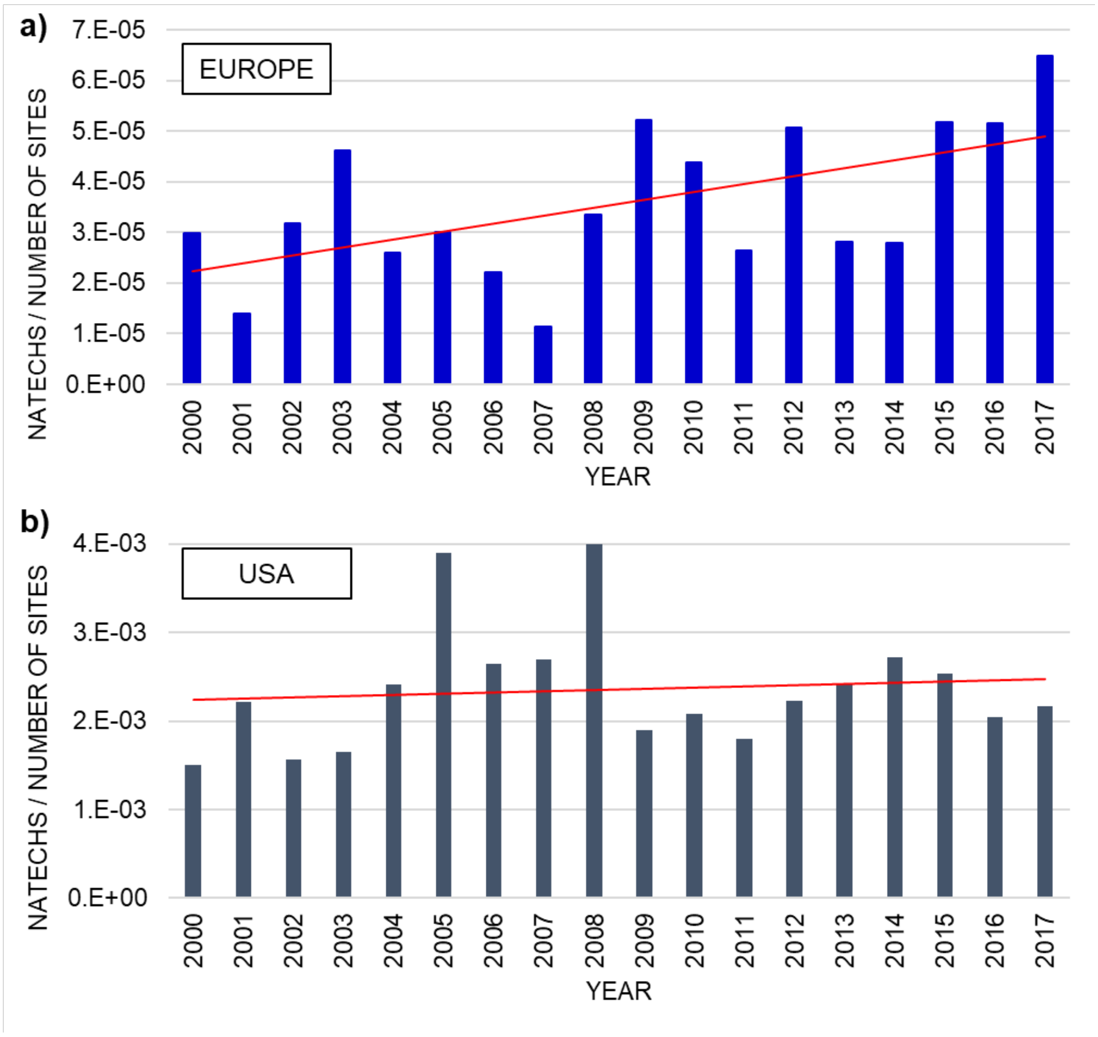

Figure 5 – Trend of Natech events normalized with respect to the active number of industrial sites for Europe (panel a) and US (panel b) in the period 2000-2017.

3.2 Natural phenomena triggering Natech events

Figure 6 shows the macro-categories of natural phenomena, as defined in Table 3, that caused the Natech events. As shown in the outer circle of panel (a), meteorological events are by far those that have caused the greatest number of Natech scenarios (7866 records, 86% of the total) followed by hydrological (895, 10%) and geophysical (336, 4%) events. The Natech events caused by climatological events (i.e. wildfires) included in the database are only three. Figure 6 also shows a comparison with the occurrence of the four macro-categories of natural events recorded by the Centre of Research on the Epidemiology of Disasters (panel (a), inner circle) (Centre for Research on the Epidemiology of Disasters (CRED), 2020). It is interesting to notice that the incidence of hydrological and geophysical events triggering Natech accidents is much lower than the overall incidence of such events on the total number of natural disasters recorded. Actually, meteorological events seem more prone to cause Natechs with respect to other types of natural phenomena, revealing a possible vulnerability of the chemical and process industry to short-term (minutes to days) medium-scale weather conditions. More in detail, as shown in Figure 6b, specific categories of meteorological events caused the accidents recorded: storms, tropical storms and extreme temperatures are responsible for 74% of the Natech events analysed. Although most of the attention in previous studies was devoted to accidents triggered by lightning, floods and earthquakes (El Hajj et al., 2015; Krausmann and Mushtaq, 2008; Renni et al., 2010), these natural events caused only around 25% of the Natech accidents recorded. Specifically, lightning caused about 12% of the accidents, while floods and earthquakes about 9% and 2%, respectively. Even so, Natech deriving from lightning, floods and earthquakes are usually characterised by severe consequences and escalation events (El Hajj et al., 2015; Krausmann and Mushtaq, 2008; Renni et al., 2010).

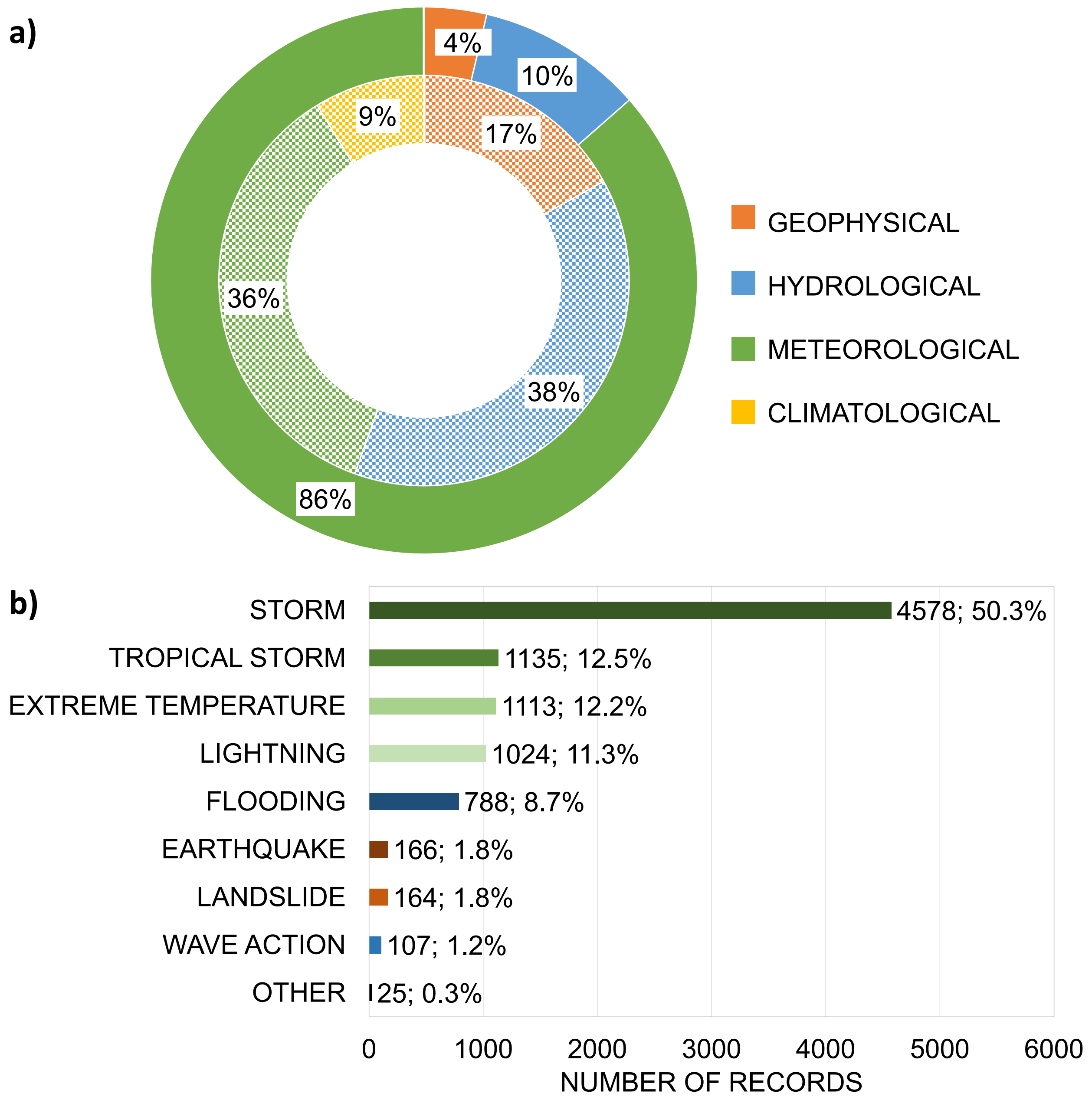

Figure 6 – (a) Distribution of Natech events (%) with respect to the macro-categories of natural events considered (outer circle, solid colour), compared with the distribution (%) of the occurrence of each macro-category reported in (Centre for Research on the Epidemiology of Disasters (CRED), 2020) (inner circle, transparent colour). (b) Number of Natech events caused by each category of natural event considered in the present study. The category "Other" includes events related to Volcanic Activity, Tsunami, Fog, and Wildfires (see Figure 2).

3.3 Features of the technological scenarios and hazardous substances involved

The share among the technological scenarios (defined in Table 2) occurred during the Natech events is illustrated in Figure 7. In more than 45% of the cases, the release of hazardous substances with no further consequences in the short term was recorded. About 44% of the events resulted in environmental contamination as a consequence of the release of relevant quantities of ecotoxic substances. All other technological scenarios considered account for the 11% of the recorded events: fire took place in 9% of the recorded events, while only in a limited number of events explosions (0.8%) and toxic gas dispersions (0.1%) were reported. Multiple scenarios took place in approximately 1% of the recorded events (101 cases). The most frequent multiple scenario was explosion combined with fire (80 events).

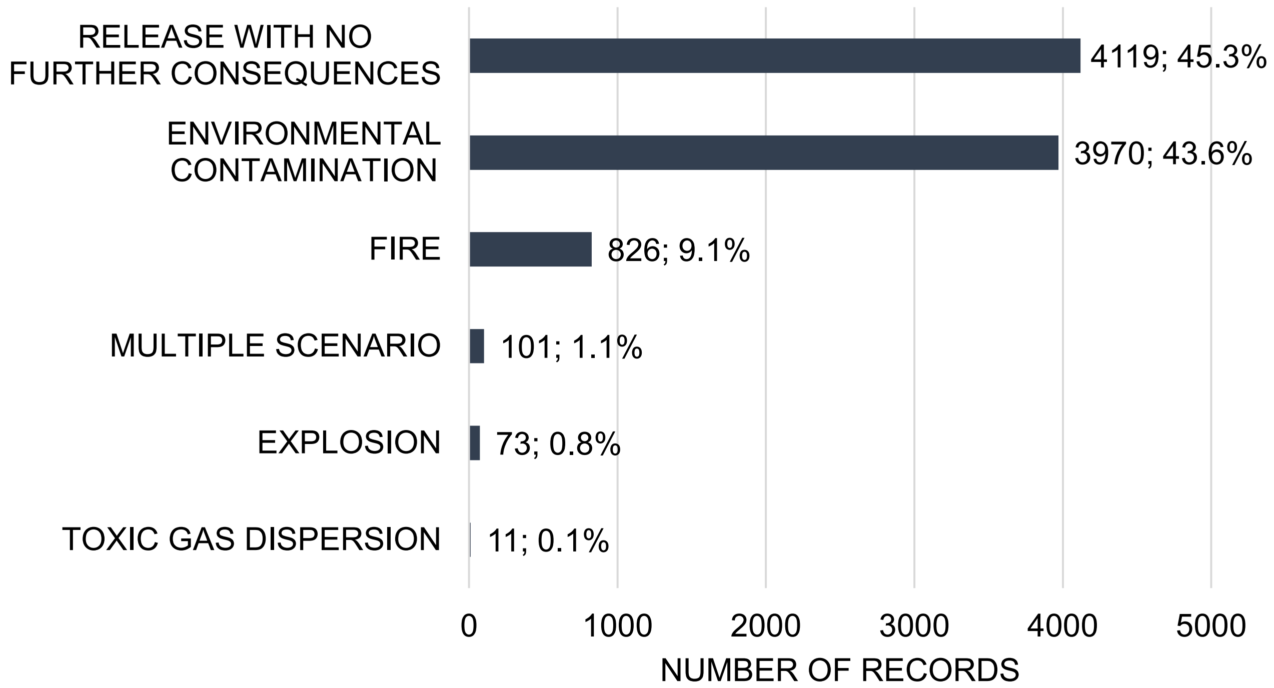

Figure 7 – Technological scenarios occurred in the Natech events included in the database.

In 7476 cases sufficient information to allow the identification of the hazardous properties of the substances involved in the Natech event was reported. Over 670 different hazardous substances involved in the Natech scenarios were identified. Table 6 reports the number of events recorded for different hazard categories defined in the Globally Harmonised System

(GHS) classification of substance hazards introduced by the United Nations (United Nations, 2011). In a considerable number of events more than one substance (453 cases) or a single substance with several hazardous properties (5758 cases) were involved. In both cases, the event was classified indicating all the hazardous properties of all the substances involved (e.g. Flammability + Acute Toxicity, Flammability + Hazardous to the aquatic environment, etc.). Table 6 also reports the final scenarios recorded for each of the categories of hazardous substances considered. Further details on the types of hazardous substances involved in the accidents are reported in Table 7, that shows the number of events involving respectively organic gases (natural gas and similar substances such as LPG), flammable organic liquids (solvents, aliphatic and aromatic compounds, etc.), and organic liquids flammable and hazardous to the aquatic environment (e.g. crude oil, fuel oil, lube oil) and the final scenarios involving such substances. The table shows that these substances were involved in about 70% of the recorded events.

Category of Hazard (United Nations, 2011)	**Number of events**	**Final scenarios**					
		F	**E**	**TGD**	**EC**	**R-NFC**	**MS**
Flammability	1053	205 (19.5%)	21 (2%)	0 (0%)	0 (0%)	799 (75.8%)	28 (2.7%)
Acute Toxicity	187	0 (0%)	0 (0%)	0 (0%)	0 (0%)	187 (100%)	0 (0%)
Hazardous to the aquatic environment	112	0 (0%)	0 (0%)	0 (0%)	34 (30.4%)	78 (69.6%)	0 (0%)
Flammability + Acute Toxicity	127	15 (11.8%)	3 (2.4%)	0 (0%)	0 (0%)	105 (82.7%)	4 (3.1%)
Flammability + Hazardous to the aquatic environment	4553	263 (5.8%)	16 (0.4%)	0 (0%)	3216 (70.6%)	1029 (22.6%)	29 (0.6%)
Flammability + Acute Toxicity + Hazardous to the aquatic environment	1372	51 (3.7%)	5 (0.4%)	4 (0.3%)	683 (49.8%)	618 (45%)	11 (0.8%)
Acute Toxicity + Hazardous to the aquatic environment	72	0 (0%)	0 (0%)	0 (0%)	32 (44.4%)	40 (55.6%)	0 (0%)
Total	7476	534	45	4	3965	2856	72

Table 6 –Distribution of the number of events recorded in the database with respect to the hazardous properties of the substances released and to the final scenarios occurred (F:

Fire. E: Explosion. TGD: Toxic Gas Dispersion. EC: Environmental Contamination. R-NFC: Release with No Further Consequence. MS: Multiple Scenario. See Table 2 for the definition of the final scenarios).

Category of hazardous substance	Number of events	Final scenarios					
		F	E	TGD	EC	R-NFC	MS
Flammable organic gases	629	156 (24.8%)	16 (2.5%)	0 (0%)	0 (0%)	439 (69.8%)	18 (2.9%)
Flammable organic liquids	315	24 (7.6%)	2 (0.6%)	0 (0%)	0 (0%)	282 (89.6%)	7 (2.2%)
Flammable and Hazardous to the aquatic environment organic liquids	4353	232 (5.3%)	16 0.4%)	0 (0%)	3111 (71.5%)	968 (22.2%)	26 (0.6%)
Total	5297	412	34	0	3111	1689	51

Table 7 – Number of events involving different types of flammable hazardous substances. (F: Fire. E: Explosion. TGD: Toxic Gas Dispersion. EC: Environmental Contamination. R-NFC: Release with No Further Consequence. MS: Multiple Scenario. See Table 2 for the definition of the final scenarios).

The information reported in Tables 6 and 7 were used to derive the quantified event trees reported in Table 8 for the three categories of hazardous substances more frequently involved in Natech scenarios: flammable liquids, flammable gases and ecotoxic liquids (i.e. liquid hazardous to the aquatic environment). Event trees were developed excluding accidents occurred in the transportation sectors (as defined in Table 1). A total of 6408 records were thus used to derive Table 8 and Table 9.

Observing the results in Table 8, in the case of flammable liquids delayed ignition resulted the less frequent scenario (≈ 0.1%), while the most common scenario is the release where no ignition takes place (> 90%), independently from the natural event triggering the Natech scenario. Nevertheless, immediate ignition resulted more likely in the case of meteorological events, since Natech events triggered by lightning are comprised in this category.

Also, in the case of flammable gases, release with no further consequences is the most common scenario, even if, as expected, occurrence of scenarios involving ignition (both immediate and delayed) is higher. Finally, the event tree associated to ecotoxic liquids shows that environmental damage occurred in 20% of the events analysed, while in all other events the release was contained or the quantities were limited, so that no significant damage to the environment was recorded.

Event tree	All	Geo	Hydro	Meteo
Release of Flammable liquid — **Nuber of events**	**5389**	166	599	4616
Flammable Liquid — Immediate ignition: Yes → Pool fire	**6.5 %**	4.0 %	1.3 %	7.3 %
Flammable Liquid — Immediate ignition: No; Delayed ignition: Yes → VCE / Flash Fire	**0.1 %**	No records found	No records found	0.1 %
Flammable Liquid — Immediate ignition: No; Delayed ignition: No → R-NFC[A,B]	**93.4 %**	96.0 %	98.7 %	92.7 %
Release of Flammable Gas — **Nuber of events**	**959**	82	54	822
Flammable Gas — Immediate ignition: Yes → Jet fire	**19.6 %**	13.4 %	3.7 %	21.2 %
Flammable Gas — Immediate ignition: No; Delayed ignition: Yes → VCE / Flash Fire	**1.8 %**	13.4 %	No records found	0.7 %
Flammable Gas — Immediate ignition: No; Delayed ignition: No → R-NFC[A]	**78.6 %**	73.2 %	96.3 %	78.1 %
Release of Liquid Hazardous to the aquatic environment — **Nuber of events**	**60**	0	4	56
Ecotoxic Liquid — Catch Basin: Yes → R-NFC	**80 %**	No records found	0 %[C]	85.7 %
Ecotoxic Liquid — Catch Basin: No → Enviromental contamination	**20 %**		100 %[C]	14.3 %

[A] Toxic dispersion when the substance is also toxic
[B] Environmental contamination when the substance is also ecotoxic
[C] Obtained from a very limited number of events (i.e. 4)

Table 8 – Quantified event trees obtained from the analysis of the database. Distribution of final outcomes is reported either considering all the event or the specific category of natural event that triggered the Natech (VCE: Vapour Cloud Explosion; R-NFC: release with no further consequences; Geo: geophysical natural events; Hydro: hydrogeological natural events; Meteo: meteorological natural events).

Table 9 reports the specific values calculated for the conditional probability of ignition in Natech scenarios involving the release respectively of flammable gases or liquids. The comparison of the data in the table with values reported in literature for conventional scenarios (Uijt de Haag and Ale, 1999) show that overall (i.e. not considering the specific type of natural event) the ignition probabilities obtained for the case of Natech are similar to those suggested for conventional scenarios. This is also true when considering the specific data for Natech events triggered by earthquakes. Differently, values much lower than those suggested for conventional scenarios are obtained for Natech events triggered by floods, and values much higher than conventional are obtained in the case of Natech scenarios triggered by lightning.

Triggering Natural event	**Probability of ignition**	
	Flammable liquid	**Flammable gases**
Earthquake	5.8 %	32.1 %
Flood	1.3 %	4.1 %
Lightning	49.8 %	52.8 %
Overall	6.6 %	21.4 %
Reference value for conventional scenarios (Uijt de Haag and Ale, 1999)	6.5 %	20 - 70 %

Table 9 – Probability of ignition obtained from the analysis of the database compared with probabilities of ignition for conventional scenarios reported in the literature (Uijt de Haag and Ale, 1999).

3.4 Severity of Natech events

An analysis of the severity of the consequences of the Natech events collected in the database was carried out evaluating the impact on humans and assets for the records where such information was available.

A total of 1734 fatalities and 7320 injuries were reported in the events included in the database. A simplified severity scale was introduced to classify the 210 accidents where damage to humans was reported. Four severity classes were introduced: “one injury”, “multiple injuries”, “one fatality” and “multiple fatalities”. If both injuries and fatalities were recorded, the categories referring to fatalities were applied to classify the severity. Figure 8a reports the results obtained, also showing the probability associate to each severity class and the breakdown with respect to the macro-category of natural event that triggered the

Natech scenario. As shown in the figure, Natech events caused by geophysical disasters are those that resulted in the highest probability of causing damages on humans.

A similar analysis was carried out on asset damage. Severity classes based on the economic damage reported were defined and occurrence probabilities were calculated for the 151 records for which such information was available. Figure 8b reports the results obtained. The figure clearly shows that similar trends are obtained for damage to humans and to assets.

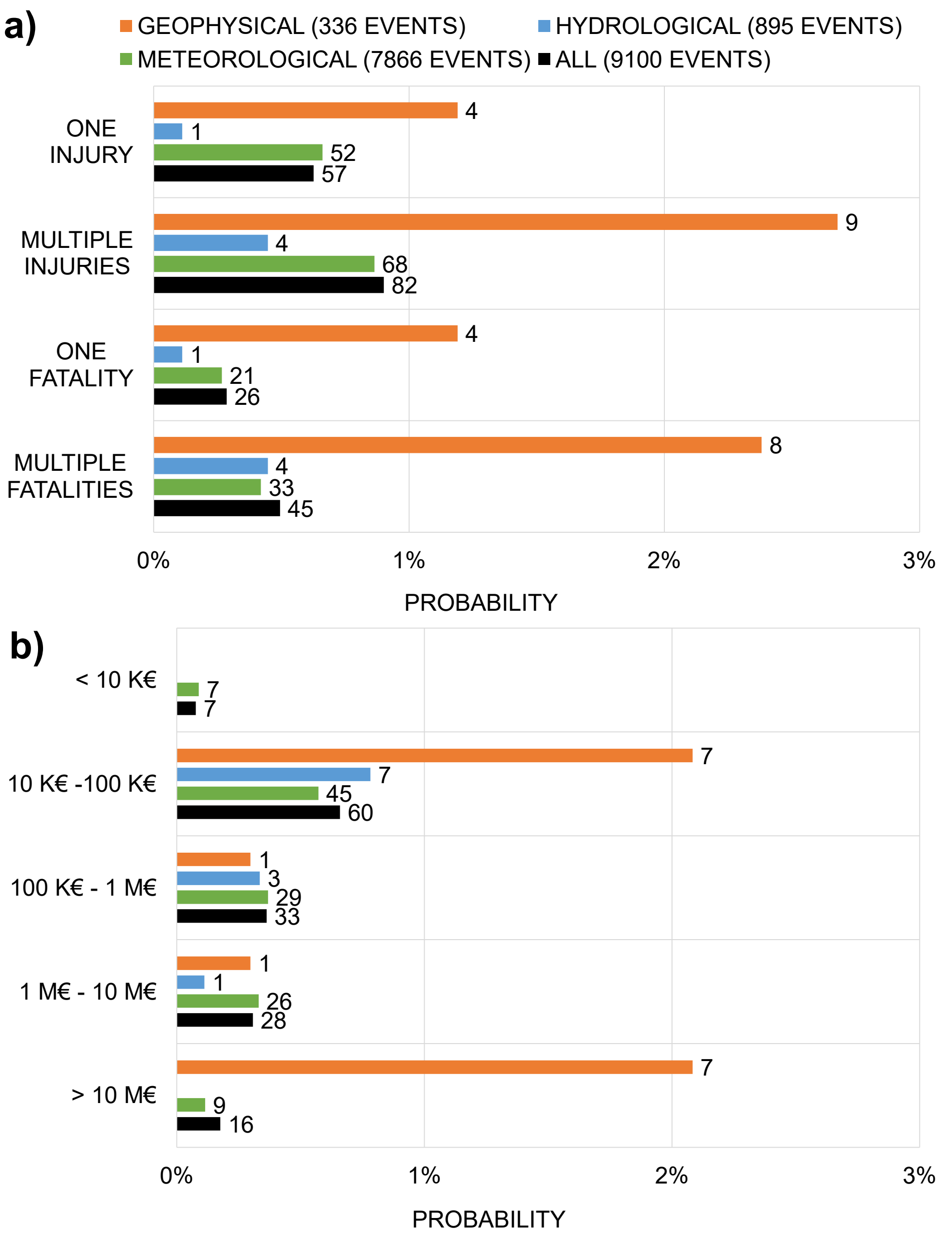

Figure 8 – Severity reported for the Natech events included in the database considering (a) damage to humans and (b) economic losses. The probability of occurrence calculated for each severity class is also reported.

3.5 Societal risk associated to Natechs

Figure 9 shows several f/N (cumulated frequency / fatalities) societal risk curves calculated from the analysis of the accident data, considering only events involving fixed installations. The f/N curves where calculated considering either the entire data set (t_{ref} = 70 years), or specific data subsets. In particular, the figure also reports:

- the f/N curve calculated considering only the accidents reported in the period 1970-2018 (t_{ref} = 50 years), to check the possible influence of under-reporting of "old" accidents, that took place far before the activation of the original data sources considered in the present study;
- the f/N curve calculated considering only the accidents reported in the period 1990-2018 (t_{ref} = 30 years), to assess the influence of the data provided by the NRC database (only activated in 1990) on the overall trend.

The calculations were carried out according to the methodology described in section 2.3. As evident from the figure, limited differences (less than one order of magnitude) are present in among the different f/N curves, and, as expected, curves having a lower reference time show slightly higher values of the cumulated frequency. The f/N curves calculated clearly show that the societal risk estimated for Natech events is outside the critical regions defined by the UK Health and Safety Executive (HSE, 2009). However, the f/N curve falls inside the unacceptability region according to the criteria used at the time in the Netherlands for societal risk acceptability (Lees, 2012) when considering extremely severe accidents (> 100 fatalities). These results thus suggest that when considering site-specific f/N curves in areas prone to natural disasters, societal risk may become critical, in particular when considering events resulting in a high number of fatalities. Specifically designed safety barriers (Misuri et al., 2020, 2021) and adequate emergency response procedures (Krausmann et al., 2017) are among the priorities that should be considered for risk reduction based on lessons learnt (Misuri et al., 2019). These should be considered as climate adaptation measures, aimed at increasing the resiliency of industry to Natech (Stewart and Bastidas-Arteaga, 2019).

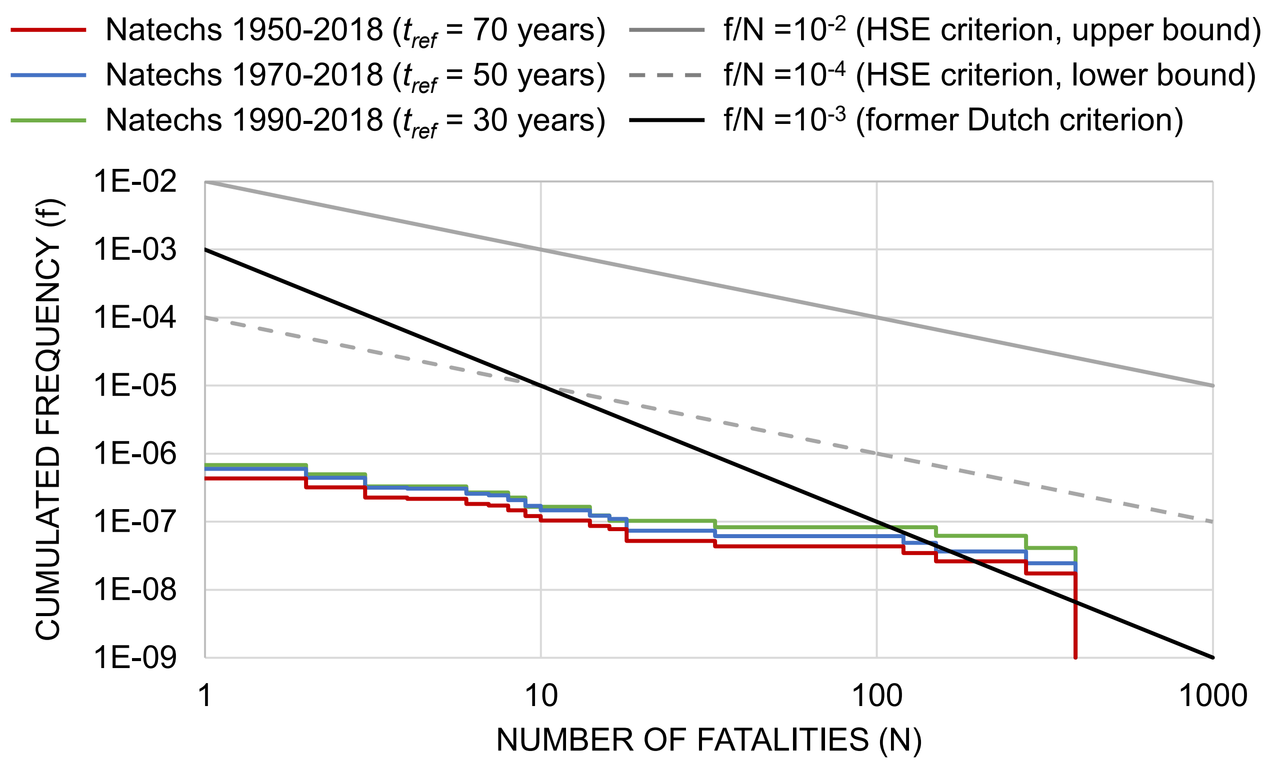

Figure 9 – Societal risk curve deriving from the Natech accidents analysed in the present work for 3 different reference time (t_{ref} = 70 years, 50 years and 30 years) compared with the acceptability limits for societal risk applied by the UK Health and Safety Executive (HSE, 2009) and formerly applied by the Dutch regulatory authorities (Lees, 2012).

4 CONCLUSIONS

An extended dataset of Natech accidents was collected and analysed. The results evidence the relevance of Natech accidents and the severe consequences that these accident scenarios may have, both considering damage to humans and to assets. The analysis of the data also allowed the identification of the natural events that more frequently caused Natech scenarios and of the substances involved, thus supporting the hazard identification related to Natech events. The quantified event trees obtained for the categories of substances more frequently involved in Natech scenarios, and the Natech-specific conditional ignition probabilities in perspective may support a more effective assessment of the final outcomes of Natech scenarios and the quantitative assessment of Natech risk. Overall, the results obtained from database analysis represent a step forward in the consolidation of the hazard and risk assessment of Natech scenarios.

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