Understanding Natech Risk Due to Storms: Analysis, Lessons Learned and Recommendations

Technical Report · December 2018
DOI: 10.2760/21366

CITATIONS
2

READS
431

3 authors:

Amos Necci
European Commission
32 PUBLICATIONS 181 CITATIONS
See Profile

Serkan Girgin
European Commission
75 PUBLICATIONS 191 CITATIONS
See Profile

Elisabeth Krausmann
European Commission
114 PUBLICATIONS 1,374 CITATIONS
See Profile

Some of the authors of this publication are also working on these related projects:

- Natural-hazard impacts on strategic non-civilian infrastructure View project
- Reducing the risks of technological disasters caused by natural hazards (NATECH) View project

All content following this page was uploaded by Serkan Girgin on 25 January 2019.
The user has requested enhancement of the downloaded file.
Understanding Natech Risk Due to Storms

Analysis, Lessons Learned and Recommendations

Necci, A., Girgin, S., Krausmann, E.

2018
Contents

Abstract ................................................................................................................................. 1

1 Introduction .......................................................................................................................... 2

2 Storm categories and effects .............................................................................................. 4
   2.1 Types of storm ............................................................................................................... 4
      2.1.1 Tropical cyclones ................................................................................................. 4
      2.1.2 Windstorms ......................................................................................................... 5
      2.1.3 Polar lows ............................................................................................................. 5
      2.1.4 Medicanes ............................................................................................................ 6
      2.1.5 Thunderstorms ..................................................................................................... 6
   2.2 Climate change ............................................................................................................. 6
   2.3 Effects of storms ......................................................................................................... 6
      2.3.1 Wind action ......................................................................................................... 6
      2.3.2 Heavy precipitation ............................................................................................ 7
      2.3.3 Storm surge ......................................................................................................... 7
      2.3.4 Lightning ............................................................................................................. 7

3 Natech Statistics ................................................................................................................. 8
   3.1 Data sources ............................................................................................................... 8
   3.2 Method used ............................................................................................................... 9

4 Results .................................................................................................................................. 10
   4.1 Analysis of Natech events ............................................................................................ 10
   4.2 Analysis of storm-triggered Natech events ................................................................. 12
      4.2.1 Storm-triggered Natech events in TAD .............................................................. 13
      4.2.2 Storm-triggered Natech events in MHIDAS ....................................................... 19
      4.2.3 Results summary ................................................................................................. 26

5 Analysis of accident case studies ....................................................................................... 27
   5.1 Hurricane Hugo, Virgin Islands, 1989 ........................................................................ 27
   5.2 Hurricane Katrina, USA, 2005 ................................................................................... 29
      5.2.1 Murphy Oil spill ................................................................................................... 30
      5.2.2 Dynegy ................................................................................................................ 31
      5.2.3 Shell Pilot Town ................................................................................................. 31
      5.2.4 Shell Nairn .......................................................................................................... 33
      5.2.5 Sundown Energy ............................................................................................... 34
      5.2.6 Bass Enterprises ............................................................................................... 34
      5.2.7 Chevron Empire ............................................................................................... 35
   5.3 Hurricane Rita, USA, 2005 ......................................................................................... 36
   5.4 Hurricane Ike, USA, 2008 ......................................................................................... 36
Abstract

As standards of living generally improve across the globe, there is a corresponding change in people’s perception and acceptance of risk. The impact of natural hazards is an emerging threat to industrial facilities, pipelines, offshore platforms and other infrastructure that handles, stores or transports hazardous substances. When accidentally released, hazardous substances can lead to fires, explosions, and toxic or radioactive releases. These so-called Natech accidents are a recurring but often overlooked feature of many natural disasters and have often had significant human, environmental and economic impacts. Industries and authorities must be able to learn from incidents and capture the lessons that are needed to safely conduct business and produce goods for the whole of society.

Among natural events, storms can seriously affect the integrity of an industrial installation and lead to accident scenarios such as fires, explosions and the dispersion of chemicals in the environment. In addition, scientists expect an overall worsening of extreme weather events in this century due to climate change, which will further increase the threat to industrial facilities.

This report analyses past technological incidents with hazardous materials releases and damage to industrial facilities caused by the impact of storms. It discusses the vulnerability of industrial sites including that of the main equipment types present at the facility and analyses how they are damaged.

The first part of the report describes the storm hazard. It discusses storm types and their occurrence, as well as the main effects that cause damage to human settlements and the environment. The report lists strong winds, heavy precipitation, lightning and storm surge as the main effects responsible for damage to industrial installations.

In the second part of the report, we perform an analysis of past storm-triggered Natech events. Using different sources of public information on technological incidents, this study:

1. Analyses incident statistics;
2. Reviews a number of “landmark” accidents;
3. Discusses the lessons learned.

From the analysis of past events, the report concludes that Natech events caused by storms are frequent and that their relative occurrence is increasing compared to the overall occurrence of technological incidents from other causes in the analysed databases. The largest losses were generally triggered by heavy rain and flooding, while the most frequent trigger was lightning. The study also highlighted the role of a loss of power supply in triggering an incident or hampering the mitigation of its consequences.

The study presents lessons learned from the forensic analysis of past events and puts forward recommendations for future risk reduction for all storm effects. The most important lesson is that storm predictions based on past events are not sufficient to be well prepared for future events, in particular in the face of climate change.
1 Introduction

Storms are responsible for a number of accidents at industrial installations each year, resulting in fatalities, injuries, pollution and economic losses. Natural hazard triggered technological (Natech) accidents are frequent in the wake of natural disasters, and they have repeatedly had significant and long-term social, environmental and economic impacts (e.g. Krausmann and Cruz, 2013; Girgin, 2011; Krausmann et al., 2010; Godoy, 2007). While awareness of this risk is growing, and national and international initiatives have been launched to better assess and manage this type risk, there are still significant gaps that have hampered the effective Natech risk management (Krausmann and Baranzini, 2012).

In Europe, the “Seveso III” Directive 2012/18/EU, which lays down rules for the prevention of major accidents which might result from certain industrial activities and the limitation of their consequences for human health and the environment, requires specifically the assessment of Natech risks. In support of the European Union Member States but also other international players, the European Commission’s Joint Research Centre (JRC) has been involved – for almost a decade now – in the development of methods for the analysis of the risks of Natech accidents.

Like other natural hazards, storms may seriously affect the integrity of an industrial installation and lead to accident scenarios such as fires, explosions and the dispersion of chemicals in the environment. Some of the most iconic storm-triggered Natech events were recorded when hurricanes Katrina and Rita hit Texas, Mississippi and Louisiana in 2005. The two storms caused extensive damage to both onshore and offshore oil and gas infrastructure and triggered a number of hydrocarbon spills responsible for environmental emergencies (Ruckart et al., 2008; Cruz and Krausmann, 2009; Santella et al., 2010) and enormous economic losses (Blake et al., 2011). More recently, during Hurricane Harvey, the US Coast Guard National Response Center filed 96 reports of spills of hazardous chemicals, crude oil and fossil fuels which contaminated the coast of the Gulf of Mexico, while 46 facilities in 13 counties reported to the authorities airborne emissions totalling 4.6 million pounds (Griggs, 2017).

Moreover, the global worsening of extreme weather and sea conditions poses a great threat to industrial operators. The climate in the Atlantic Ocean has changed and the strength of storms and cyclones has grown in recent years (Gulev and Hasse, 1999), suggesting that even worse extreme events might occur in the years to come due to climate change. Hewson and Neu (2015) give an overview of the most important assessments with climate models of the expected climatic changes in the extra-tropical Atlantic Ocean and their impacts on extreme weather events on the neighbouring seas.

Despite efforts to reduce the occurrence of man-made disasters, incidents related to environmental triggers have been occurring continuously, some of which with dramatic consequences. This report analyses past incidents triggered by storms aiming to understand lessons as to why these events happened, what the accident mechanisms, vulnerabilities and criticalities of existing installations were, and how those events can be prevented.

In section 2 of this report, the hazard posed by storms is described. In sections 3 and 4, incident datasets composed of events collected from the main industrial accident databases are analysed. In section 5, a set of iconic case studies are reviewed, highlighting the critical factors that led to past events. In section 6, the most vulnerable infrastructure components and the riskiest operations are identified, while causes and modes of failure are described. Lessons learned are summarized in section 7 and conclusion are drawn in section 8.

This report will help the development of tailored accident scenarios that can be used in risk assessment to better understand Natech risks. In addition, this knowledge can help to

---

improve design standards to improve the resistance of industrial installations to extreme meteorological events.

A discussion involving design, operations, practice, maintenance and planning close this document aiming to improve safety at hazardous installations, strengthen the resilience of critical infrastructure, avoid future major losses and protect the environment from accidental pollution.
2 Storm categories and effects

2.1 Types of storm

Storms comprehend a large variety of phenomena that differ from each other by a number of factors, such as the geographic location and morphology of the territory. Meteorology classifies the study of weather phenomena on the basis of their scale. The synoptic scale is a horizontal length scale of the order of 1000 kilometres or more (XWS, 2016). The largest low-pressure systems, such as extratropical cyclones are on the synoptic scale. Warm-core storms such as tropical and subtropical cyclones also lie within the synoptic scale. The mesoscale studies weather systems smaller than synoptic-scale systems but larger than microscale (or storm-scale) cumulus systems (NSSL, 2018). The microscale is concerned with systems of the order of 1 km that last less than a day, with many localized effects.

Severe storms have historically affected Europe. For example, the Xynthia storm in 2010 was the largest European coastal disaster of the last 50 years, with 47 people killed in France alone (Chadenas et al., 2014). The 1953 storm surge in the southern North Sea, which resulted in over 2,000 deaths and extensive flooding across The Netherlands, England, Belgium and Scotland, led to strengthened flood defences and the development of modern flood warning systems (Wadey et al., 2015). The impact of each storm is evaluated in different ways in different countries, often using local socio-economic impact criteria (e.g. loss of lives and damage to property).

2.1.1 Tropical cyclones

A tropical cyclone is a rotating storm system characterised by a low-pressure centre and a spiral arrangement, which forms over tropical or subtropical waters (NHC, 2018). It features strong winds and torrential rain. Depending on the region it occurs and its strength (wind speed), a tropical cyclone is referred to by different names, for example hurricane, typhoon, tropical storm, cyclonic storm, tropical depression, or simply cyclone (WMO, 2018). Tropical cyclones usually form over large bodies of warm water. They obtain their energy from the evaporation of water from the ocean surface, which then condenses into clouds and rain when moist air rises and cools (Evans, 2017). Tropical cyclones are typically between 100 and 2,000 km in diameter.

Tropical cyclones are natural phenomena that have greatly contributed to the morphology of modern shorelines (Woodruff et al., 2013). On average, about 90 tropical cyclones occur worldwide per year, with the annual distribution of these events varying among the various tropical cyclone basins (Frank and Young, 2007). Only about 20% of tropical cyclones make landfall with the intensity of a hurricane, but coastal impacts by tropical cyclones are due largely to this important subset of storms (Weinkle et al., 2012).

Although tropical cyclone activity is low in the North Indian Ocean and the North Atlantic compared to the Pacific, the frequency of coastal flooding is much higher. Extreme flooding is prevalent mainly on low-gradient shores, including barrier and deltaic systems; these areas have often also attracted the development of dense population centres (Woodruff et al., 2013). In the regions they affect, tropical cyclones are often the most damaging storms and, therefore, of primary importance when assessing flood risk. Figure 1 shows hurricane tracks and landfall location points for storms that make landfall at hurricane intensity.
2.1.2 Windstorms

Most European windstorms originate from extra-tropical cyclones (synoptic-scale low pressure systems) with very strong winds or violent gusts that are capable of producing devastating socioeconomic impacts. In order for cyclones to grow, a strong north-south temperature gradient is needed, and a strongly baroclinic atmosphere. During the months October to March the North Atlantic Ocean satisfies these conditions, allowing extra-tropical cyclones to form (cyclogenesis) which travel eastwards towards Europe (XWS, 2016).

The path that these storms follow (storm track) tends to curve toward northern European countries (e.g. the Faroe Islands, Ireland, the UK, and Scandinavia). However, occasionally the storms can travel further southwards, affecting countries such as France, Portugal, and Spain.

Windstorms are strong wind phenomena that give rise to "damage footprints" at the ground. Windstorms can lead to structural damage, power outages to millions of people, and closed transport networks, resulting in severe disruption and even loss of lives (Roberts et al., 2014). While larger-scale aspects of extra-tropical cyclones can be easily forecast, the occurrence, location, and severity of the local major wind damage, are not. Windstorms in Europe can be divided into three main categories, namely: the warm jet, the cold jet and the sting jet. These phenomena vary in terms of physical mechanisms, atmospheric structure, spatial extent, duration, severity level, predictability, and location relative to the cyclone and its fronts. The sting jet is the type that results in the highest level of damage, but it is also the rarest. Windstorms are a major problem for Atlantic and Central Europe (XWS, 2016; Roberts et al., 2014).

2.1.3 Polar lows

A polar low is a small-scale cyclones that is found over ocean areas poleward of the main polar front in both the Northern and Southern Hemispheres. In Europe, they frequently occur in the northern Norwegian Sea and at the Barents Sea and only occasionally in the north of United Kingdom (Mallet et al., 2013). Because of their hurricane-force winds and circular shapes with an eye in the centre, they are often referred to as Arctic hurricanes. These systems expire quickly and they usually exist for no more than a couple of days. They can produce high-speed surface winds, large-amplitude ocean waves and heavy snow precipitation (Mallet et al., 2013)
2.1.4 Medicanes

High winds in Europe can also be a result of convective storms (e.g. tornadoes which are the most severe) and cyclones formed in the Mediterranean basin (XWS, 2016). Similar to tropical cyclones, Mediterranean cyclones (sometimes called “medicanes”) are rare meteorological phenomena observed in the Mediterranean Sea. Due to the dry nature of the Mediterranean region, formation of medicanes is infrequent, with only 100 recorded events between 1948 and 2014 (Reale and Atlas, 2001). According to recent studies conducted on global warming effects on the Mediterranean region, tropical-like cyclones are likely to happen with lower frequency in the next 100 years, yet with stronger intensity (Reale and Atlas, 2001). Even though these events are less violent than most of the tropical cyclones, the wind speed reaches hurricane strength.

2.1.5 Thunderstorms

A thunderstorm is a storm characterised by the presence of lightning and thunder. Thunderstorms occur in a type of cloud known as a cumulonimbus, a cumulus cloud, modelled in the shape of a tower by rising air masses. There are four types of thunderstorms: single-cell thunderstorms, multi-cell storms or clusters, squall lines, and supercells. Supercell thunderstorms are the strongest and most severe and can rotate as do cyclones (NSSL, 2018). Downburst winds, large hailstones, and flash flooding caused by heavy precipitation can wreak havoc on human settlements, technological systems and agriculture. Stronger thunderstorm cells are capable of producing tornadoes and waterspouts. Thunderstorms can form at any geographic location but most frequently within the mid-latitude, where warm, moist air from tropical latitudes collides with cooler air from polar latitudes (NSSL, 2018).

2.2 Climate change

Hewson and Neu (2015) give an overview of the most important assessments with climate models on the expected changes in European climate and their impacts on extreme weather events. In the current climate, the main hazard for Europe are severe winter storms, which are typically local effects of extratropical cyclones, while tropical cyclones rarely reach Europe. However, this situation can quickly change. According to Haarsma et al. (2013), both the number and the severity of hurricanes reaching Europe are expected to increase due to climate change.

Sea climate is also expected to change. According to Kushnir et al. (1997), North Atlantic wave heights have increased in the past years. The same conclusion was drawn by Gulev and Hasse (1999), who also relate the increase of wave height with the increase of wind speed in the northern Atlantic. This raises concern regarding the possibility of storm intensity increase in the northern Atlantic region, in the near future. Furthermore, based on global warming scenarios, rougher wave conditions and higher sea levels should be expected (Debernard et al, 2002).

2.3 Effects of storms

2.3.1 Wind action

Winds can exert strong forces on buildings and other structures. The study of storm outflows and their loading of structures is an important topic of modern wind engineering (Letchford et al., 2002; Solari, 2014). The methods currently used to determine wind actions on structures are still mostly based on the synoptic extra-tropical cyclone model (Zhang et al., 2018) introduced by Davenport (1961).

In addition, wind can carry objects that can become very dangerous projectiles. In Germany, the Technical Rule TRAS 320 (TRAS 320, 2015) differentiates the types of missiles that are propelled by the wind. If parts of industrial installations or objects are detached or lifted by the wind and carried through the air, they are referred to as 'airborne projectiles'. If objects slide or roll along the ground by the wind, they are referred to as
'ground-level projectiles'. Collapsing parts of installations, trees, etc. are referred to as other 'wind-induced projectiles'.

Thunderstorms, hurricanes, and tornadoes often induce trees to fall due to high wind forces. In addition to the direct threat to humans, fallen trees and branches may interfere with overhead power lines and cause also prolonged power outages which, in turn, may result in loss of services from a number of critical infrastructure systems (Kabir et al., 2018).

Wind can endanger technological systems housing hazardous substances in the following situations (TRAS 320, 2015):

1. When the stability and/or integrity of safety-relevant parts of sites and installations where particular substances are present is immediately threatened.
2. When the functioning of safety-relevant parts of sites and installations is threatened.
3. When safety-relevant operating procedures or work processes cannot be carried out or only carried out under more difficult conditions.

2.3.2 Heavy precipitation

Storm activity may produce intense rainfall, potentially resulting in flash floods, mudslides, and landslides. Water can cause damage to the power grid and to electrical equipment, disrupting businesses and critical infrastructure. Buoyancy can float and displace lighter objects in flooded areas. Heavy rain or snow accumulating on structures can cause failure due to weight loading. Numerous floating roof storage tanks were damaged by heavy rain accumulation during hurricane Harvey in 2017, allowing the release of their content of hazardous material (Blum, 2017)).

2.3.3 Storm surge

Storm surge is associated with either tropical or extra-tropical storms. This includes effects driven by wind, pressure and waves, but not the effects of tides or wave run-up (Wu et al., 2018). Storm surge can flood large areas and cause water damage. Storm surge and heavy rain both contribute to the flooding of coastal areas, especially in low floodplains and river deltas.

2.3.4 Lightning

The impact of lightning strikes can trigger different accident scenarios, depending on the features of the industrial equipment and on the properties of the stored hazardous substance. The direct action of lightning impact on metal enclosures may result in the damage of the shell or pipe (puncturing) and in the subsequent release of liquid (Necci et al., 2013). When flammable substances are contained, direct and indirect lightning strikes may cause fires and/or confined explosions, even in the absence of direct damage to the tank shell (Necci et al., 2014).
3 Natech Statistics

3.1 Data sources

The data sources for the present analysis were the European industrial incident databases ARIA (BARPI, 2018a), MHIDAS (HSE, 2007), TAD (IChemE, 2004) eMARS (eMARS, 2018) and FACTS (FACTS, 2018). The ARIA database is publicly accessible, while access to FACTS requires a licence. The eMARS database contains confidential information on major accidents submitted to the European Commission by the Competent Authorities. The MHIDAS and TAD databases are no longer supported.

The ARIA database (Analyse, Recherche et Information sur les Accidents) is managed by the French Ministry of Ecology and Sustainable Development (BARPI, 2018a). This database contains records involving accidents in industrial plants or storage farms as well as “near misses” which may compromise health, public safety, and the environment. BARPI prepared a detailed report on Natech accidents (BARPI, 2013), which was used as a source of information for the current report.

The FACTS database (Failure and ACcidents Technical information System) is managed by TNO Industrial and External Safety Department, and contains information on events which caused (accidents) or could cause (near misses) severe consequences (FACTS, 2018). Although FACTS requires a licence to access the report of the incidents, some summary information about the incidents is available for free. This summary information include: year, country, type of activity, location, list of chemicals involved, generic cause, and the occurrence of deaths and injuries. In addition each incident has a number of keyword-tags that can be used to obtain additional information and to filter search results (Campdel, 2008).

MHIDAS (Major Hazard Incident DAta Service) was a database managed by AEA Technology Ltd. (Warrington, UK) on behalf of the British Health and Safety Executive (HSE, 2007). The MHIDAS database is no longer in service. For this reason, the dataset we collected from this source is outdated to the date of our last licence purchase in 2007. Nevertheless, the database contains information on more than 7000 incidents that occurred in industrial sites and during the transport of hazardous materials that actually or potentially had off-site impact (Campdel, 2008).

The IChemE database (TAD) is a product of the Institution of the Chemical Engineers (IChemE), an international professional membership organization that promotes research activities and knowledge development in all the sectors of chemical engineering, including process safety (Campdel, 2008). The IChemE database contains data from different sources, including the “Loss Prevention Bulletin” and reports of the US Chemical Safety and Hazard Investigation Board. The information stored in the records of the database is often very concise and usually limited details are reported on the installation where the incident took place and on release mechanism and path (Campdel, 2008).

The Major Accident Reporting System (MARS and later renamed eMARS after going online) was first established by the EU’s Seveso Directive 82/501/EEC in 1982 and has remained in place with subsequent revision of the Seveso Directive in effect today. eMARS contains reports of chemical accidents and near misses provided to the Major Accident Hazards Bureau (MAHB) of the European Commission’s Joint Research Centre (JRC) from EU, EEA, OECD, and UNECE countries (under the TEIA Convention). Reporting an event into eMARS is compulsory for EU Member States when a Seveso establishment is involved in an accident and the event meets the consequence criteria of a “major accident” as defined by Annex VI of the Seveso III Directive. For non-EU OECD and UNECE countries, reporting accidents to the eMARS database is voluntary. The information of the reported event is entered into eMARS directly by the official reporting authority of the country in which the event occurred.
3.2 Method used

For the data extraction, selection criteria were defined in agreement with the following rules:

- The loss of containment of a hazardous substance occurred or could have occurred.
- An industrial activity processing or storing hazardous substances was involved.
- The event generated (or had the potential to generate) an accident scenario with off-site consequences (major accident).

In the analysis of industrial sites, we included mainly activities falling under the provisions of the European Seveso III Directive and similar legislation outside Europe. However, the databases include also incidents in other industrial sites not covered by these types of legal frameworks, which were also considered in the present study for lessons learning purposes. Although of general interest, incidents at offshore oil and gas operations, transport by vessel, by train and by truck and pipelines are beyond the scope of this study and were therefore excluded from the analysis.

During the data selection process only incidents with an obvious role of natural events as a main event trigger were included in the analysis as Natech incidents. In order to identify these events, the data set was filtered according to the following steps:

- Analysis of incidents tags or keywords based on cause. When the tag or keyword referred to natural causes or to one specific natural event (e.g. lightning, flood, earthquake) the incidents was added.

- Analysis of incidents description or summary. When the summary texts include references to natural causes or to one specific natural event (e.g. lightning, flood, earthquake) the incidents was added.

Among these, storm-triggered Natech incidents were filtered out and further analysed. When possible, the categories available in the databases were used to filter the results. When such information was not available, a keyword-based selection with manual verification was performed.

For the purpose of this study we use the following definitions:

An incident is an event resulting in unwanted consequences, including near misses and accidents. An accident is an incident which results in serious consequences and possibly creates an emergency situation.
4 Results

4.1 Analysis of Natech events

Table 1 summarizes the number of Natech incidents recorded in each database. The table contains three different categories, depending on the type of operation, which are: "Transport vehicles" (i.e. train, truck or vessel), "Pipelines" and "Fixed installations". This is important since the mechanisms that can trigger a Natech accident can be completely different for industrial installations or for transport, such as a truck accident. For this reason, the analysis of Natech incidents regards fixed installations only, and in the statistics, the other events were excluded.

Table 1. Number of Natech events in each database

<table>
<thead>
<tr>
<th>Database name</th>
<th>Total Natech</th>
<th>Transport vehicles</th>
<th>Pipelines</th>
<th>Fixed installations</th>
</tr>
</thead>
<tbody>
<tr>
<td>MHIDAS</td>
<td>705</td>
<td>359</td>
<td>93</td>
<td>254</td>
</tr>
<tr>
<td>FACTS</td>
<td>962</td>
<td>137</td>
<td>136</td>
<td>689</td>
</tr>
<tr>
<td>eMARS</td>
<td>33</td>
<td>0</td>
<td>0</td>
<td>33</td>
</tr>
<tr>
<td>ARIA</td>
<td>920</td>
<td>N.A.(^3)</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>TAD</td>
<td>560</td>
<td>185</td>
<td>39</td>
<td>336</td>
</tr>
</tbody>
</table>

Source: JRC

In order to identify Natech incidents due to storms the natural event that triggered the incident should be analysed. For the databases MHIDAS, ARIA, TAD and eMARS it was possible to identify one major natural hazard that triggered the Natech, by looking at the incident description (or abstract). Table 2 shows the relative occurrence of Natech incidents according to natural causes for the databases: MHIDAS, FACTS, ARIA, TAD and eMARS. For the database FACTS, the full report of the incidents was not available, and keywords were used to identify the natural hazards. However, many records list multiple natural hazards. In the absence of a detailed incident description to which we had no access, it was not possible to identify the triggering natural hazards among those listed. Therefore, Table 2 reports only the occurrence of each keyword. It should be noted that none of the keywords in FACTS refers to storms explicitly.

Results for the databases are not uniform, possibly due to geographical differences in the data source. The tags for natural events were sometimes very specific. For this reason, they were grouped in larger harmonized categories, namely: Freeze, Landslide/erosion, Wind/storm, Lightning, Flooding, Temperature, Heavy rain, Earthquake, and Snow. Figure 2 shows the distribution of Natech incidents per natural hazard and database. MHIDAS and TAD, which have a global coverage on incident reporting, have a similar distribution of incidents among the same natural event triggers. In fact, for both lightning has the biggest share of records, while records labelled under Temperature (or Freeze) takes the second place. These categories were followed by other atmospheric phenomena: Flooding, Wind/storm and Heavy rain, while the least frequent categories were Earthquake and Landslide. The main difference between the two databases is the size of the category Other, which is much bigger for TAD, due to the presence of numerous events under the label Weather effects (including additional events due to heavy rain and temperature).

---

\(^3\) Not Available
Table 2. Number of records per each tag or keyword

<table>
<thead>
<tr>
<th>TAD</th>
<th>MHIDAS</th>
<th>eMARS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avalanche</td>
<td>1</td>
<td>Earthquake</td>
</tr>
<tr>
<td>Cold weather</td>
<td>43</td>
<td>Floods</td>
</tr>
<tr>
<td>Earth movement</td>
<td>2</td>
<td>Ground</td>
</tr>
<tr>
<td>Earth tremor</td>
<td>2</td>
<td>High winds</td>
</tr>
<tr>
<td>Earthquake</td>
<td>16</td>
<td>Lightning</td>
</tr>
<tr>
<td>Flood</td>
<td>7</td>
<td>Other</td>
</tr>
<tr>
<td>Fog</td>
<td>1</td>
<td>Temperature</td>
</tr>
<tr>
<td>Freezing</td>
<td>9</td>
<td>ARIA</td>
</tr>
<tr>
<td>Hot weather</td>
<td>5</td>
<td>Earthquake</td>
</tr>
<tr>
<td>Lightning</td>
<td>126</td>
<td>Extreme temperature</td>
</tr>
<tr>
<td>Rain</td>
<td>10</td>
<td>Flooding</td>
</tr>
<tr>
<td>Settlement</td>
<td>1</td>
<td>Frost</td>
</tr>
<tr>
<td>Storm damage</td>
<td>3</td>
<td>Heavy rain</td>
</tr>
<tr>
<td>Subsidence</td>
<td>2</td>
<td>Landslide/Erosion</td>
</tr>
<tr>
<td>Sunlight</td>
<td>3</td>
<td>Lightning</td>
</tr>
<tr>
<td>Thermal expansion</td>
<td>12</td>
<td>Snow</td>
</tr>
<tr>
<td>Typhoon</td>
<td>24</td>
<td>Wind/Storm</td>
</tr>
<tr>
<td>Weather effects</td>
<td>23</td>
<td></td>
</tr>
</tbody>
</table>

Source: JRC

eMARS has a lower number of records and a prevalence of European incidents. The biggest category is Freeze, and together with Temperature they exceed one third of the set’s size. Wind/storm follows and Lightning takes the third place. Heavy rain and Flood have a low impact with only 15% of the set share combined. None of these accidents was triggered by Earthquake or Landslide.

ARIA has a big set of Natech incidents (920 records), but they are reported mainly from France (747). For this dataset, the main hazards are Heavy rain and Flood which account for almost half of the set’s records combined. Lightning is the second hazard, and Temperature and Freeze follow. Wind/storms, Earthquake and Landslide/erosion are the categories with the lowest number of records.
4.2 Analysis of storm-triggered Natech events

In order to describe storm-triggered Natech events, records of storm-triggered events were collected in a separate subset. All incidents that refer to storms or hurricanes were included, as well as all incidents that contain one or more effects of storms (see section 2.2). Table 3 shows the number of storm-related Natech incidents for the databases analysed.

Table 3. Number and ratio of storm-triggered Natech events for the database considered.

<table>
<thead>
<tr>
<th>Database</th>
<th>Number</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>MHIDAS</td>
<td>192</td>
<td>76.0%</td>
</tr>
<tr>
<td>ARIA</td>
<td>677</td>
<td>73.6%</td>
</tr>
<tr>
<td>eMARS</td>
<td>20</td>
<td>60.6%</td>
</tr>
<tr>
<td>TAD</td>
<td>192</td>
<td>57.4%</td>
</tr>
</tbody>
</table>

This following sections provide a deeper analysis of storm-triggered incidents for the databases MHIDAS and TAD.
4.2.1 Storm-triggered Natech events in TAD

Figure 3 shows the trend of storm-triggered incidents in the TAD database (blue bars) and compares this trend with the record trend for all the incidents in the database (red line). The overall number of records is continuously increasing (possibly due to an increase in the number of industrial activities as well as the chances for reporting incidents) except for the late 90s, where the trend is decreasing. At the same time however, the number of storm-triggered incidents also increases up to the 80’s and then remains almost steady. The relative increase of the number of storm-triggered Natechs compared to other incidents could reflect the fact that new safety requirements effectively mitigated the risk due to conventional technological accidents, but failed to reduce the risk posed by storm-triggered Natech events. However, we cannot be certain due to fragmentation of the data source itself. In addition, this data represents the information available in the database and not the total number of incidents in the period, which causes uncertainties in the assessment.

Figure 3. Number of storm-triggered Natech events (blue bars) and total number of technological incidents (orange line) collected since 1960 and grouped in 5 year periods for the TAD database

Figure 4 shows the distribution of storm-triggered incidents with respect to the type of equipment or structure that was involved or damaged. Storage facilities were most frequently hit by storms, showing not only a vulnerability to these events, but also a potential for major accidents due to the large storage volume. Process equipment follows with less than half the records compared to storage. Other interesting categories are electrical equipment, building and structures, safety equipment and instrumentation, each with ten or less records.

The number of incidents due to lightning strikes overshadows the other storm effects, which have a very small statistical significance. It is thus necessary to analyse Natech incidents separately, on the basis of the natural effect that triggered the incident. Figure 5 shows the distribution of storm-triggered Natech events that were caused by lightning strikes. The results are similar to that of the whole dataset, except that lightning strikes have a higher relative impact on storage equipment and a lower impact on process equipment, if compared to the distribution of the entire set (Figure 4).

Conversely, Figure 6 shows the distribution of storm-triggered Natech events that were caused by all effects except lightning divided by the type of equipment affected. Also in this case the results are similar to that of the whole dataset, except that the categories
process equipment and building or structure have a higher relative occurrence if compared to distribution of the entire set (Figure 4), while storage has a lower occurrence.

**Figure 4.** Distribution of storm-triggered Natech events by the type of structure (all storm effects)

![Pie chart showing distribution of storm-triggered Natech events by the type of structure.]

Source: JRC

Going more into the details of the single causes, Figure 7 shows the distribution of storm-triggered Natech events due to rain or flood. These also show a similar distribution of that...
depicted in Figure 4, but with a larger relative occurrence of the categories building or structure, instrumentation and blank (no information) and a slightly lower occurrence of storage and process equipment. The label blank usually refers to damage to the factory as a whole, which is a very common scenario when the industrial site gets flooded.

**Figure 6.** Distribution of storm-triggered Natech events by the type of structure (lightning triggered incidents excluded)

![Figure 6](image6.png)

Source: JRC

**Figure 7.** Distribution of storm-triggered Natech events by the type of structure (only incidents triggered by rain and flood)

![Figure 7](image7.png)

Source: JRC
Finally, Figure 8 shows the distribution of Natech events triggered by the effects of wind and based on the type of affected equipment. Wind-induced incidents have a completely different trend compared to that of the whole TAD data set. Process equipment is in this case the tag with the highest relative occurrence, followed closely by storage. All other categories have marginal relative occurrence, and the label electrical does not appear at all in case of wind-triggered incidents.

Another important parameter to describe storm-triggered Natech events is the consequence of the incident. We created a list of consequence categories, each describing a different scenario. A category was assigned to each event, using the same categories as the database. The list of labels used is as follows: Blow-out, Collapse, Damage to equipment, Evacuation, Explosion, Explosion and fire, Fatality, Fire, Gas/Vapour release, Near miss, Plant shutdown, Spill (liquid) and Vapour Cloud Explosion (VCE).

Figure 9 shows the distribution of storm-triggered Natech events as a function of the consequences that resulted from the event. Each colour represents a different natural action that triggered the incident, as for the labels used by TAD. The most common events are those filed under the Fire and Explosion and fire tags. In fact, these accidents where mostly the result of lightning strikes hitting chemical facilities and in particular oil refineries and tank terminals. Damage to equipment is the second most frequent category and was caused mainly by Typhoons, Weather effects and Flood. Spills are mainly caused by Rain, Flood or generic Weather effects. Since the results of Figure 9 suggest that each natural hazard produces different scenarios, each triggering effect was analysed separately. For this reason the labels that were too generic (i.e. Typhoon and Weather effects) were further analysed to understand whether the incident was due to wind, rain, lightning or flood action.
Figure 9. Distribution of storm-triggered Natech incidents by consequence. The specific storm effects that triggered the events are identified with different colours.

Figure 10 shows the distribution of lightning-triggered Natech events, sorted by the type of consequence. Fire, Explosion and Explosion and fire together sum up to over 80% of all lightning-triggered events. Among the remaining scenarios, Damage to equipment is the most numerically relevant. It should be noted that lightning is the only natural hazard that triggered Vapour cloud explosion and Blowout scenarios.

In Figure 11 the distribution of consequences for Natech events triggered by the effect of rain or flood due to a storm is shown. The consequence types are well distributed, but the category with the highest relative occurrence is Spill (29%). Actually, rain and flood are the only types of natural hazard that feature this scenario. In this case, the categories Fire, Explosion and Explosion and fire have also a high relative occurrence, summing up to 40% of the Natech events triggered by rain and flood. Other relevant scenarios are Damage to equipment and Gas/vapour release.

Figure 12 shows the distribution of the consequence of wind-triggered Natech events. In this case Damage to equipment and Fire have the highest relative occurrence, with over one half (53%) of the wind-triggered incidents set, followed by Collapse. Explosion and fire has a lower occurrence, if compared to the previous natural hazards with 8%. Other scenarios are Gas/vapour release and Near miss.
**Figure 10.** Distribution of storm-triggered Natech incidents by consequence (only incidents triggered by lightning)

Source: JRC

**Figure 11.** Distribution of storm-triggered Natech incidents by consequence (only incidents triggered by heavy rain or flooding)

Source: JRC
4.2.2 Storm-triggered Natech events in MHIDAS

Similar to Figure 3 for TAD, Figure 13 shows the trend (in 5-years increments) of storm-triggered incidents in the MHIDAS database (blue bars) in comparison with the trend of all technological incidents in MHIDAS (red line). The overall number of records is continuously increasing (possibly due to an increase in the number of industrial activities as well as the requirements for reporting, or data availability). At the same time the number of storm-triggered events also increases, possibly at a higher rate than the red line.
To better appreciate the relative trend of storm-triggered Natechs compared with the overall database, Figure 14 reports the trend (in 5-years increments) of the numerical value of the ratio between storm-triggered Natechs and the overall records. The graph shows an initial reduction of the ratio of storm-triggered Natechs, but then a sudden increase, starting from the late 90s. Similar to what was observed for TAD in Section 4.2.1, the relative increase of the number of storm-triggered Natech event compared to other incidents could indicate that new safety requirements effectively mitigated the risk due to conventional technological accidents, while failing to reduce the risk posed by storm-triggered Natech events.

The focus of MHIDAS is on the actual technological accidents with hazardous-substance releases, thus damage to structures or to auxiliary equipment that did not result in an accident was not reported. For this reason, in MHIDAS only three categories that describe the affected type of equipment or structure were identified: electrical equipment, process equipment and storage. Figure 15 shows the distribution of storm-triggered accidents with respect to the type of equipment or structure that was involved or damaged. Storage facilities were the most frequently hit by storm events (84%). Process equipment follows with only 15% relative occurrence. Electrical equipment has only one record.

We decided to analyse Natech accidents separately, on the basis of the natural effect that triggered the event. In all the cases analysed, the majority of equipment affected was storage, followed by process equipment. Still, for specific natural hazards there are variations that require some considerations.

Figure 16 shows the distribution of storm-triggered Natech events that were triggered by lightning strikes. The results are similar to that of the whole dataset, except that lightning strikes had a higher relative impact on storage equipment and a lower impact on process equipment, if compared to the distribution of the entire set (Figure 15). Figure 17 shows the distribution of storm-triggered Natech events that were triggered by all effects except lightning. In this case, the category process equipment has a higher relative occurrence if compared to the distribution of the entire set (Figure 15), while storage has a lower occurrence.
The results for accidents caused by heavy rain or floods (Figure 18) show that the percentage of records in which storage equipment was damaged is slightly higher compared to the distribution of the entire set of storm-triggered Natech events. Figure 19 shows the distribution of storm-triggered Natech events that are caused by wind. In this case, the category process equipment has much higher relative occurrence (39%) by comparison with the distribution of the entire set (Figure 15) with a value that is more than twice as high.
Figure 17. Distribution of storm-triggered Natech events by the type of structure (lightning triggered accident excluded)

Source: JRC

Figure 18. Distribution of storm-triggered Natech events by the type of structure (only accidents triggered by rain and flood)

Source: JRC
Figure 19. Distribution of storm-triggered Natech events by the type of structure (only accidents triggered by wind)

Source: JRC

Figure 20 shows the distribution of storm-triggered Natech events by the type of consequences that followed. Each colour represents a different natural action that triggered the accident, as for the labels used by MHIDAS.

The most common consequences were Fire and Explosion and Fire. In fact, these accidents were mostly due to lightning strikes at chemical facilities and in particular oil refineries and tank terminals. Spills are the second most important consequence category and they were mainly caused by rain, flood or generic weather effects.

Since the results of Figure 20 suggest that each natural hazard produces different scenarios, each triggering effect was analysed separately. Figure 21 shows the distribution of lightning-triggered Natech events, sorted by the type of consequence. Fire, Explosion, and Explosion and fire are the three main categories, which together sum up to over 90% of all lightning-triggered events. A small percentage of releases were also recorded (2%).

Figures 22 and 23 show the distribution of consequences for Natech events triggered by the effect of rain or flood and the effect of wind, respectively. In both images, the category with the highest relative occurrence is Release/Spill (about 70% for both). Fire, Explosion, and Explosion and fire have a lower occurrence, if compared to lightning-triggered Natechs, and sum up to 24% and 28% of rain/ flood-triggered and wind-triggered Natechs, respectively. The scenario Gas/vapour release was only observed for rain or flood-triggered Natechs.
Figure 20. Distribution of storm-triggered Natech accidents by consequence. The specific storm effects that triggered the accidents are identified with different colours.

Source: JRC

Figure 21. Distribution of storm-triggered Natech accidents by consequence (only accidents triggered by lightning).

Source: JRC
Figure 22. Distribution of storm-triggered Natech accidents by consequence (only accidents triggered by heavy rain or flooding)

Source: JRC

Figure 23. Distribution of storm-triggered Natech accidents by consequence (only accidents triggered by wind)

Source: JRC
4.2.3 Results summary

From the analysis of the incidents in TAD and MHIDAS it is possible to conclude that:

- Storage equipment is the most vulnerable to storm damage (see Figure 15);
- Fires and explosions are the most common scenarios (see Figure 20);
- Lightning has the highest number of records and the highest relative number of major accidents recorded (over 80% of lightning-triggered accidents are fires or explosions) (see Figure 21);
- Rain and flood have also a very high relative occurrence of major accidents (75% are either fires or releases of hazardous substances) and if compared to other hazards they have the highest potential for environmental damage due to the high occurrence of spills (see Figure 22);
- The effect of wind is the least probable to trigger Natech accidents. Even when wind does cause damage to equipment, it is more likely to be process equipment (and in particular tall structures), which has a lower holding capacity compared to storage equipment and thus less potential for a major accident (see Figure 19).
5 Analysis of accident case studies

5.1 Hurricane Hugo, Virgin Islands, 1989

Hurricane Hugo reached category 5 intensity on September 15, 1989. The storm intensity decreased to category 4 when it crossed the Lesser Antilles, making landfall in Guadeloupe, with sustained winds of 140 mph (225 km/h) and a storm surge of 12 ft (3.7 m), causing severe damage to the island. Then, the storm continued moving West over the island of Monserrat, the US Virgin Islands and Puerto Rico, where it made landfall with winds of up to 130 mph at 7am on September 18. The storm then made landfall near Charleston, South Carolina, on September 21, 1989, becoming the costliest storm in US history at the time with 7 billion dollars in damage (Bills and Whiting, 1991F).

This hurricane carried sustained winds of over 140 mph and created a storm surge as high as 3.6 m as it came ashore on the south side of St. Croix, United States Virgin Islands (Bills and Whiting, 1991). The hurricane triggered a major oil spill at the Virgin Islands Water and Power Authority (VI WAPA) facility in Christiansted, St. Croix. It destroyed the containment wall around a 54,000-barrel storage tank filled with No. 6 fuel oil, and severed a discharge line at the bottom of the tank when the wall fell on the pipe (Bills and Whiting, 1991). Fuel oil leaked from the tank at an estimated rate of 1,750 barrels per day, onto the facility grounds. An open valve had permitted the oil to escape through the broken pipe (NOAA, 2018). Oil then overflowed the containment dike and began to leak through the trenches. A total of 14,076 barrels escaped from this tank between September 18 and 25. More than 1,000 barrels overflowed the containment area and entered the water. Because of the spill, three miles of sand beaches were heavily polluted. The contaminated beaches consisted mostly of fine-grained sands. Over 400 beach clean-up workers were hired and trained to perform manual removal of oiled sands. A total of 30,000 cubic meter of polluted sand was removed. Recontamination of previously cleaned beaches during high tides required repetitive removals for several weeks. The beaches were declared substantially clean after 60 days of continuous decontamination (Curl et al., 1992).

On the south coast of St. Croix, the hurricane destroyed five large oil storage tanks (Figure 24) and damaged several others at the Hess Oil Virgin Islands Corporation (HOVIC) refinery. Oil spilled but was contained on the facility grounds, within containment bunds with earthen dykes. Only a small portion of the oil reached the HOVIC tanker harbour. However, the oil remained within the narrow harbour limits, pressed against the shoreline, by wind and wave action. The damaged storage tanks at HOVIC spilled some 10,000 barrels of oil (Figure 25). A harbour boom had been deployed from the end of the pier to the shoreline, allowing the containment of most of the oil (Bills and Whiting, 1991).

Due to the destruction from hurricane Hugo, all agencies were lacking vital communication facilities. Normal modes of communication did not exist. Therefore, mobile satellite communications were critical to the success of the response. Other parts of the island's infrastructure, such as potable water, electricity, and sanitation facilities, were also destroyed by the hurricane and hampered response efforts. Pollution responders overcame the lack of power, water, food, lodging, communications, and transportation to perform an effective clean-up of these spills (Bills and Whiting, 1991).

The events in St. Croix showed that worst-case scenarios may be exceeded by unimaginable catastrophic events. A 1.5-million-barrel catastrophic tanker grounding, originally postulated as the worst oil spill imaginable in St. Croix, was replaced by a 14-million-barrel catastrophic destruction of the HOVIC tank farm (Bills and Whiting, 1991).
**Figure 24.** Damage by Hugo to oil tanks in St. Croix

![Damaged oil tanks](image)

Source: National Archives catalog

**Figure 25.** An oil slick pollutes the water off the coast of St. Croix after oil leaked from storage tanks damaged during hurricane Hugo

![Polluted water](image)

Source: National Archives catalog
5.2 Hurricane Katrina, USA, 2005

Katrina made its first landfall in the United States as a Category 1 hurricane near the border of Miami-Dade County and Broward County in Florida and spent only about six hours over land. The storm then made landfall in Louisiana on August 29, 2005. As the centre of the eye made its closest approach to the east of downtown New Orleans, the hurricane was downgraded to a Category 3 (Davis, 2006).

The impact of hurricane Katrina on the US coast was the costliest natural disaster in US history. It triggered a large number of spills of petroleum products and chemicals in Texas, Louisiana, Mississippi, Alabama and Florida. Hurricane Katrina resulted in over 200 onshore releases of hazardous chemicals, petroleum, or natural gas. In addition, there were over 800 releases of these materials from offshore platforms, vessels, and pipelines in the Gulf of Mexico where Katrina had category 5 severity (Cruz and Krausmann, 2009). The region impacted by hurricane Katrina has a long history of hurricane impacts. Many facilities severely affected by hurricane Katrina had been operating for decades and were aware of the risks posed by hurricanes (Santella et al., 2010).

The releases of petroleum products caused by hurricane Katrina were extraordinarily large (Figure 26). There were at least 10 onshore releases greater than 10,000 gallons (38 m$^3$) each. In sum, these 10 releases totalled approximately 8 million gallons (30,000 m$^3$). Failures of storage tanks were a major cause of petroleum releases. Indeed, large releases were generally of crude oil that leaked from storage tanks damaged by storm surge. Catchment basins, which offer secondary containment around the tanks, were flooded, allowing the oil to spread into surrounding areas. These sites were only accessible by boat until the flood waters receded, and much of the oil had been lost before containment and recovery operations started. (Santella et al., 2010).

![Figure 26. Large oil spill reaches a residential area floating on floodwaters](source: NOAA Office of Response and Restoration)
Santella et al., (2010) carried out an analysis of 1,070 releases attributed to hurricane Katrina between 2005 and 2008. The majority of releases were petroleum (76%) with some chemicals (18%) and natural gas (6%). Damage to above ground oil storage tanks from hurricane Katrina occurred due to wind pressures in facilities that were along the path of the hurricane, but most of the damage and the most significant consequences occurred due to flooding during the days after the hurricane (Godoy, 2007). On the other hand, damage due to hurricane Rita a month later, occurred almost exclusively due to direct wind action. In addition, a majority of records (64%) showed releases at storage tanks.

Nine refineries in the area were shut down completely and four refineries reduced operations before the hurricane. Ruckart et al. (2008) observed that a large percentage (72%) of events reported to the Hazardous Substances Emergency Events Surveillance System (HSEES) were related to system shutdown or startup. Many releases of chemicals occurred in the form of orphaned containers, the discoveries of which were only occasionally recorded.

Spill response was inhibited by the fact that many responders were themselves displaced or otherwise impacted by the hurricane. Displacement of workers due to evacuation, home loss, and gasoline shortages reduced available manpower and disrupted their operations. Loss of communication systems was another hindrance, as well as the difficulty in acquiring supplies and contractors for reconstruction or operation (Santella et al., 2010).

### 5.2.1 Murphy Oil spill

The oil spill from Murphy Oil refinery in St. Bernard Parish (Meraux) was the most significant spill that followed hurricane Katrina. The refinery was inundated with 12 feet of water by the storm surge. A 250,000-barrel above ground storage tank, only partially filled with mixed crude oil floated and ruptured (Figure 27). The 25,110 barrels of crude oil spilled from Murphy’s refinery flooded an area of about a square mile that contained approximately 1,800 houses. Twenty-six different class action lawsuits were filed against the company (NOAA, 2018).

**Figure 27.** Displaced and damaged oil storage tank at Murphy oil

![Displaced and damaged oil storage tank at Murphy oil](source: NOAA Office of Response and Restoration)
5.2.2 Dynegy
At the Dynegy plant in Venice two tanks failed due to the hurricane and light crude oil was discharged near the main channel leading into the Gulf. The oil was contained in the berm, with 3 inches of freeboard. Recovery was hampered by the presence of masses of roseau cane (Figure 28), deposited by the storm surge, which covered the facility under a coat of dead vegetation (NOAA, 2018).

Figure 28. Local vegetation deposited at the facility by the storm surge hampers oil recovery operations

5.2.3 Shell Pilot Town
At Shell Pilot Town facility, an oil spill was caused by a microwave tower that fell and pierced a storage tank. Another tank had floated and was displaced due to the storm surge. A pipe was bent and severed as the tank moved. The spills occurred within the containment bund of the facility, but the hurricane dispersed most of the oil (Figure 29). The oil-water mixture in the retention area was collected in tanks and decanted. Approximately 22,685 barrels were recovered (NOAA, 2018).
Figure 29. Damage to oil terminal due to storm surge: a) aerial view of the facility showing a displaced tank; b) details of the damage sustained by two storage tanks; c) close view of a detached line and operators recovering the spilled oil.

Source: NOAA Office of Response and Restoration
5.2.4 Shell Nairn

One of the biggest releases during hurricane Katrina was an oil spill from a pipeline at Shell Nairn Pipeline Company in Port Sulphur, Louisiana. The 20-inch diameter pipeline, supported by a berm, ruptured with a 2-inch by 6-inch hole. The Shell Nairn facility was extensively flooded and amount of oil was released into a nearby marsh where it created a sheen with a length of 5 to 6 miles (Figure 30 and 31). With its 139,000 gallons of oil released, this was the major onshore pipeline releases that followed Katrina impact (Santella et al., 2010). This flooded area is adjacent to the Mississippi River, and lower in elevation than both the river and sea (NOAA, 2018).

**Figure 30.** Example of a flooded catchment basin at Shell Nairn following hurricane Katrina

![Figure 30](image)

*Source: NOAA Office of Response and Restoration*

**Figure 31.** Marsh contaminated by oil near Port Sulfur

![Figure 31](image)

*Source: NOAA Office of Response and Restoration*
5.2.5 Sundown Energy
The storm surge caused by hurricane Katrina ruptured two tanks and piping at Sundown East and West facilities causing a spill of 450 and 320 barrels of oil, respectively. The sites are located at Potash in a very remote location along the banks of the Mississippi, where access was very difficult (NOAA, 2018). Floating vessels that were carried by hurricane Katrina's storm surge impacted the facilities and contributed to the damage. (Figure 32).

**Figure 32.** Flooded retention area around oil storage tanks at the Sundown Energy east facility on the Mississippi River.

Source: NOAA Office of Response and Restoration

5.2.6 Bass Enterprises
Oil spilled at Bass Enterprises in Cox Bay from two storage tanks. Each tank was 16 ft (5m) high and 290 ft (88 m) in diameter (Figure 33). About 90,000 barrels of crude oil were released, with 10,000 barrels remaining in the tanks. Roughly half of the oil was contained in the berm, and another 25% was recovered, but a significant amount of oil either evaporated or reached the river and the adjacent marsh. Additionally, a second large oil spill of about 460,000 gallons (1700 m³) occurred at another Bass Enterprises facility in Point a la Hache (NOAA, 2018).
Figure 33. Aerial view of crude oil spill into the Mississippi River coming from two damaged storage tanks of Bass Enterprises in Cox Bay.

Source: NOAA Office of Response and Restoration

5.2.7 Chevron Empire
At the Chevron Empire terminal, storage tanks were so heavily damaged that their contents were dispersed before response teams could reach the site (Santella et al., 2010). Approximately 24,000 barrels of crude oil were released from the damaged tanks (NOAA, 2018). One of the tanks was almost completely destroyed by the force of the storm (Figure 34).

Figure 34. Close-up picture of a heavily damaged tank at Chevron Empire.

Source: NOAA Office of Response and Restoration
5.3 Hurricane Rita, USA, 2005

Several facilities suffered intense wind damage to storage tanks and to some process equipment. The wind caused buckling, bending and even overturning of storage tanks. Storage tanks with the lowest inventory showed the highest vulnerability to wind damage.

Many small storage tanks were dislodged and carried by the storm surge, and some were found up to 10 miles inland (NOAA, 2018). A diesel tank stranded in the Texas Point Wildlife Refuge landed right side up showing evidence of leaking (Figure 35). The amount of product lost during the storm is unknown.

An alkali and chlorine manufacturing plant released 1082 pounds of toxic chlorine when a power failure caused excess pressure in the chlorine tank. Operators had to vent the storage tank manually to reduce pressure and protect the tank integrity. Some 500 persons lived within a 500 m radius of the release (Ruckart et al., 2008).

Figure 35. Damaged and overturned diesel storage tank at the ASCO Facility in Cameron, LA.

5.4 Hurricane Ike, USA, 2008

Hurricane Ike made landfall along the north end of Galveston Island, Texas, at 0700 UTC on 13 September. Ike weakened to a tropical storm on 13 September just east of Palestine, Texas, and then became extra-tropical when it interacted with a front on 14 September. The extra-tropical low moved quickly northeast, producing hurricane-force wind gusts across Arkansas, Missouri, and the Ohio Valley (Burleson et al., 2015).

Media reports indicate that 21 people died in Texas, Louisiana, and Arkansas as a direct result of Ike. Twelve fatalities were reported in Galveston and Chambers Counties alone, where the worst storm surge occurred (Berg, 2009). As many as 64 additional indirect deaths were reported in Texas (e.g. due to electrocution, carbon monoxide poisoning, and pre-existing medical complications). The insured damage (not including inland flooding or storm surge) from Ike in Texas, Louisiana, and Arkansas topped 9.7 billion USD (Berg, 2009).

Significant storm surge and wave damage occurred along a large portion of the Texas and Louisiana coasts. The Bolivar Peninsula and parts of the Galveston Island were particularly...
affected. Almost every structure on parts of the Bolivar Peninsula, including the communities of Crystal Beach, Gilchrist, and High Island, were completely razed from their foundations due to the surge and accompanying waves (Berg, 2009). Hurricane Ike downed power lines, flooded streets, wetlands and low-lying areas, tore roofs and windows from buildings, and damaged or destroyed emergency equipment. Following the storm, nearly two million people were without power (FEMA, 2008). In areas like Galveston Island and the Bolivar Peninsula, water and wastewater plants had to be rebuilt.

**Figure 36.** Crumpled storage tanks in a marsh which were displaced by the storm surge of hurricane Ike in the Galveston area

The storm shut 14 oil refineries and two Texas strategic petroleum reserve sites, causing rising gas prices and gas shortages across parts of the United States (Berg, 2009). The Minerals Management Service (MMS), which oversaw oil production in federal waters offshore at the time, reported that the storm destroyed at least 52 oil platforms in the Gulf of Mexico, and additional 32 platforms suffered severe damage (FEMA, 2008). The damage to the industry went, however, far beyond the oil platforms and refineries. Eight chemical companies in an area referred to as “chemical row” were severely damaged by Ike; all but one had 4 to 10 ft of salt water inside the plants (FEMA, 2008). Figures 36 to 38 show damage to refineries and chemical industries due to the impact of Ike.

Hurricane Ike caused hundreds of localized oil and other toxic spills that threatened fish and wildlife throughout the affected area (see Figures 39 to 42). The Environmental Protection Agency, U.S. Coast Guard (USCG), Texas General Land Office (GLO) and the Texas Commission on Environmental Quality (TCEQ) formed a Unified Command for spill response, which assessed more than 200 pollution reports (i.e. 180 sites in the Houston-Galveston area and 47 in the area from Port Arthur to Lake Charles). The type and amount of pollution included oil and diesel from vessels, as well as industrial chemicals (FEMA, 2008). In total, 448 releases of oil, gasoline and other substances were reported by news
outlets (Amos, 2008). The worst spill totalled nearly 266,000 gallons of oil released from a battery of storage tanks on Goat Island, Texas (Amos, 2008).

**Figure 37.** Atmospheric storage tanks collapsed in the Galveston/Houston area

![Atmospheric storage tanks collapsed in the Galveston/Houston area](source)

Source: NOAA Office of Response and Restoration

**Figure 38.** Collapsed storage tanks while under construction in Beaumont, TX.

![Collapsed storage tanks while under construction in Beaumont, TX.](source)

Source: NOAA Office of Response and Restoration
**Figure 39.** Oil spills from storage tanks damaged by Hurricane Ike in Goat Island, TX

Source: flickr/Skytruth

**Figure 40.** Several hydrocarbon spills in the flooded area of Galveston after the passage of hurricane Ike

Source: NOAA Office of Response and Restoration
Figure 41. Toppled storage tanks and oil sheen in the Galveston area after the passage of hurricane Ike

Source: NOAA Office of Response and Restoration

Figure 42. Tanks floated and pipe joint separation at Chevron Lube Plant in Port Arthur where 1041 barrels of lube oil spilled

Source: NOAA Office of Response and Restoration
5.5 Super-typhoon Pongsona, Guam, 2002

Either a build-up of static electricity or sparks caused the fire at the commercial port tank farm in Piti that ignited when Supertyphoon Pongsona pounded the island on 13 December 2002 (Waldrop, 2003).

At the Mobil tank facility, two tanks, one with gasoline and the other with jet fuel, erupted in flames. The fire burned for six days, and destroyed a total of four of the petroleum company’s fuel storage tanks (Figure 43). Officials shut down gasoline sales to the public (Waldrop, 2003).

Static electricity may have occurred inside one of the gasoline tanks at the Mobil facility due to friction caused by extremely high winds rushing through the ventilation system. The tank had previously been damaged in July of the same year, during typhoons Chata’an and Halong. The tank’s side walls buckled, preventing the free-floating internal roof from moving more than seven feet from the bottom of the tank, allowing accumulation of gasoline vapours inside the tank. Other tanks at different locations in the same facility showed buckling damage due to wind in the upper section (Waldrop, 2003).

The tank that first caught fire contained less than 15 percent of its total capacity of unleaded gasoline. When flammable vapours ignited, the explosion projected the tank’s roof in the air, causing it to travel for more than six hundred feet, before landing (Waldrop, 2003).

Figure 43. Storage tanks damaged and destroyed in Guam after the passage of Super-typhoon Pongsona

5.6 Cilacap refinery, Indonesia, 1995

On October 24 1995, lightning struck the Indonesian oil refinery Petramina in Cilacap in the south coast of Java. Lightning struck the automatic gauging device of a 38,800 m³ fixed-roof tank being filled with kerosene at 43.5°C (temperature higher than the flash point), causing a fire. The reason was incomplete equipotential bonding, generating sparks that triggered the fire. The gaseous cloud over the tank exploded, destroying the roof.
burning liquid spread the fire to six other tanks in the dike. Thousands of residents and 400 staff members were evacuated and no victims were reported. Nearly 600 homes were damaged and some hundred water bodies were polluted. The fire was extinguished after three days. The damages were assessed at 560 million francs (BARPI, 2018b).

The refinery which supplied 34% of Indonesian inland need was shut down for about 18 months. Oil, petrol, kerosene and diesel, worth about 350,000 USD, had to be imported daily for the supply of Java (Hasse, 2000).

5.7 Storm Surge, UK, 2013

The winter of 2013–2014 over NW Europe was characterised by a powerful jet stream driving a succession of low pressure systems across the Atlantic Ocean (BARPI, 2015). The first of these major systems formed near Iceland on 4 December 2013 and deepened to form an intense easterly-tracking cyclone, passing across northern Scotland and accompanied by Beaufort Force 9 (strong gale) to 11 (violent storm) winds, on 5 December. Severe coastal flooding was experienced on the west coast of North Wales, in NW England and on the west coast of Scotland. Into 6 December, the storm then moved across Southern Norway and Sweden, intensifying further to reach its lowest pressure of 960 hPa over the Baltic Sea (Spencer et al., 2015).

The storm surge affected the north-west coast of England, and on 5 and 6 December 2013, a storm surge coincided with high spring tides to produce similar water levels to those seen in the catastrophic East Coast Floods of 1953 on the east and south coasts of England. Four Seveso regulated establishments were extremely badly affected by the event. A large number of other industrial establishments was affected indirectly, partly because they halted production, but also because their logistics suffered impacts. Effective protection measures and adequate incident preparedness prevented a widespread disaster. Luckily, no hazardous material was released in any of the events presented. However, the severity of the impact, the recovery times and restoration costs suggest that important lessons can be learned from those “near misses” (BARPI, 2015).

5.7.1 Inter Terminals Riverside Terminal

Inter Terminals Riverside Terminal, is located on the north bank of the River Tees. The site provides bulk liquid chemical storage in above ground storage tanks with facilities to carry out import/export operations associated with shipping, road vehicle and pipeline transfers.

With the site being located several miles inland from the east coast, the impact of the potential surge was not fully acknowledged until December 5. The storm surge caused a rise in the tidal river level to 4.3 m AOD\(^4\) which overtopped the flood defence and Billingham Beck. The water overtopping the wall also caused erosion of the barrier and lowered the effective protection level (Whitfield et al., 2015).

As a consequence, the whole site was flooded to a depth of 1.8 m. Most of the bund walls were overtopped and several tanks with low inventory were displaced, damaging pipework and supports. Mobile equipment floated and moved with the inrush of flood water to cause impact on other stationary infrastructure. There was, however, no release of hazardous substances (BARPI, 2015).

Following the event, the river defence embankment was raised to 4.85m AOD and work to protect the rest of the site boundary to this level was also planned. The final protection of the site should be for a flood with 100-year return period (BARPI, 2015).

5.7.2 SABIC UK Brinefields

SABIC UK Petrochemicals Limited manufactures bulk petrochemical products (ethylene, propylene, butadiene, cyclohexane, and benzene) at a number of plants on the Tees

\(^4\) AOD: Above Ordnance Datum
Estuary. The Brinefield plant is part of an upper-tier Seveso site. Its storage facilities hold large inventories of products and intermediates.

SABIC participated in the National Flood Preparation Exercise ‘Watermark’ in 2011 and the lessons learned from that exercise were incorporated into the existing emergency response protocols (Whitfield, et al., 2015). When flood warnings were received during the first week of December, SABIC implemented standard operating practices to prepare for the storm surge. These preparations included: emptying the effluent treatment facilities, isolation of all non-essential electrical equipment, sandbagging of vulnerable areas such as switch houses, and removal of all containers that could float. While some localised flooding occurred, it was considered manageable given that prior flood preparations had taken place (BARPI, 2015).

The operators were, however not prepared for what happened next. It was unprecedented, unforeseen and therefore not planned for in any flood damage assessment or Seveso major accident scenario. A flash flood came from a nearby creek and headed toward the Cavities area, which stores thousands of tonnes of hydrocarbons in underground salt cavities. The Crisis Management Team was mobilized to initiate SABIC’s Crisis Management protocol (Whitfield et al., 2015).

Damage inspection during low tide showed that all the equipment containing hazardous materials under pressure was secure and that there had been limited damage to the cavity wellheads and piping infrastructure. The major damage sustained was to the electrical distribution, instrumentation and control systems including all telemetry networks. Repair and replacement activities took 5 months. The SABIC insurance loss assessment was over £10 million (BARPI, 2015).

### 5.7.3 Inter Terminals, Immingham

Inter Terminals, Immingham, is located on the south bank of the River Humber. The site provides bulk liquid oil and chemical storage in above ground storage tanks. Its operations include transport by road, shipping, rail and pipeline. It is an upper-tier Seveso site. The Terminal is situated in a highly vulnerable flood zone (Whitfield et al., 2015). A flood risk assessment had been carried out and site plans with topographical information were available. Emergency response plans and evacuation plans were started in preparation for the storm surge. Just prior to the flood, precautions were taken to protect key equipment as much as possible and to restrict transfer operations. All operations were ceased and electrical power was isolated (BARPI, 2015).

The surge caused a rise in the river level to 5.1 m AOD which overtopped the dock entrance gates and filled it until it overflowed into the dock estate. The terminals were inundated up to 1 m flood depth. The embankment protection itself failed in several places which caused a further flow into the terminal. None of the tank bund walls were overtopped and the bunds remained dry throughout the flood. Although mobile plant equipment was floated, there was little mechanical damage to infrastructure. There was no loss of containment of any hazardous product. The terminal remained inoperable during the immediate recovery period. The electrical infrastructure was badly affected and temporary power allowed only priority systems to be brought back on line (BARPI, 2015).

### 5.8 Hurricane Harvey, USA, 2017

Hurricane Harvey made landfall in Texas near Houston as a Category 4 hurricane, on August 24, 2017. This area home to more than 500 industrial sites and it is the centre of the oil and chemical industry in the US. Harvey knocked out about 25% of the U.S. refining capacity, and halved the nation’s ethylene synthesis rate (Ward, 2017). It shut down onshore and offshore oil and natural gas production in southern Texas, and shut oil product storage terminals, as well as ports in both Texas and Louisiana (Newbery, 2017). Transport of oil and fuels trough pipeline was either closed or running at a reduced rate (Newbery, 2017).
Following Harvey, the damaged refineries and other oil facilities released into the air and floodwaters millions of pounds of hazardous substances (Tabuchi and Kaplan, 2017), showing once more the tremendous combined impact of natural and technological hazards on society and the environment.

### 5.8.1 The rain

The amount of rain during Hurricane Harvey caused unprecedented flooding, when it made landfall in the Galveston Bay. In a four-day period, many areas received more than 60 inches (1,500 mm) of rain (Trenberth et al., 2018). Harvey was the wettest tropical cyclone on record in the United States. In a briefing, the World Meteorological Organization stated that the quantity of rainfall from Harvey had very likely been increased by climate change (Trenberth et al., 2018). In a recent paper, Cruz and Krausmann (2013) describe how extreme weather and climate change could be a threat to the oil and gas sector.

### 5.8.2 The damage

Industrial facilities were damaged by wind or water with releases of hazardous substances. In more than a dozen Texas chemical and refining plants, damaged storage tanks, ruptured containment systems and broken pressure relief valves were reported (Ward, 2017). Among those, for at least 14 tanks damage occurred when their “floating roof” sank under the weight of the record rainfall (Blum, 2017).

When Hurricane Harvey reached Texas, four 500-barrel steel tanks sprung free from their piping and toppled over at Burlington Resources, some 100 miles west of Houston (Eaton, 2017). Knocked down by the flood waters, the tanks tore flowlines and spilled hundreds of barrels of oil and waste water (Eaton, 2017). Two tanks floated at Magellan Galena Park Terminal in Houston and released their contents (approximately 11,000 barrels of gasoline) into the standing floodwater (Sutherland et al., 2018).

### 5.8.3 The spills

Benzene, vinyl chloride, butadiene and other known human carcinogens were among the dozens of tons of industrial toxic substances spilled in the wake of Harvey (Bajak and Olsen, 2018). Overall, more than 100 Harvey-related releases of toxics and chemicals were catalogued (Sutherland et al., 2018).

The largest spill occurred at Magellan Midstream Partners Galena Park terminal, where two gasoline storage tanks failed after the site flooded (Sutherland et al., 2018). The company reported an impressive amount of fuel loss totalling 10,988 barrels (TCEQ, 2017). Other major releases include a spill of about 100,000 gallons (378 m³) of glycerine and 80,000 gallons (300 m³) of methyl alcohol into the floodwaters at the Channel Biorefinery and Terminals (EIP, 2017). EnerVest Operating told state regulators its storage tanks spilled 1,117 barrels of crude oil and wastewater at eight separate well sites in Fayette County (Eaton, 2017). Some of the crude flowed with the flood waters into the Colorado River. At least 15 energy companies spilled almost 2,000 barrels of oil and an unknown quantity of waste water in two dozen Harvey-related incidents (Eaton, 2017).

Samples taken in sediments one month after the cyclone at Houston public parks showed elevated levels of dioxins, benzo(a)pyrene, PCBs (polychlorinated biphenyls) and hazardous chemicals typically created during the combustion of oil, coal and gas (Griggs et al., 2017).

### 5.8.4 Rainwater treatment facilities overflows

A waste oil spill occurred at Motiva Enterprises LLC in Port Arthur, when the wastewater treatment plant was flooded (Flitter, 2017). Nearly half a billion gallons of industrial wastewater mixed with storm water were released from a chemical plant in Baytown, east of Houston (Bajak and Olsen, 2018). The spills travelled on the floodwaters and were not contained. This release mechanism is very frequent in flood events and the hydrocarbons
that stratify on the floodwaters pose a serious fire hazard which is difficult to mitigate. For example, only one month earlier, tropical storm Calvin produced a flood at a PeMex refinery in Salina Cruz in Mexico, but this time the consequences were much more serious. Hydrocarbons from an overflowed wastewater treatment facility floated on the floodwaters until they found an ignition source. A huge fire started in which one operator was killed and many others were injured (Pemex, 2017).

5.8.5 Contaminated sites

More than two dozen current and former toxic waste sites, whose grounds are contaminated with dioxins, lead, arsenic, benzene or other compounds from industrial activities are hosted in Harris County (Tabuchi and Kaplan, 2017). At least 14 of these were affected by the flooding or damaged by Hurricane Harvey (Griggs et al., 2017). Even liquid mercury appears to have washed or blown ashore east of Houston, a few hundred yards from the San Jacinto Waste Pits, in the aftermath of Hurricane Harvey (Healy and Kaplan, 2017). Contaminated sites, as well as tailing dams, are known to be vulnerable during flood events. Nevertheless, little has been done to mitigate the risk they pose to the environment and to the public, should they release their contaminant into the floodwaters. A better regulation that aims to ensure some level of protection is required. In particular measures should be taken to reduce the lifespan of these sites. Because of the large number of sites that has to be treated, remediation activities usually last for decades. The longer those sites are idle, waiting for decontamination, the more flood events are likely to wash those contaminants into the environment.

5.8.6 Shut-down and restart

One of the main lessons from Harvey is that there can be contamination even without an accident. A large portion of the substances released during Harvey were produced by the burning (flaring) of fuels and chemicals during shut-down and restart operations. Among the 102 releases reported to the authorities, 44 originated from the facilities’ flare (Sutherland et al., 2018). A temporary increase in pollution can be tolerated by the environmental authorities in critical circumstances. However, the area of Houston is home to more than 500 industrial activities, many of which are petrochemical industries, power plants and refineries and significant air pollution will occur when these facilities shut down or restart at the same time. A giant plastics plant in Point Comfort released, alone, about 1.3 million pounds of excess emissions, including toxic gases like benzene, when it restarted after the storm (Griggs et al., 2017). Consequently, areas with a high density of refineries and petrochemical industries, such as Houston, should have a recovery plan with a schedule for restart operations to avoid the emissions caused by the simultaneous restarting of all facilities.

5.8.7 Communication and emergency response

Harvey highlighted a need to improve communications between authorities and the industry during natural disasters. With a few exceptions, companies with spills did not call local emergency responders which meant that the public was not informed in real time about incidents that could have affected them (Bajak and Olsen, 2018). Regulatory filings were, thus, incomplete and represented only damage that produced excessive air pollution. Even when the public was alerted, there was a tendency to understate the real extent of the release. The largest gasoline release due to Harvey was dramatically underestimated at first. Oil company Magellan reported that the spill effectively reached almost 11,000 barrels (about ten times the amount initially declared), only four days after the spill had occurred. Because of the flooding, the site was not accessible by the plant operators, who then underestimated the spill amount and returned a wrong assessment to the authorities (Sutherland et al., 2018).

In situations like these, a lack of a proper assessment and of communication could have resulted in wrong decision making, preventing authorities from initiating proper emergency procedures (e.g. shelter in place, evacuation) and from informing the population on how
to behave during the emergency. On top of this, oil companies are only required to report chemical spills to state regulators in the US, and wastewater contaminated with hydrocarbon is not included (Eaton, 2017). Therefore, it is very hard to assess how much oil, chemicals and fuels really flowed into the floodwaters. Harvey demonstrated once again the need for a response plan designed to cope with Natech events and to address a situation in which the impact of a natural hazard can hamper the response operations. Emergency response plans for spills of hazardous materials should take natural hazard impact into consideration.

5.8.8 Fire and explosion at Arkema

A series of explosions and fires occurred at a chemical facility in Crosby, when the site was flooded. Some policemen were hospitalized after inhaling the noxious smoke. The explosion was caused by thermal degradation an organic peroxide, a very reactive substance that requires to be stored in special refrigerated containers (Sutherland et al., 2018). The facility lost its primary power supply when the floodwaters started to rise in their perimeter. Operators turned the emergency back-up generators on to keep the refrigerators running, but they also failed when the flood level rose. Finally, operators transferred the substances into refrigerated trucks, used to transport the substance, to gain some time. At the same time an evacuation was set for an area of 1.5 miles (2.4 km) around the facility. Eventually the temperature of the substance rose, until it started to decompose through an explosive reaction that led to the explosions and the fires. Five police officers that drove through the evacuation zones to respond to a call were hospitalized after inhaling noxious fumes coming from the facility (Sutherland et al., 2018).

This accident showed the inadequacy of conventional emergency measures at chemical facilities, which are planned with insufficient consideration of natural hazards. The identification of specific plans that take into consideration the particular features of Natech events should be required.

5.9 La Plata refinery fire, Argentina

On April 2, 2013, the city of La Plata faced the worst flood in its history in the wake of a major storm. The magnitude of the storm was such that production at the La Plata refinery, the country’s biggest refinery and operated by Yacimientos Petrolíferos Fiscales (YPF), had to be stopped and "safe conditions" established. However, the amount of water overwhelmed the storm drainage system at the refinery, resulting in hydrocarbons being washed out of the drains and around the site (Marsh, 2014). They hydrocarbons found an ignition source, resulting in the largest fire the facility had ever experienced (Moreno, 2015).

An explosion in the crude distillation unit (CDU) was caused by hydrocarbons igniting in one of the coke furnaces. The furnaces had been shut down, but were still hot enough to ignite the hydrocarbons. There were two fires in the CDU and one in the coke oven (Marsh, 2014). It was indicated that aging and a lack of safety measures could have contributed to the accident (Moreno, 2015).

The accident also highlighted the difficulty associated with emergency response during natural-disaster conditions. Since the refinery was flooded, employees engaged in emergency response were unable to access the locker room to wear the proper security clothing. Some left without the proper clothing or equipment to try to fight the flames in the flooded area, with the risk of catching fire themselves. Moreno (2015) indicates, that the situation was such that the morale of the men was broken, some of them arriving in a state of panic.

Overall, about 40 fire fighters were involved in first response which was probably insufficient considering that two blocks of land burned with flames of 70 m height. Also, many of the fire fighters were not trained for this type of fire and incorrect response procedures may have been applied (Moreno, 2015). For example, fire fighters began to attack the areas of the accumulator and the plant with burning gases, before the gas flow
was shut. As a consequence, each time the fire fighters extinguished the flames, the flammable gases dispersed and ignited again in puffs of fire (Moreno, 2015). It took responders ten hours to completely extinguish and control the fire. Luckily, there were no fatalities or injuries, but the estimated costs for reconstruction were 500 million USD (Marsh, 2014). The fire left the topping plant only partially functional, and the coke plant completely destroyed (Moreno, 2015).
6 Damage mode analysis

The previous sections showed that storms can cause significant damage to industrial installations and in particular to their storage facilities. In this section, we attempt to summarize the main damage modes that manifested in past storm-triggered Natach events as a function of the different storm effects. In particular, we will focus on damage modes for large storage tanks designed to hold hazardous materials. Not only are storage tanks the type of equipment with the highest frequency of releases due to natural disasters and storms, but they also contain the largest quantities of hazardous materials in industrial establishments. Because of this, both the likelihood and severity Natach events are higher for storage tanks than for any other piece of equipment. Due to their length, pipes and pipelines are also vulnerable to storm events. Table 4 summarizes the damage modes and puts them into relation with the natural event action that triggered them.

Table 4. Damage modes triggered by storm events

<table>
<thead>
<tr>
<th>Damage mode</th>
<th>Heavy rainfall and flash flood</th>
<th>Storm surge</th>
<th>Lightning</th>
<th>Strong wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sinking of floating roof</td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Damage to electrical equipment</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Power loss</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Flotation</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Displacement</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Vessel buckling</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impact with floating objects</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ignition of flammables</td>
<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Thermal puncturing of containment</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Roof damage</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Impact with airborne objects</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Displacement</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Falling objects</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>

Source: JRC

6.1 Roof damage

Roof damage can occur during the strongest windstorms and tropical storms. The strongest winds were not only able to damage the external insulation, removing entire sections from several equipment items during the most recent hurricanes, but they also ripped off thinner metal plates from their main roof structures. Damage to the roofs of atmospheric tanks was associated with wind suctions in that part of a tank, with the highest pressures
occurring on the windward meridian at the junction with the cylinder and at the centre of the roof. Many of the storage tanks damaged by hurricanes Katrina and Rita showed different degrees of roof damage (Godoy, 2007).

6.2 Falling objects
When tall structures like chimneys, racks, towers and buildings collapse, they can involve other structures and equipment when falling. Not only structures, but also mobile objects can do a significant amount of damage if they fall from a height. Manufactured objects can tear loose from the highest sections of tall building because of wind actions. Natural objects, like stones and rocks may fall from cliffs right above the establishments. An example of this type of damage is the oil spill at Shell Pilot Town during hurricane Katrina (section 5.2.3), in which a falling microwave tower punctured one of the storage tanks triggering a release.

6.3 Vessel buckling
The shell buckling of the highest section of equipment, and in particular of storage tanks, is frequently caused by high winds during storms and hurricanes, while buckling of the lower section is more likely due to floods (Godoy, 2007).

Vessels that suffered buckling during tropical storms had very large deflections in the cylindrical part and in the base plate. In these cases, wind damage of tanks occurred in peripheral locations in a plant, where the tanks were more exposed (NIST, 2006). Buckling can cause tears in the plates composing the vessel, from which the contained material can escape. Buckling can be accompanied by leakage of the content due to failure of the bottom/shell welding, manhole failure, pipe/fitting failure or failure of riveted seams (Cooper, 1997).

When a vessel is empty, the structure is at its lowest strength against buckling and it is vulnerable to either wind or water pressure. Ring stiffeners may reduce the risk of tank deflections. In past hurricane events, tanks with ring stiffeners did not exhibit buckling, even in areas where buckling damage was instead observed in unreinforced tanks (Godoy, 2007).

Godoy (2016) highlights the three main parameters that drive the buckling of atmospheric vertical storage tanks: the tank shape (height on diameter ratio), the distribution (spacing, relative position and pattern) of tank groups and topographic effects (e.g. hills, containment dikes).

Many examples of this damage mode are available for hurricanes Hugo, Katrina and Rita (sections 5.1, 5.2 and 5.3). Supertyphoon Pongsona and its damage in the island of Guam (section 5.5) shows another interesting example of shell buckling damage.

6.4 Displacement
Displacement of equipment and pipes is one of the most common damage modes during natural disasters. In storms, strong winds with speeds of several hundred km/hour can drag lighter objects, while in the areas affected by flooding buoyant equipment can be dragged along by the water current or by winds (Godoy, 2007). Some very intense tropical storms were reported to have toppled slender structures and storage tanks, under the combined effect of strong winds and rising floodwaters (Godoy, 2007) (see hurricanes Katrina, Rita and Ike in sections 5.2, 5.3 and 5.4). In case of storm surge, high-momentum tides can slam into objects, pushing and overturning them without actually needing to lift them. Displaced equipment items can hit any other object in their path. This often results in further damage to the stationary object, to the displaced item or to both of those (Godoy, 2007).

Usually, when storage and process equipment is displaced, the piping system is dragged along, usually also sustaining damage. Pipes can be breached, bent or torn, while flanges
and fittings can lose their seal (Cooper, 1997). Storms can also directly affect pipes and pipelines.

6.5 Damage to electrical equipment

Electrical equipment is responsible for the correct functioning of the processes of industrial activities. Water intrusion can cause short circuits that can destroy electrical equipment or disrupt their functions. Flooding also seriously affects the functioning of uninterruptible power supply (UPS) and back-up power generators (see Fires and explosions at Arkema, section 5.8.11). All transformers and inverters, as well as all electric motors and ovens are at risk. In addition, the control room of an industrial activity, as well as most sensors, actuators, alarms and transmitters, are either electric or rely on electrical equipment for functioning.

Water can enter electrical facilities during heavy rain or floods. Less frequently, storm surge was also responsible for extensive damage to the electrical equipment of installations built on the coast. Short-circuits can generate electric arcs and ignite flammable materials floating on the water or hovering in the air. Lightning strikes can damage electric components either through current surge or via electromagnetic pulse (EMP) (Hasse, 2000).

6.6 Flotation

Uplifting of vessels and tanks mainly due to buoyancy forces is the main flood-induced failure mode for empty or nearly empty storage tanks following flood, flash flood and storm surge events (Krausmann and Salzano, 2017). Vertical forces are able to bend equipment and pipes, break connections or flanges. Even large storage tanks were forced out of their foundations by the massive storm surge that followed the strongest storms (Santella et al., 2010). Floating equipment can be carried by the water current, hitting any other objects in their path, including parts of the industrial facility itself. To avoid damage due to flotation, anchoring systems may be installed on critical equipment. Empty vessels are reported to be much more vulnerable to flotation. For this reason, it is recommended to fill empty vessels with water in preparation for a storm or a flood (Krausmann et al., 2011).

The oil spill at Murphy oil (section 5.2.1) is a perfect example of damage due to flotation.

6.7 Impact with floating objects

Objects floating on floodwaters can contain high momentum due to the water current they are carried along with. In case of storm surge, strong wind and waves can grant additional motion to floating objects. Impacting objects can buckle vessels, puncture through metal enclosures, bend steel structures and break pipe connections (Krausmann and Salzano, 2017). The water can carry any floating item, tank, barrel, vehicle, tree or building away. Objects from both inside and outside an industrial establishment can damage industrial equipment and trigger Natechs. A storm surge can bring onshore large vessels, barges and floating oil rigs. Good practices recommend the removal of all unnecessary floating objects from the establishments in preparation for a storm or a flood event (Santella et al., 2010; USCSB, 2005).

The oil spill at Sundown Energy during hurricane Katrina (section 5.2.5) is a perfect example of this damage mechanism as a barge carried by the storm surge grounded inside the facility, damaging equipment and breaking pipes.

6.8 Impact with airborne objects

The strong winds of a windstorm, hurricane or tornado can carry any sort of object when the air reaches a very high speed (NIST, 2006). These objects, even if usually not big in size, have a very high momentum because of their high velocity and can damage equipment upon impact. In addition, some airborne objects have sharp edges that increase their potential damaging capability (TRAS 320, 2015).
6.9 Sinking of floating roof

When a floating roof of a tank sinks, the exposed liquid can evaporate, releasing large quantities of toxic, carcinogenic or pollutant substances into the air. Exposed flammable liquid can ignite, setting the entire tank on fire and projecting plumes of noxious smoke in the air (Krausmann and Salzano, 2017).

In the event of rainfall, open-topped atmospheric floating roof tanks can collect large amounts of water on the deck of their floating roofs. Water is drained through a dedicated drainage system, which is designed to prevent water accumulation on top of the tank. However, when the amount of rain exceeds the design limit of the equipment, or if the system does not function properly, water starts to accumulate on the deck, up to the point in which the weight on the roof exceed its buoyancy force and the roof sinks in the liquid beneath (Blum, 2017). Installation of a geodesic dome is a possible solution for preventing floating roof flooding due to intense rainfall (API, 2012). During hurricane Harvey at least 14 floating roofs of atmospheric storage tanks failed under the heavy rain and released noxious vapours in the air (see section 5.8).

Wind can also be responsible for floating roof damage and sinking. Wind pressure can cause the water on tank to accumulate on a side, creating an uneven load and causing the structural failure of the roof (Krausmann and Salzano, 2017). Three records in TAD specifically refer to damage to floating roofs due to high wind. This type of damage occurred when the tanks were nearly full and the roofs at their highest position.

An uncontrolled fire on the roof (e.g. spill on roof fire or rim seal fire) can also cause floating roof damage and sinking. Lightning strikes and friction between the roof and the tank walls which can cause sparks, are the main starters of fires on tank roofs (Hasse, 2000; Waltrop, 2003).

6.10 Power loss

Electricity is a critical utility for the proper operation of an industrial installation and it is a lifeline that might be unavailable due to natural hazard conditions. This includes the primary power grid, but also back-up generators. Cable snapping, short circuits and floods are frequent causes of onsite power loss at industrial installations. As documented in past events, power loss alone can trigger a Natech accident (BARPI, 2009). Other examples of Natech events due to power loss are reported by Ruckart et al., (2008). In addition, safety systems and barriers implemented to prevent or mitigate accidents may be unavailable due to lack of electricity.

6.11 Breach/overfill

Flooding of entire areas of industrial installations handling liquid fuels, and in particular of oil refineries, may cause the overflow of water with residual hydrocarbons from the sumps of the storm water drainage systems. Such systems are designed to separate water from hydrocarbon residues, which are collected and stored. In case of heavy rain or flood, such containers overfill with water, while the lighter hydrocarbons float on the floodwater (see section 5.8.4). The resulting oil spills may subsequently ignite and start huge conflagrations such as the fire at the La Plata YPF refinery (Section 5.9).

6.12 Ignition of flammables

Some natural hazards can locally generate sparks due to friction or electric currents, which in turn can ignite flammable materials. Lightning strikes are responsible for a very high number of fires at oil refineries every year (see section 5.6). Wind can also create friction between mobile metal parts, generating sparks that can also ignite flammable vapours (see section 5.5). Counterintuitively, flooding at industrial facilities can also create a source
of ignition, since flooded electrical equipment, like transformers, engines or substations, is likely to generate short circuits and sparks (see section 5.9).

6.13 Thermal puncturing of metal enclosures

Lightning strikes can melt or vaporize a small portion of material at its striking point. A sufficiently energetic direct lightning strike can create holes in metal enclosures of vessels and pipes and cause the loss of the containment function. Thicker metal plates can resist better to puncturing than thinner metal sheets (Necci et al., 2013).
7 Lessons learned and recommendations

In regions prone to storms with extreme intensity, controlling the risk of processing, storing or transporting hazardous substances can be very difficult. Based on the analysis in the previous sections, here we present a number of lessons and recommendations that can be used to more effectively manage the risk from storm-triggered technological accidents. The lessons generated from the analysis are as follows:

- When violent storms hit, several facilities may be affected simultaneously overwhelming the capacity of responders to cope with the disaster;
- Storage equipment is the most vulnerable to storm damage;
- Fires and explosions are the most common consequence scenarios;
- Lightning is the most frequent cause of storm-triggered Natech accidents;
- Rain and flood can also trigger Natech accidents with a high frequency, and these events result in the highest costs and the highest damage to the environment;
- The effects of wind are the least probable to trigger Natech events, end even when they do they usually have a lower severity if compared with other effects;
- Not only is the loss of the power supply due to storms sufficient, by itself, to trigger Natech events, but emergency response and the initial recovery phase can also be seriously hampered by the lack of electricity supply;
- Planning for emergencies requires consideration of the possible natural events, otherwise insufficient or inadequate emergency procedures can exacerbate the severity of an accident, instead of mitigating it;
- Storm predictions based on past events are not sufficient to be well prepared for future storm–triggered Natechs, in particular in the face of climate change.

The following is a set of recommendations for better preparedness against storm-triggered Natechs:

- Industrial facilities should be better protected from the effect of storms, and in particular storage tanks;
- An effective response to storms can be better achieved if emergency exercises include storm-triggered Natech scenarios;
- Emergency plans should use early warnings as trigger points to initiate emergency procedures and the triggering conditions should be clear;
- Risk assessments and emergency plans should be reviewed on a regular basis to ensure they are up to date in particular in view of climate change;
- Operators should provide reliable backup electric power supply and ensure that the backup power does not fail under the same condition as the primary power supply;
- Worst case storm events should not be predicted as if they were a recurrence of events that already happened in the past; instead, industry should increase safety factors to account for changes (both actual and potential) in the environment and in the climate;
- Areas with a high density of refineries and chemical facilities should have local recovery plans with a schedule for restart operations to avoid simultaneous emissions and preserve air quality;
- Responders should prepare for scenarios in which they have insufficient resources to cope with all the simultaneous events, and their management should learn how to decide priority targets for intervention.

Another recommendation regards industrial plants which survived the impact of an extreme storm by being in a state of shutdown while riding out the storm. Given that restarting after an emergency shutdown is probably the most hazardous operation for industry (even more so if the facilities suffered damage in the storm), plant operators should handle start-ups with extreme caution. The U.S. Chemical Safety and Hazard Investigation Board (CSB) issued a safety bulletin for precautions needed during oil and chemical facility start-up following hurricanes. The precautions include checklists of equipment, tanks, and instrumentation to be examined for damage prior restart (USCSB, 2005). Particular attention should be given to examining large bulk storage tanks and pressure vessels for
evidence of floating displacement or damage. In addition, different types of equipment items should be examined for trapped floodwater and debris-impact damage, for example: sewers, drains, furnace systems, electric motors and drives, switchgear, conduit, electrical boxes, electronic and pneumatic instrumentation, emergency warning systems, emergency equipment, and insulation systems for piping, vessels, and tanks (USCSB, 2005).

In addition, operators should coordinate with government entities responsible for civil protection and air quality in order to minimize the exposition of the public to simultaneous flare emissions due to bulk shut-down and start-up operations, which could be a threat to human health and to the environment, even in the absence of an accident.

Considering that rain and flood events have the potential to trigger accidents with the highest consequences, the following are flood-specific lessons and recommendations based on our analysis and a study conducted by Krausmann et al. (2011):

- Flood defence structures can fail completely during floods and cannot be relied on in case of extreme flooding. Different layers of protection should be implemented to compensate;
- **De-inventorying of storage tanks can reduce the impact of accidental spills.** However, it can also increase the vulnerability of the tanks to floating and thus the likelihood of spills in case tanks are not completely empty;
- To avoid floating, **empty storage tanks could be partially filled with water.** This necessitates the implementation of safety procedures to avoid contamination, reaction or other damage and, therefore, requires early warning;
- Adequate **anchoring with bolts or other types of restraining systems** should effectively prevent tanks and other equipment from floating off their foundations for most flood conditions;
- In preparation for a flood, **objects that can float** and become a threat to other parts of the facility should either be secured or removed where possible.
- The drainage system for waste flammable substances and surface run-off water should be segregated.
- It would be sensible **land-use planning practice to relocate hazardous industry to areas that are not flood-prone.** Where this is not possible, safety-critical equipment or high-risk units should be placed outside the estimated inundation zone.
- Measures should be taken to quickly **remediate decommissioned contaminated sites** to avoid that flood events wash contaminants into the environment.
8 Conclusions

This study analysed past technological incidents involving hazardous materials caused by the impact of storms. The study concluded that incidents caused by storms were frequent and resulted often but not always in consequences to people, the environment and the economy.

The different types of storm events were analysed with respect to their ability to leave a “damage footprint” on the ground. A number of effects are responsible for damage to the natural and built environment. The study concluded that the main effects responsible for damage are: strong winds, heavy precipitation, lightning and storm surge.

A large number of technological incidents were collected and analysed to get a statistical description of storm-triggered events. Several accident databases were consulted and analysed to identify Natech events and in particular storm-triggered accidents. The main finding of this study is that the relative occurrence of storm triggered Natech events appears to have increased when compared to the occurrence of technological incidents from other causes. Another important conclusion of this analysis is the high vulnerability of storage tanks to all the effects of storms. In addition, while lightning is the most frequent trigger of incidents, rain and flood is responsible for the largest losses.

The number of storm-triggered incidents recorded over the last years could have been lower if natural hazards were not underestimated during both facility design and operation. The lessons and recommendations identified in the frame of this study should help to prevent such events in the future and to better mitigate their consequences.

In addition, although a proactive attitude of the industry is required to prevent incidents, other actors, such as engineering companies, manufacturers, workers’ unions, authorities and policy makers need to work together to build a safer future for industries handling hazardous materials in natural hazard prone areas.
References


API (2012) API 650: Welded Steel Tanks for Oil Storage, American Petroleum Institute (API), Washington D.C., USA


BARPI (2018a) The ARIA Database. Bureau for Analysis of Industrial Risks and Pollutions, Ministère de la Transition écologique et solidaire, France. Available at: https://www.aria.developpement-durable.gouv.fr/the-barpi/the-aria-database/?lang=en


Cruz, A.M., Krausmann, E. (2013) Vulnerability of the oil and gas sector to climate change and extreme weather events. Climatic change 121 (1), 41-53


HSE (2007) Major Hazard Incident Data Service (MHIDAS), AEA Technology, Major Hazards Assessment Unit, Health and Safety Executive, UK

ICHEME (2004) The Accident Database - Version 4.1, Institution of Chemical Engineers (ICHEME), United Kindgdom


PIReport (2003, January 2) GUAM TANKER FIRES TRACED TO STATIC ELECTRICITY. Available at http://www.pireport.org


List of figures

**Figure 1.** Hurricane tracks (dark lines) and landfall location points (red dots) for storms that make landfall with hurricane intensity................................................................. 5

**Figure 2.** Pie charts describing the distribution of Natech incidents by triggering natural event for the databases: MHIDAS, ARIA, TAD and eMARS .................................................... 12

**Figure 3.** Number of storm-triggered Natech events (blue bars) and total number of technological incidents (orange line) collected since 1960 and grouped in 5 year periods for the TAD database ........................................................................................................... 13

**Figure 4.** Distribution of storm-triggered Natech events by the type of structure (all storm effects) .................................................................................................................... 14

**Figure 5.** Distribution of storm-triggered Natech events by the type of structure (lightning triggered incidents only) ................................................................................................. 14

**Figure 6.** Distribution of storm-triggered Natech events by the type of structure (lightning triggered incidents excluded) ..................................................................................... 15

**Figure 7.** Distribution of storm-triggered Natech events by the type of structure (only incidents triggered by rain and flood) .................................................................................. 15

**Figure 8.** Distribution of storm-triggered Natech events by the type of structure (only incidents triggered by wind) ........................................................................................................ 16

**Figure 9.** Distribution of storm-triggered Natech incidents by consequence. The specific storm effects that triggered the events are identified with different colours ......................... 17

**Figure 10.** Distribution of storm-triggered Natech incidents by consequence (only incidents triggered by lightning) ................................................................................................. 18

**Figure 11.** Distribution of storm-triggered Natech incidents by consequence (only incidents triggered by heavy rain or flooding) ............................................................................. 18

**Figure 12.** Distribution of storm-triggered Natech incidents by consequence (only incidents triggered by wind) ........................................................................................................ 19

**Figure 13.** Number of storm-triggered Natech events (blue bars) and the overall number of records in the MHIDAS database (orange line), since 1960 and every in 5-years increments ......................................................................................................................... 19

**Figure 14.** Ratio of the number of storm-triggered Natech events and the overall number of records in the MHIDAS database, since 1960 and every in 5-years increments .................................................. 20

**Figure 15.** Distribution of storm-triggered Natech events by the type of equipment or structure (lightning triggered accidents only) ............................................................................. 21

**Figure 16.** Distribution of storm-triggered Natech events by the type of structure (lightning triggered accident excluded) ................................................................................................. 22

**Figure 17.** Distribution of storm-triggered Natech events by the type of structure (only accidents triggered by rain and flood) ..................................................................................... 22

**Figure 18.** Distribution of storm-triggered Natech events by the type of structure (only accidents triggered by wind) ........................................................................................................ 23

**Figure 19.** Distribution of storm-triggered Natech accidents by consequence. The specific storm effects that triggered the accidents are identified with different colours ......................... 24

**Figure 20.** Distribution of storm-triggered Natech accidents by consequence (only accidents triggered by lightning) ................................................................................................. 24

**Figure 21.** Distribution of storm-triggered Natech accidents by consequence (only accidents triggered by heavy rain or flooding) ............................................................................. 25
Figure 23. Distribution of storm-triggered Natech accidents by consequence (only accidents triggered by wind) .................................................................25

Figure 24. Damage by Hugo to oil tanks in St. Croix .................................................................28

Figure 25. An oil slick pollutes the water off the coast of St. Croix after oil leaked from storage tanks damaged during hurricane Hugo .........................................................28

Figure 26. Large oil spill reaches a residential area floating on floodwaters ..................29

Figure 27. Displaced and damaged oil storage tank at Murphy oil ..................................30

Figure 28. Local vegetation deposited at the facility by the storm surge hampers oil recovery operations .................................................................31

Figure 29. Damage to oil terminal due to storm surge: a) aerial view of the facility showing a displaced tank; b) details of the damage sustained by two storage tanks; c) close view of a detached line and operators recovering the spilled oil. ...............31

Figure 30. Example of a flooded catchment basin at Shell Nairn following hurricane Katrina ...............................................................................................32

Figure 31. Marsh contaminated by oil near Port Sulfur .........................................................33

Figure 32. Flooded retention area around oil storage tanks at the Sundown Energy east facility on the Mississippi River .............................................................34

Figure 33. Aerial view of crude oil spill into the Mississippi River coming from two damaged storage tanks of Bass Enterprises in Cox Bay ........................................35

Figure 34. Close-up picture of a heavily damaged tank at Chevron Empire ..................35

Figure 35. Damaged and overturned diesel storage tank at the ASCO Facility in Cameron, LA .........................................................................................36

Figure 36. Crumpled storage tanks in a marsh which were displaced by the storm surge of hurricane Ike in the Galveston area .........................................................37

Figure 37. Atmospheric storage tanks collapsed in the Galveston/Houston area ...........38

Figure 38. Collapsed storage tanks while under construction in Beaumont, TX ..............38

Figure 39. Oil spills from storage tanks damaged by Hurricane Ike in Goat Island, TX ..39

Figure 40. Several hydrocarbon spills in the flooded area of Galveston after the passage of hurricane Ike .................................................................39

Figure 41. Toppled storage tanks and oil sheen in the Galveston area after the passage of hurricane Ike .................................................................40

Figure 42. Tanks floated and pipe joint separation at Chevron Lube Plant in Port Arthur where 1041 barrels of lube oil spilled ........................................40

Figure 43. Storage tanks damaged and destroyed in Guam after the passage of Super-typhoon Pongsona ........................................................................41
List of tables

Table 1. Number of Natech events in each database ......................................................10
Table 2. Number of records per each tag or keyword ..........................................................11
Table 3. Number and ratio of storm-triggered Natech events for the database considered ...........................................................12
Table 4. Damage modes triggered by storm events .................................................................48
GETTING IN TOUCH WITH THE EU

In person
All over the European Union there are hundreds of Europe Direct information centres. You can find the address of the centre nearest you at: https://europa.eu/european-union/contact_en

On the phone or by email
Europe Direct is a service that answers your questions about the European Union. You can contact this service:
- by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),
- at the following standard number: +32 22999696, or
- by electronic mail via: https://europa.eu/european-union/contact_en

FINDING INFORMATION ABOUT THE EU

Online
Information about the European Union in all the official languages of the EU is available on the Europa website at: https://europa.eu/european-union/index_en

EU publications
You can download or order free and priced EU publications from EU Bookshop at: https://publications.europa.eu/en/publications. Multiple copies of free publications may be obtained by contacting Europe Direct or your local information centre (see https://europa.eu/european-union/contact_en).
The European Commission's science and knowledge service
Joint Research Centre

JRC Mission
As the science and knowledge service of the European Commission, the Joint Research Centre’s mission is to support EU policies with independent evidence throughout the whole policy cycle.