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The Quantitative Assessment of Damage to the Environment in Major Accidents Caused by Natural Events

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The release of hazardous materials induced by natural events affecting industrial facilities presents peculiar characteristics because of the huge potential extension of the affected areas. The reduction of both the likelihood and the magnitude of such events represents an essential step to reduce the risk associated with Natech accidents. Nevertheless, the evaluation of damage to the environment in Natech events has been poorly addressed. In the present study, past accidents analysis was carried out, using both a detailed description of specific accidents and an extended database of Natech events. Lessons learnt as well as possible common patterns and main features related to such accidents were identified and discussed. The results of the present study can be intended as a preliminary step for the development of models for the quantitative assessment of damage to the environment in major accidents caused by natural events.

1. Introduction

Climate change and global warming have increased the frequency and the magnitude of natural events and disasters worldwide (Centre for Research on the Epidemiology of Disasters, 2021). As a consequence, Natech accidents (technological accidents triggered by natural events) are becoming a significant issue for policy-makers, industry managers and regulators, since the natural events are the triggering factor for this class of events (Nascimento and Alencar, 2016). This resulted in an increasing number of Natech accidents in the last decades (Casson Moreno et al., 2019). Indeed, even if the probability of disruptive interactions between a natural event and an industrial site can be considerably low, Natech accidents can significantly affect the results of a quantitative risk assessment (Necci et al., 2016). Moreover, consequences generated by these accidents are typically worse than those resulting from conventional accidents, mostly because of the possible occurrence of multiple simultaneous failures of equipment items (Krausmann and Cruz, 2013). Natech accidents can also be characterized by the failure of safety and utility systems (Misuri et al., 2021b). Hence, domino effects, cascading events (Misuri et al., 2021c) or indirect accident scenarios can take place (Misuri and Cozzani, 2021). Besides, natural events affect a larger area than conventional technological scenarios, potentially impacting several industrial sites at the same time. In this perspective, the emergency response can be hampered since it has to face the technological scenario as well as the natural event itself (Krausmann et al., 2017).
Accidents can impact human health, the environment, and assets as other equipment items (i.e., cascading events), also generating economic losses (Krausmann et al., 2017). In spite of its relevance, less attention was devoted in previous studies to the potential environmental contamination and damage to the environment that may take place in Natech events. In fact, most of the previous studies addressing Natech risk assessment are mostly focused on the quantification of the failure probability (Salzano et al., 2009), as well as on damage to humans and safety distances (Ricci et al., 2021b). Regardless of the initiating factor, the potential consequences of an accident can be reduced by the installation and implementation of proper strategies, i.e., safety barriers (CCPS, 2001). However, the possible disruption or reduced effectiveness of safety systems is strongly increased by the occurrence of natural events (Misuri et al., 2020). Hence, in Natech events, the probability of environmental contamination is significantly enhanced with respect to conventional accidents. As an example, the failure of a catch basin can be considered as a credible event in the case of Natech accidents, while it is

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extremely unlikely in conventional technological accidents. Quite obviously, the failure of catch basins may lead to the unconfined spread of released substances in a wide area surrounding the industrial facility.
When considering accident consequences, assessing the potential damage to the environment is a highly complex task, since the environment is characterized by the presence of several inherently different compartments, such as, for example, the atmosphere, soil, groundwater, rivers, lakes, and the sea. Due to the much different features in each compartment, the study of the damage to the environment is a complex, challenging, and multidisciplinary issue. Robust and comprehensive models to evaluate the effects on the environment generated by the release of hazardous substances are still under development. Moreover, more than one compartment may be affected at the same time, possibly worsening the consequences on the environment. A pioneering methodological approach for the quantitative assessment of the damages on the environment in the case of conventional accidents has been proposed by Bonvicini et al. (Bonvicini et al., 2015). Conversely, the approach is limited to the soil and groundwater compartments, with specific reference to the case of accidental release from a pipeline.
A comprehensive understanding of Natech events and their main factors is needed to develop models for the assessment of the damage to the environment in Natech accidents. In this framework, the main source of trustworthy and reliable data is the analysis of past accidents. The aim of the present study is thus to analyze past accidents in order to derive the main features of Natech events that resulted in damage to the environment, highlighting the peculiar characteristic that has led to environmental contamination scenarios.

2. Methodology

In the present study, information from Natech accidents that led to damage to the environment that occurred in the past is analyzed with two different methods. On the one hand, detailed information and specific lessons learned were collected and derived from the analysis of detailed reports available for relevant past Natech accidents, addressing the specific issue of environmental contamination. On the other hand, general information and overall analysis are derived from the analysis of a wide database containing more than 9000 Natech accidents.
Concerning the detailed analysis of accident reports, four representative accidents are considered: the Saga prefecture oil spill (Misuri et al., 2021a) and the Livorno oil spill (eNatech, 2021) caused by floods, the oil spill and fire due to the Great East Japan earthquake and tsunami (Krausmann and Cruz, 2013), and eventually the release of acrylonitrile during the Kocaeli earthquake (Girgin, 2011). The selection of accidents was based on the availability of detailed information in the literature as well as the significance of the events.
As for the second part of the study, the data repository was built consulting several existing databases: eMARS, MHIDAS, TAD IChemE, ARIA, NRC, and CONCAWE. Records were searched within the sources, using natural events as keywords: e.g., earthquake, flood, lightning, storm, etc. The following inclusion criteria were defined to decide whether to include or not records found in the database: (i) events should be loss of containment (Uijt de Haag and Ale, 1999), accident, or incident (Rathnayaka et al., 2011); (ii) events should be triggered by natural events (Krausmann et al., 2017); (iii) events should have occurred in chemical and process industries (Ricci et al., 2021a). Specific attention was given to avoid the inclusion of duplicated records due to the high number of sources consulted. The time span covered in the database range from 1950 to 2018, included. More details on the database construction as well as analysis of the entire dataset can be found in the work of Ricci et al. (Ricci et al., 2021a).

3. Description of representative past accidents

The description of representative examples of Natech accidents that resulted in damages to the environment is presented in this section. More detailed information on the accidents discussed can be found in the reference literature and the literature cited therein.

3.1 The Saga prefecture oil spill (Misuri et al., 2021a)

On August 28th, 2019, an intensive rainfall has occurred in the Saga prefecture, southwestern Japan. The huge precipitation has caused a critical water inflow to the Rokkaku and the Ushizu rivers, which belong to the same water system. This has led to the collapse of the water system, originating nine breaches and large-scale flooding impacting an area of about 69 km^2. The area is prone to such events, as demonstrated by the occurrence of around 20 previous floods since 1900. Despite this, the unexpected magnitude of the events that occurred in 2019 has caused the failure of safety systems installed to protect the area from floods. The industrial site involved in the accidents is an ironwork factory located 100 m far from the Rokkaku River embankment. One of the processes at the site is quenching, which is performed through an oil bath kept in open atmospheric storage tanks located 3 m below ground level for safety matters. The water level inside the plant has ranged

between 40 to 60 cm, and protection measures for flood prevention within the industrial site were not effective, allowing floodwaters to flow into tanks and to lift the oil. Once the oil spill was detected, evacuation procedures of the plant have been implemented. The accident resulted in the spill of 103 m^3 of oil, 54 m^3 of which outflowed from the premises of the factory, impacting an area of around 420,000 m^2. The oil sheen spread in residential areas and agricultural fields, reaching a hospital. Emergency procedures aiming at the rescue and the evacuation of residents and at collecting the oil were delayed by floodwaters still present in the area. The clean-up and recovery procedures have taken more than 10 days before being concluded. After one month from the accident, residual oil was still present in agricultural fields and damaged houses. Learning from the accident, the company implemented additional safety measures to reduce the probability of events with such a great magnitude.

3.2 The Livorno oil spill (eNatech, 2021)

Between September 9th and 10th, 2017, the Tyrrhenian area nearby Livorno was hit by a huge rainfall event, locally leading to intensity of up to 260 mm of rainwater (Arrighi and Castelli, 2020). The area impacted by the flash flood was estimated as larger than 45 km^2. The magnitude was increased by the overflow of a small creek, called Ugione, which was the main cause of the flooding of an oil refinery. Despite no equipment items have been damaged by the natural event, the stormwater catchment network was filled up to the maximum level and overflowed. The residual oil present in the network, as well as in the industrial site, was washed away and spread on the floodwater. The detection of the oil spill was delayed by the evacuation procedure already implemented at the site. Subsequently, the contaminated water breached the wall limiting the site and part of the oil has reached the sea. It is worth mentioning that the walls of the site were not designed to be a containment measure, but they were only a perimetral fence. Containment booms were implemented to avoid the spread of spilt oil. Clean-up and recovery procedures have been applied. The contaminated waters have been collected from the site and the nearby areas and therefore treated. Additional safety measures were implemented within the site to avoid the event to be repeated in the future.

3.3 The Tohoku oil spill and fire (Krausmann and Cruz, 2013)

A high magnitude earthquake and tsunami occurred on March 11th, 2011, causing several accidents in the area of the pacific coast of Japan. The Sendai port was one of the areas hit by these natural events. Several different kinds of accidents, including damages to the infrastructures, fire and explosions of stored compounds, failure of equipment items, and environmental contamination took place in the industrial sites within that area. Besides the huge fire that involved a significant section of the Sendai refinery, crude oil spills also occurred. The crude oil was spilt by the rupture of a pipeline due to the floatation of a small tank caused by the tsunami water. Moreover, a gasoline pipeline was damaged by the tsunami. The overall spill consisted of around 8,300 m^3 and reached either the soil or the sea, causing massive pollution of the harbour. Also, trees and grass at a nearby park were covered with oil from the accident. The emergency response was hampered by debris created by the tsunami that heavily damaged the roads and infrastructures. The reported accident represents an example of relevant environmental contamination. However, a multitude of small and medium scale damages to the environment have been reported in the area (French Ministry of Ecology, 2013). Indeed, other chemical plants were hit by the earthquake and tsunami. Overall, the consequences on the environment were huge, the clean-up operations lasted 6 months.

3.4 The Kocaeli acrylonitrile release (Girgin, 2011)

An area of 42,500 km^2 close to the city of Bolu (Turkey) was hit by a severe earthquake on August 17th, 1999. The industrial area was heavily damaged, and the integrity of several storage tanks was compromised. Several fires, toxic releases, and spills were caused by the abovementioned damages to industrial facilities in the involved area. In particular, 6,500 tons of acrylonitrile (i.e., a highly volatile toxic liquid) were released from a storage tank into its catch basin, where massive evaporation took place. The vapors affected human and animals' health as well as agricultural activities. Acute toxic symptoms were registered among the population and members of the emergency response teams. Besides, animals and vegetation within 200 m from the releasing point died. A significant amount of this hazardous liquid overflowed from the catch basin and reached the sea. The contamination of the sea lasted for around one month. Moreover, cracks in the catch basin foundations allowed for the penetration of acrylonitrile within the soil and eventually it also contaminated the groundwater. Continuous treatment for 5 years was necessary to remediate the contamination of the groundwater, processing around 53,000 m^3 of water.

4. Results and discussion

This section presents a qualitative and quantitative analysis of the past Natech accidents resulting in environmental contamination, among those included in the database containing 9,100 accident records developed by (Ricci et al., 2021a). According to the technological scenarios that occurred in records collected, around 44 % of the accidents (3,970 records) resulted in environmental contamination, as illustrated in Figure 1. The elevated percentage highlights that the damages to the environment are significant when considering Natech accidents. Thus, the neglection of this possibility in the framework of Natech risk assessment can lead to an underestimation of the overall consequences of Natech events and therefore of the risk.

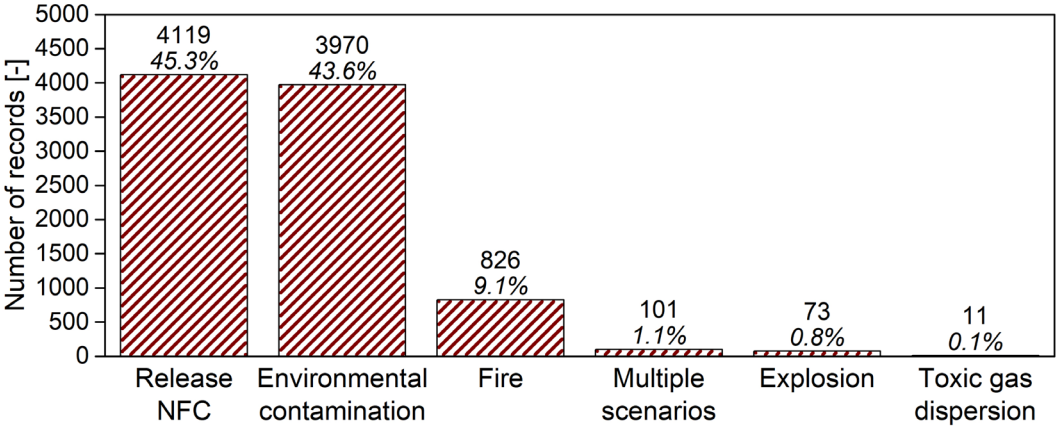

Figure 1: Consequences of the technological scenarios resulting from the Natech accidents included in the database by Ricci et al. (Ricci et al., 2021a)*. Release NFC: release with no further consequences.*

The natural events that generated the 3,970 records that resulted in environmental contamination were further investigated.
Three natural events were found to have caused more than the 92 % of accidents. These are storm (2579 records, 65.0 %), tropical storm (646 records, 16.3 %), and flood (430 records, 10.8 %) as shown in Figure 2. The category "other" collects natural events that have triggered environmental contamination with less relevance in the database. Specifically, extreme temperature (133 records, 3.4 %), wave action (78 records, 2.0 %), landslide (44 records, 1.1 %), lightning (38 records, 1.0 %), and earthquake (22 records, 0.6 %).

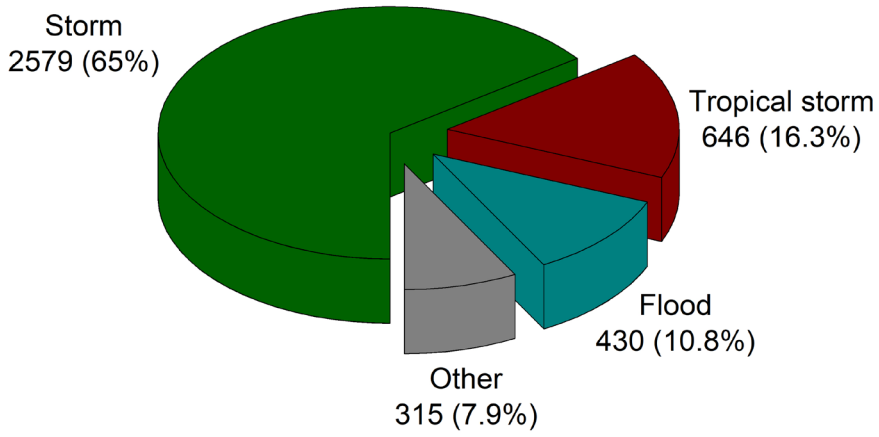

Figure 2: Share among the natural events that have triggered Natech accidents resulting in environmental contamination. The category other includes environmental contamination triggered by extreme temperature, wave action, landslide, lightning, and earthquake: Total number of records: 3,970.

It is important to remark that Natech accidents resulting in damages to the environment are mainly triggered by natural events characterized by the presence of water. This is confirmed also by the representative accidents described in Section 3. Actually, 3 out of 4 have tsunami or floods as triggering natural events.

The detailed description of the chain of events highlights that the presence of water worsens the consequences since it promotes a wide spreading of the contaminating substances. The spread of contaminants over the water is also promoted by the progressive decrease of the thickness of oil contaminants, thus further enlarging the impacted area (Van den Bosch et al., 1997). Although the database analysis showed a limited number of records related to earthquake-induced scenarios, the consequences on the environment deriving from these scenarios can be extremely severe, as in the case of the Kocaeli earthquake Natech events. Besides, the Kocaeli accident is also relevant since its chain of events represents a possible typical pattern in earthquake-induced accidents. Hence, the failure of safety barriers such as catch basins is a specific feature of Natech accidents (Misuri et al., 2020). Another important issue concerning environmental contamination is the type of substances involved in accidents. Figure 3 reports the result obtained from the analysis of past accidents, showing that 97% of the accidents resulted in a release of oil and hydrocarbon liquids. In several events, the specific oil fraction was not reported ("Other oil", including oil fractions and hydrocarbon liquids, 1603 records, 40.4 %). Crude oil (1434 records, 36.1%) and fuel oil (814 records, 20.5 %) were released in a relevant number of events.
As shown in Figure 3, the release and involvement in Natech events generating consequences for the environment of water soluble substances is much less frequent (2.6% of events – "Other substances"). This is confirmed by the above analysed reference accidents, where only in the Kocaeli earthquake a water-soluble substance (acrylonitrile) was involved.

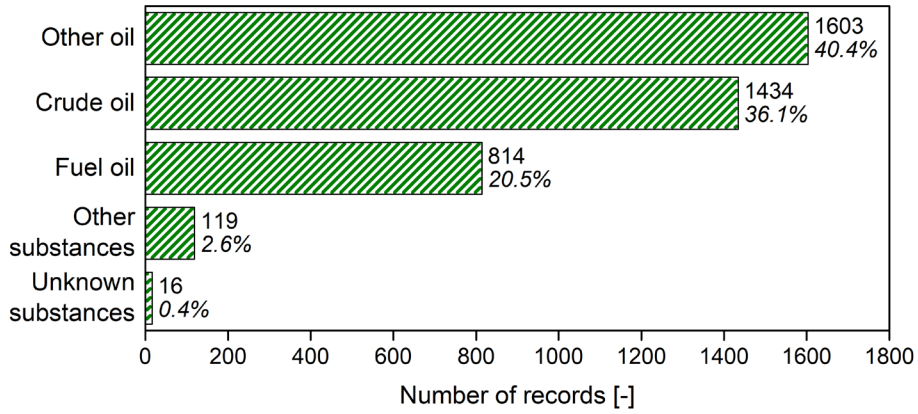

Figure 3: Share among chemical substances involved in Natech accidents resulting in environmental contamination. Other oil: all oil fractions or other hydrocarbon liquids not specified as crude oil or fuel oil. Other substances: all species not classified as oil (e.g., ammonia, water solution). Unknown substances: records with no information on the substance involved in the accident. Total number of records: 3,970.

Based on the accidents described in Section 3, it can be inferred that the contamination can impact several environmental compartments simultaneously. Moreover, the accidents analysed also demonstrate the role of safety barriers in these specific events. In fact, in all accidents the safety barriers suffered critical damages, enhancing the probability of environmental contamination.The results of the analysis performed in the present study allow highlighting which are the main features related to the environmental contamination triggered by Natech accidents. Eventually, they prioritize the aspects to be considered for the development of models suitable for the quantitative assessment of damages on the environment in major accidents triggered by natural events.

5. Conclusions

In the present study, a specific database is used to collect data on past accidents resulting in damage to the environment. In addition, four detailed accident reports were analysed in detail. About 4,000 accidents among the 9,100 included in the database resulted in damage to the environment. These were classified based on the triggering natural event and the type of substance involved in the accident. The relevance of water-related natural events was highlighted. Although the limited number of past events resulting in environmental contamination reported, earthquakes represent a threat to the environment due to the magnitude of the consequences and to the specific patterns they can generate. Oil-based substances and hydrocarbon liquids were involved in the majority of the collected reports. The results obtained in the present analysis allow the identification of the more critical substances and scenarios resulting in environmental damage caused by Natech events, prioritizing the aspects to be considered for the development of models suitable for the quantitative assessment of damages on the environment in major accidents triggered by natural events.

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