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ORIGINAL PAPER

A qualitative Natech damage scale for the impact of floods on selected industrial facilities

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Abstract There is increasing evidence that natural disasters can trigger technological accidents and damage. These so-called Natech accidents can pose a significant risk to regions that are unprepared for responding to them. The European Commission's Joint Research Centre has recognised the risk associated with Natech events and has started systematic research into Natechs and their underlying dynamics. This work investigates the risk associated with the flooding of industrial installations through an analysis of past case histories and using expert judgement. The potential impact of three levels of flood severity on selected industrial facilities storing and/or processing (eco-)toxic, flammable or explosive materials is analysed qualitatively and a scale is developed that links the flood intensity to the level of potential damage. Our analysis indicates that natural disasters have the potential for triggering hazmat releases and other types of technological accidents. Hence, natural disasters should be considered as separate accident-triggering events in the planning, design and operating stages of industrial facilities that process or store hazardous substances. Our work revealed a lack of detailed information on the occurrence of Natech events which indicates not necessarily a scarcity of Natechs but rather a lack of standardised reporting and record keeping.

Keywords Natech · Flood · Chemical installation · Critical infrastructure · Hazardous materials · Damage assessment

1 Introduction

Natural disasters have the potential to trigger technological accidents with severe consequences to the population and/or the natural and built environment due to the release

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of hazardous materials processed or stored on site. These so-called Natech accidents have revealed themselves to be particularly deserving of attention, as they can cause multiple and simultaneous hazardous-materials (hazmat) releases whose containment becomes a challenge in the face of a concurrent natural disaster and technological accident that require simultaneous response efforts. Moreover, lifeline systems needed for disaster mitigation, such as electricity or water for fire fighting or cooling, may be badly damaged by the natural disaster, so as to be unavailable for responding to the technological accident.

A study conducted by Showalter and Myers (1994) found that the majority of natural-disaster induced hazmat releases in the United States between 1980 and 1989 was related to earthquakes, followed by hurricanes, floods, lightning and high winds. Numerous hazardous-materials releases triggered by storm surge, flooding and high winds have been documented in the aftermath of Hurricanes Katrina and Rita that wreaked unprecedented havoc on the oil and gas infrastructure both on- and off-shore in the Gulf of Mexico in autumn 2005 (Sengül et al. 2006). In addition to short- and medium-term consequences, such as loss of life, damage to the environment, community disruption and economic loss, the widespread pollution from floating chemicals has raised concerns about long-term soil contamination. In Europe there is little first-hand data on hazmat releases caused by flooding although in recent years there appears to be a marked increase in heavy precipitation and thus in flooding events (Munich Re Group 2006), and flood-triggered Natechs have been reported. German authorities and plant managers were reminded of the vulnerability of industrial installations to natural hazards and the need to prepare for them during the summer 2002 floods, when a dam on the Mulde River burst, causing inundation of a chemical complex. Military action had to be launched to stop hazardous materials flowing into the river, posing a drain on emergency-management resources needed elsewhere (Organisation for Economic Cooperation and Development 2006).

A recent study has shown that the lack of basic information on the potential consequences of a Natech event has resulted in only minimal existing mitigation and emergency response practices in Europe (Cruz et al. 2006). The European Commission's Joint Research Centre (JRC) has recognised the risk posed by Natechs and has started systematic research into their underlying mechanisms. Initial work at the JRC has endeavoured to capture the status of Natech awareness and preparedness in selected EU Member States and the United States (Cruz et al. 2004). Further work is underway to develop methodologies and tools to assess and represent Natech risk and to suggest approaches for its effective management including recommendations for their inclusion into European and/or national legislation.

This work investigates the risk associated with the flooding of chemical installations that store and/or process (eco-)toxic, flammable or explosive substances. This goes beyond the scope of, for example, the US Federal Emergency Management Agency's HAZUS-MH flood model, which estimates potential flood damage and losses for example, the general building stock and lifeline systems (Scawthorn et al. 2006). More specifically, our study analyses the potential impact of floods in terms of hazmat releases and proposes a qualitative damage scale linking the expected consequences to different levels of flood severity. The main objective of this work is to raise awareness of the danger of Natech events among the various stakeholders, such as civil-protection services, land-use planners and decision makers. Second, the derived damage scale provides a qualitative measure of the likely damage before a Natech event, but can also be used as an indicator for after-event characterisation and decision making.

2 Description of the analysis process

The present study was undertaken in three steps. First, the industry types to be investigated were selected. Second, the data required for the analysis was identified and collected, and assumptions on both the natural and technological hazard were formulated. As a final step, the available data was analysed and evaluated, and a tentative damage scale was created that collects the results of the analysis in tabular form.

2.1 Selected industry types

The different industrial facilities considered in this study were selected on the basis of the risk they represent and an analysis of major accidents in the European chemical-process industry collected in the European Commission's Major Accident Reporting System (MARS) (2006). The risk originating from the various activities is a function of the type and quantity of the hazardous substances present, which in this work are considered to be (eco-)toxic, flammable and/or explosive, the types of processes and plants involved, and the sheer number of sites. With this in mind, the following seven industry types were selected for analysis:

- Petrochemical installations/oil refineries;
- Metal processing;
- Mining-waste disposal facilities (tailings dams);
- Wholesale and retail storage and distribution (incl. LPG, fuel etc.);
- Production and storage of explosives (incl. fireworks)
- Fine-chemicals manufacture (e.g. pharmaceuticals, pesticides and fertilisers);
- General-chemicals manufacture.

All the selected industry types are regulated by the provisions of the European Seveso II Directive on the control of major accident hazards (European Union 1997) and its amendment (European Union 2003). Due to the type and quantity of hazardous materials normally processed or stored on site, and the ensuing danger in the case of an accident, the Directive requires stringent standard protection measures to be implemented. There are, however, no specific provisions to guard against flooding. In order to assist the European Union Member States with the implementation of the Seveso II Directive a number of guidelines have been prepared that strongly recommend analysing the potential impact of natural hazards on Seveso II installations (Fabbri et al. 2005; Mitchison and Porter 1998; Christou and Porter 1999). While providing general guidance on certain aspects of the Directive they do not suggest specific actions or methodologies to reduce Natech risk.

2.2 Data sources

Given the diversity of industrial installations and activities it is obvious that there is no generic chemical facility for which a universal Natech flood-damage characterisation could be applied. In fact, a variety of parameters, such as the specific industrial activity undertaken, the type and quantity of substances present, the age and design of a specific chemical plant, and the operating regulations in place, define the vulnerability of an industrial installation to floods or other types of natural hazards. Consequently, a copious amount of industry-specific data is required for the identification of potential consequence scenarios.

In the course of this work we found that while some data on flood-triggered Natechs is available, the information is usually fragmented, lacking the required level of detail for a quantitative analysis and is often not openly available. Despite these complications, a sufficient amount of data was collected from accident databases and other public and restricted sources that allowed us to arrive at qualitative conclusions concerning the vulnerability of industrial installations to inundation events. The main sources for case histories were the Major Accident Reporting System (2006), IChemE's The Accident Database (2004) and the French ARIA (2006) database, as well as other publications from academia or national research centres listed in the References section. Where necessary, and in particular for linking the flood severity levels with the potential consequences in the absence of quantitative data, the authors used their own expert judgement to supplement the in-depth analysis of the available data.

2.3 Assumptions

A number of assumptions were made with respect to both the technological and the natural hazard to focus this study and to balance the lack of detailed and quantitative data. As already discussed in Sect. 2.1, the scope of this work are chemical installations falling under the Seveso II Directive and equivalent sites outside the European Union. Flood damage to lifelines (e.g. electrical power grids, water distribution systems, pipelines, transportation routes) and the corresponding potential aggravation of a Natech event are not considered. The emphasis of our analysis is on the main, average-sized chemical plants and installations whose structural and organisational safety systems operate at peak efficiency. We do not consider the risk originating from auxiliary buildings or waste treatment and storage (except for tailings dams). Moreover, the analysis is based on the main industrial activity and not on a specific design. Consequently, installations that run prototype or test processes, or those that handle particularly hazardous substances normally not in use were excluded. The overall purpose of this study is to illustrate the major flood-triggered technological damage or failure routes that have the potential to result in extensive hazmat releases. It does not claim to be exhaustive in identifying all possible consequences.

The severity of a flood event is influenced by the water height, the flow velocity and the duration of the flooding where the greatest hazard is associated with rapidly moving and rising waters. Strong winds, torrential rains, storm surges and hurricanes can exacerbate flood threats. These secondary events will, however, not be considered in our analysis as our main interest in this study is to capture standard situations and not extreme cases. Building on the results of a French research project that produced intensity scales for natural hazards (Guillande and Buton 2006) we divided the flood hazard into the three severity classes low, intermediate and high. These severity classes were linked with a qualitative hazard-level description due to the scarcity of quantitative flood-hazard data during past Natech events. For the purpose of this work a low flood level was associated with slowly rising flood events that would allow time for activating anti-flooding measures. The inundation would be of short duration, typically not more than one day, with maximum water heights not exceeding half a metre. The intermediate level corresponds to water levels of less than 1.5 m with the possible duration of a few days. Moving would be dangerous for people, and damage to buildings would affect both basements and ground floors. The high flood level is accompanied by maximum water heights exceeding 1.5 m and could last for several days or even weeks. The risk of drowning would be high and buildings could suffer extended damage to basements, ground and upper floors or possibly be completely destroyed.

3 The potential impact of floods on selected industry types

Our review of flood-triggered Natech case histories highlighted the vulnerability of chemical installations in and outside Europe to inundations, and the risk they represent in terms of accompanying hazmat releases. By their very nature, floods are difficult to contain, and while walls or sandbags may provide a reprieve, eventually the sheer volume of water would overcome the barriers and find a way to enter a site. This is especially true for rapid-onset river floods or for flash floods and/or long-duration inundation. Every industrial activity analysed has its particularities in terms of production processes or hazardous materials used or manufactured. Consequently, also the vulnerability among the discussed activities, as well as the potential consequences may vary. In order to underline these differences the following sections give a brief description of the industry types and discuss the potential for flood-related damage and releases including example case histories. The main outcome of our analysis, a tentative qualitative scale linking flood severity to potential damage per industry type, is presented in Table 1.

3.1 Petrochemical installations/oil refineries

Oil refineries process and refine crude oil into useful petroleum products. This is done via a fractional-distillation process which separates the hydrocarbons contained in the crude oil by exploiting their different boiling points. The fractions thus generated are chemically processed and converted into other products by cracking, unification or alteration, treated to remove impurities, or combined to produce mixtures (United States Occupational Safety and Health Administration 2006). Refinery products, such as heavy gas or fuel oil, lubricating oil, gas oil or diesel distillate, kerosene, gasoline, naphtha and liquefied petroleum gas (LPG), are usually stored on-site before their delivery to the markets. Other hazardous materials potentially stored on-site in smaller quantities include, for instance, hydrogen fluoride, ammonia and hydrogen sulphide (Cruz et al. 2001). Therefore, the average site stores large quantities of substances, which can be flammable, explosive or (eco-)toxic and which constitute a major environmental hazard. In general, any accident on site has the potential to cause severe damage off site.

The presence of large quantities of hazardous materials at refineries requires strict measures for accident prevention and mitigation. In the European Union stringent safety measures for operation and storage are in place in accordance with the Seveso II Directive. Environmental and safety concerns normally require that oil refineries and petrochemical installations be located a safe distance away from major urban centres which is, whenever possible, considered in land-use planning. Frequently, chemical installations are sited next to a refinery to utilise products from oil refining for the manufacture of a wide variety of petrochemicals such as olefins and aromatics which in turn are utilised for the production of e.g. plastics or agrochemicals. This increases the risk of a so-called domino effect where the primary accident sets off one or more secondary events, thereby increasing the consequence severity. The implications of domino effects should also be considered in the regulatory process and are explicitly mentioned in the Seveso II Directive. From a technical point of view one example of standard safety measures would be the presence of

Table 1 A qualitative damage scale of flood-triggered Natech events for selected industry types

Flood-severity level	Low	Intermediate	High
Petrochemical/Oil refineries	Shut-down of processes to a "safe mode"; bunds around storages hold; no displacement of vessels; no loss of containment.	Flotation and displacement of small storage tanks; potential release of small quantities of petrochemical substances on-site; risk of fire and explosion in the presence of an ignition source.	Flotation and displacement of large storage tanks, leading to damage to equipment; release of large quantities of petrochemical substances from failed tanks or torn pipe connections; tank breach due to collision with debris; potential for severe off-site pollution; risk of fire and explosion with serious off-site consequences in the presence of an ignition source.
Metal processing	Shut-down of processes to a "safe mode"; bunds around storages hold; no displacement of vessels; no loss of containment.	Flotation and displacement of small storage tanks; potential release of small quantities of (eco-)toxic substances on-site, e.g. heavy metals, cyanide etc.; potential for overwhelming the effluent-control systems with possibly minor off-site pollution.	Flotation and displacement of vessels, leading to damage to equipment; release of (eco-)toxic substances from failed tanks and torn pipe connections into the water including heavy metals, cyanide etc.; potential for serious off-site consequences including damage to the environment and contamination of the drinking-water supply and the food chain. Minor risk of steam explosions due to melt-water interaction.
Mining-waste disposal facilities (tailings dams)	Increase of pool water level; small slips and minor dam-toe erosion; negligible risk of hazardous-materials release.	Significant dam-toe erosion; larger slips; possible overtopping and slope failure; potential for release of highly toxic substances into the water, including heavy metals and cyanides, and pollution of the environment.	Dam overtopping and destruction; wide-scale release of highly toxic substances into the water, including heavy metals and cyanides, resulting in severe damage to the environment, potential contamination of the drinking-water supply and the food chain.

Table 1 continued

Flood-severity level	Low	Intermediate	High
Wholesale and retail storage and distribution (incl. LPG, fuel etc.)	Shut-down of operations and flood-protection measures implemented on warehouse buildings; bunds around storages hold; no displacement of vessels; low risk of displacement of small cylinders.	Damage to warehouse buildings, hazardous substances carried away by flood water; flotation and displacement of small storage tanks; potential release of hazardous materials on-site; potential for minor off-site pollution, and fires and explosions in the presence of an ignition source.	Severe damage to warehouse buildings; flotation and displacement of vessels, damaging equipment; potentially major release of (eco-)toxic substances from failed tanks or torn pipe connections into the water or air; potential for severe off-site pollution; in the presence of an ignition source risk of fires and explosions if flammable and/or explosive materials released; increased risk of release, fires and/or explosion due to collision between tanks and vessels and with debris; risk of unexpected side-reactions due to a wide variety of substances present.
Production and storage of explosives (incl. fireworks)	Shut-down of production to a “safe mode”; securing of storage areas; negligible risk of adverse consequences due to designed structural protection measures.	Minor risk of release; possible displacement of explosives in ground-floor storage and non-negligible risk of explosion of shock-sensitive explosives due to collision with obstacles; non-negligible risk of spontaneous ignition and explosion due to chemical reaction with the floodwaters.	Hazmat release from explosives production through pipe breaks and tank breaches; potentially severe damage to fireworks-storage buildings leading to the displacement of explosive materials and significant risk of explosion of shock-sensitive explosives due to collision; significant risk of spontaneous ignition and explosion due to chemical reaction with the floodwaters; low risk of off-site toxic pollution from final products.

Table 1 continued

Flood-severity level	Low	Intermediate	High
Fine-chemicals manufacture (e.g. pharmaceuticals, pesticides, fertilisers, etc.)	Shut-down of processes to a "safe mode"; bunds around storages hold; no displacement of vessels; no loss of containment.	Flotation and displacement of small storage tanks; potential release of small quantities of very (eco-)toxic substances on-site; potential for overwhelming the effluent-control systems with possibly minor off-site pollution.	Flotation and displacement of vessels, leading to damage to equipment; release of (eco-)toxic substances; potential for significant off-site consequences including damage to the environment and contamination of the drinking-water supply and the food chain; additional concerns: possible release of biochemical substances, unexpected side-reactions or detonation of highly explosive compounds from fertiliser production.
General-chemicals manufacture	Shut-down of processes to a "safe mode"; bunds around storages hold; no displacement of vessels; no loss of containment.	Flotation and displacement of small storage tanks; potential release of small quantities of (eco-)toxic substances on-site; potential for overwhelming the effluent-control systems with possibly minor off-site pollution.	Flotation and displacement of vessels, leading to damage to equipment and major release of (eco-)toxic substances resulting in potentially significant off-site consequences; risk of unexpected side-reactions due to a wide variety of substances present.

oil-retaining dikes around tanks and a secondary oil-retaining wall to prevent off-site spillage. Fire-prevention and fire-fighting efforts are another key element of accident-management procedures.

Often the vicinity to rivers or the sea for easy transportation of products and/or cooling purposes increases the risk of flood-related damage to refineries and petrochemical facilities while the flood water itself provides a vector for the distribution of hazardous materials over wide swathes of land. Past flood-triggered Natech events have shown that floods have the potential to cause flotation and the displacement of storage tanks, thereby tearing pipe connections and resulting in hazmat releases (Cruz et al. 2001). Additionally, collisions with debris transported by the floodwaters may cause tanks to breach. Therefore, the risk of leaks and subsequent on-site and off-site pollution, fires and explosions is significant. Flooding of electrical equipment may cause short-circuiting and power outages, which could result in the failure of cooling units, pumps and electrically operated safety systems. In the case of flood-related oil spills or flooding of internal plant drainage systems containing waste oil, the oil may be lifted by the floodwaters and may spark fires and explosions upon contact with ignition sources (e.g. hot refinery parts). This occurred in Morocco's Samir refinery in Mohammedia where flooding by the rain-swollen El Maleh

River in November 2002 resulted in water levels of about 1.5 m inside the refinery, causing fires and explosions. As a result, two people died and over 70% of the thermo-electric power plant that was part of the refinery complex was destroyed (United Nations Office for the Coordination of Humanitarian Affairs 2006; Vallee and Dolladille 2003). Hurricane Katrina and the ensuing flooding caused oil tanks to float off their foundations, resulting in oil spills totalling over 30,000,000 l in the affected areas. While most spills were less than 40,000 l, 6 major oil spills of a volume of over 400,000 l each occurred (Sengül et al. 2006). Storm surge and the floodwaters dispersed the contaminants throughout the region resulting in increased levels of mostly arsenic, diesel fuel, lead and benzo(a)pyrene in the sediments in the greater New Orleans area (Solomon and Rotkin-Ellman 2006). The results of our analysis of the potential impact of floods on petrochemical facilities and refineries are presented in the first row of the damage scale in Table 1.

3.2 Metal processing

The basis of metal processing is extractive metallurgy, which liberates the desired metal from the minerals existing in the Earth's crust, and purifies it. Several extraction processes are in use and their selection depends on the type of ore to be treated. The extraction can be carried out by separation, which exploits the physical or chemical properties of the ore, by pyrometallurgy, which involves the treatment of ores at high temperature, such as roasting, smelting and converting, or hydrometallurgically by leaching of the ore with ammonia, sulphuric acid or cyanide. The hydrometallurgical route is questionable from an environmental point of view due to the toxicity of the chemicals employed (World Bank Group 1999). Following extraction the metals undergo production engineering where they are refined and cast into shapes.

In addition to the ores and metals being processed a number of other, often hazardous substances are present on-site dependent on the type of processing performed. These may include electrolyte solutions, acidic solutions, ammonia, sulphuric, hydrofluoric or nitric acids. Smaller quantities of chemicals for specific purposes, e.g. toxic metals, such as chromium for electroplating, or chlorine gas for the removal of magnesium from molten aluminium may also be present. The heating operations require large amounts of fuel, e.g. oil, LPG or natural gas, which therefore adds to the hazard on site. The extraction and refining processes produce airborne and liquid waste that is dealt with by effluent-treatment systems. Air emissions are dominated by sulphur dioxide and particulate matter, which can contain toxic metal oxides, fluorides and sulphates (World Bank Group 1999). Additionally, any or all of the substances used in chemical reduction (such as acidic solutions, toxic metals, solvents, and cyanides) can be found in the wastewater, either via rinsing of the product or from spillage and dumping of process baths. Emission-control systems ensure that the prescribed release thresholds are not exceeded. Problems would arise should the capacity of these systems be overcome by excessive throughput during an accident or a natural disaster.

The main concern during the flooding of a metal-processing plant would be the release of toxic metals and other chemicals spilled on the ground or discharged due to equipment damage, pipe breaks or breached storage vessels. If not contained, the release would do considerable damage to the environment, and have potentially severe consequences if toxic metals entered the food chain and drinking-water supplies. Moreover, steam explosions from floodwater-melt interaction could start fires and result in further damage and releases to the atmosphere. The second row in Table 1 summarises the potential damage as a function of flood severity. The biggest safety concern during flood events would, however, be the integrity of the facilities disposing of the waste from ore mining. This is discussed in the next section.

3.3 Mining-waste disposal facilities (tailings dams)

The recovery of metals and other minerals required for industrial processes or consumer products entails the mining of large quantities of ore and its subsequent processing. The waste accompanying these activities is called tailings, which is dealt with in several ways. These include the disposal of dry or thickened tailings in impoundments or freestanding piles, the backfilling of underground mine workings and open pits, sub-aqueous disposal, or the storage of tailings slurry in sedimentation ponds (which is the most common method). These ponds are surrounded by natural barriers and/or dams to keep the tailings from being discharged (United States Environmental Protection Agency 1994; Benckert and Eurenius 2001).

The largest proportion of the mined ore ultimately becomes waste and tailings disposal is a significant part of the overall mining operations. The majority of chemicals and substances intentionally or accidentally released to the environment from mining operations are naturally occurring minerals within the rock that is being mined. Moreover, certain types of ore-extraction methods leave behind toxic compounds in the tailings (e.g. the heap leaching of low-grade ores carried out with cyanide or sulphuric acid). Depending on the minerals or metals processed, compounds frequently found in tailings are cyanide, arsenic, fluorite, mercury, copper, cadmium and other heavy metals (United States Environmental Protection Agency 2006).

The major risks associated with mining waste are those connected to the pollutant source (e.g. acidity and heavy metals) and those linked with the stability of tailings dams, in particular with respect to exceptional climatic conditions (Bureau de Recherches Géologiques et Minières France 2001). As a consequence, all impoundments and their retaining dams have to be able to accommodate extreme hydrological events. Water-retaining dams are normally provided with spillway facilities designed to pass the probable maximum flood. Usually, however, the tailings fluids are not permitted to be discharged, so upstream floodwaters must be fully diverted so as not to enter the impoundment. Storage capacity and careful management of tailings-pond water must be sufficient to accept all flood waters falling directly onto the impoundment or entering via incorrectly diverted streams (International Commission on Large Dams 2001).

An analysis of recent waste-containment failures has shown that the reliability of mining-waste containment structures is generally low and that the technical and managerial challenges of responsible mine-waste management are not sufficiently recognised (Morgenstern 2001). River and flash floods but also intense precipitation or snowmelt events and spring runoff have on several occasions resulted in tailings-dam failures and the release of heavily contaminated mining waste, demonstrating the possible cost to life, the environment and to asset value. The weight of tailings can cause serious damage in the downstream valley system, demolishing buildings rather than flowing through them as floodwaters would do. Moreover, the release of contaminated tailings would have severe consequences if they entered the food chain or the drinking-water supplies.

The mechanisms by which hydro-meteorological phenomena can affect tailings dams are dam-toe erosion due to river floods, the increase of the pool water level, eventual slips and overtopping, dam failure and ensuing tailings flow slides. A cascade failure due to a

100-year flood of three impoundments at the Galena (United States) silver mine that were built in sequence in a narrow valley released about 4,000 m^3 of tailings in 1974. Another example is the near miss that occurred in Montenegro at the lead and zinc mine in Mojkovac in 1992. The toe of a tailings dam retaining highly toxic waste was eroded by a flooded river that led to a rotational slip. Dam failure and thus a major ecological disaster could only be prevented under a United Nations emergency project that diverted the river away from the dam toe (International Commission on Large Dams 2001). Nothing highlighted the vulnerability of tailings dams to hydro-meteorological events and the potential for transboundary consequences better than the dam failure in the gold mine in Baia Mare (Romania) in 2000. Heavy precipitation coupled with a sudden increase in temperature and snowmelt increased the water level in the pond until the crest of the dam failed. About 100,000 m^3 of cyanide-rich liquid was spilled, contaminating the Somes, Tsiza and Danube rivers, poisoning drinking water and destroying the fishing and tourism industry in the affected areas for the foreseeable future (Mara 2004). The potential consequences of floods impacting tailings dams are shown in the third row of the damage scale in Table 1.

3.4 Wholesale and retail storage and distribution

A wide variety of hazardous chemical substances, e.g. LPG, liquefied natural gas, ammonia, sodium chlorate, etc. are stored by industrial facilities that receive and stock raw materials and products and distribute them upon request. The sites that fall in this category include LPG bottling and bulk distribution, tank-storage farms, cold-storage distribution and warehousing. Depending on the physical form of a chemical (solid, liquid or gas) and the quantity to be stored different storage types and designs are in use. These include bulk storage tanks and vessels that can be at atmospheric pressure, pressurised and/or refrigerated, drum and cylinder storage or warehousing (Mannan 2005). The liquefied petroleum gases propane and butane are stored in large quantities under pressure in spherical pressure vessels or in smaller quantities in horizontal cylinders. Fully refrigerated LPG storage is possible at atmospheric pressure. Chlorine is generally stored as a liquid under pressure. The same holds for ammonia, which is, however, also often found fully refrigerated in atmospheric tanks. Warehouses constitute a different type of storage where material, including hazardous substances in packages or drums may be stockpiled on the floor or in bays that hold discrete items.

The hazard presented by the storage of chemical raw materials or products depends on the characteristics of the chemical itself, its inventory and the type of storage, which determines its emission and dispersion. Many of the stored substances are flammable liquids or liquefied gases and may also be explosive. Others may be highly toxic and eco-toxic and loss of containment from the storage of these substances could have particularly serious consequences. The storage conditions influence the release dynamics in the case of loss of containment, where a leak in atmospheric storage of a volatile liquid would result in only slow evaporation while a leak in pressure storage at atmospheric temperatures would cause instantaneous flashing of a large proportion of the stored liquefied gas. Safety and protection measures need to meet the challenges posed by storing large quantities of substances with different physical and chemical properties. The sheer amount of materials may make a spill, a fire or an unforeseen chemical reaction difficult to contain or may lead to the escalation of an initially small event. Under these circumstances there is the risk of spreading of an event to adjoining buildings or vessels and tanks. Another consideration is the potential incompatibility of substances stored within a site, which might lead to undesirable reactions upon accidental mixing and possibly toxic by-products. The segregation of hazardous materials and the observance of minimum separation distances significantly reduce the risk of an accident, as well as the likelihood of a cascading or domino event. Secondary containment, such as bunds or dikes, surrounding some types of storage tanks allows the retaining of any accidental spillage in a controlled way. Fire prevention and protection systems are designed to keep flammables from igniting and to minimise losses due to the initial fire. The technical safety systems need to be supplemented by a comprehensive safety-management programme. An overview of the various types of storage for different hazardous materials and a discussion of the accompanying safety aspects can be found in Mannan (2005).

Several natural hazards, such as high winds, lightning, flooding or earthquakes, could pose a threat to storage and have resulted in loss-of-containment events in the past (Chang and Lin 2006). River floods, storm surge or flash floods can impact storage tank systems by causing them to float, collapse or move laterally, thereby leading to a direct release of potentially hazardous liquids or vapours from the failed tank or indirectly through severed pipe connections. In the presence of an ignition source the released flammable vapours can catch fire. The release of (eco-)toxic substances is particularly problematic, as they would be carried away by the floodwaters and contaminate larger areas. Collision between tanks or vessels and debris swept along by a flood could damage or destroy storage systems left unscathed by the floodwaters themselves. The potential effects of floods on storages is summarised in the fourth row in Table 1. An illustrative example for a flood-triggered Natech is the inundation of a propane tank farm in St. Louis, Missouri, during the 1993 Mississippi river-basin floods that caused 51 tanks of over 100,000 l each to float, resulting in vapour leakage from the pipe connections. This and the danger of tanks being carried away from the storage farm, colliding with downstream obstacles and exploding led to the preventative evacuation of about 12,000 residents for 12 days (Hickey and Salas 1995; The Accident Database 2004). Heavy rain and ensuing floods in southwest France and northern Spain in September 1983 washed out to sea 80 drums containing sodium and potassium cyanide from a flooded chemical warehouse in Spain. Beaches were closed and fishing was restricted for a week. Four people were hospitalised after inhaling cyanide fumes from the leaking drums (The Accident Database 2004). Another example is the flooding of a Seveso site storing and distributing pesticides in Arles (France) in December 2003. Due to a dike failure on the Rhone River the site was flooded with water levels of up to 1.4 m. With some of the merchandise stored on the ground only a quarter of the stock was saved, resulting in economic losses of 4 million Euros. While the packaging of most of the stored hazardous materials suffered only light damage, the drums containing sodium dichloroisocyanurate tablets sagged due to the interaction with the floodwaters and released small amounts of chlorine (French Ministry of the Environment 2005).

3.5 Production and storage of explosives

The production of explosives ranges from the manufacture and storage of general explosives to that of high explosives which require special licenses. The final products, such as munitions, dynamite, TNT, fireworks or black powder are used in the construction industry (demolition), for quarrying, or for fireworks displays. This industry is by its very nature high risk and more often than not the sites are situated in rural areas away from highly populated zones.

Explosive materials always pose a high risk as the consequences of any incident or accident can be very severe. In fact, the largest number of fatalities in the European chemical process industry stems from explosion accidents, as they occur without warning and leave no time for evacuation or mitigation action (Sales et al. 2007). In addition to blast (pressure) waves and fire/heat radiation as the primary hazards associated to explosions, flame spread and missiles add to the overall risk. The most stringent measures are in place to ensure that explosives facilities are appropriately located and that the risk of explosion is properly controlled. The basic principles in managing the explosion risk are the minimisation of the inventory and of exposure, the use of blast walls and the separation by distance (Mannan 2005). Separation distances are governed by quantity-distance relations that are a function of the hazard types and quantities of explosives being produced and stored, the construction of the storage and the number of dwellings within the area around the storage (Health and Safety Executive 2005). In addition to keeping appropriate safety distances between explosives factories and inhabited areas off-site, operators are generally also required to maintain internal separation distances between explosives production buildings and storages to limit the severity of consequences to a manufacturing area (Health and Safety Executive 2002). Generous separation distances between stores reduce the risk of sympathetic detonation of one explosives store by an adjacent one by preventing the instantaneous communication of an explosion (Mannan 2005).

Explosives are usually stored underground, inside mounds or in buildings with thick walls. Therefore, it appears unlikely that flooding events could do more than minimal damage to an explosives storage facility. Nevertheless, some explosives tend to be sensitive to shock, and should floodwaters manage to enter a storage site and displace explosives the risk of an explosion due to collision with debris, walls or other types of obstacles would be increased (Mannan 2005). In addition, some explosives might chemically react with water, as happened during the inundation of an explosives factory early in 1953 in the United Kingdom. Floodwater soaked into fireworks containing chlorate-aluminium composition, causing heating by chemical reaction with the probable generation of hydrogen, spontaneous ignition and an explosion that destroyed the entire building (Explosives Incidents Database Advisory Service 2006). Explosives production could be affected by flood-triggered pipe breaks or tank breaches, resulting in the release of hazardous starting or intermediate materials. On the other hand, the risk of off-site toxic pollution from the final products is not considered to be high. The potential consequences per flood-severity level are shown in the fifth row of the damage scale in Table 1.

3.6 Fine-chemicals manufacture

The fine-chemicals industry produces high-end custom and general-use chemical substances used in medication, agricultural products and in many other applications. For illustrative purposes pharmaceuticals, pesticides and fertilisers, and the accompanying safety issues are discussed in more detail. Pharmaceuticals manufacture consists of producing the active ingredient or drug and then converting it into products suitable for administration. The synthesis of pesticides is carried out in the same manner. Major chemical groups of active pesticide ingredients include carbamates, organochlorines, organophosphorus and nitro compounds, bio-pesticides and urea derivatives. Fertiliser manufacture can follow various distinct production routes involving different processes and raw materials, as well as intermediate and final products. Mixed fertilisers, such as ammonium phosphate and nitrophosphate, consist of two or more of the elements nitrogen, phosphorus and potassium. Ammonia, urea, ammonium sulphate and ammonium nitrate are nitrogenous fertilisers. Phosphate fertilisers like single or triple phosphate are high in phosphorus (European Fertiliser Manufacturer's Association 2000).

These examples highlight the challenges in reducing the risk of a hazmat release from the wide variety of processes and/or materials involved in the manufacture of fine chemicals both under normal operating conditions and in the case of an accident or a natural disaster. Technical and management systems are in place to maximise safety and environmental protection from the inherent hazard posed by the substances used and produced, and the gaseous, liquid or solid toxic waste generated in every step of pharmaceuticals, pesticides and fertilisers manufacture. Air emissions such as volatile organic compounds and particulate matter and liquid effluents typically containing toxic organic residues or heavy metals are dealt with by emission-control systems. The main concern in terms of risk reduction is the potential toxicity of the hazardous chemicals used in the manufacturing processes. However, with the wide variety of substances involved there are also issues with flammability and explosivity. Factors adding to the overall risk are unknown or unpredictable side reactions in the event of an accident in pharmaceuticals production, resulting in possibly toxic by-products. Moreover, there is a heightened risk in the presence of bio-chemicals and their possible release to the environment. Fertilisers can be highly explosive, especially ammonium nitrate which is specifically mentioned in the Seveso II Directive as a substance meriting particular attention (European Union 1997).

The inundation of fine-chemicals production sites poses a significant risk due to the quantities and properties of the hazardous materials present on site. Pipe breaks, the liberation of chemicals stored at ground level and the disruption of effluent-treatment systems are only examples of the possible flood-triggered hazmat-release paths that have the potential for wide-scale on-site and off-site air and water pollution including the contamination of water-distribution lines. An illustrative case is the heavy rains and floods that caused a pipe break in a fertiliser plant in Vila Parisi (Brazil) in 1995. The event resulted in the release of an ammonia cloud over a nearby town, injuring many residents and necessitating mass evacuation. Another example is the flooding in the wake of the Teton Dam collapse in Idaho (USA) in 1976 that damaged several commercial facilities and farm storehouses and triggered the release of a large amount of pesticides into the Snake River (Young et al. 2004). The damage and hazmat-release potential of floods impacting a facility producing fine chemicals is shown in the penultimate row of Table 1.

3.7 General-chemicals manufacture

Unlike the fine-chemicals industry that produces very specific substances, general-chemicals manufacture covers a large number of processes and sites that generate basic raw materials in bulk, such as acids, bases, chlorine etc. to be used for other industrial applications or low-end consumer products like e.g. plastics. The increased risk due to the presence of toxic, flammable and/or explosive substances on site requires special consideration in the design and safe operation practices of these facilities. Just as for fine-chemicals manufacture, technical and management systems are in place to ensure safety and environmental protection.

Analogous to what was discussed in the previous section flooding of a general-chemicals site has the potential to trigger hazmat releases, in particular of toxic or eco-toxic substances, through ruptured pipes or via broken pipe connections due to tank flotation. This was observed when in August 2002 a chemical plant producing plastics and raw materials for the manufacture of synthetic fibres in Spolana (Czech Republic) was flooded. Liquid chlorine containers were lifted by the floodwaters which damaged the pipe connections, resulting in the release to the atmosphere and water of over 80 tons of (eco-)toxic chlorine. Inadequate anti-flooding measures could not prevent the release (Major Accident Reporting System 2006). Although this Natech event claimed no casualties, crops in the surrounding fields were damaged or destroyed by the chlorine cloud, causing important economic losses for the farmers who will not be able to cultivate their land for years to come. Interestingly, the floodwaters themselves mitigated the consequences of the release by capturing the majority of the released chlorine in the water where it was dissolved and neutralised. The release to the air represented only a small portion of the original tank contents (Danihelka 2006). The expected consequences of the flooding of a general-chemicals manufacturing facility are very similar to those for fine chemicals, and are shown in the last row in Table 1.

4 Discussion

The overall purpose of this research was to investigate the risk associated with the flooding of industrial installations, analyse the potential impact in terms of hazmat releases and prepare a scale linking the flood intensity to the level of potential damage. Our analysis of past case histories, some of which are presented in Sect. 3, clearly indicates that floods have on numerous occasions resulted in the release of hazardous materials from chemical installations, exacerbating the damage and losses to the natural and built environment caused by the flooding itself. Low flood levels seem to be little more than an annoyance to facilities regulated by the Seveso II Directive or similar legislation as the standard protection measures in place, although not necessarily geared towards flood protection, should be sufficient to avert an emergency. Potentially significant damage and severe off-site consequences would be expected for the intermediate and high flood levels. While one could envision extreme conditions where small floods result in serious consequences or where major inundations have little impact we consider this to be highly improbable and have not considered these exceptional cases in the preparation of the damage scale.

Our analysis suggests that some industry types pose a higher Natech risk than others. This risk not only depends on the quantity of hazardous materials and possible vulnerable areas present in an industrial establishment, but it is also a function of the natural-hazard trigger. For industries manipulating large amounts of (eco-)toxic materials intermediate flood levels may be sufficient to cause hazmat releases which could be transported off site with potentially severe consequences. A forest fire would only be a minor concern, unless of considerable magnitude. The opposite holds for explosives manufacturing or storage facilities which would most likely suffer only very limited damage from low or intermediate floods. A forest fire, on the other hand, may lead to a major disaster. Another example are flash floods that are expected to cause greater damage than slowly rising plain floods of equivalent height due to the accompanying pressure forces that can damage or destroy any structures in their path. To our knowledge the vulnerability of industrial installations to flash floods has not been investigated and information on flash-flood triggered Natech events is scarce. It is therefore difficult to conclude on their damage and hazmat-release potential. However, based on our work on flood-triggered Natechs we believe that flash floods would have consequences comparable to those of the intermediate and high plain-flood classes.

The damage scale in Table 1 gives an indication of the vulnerability of industrial installations to flood events by describing the likely interaction between the natural hazard and the technological systems based on these two parameters only. Another important consideration in the assessment of the overall risk is the location of an industrial facility, which should be sited outside flood-prone areas by prudent land-use-planning policies. In fact, land use planning offers the most obvious way to stay out of harm's way. However, many floodplains are already heavily populated or industrially developed and it is hard to impose land-use restrictions retroactively due to economic and political pressures. In these situations additional safety measures such as protective dikes are implemented and may give the erroneous impression of zero flood risk behind the dike. The weakness of this approach became manifest when a number of chemical sites suffered damage by floods in France in December 2003 although the installations were not sited in areas declared as flood prone since they were protected by dikes (French Ministry of the Environment 2005). As these dikes are usually designed to withstand a 100-year flood a major rethinking is in order to prepare for Natech risk reduction in times of ongoing climate change and the expected increase in hydrological and meteorological hazards (Benfield Hazard Research Centre 2004; Mileti 1999).

One of the biggest challenges of this work was the lack of quantitative but also detailed qualitative data on the occurrence of flood-triggered Natech events. This particularly concerned data on both the natural hazard and the technological system at the time of their interaction. There is evidence that this is not due to the scarcity of Natech events but rather to a lack of standardised record keeping and the absence of reporting obligations if consequences are below a pre-defined set of criteria (Young et al. 2004). As the primary goal of every investigation into an accident or a disaster is the learning of lessons to prevent its recurrence or to mitigate its consequences, measures to improve the investigation, the reporting and the collection of data on Natech events should be implemented. The data collection would, for example, benefit significantly from the mandatory reporting of at least a minimum of information in an understandable and comparable format (Krausmann and Mushtaq 2006). This is of particular importance for non-controlled activities or industries abiding by regulations that are less strict than the Seveso II Directive and which may therefore operate at lower safety levels. The developed damage scale in Table 1 characterises the Natech risk by mapping hazards and consequences. A more sophisticated representation specific to Natechs including triggers (natural hazards), causes (possible weaknesses or failures inside the establishment), sources (vulnerable zones, such as the storage of toxic, flammable or explosive substances) and consequences (which are intensified by the natural hazard) may be beneficial but is subject to future data availability.

As mentioned in Sect. 2, the lack of data forced us to make a number of assumptions that were deemed justified for the purpose of this generic study whose aim is to give an indication to decision makers and planners of the Natech risk connected to inundations. For any application of the damage scale beyond this scope, e.g. for the preparation of site-specific safety reports (including risk assessment), extreme caution must be exercised due to the inherent limitations in this work. The most important shortcoming is the classing of industrial sites into activity-type categories, which may give the impression that standardised sites exist. In reality, there is no such thing and no two installations undertaking the same activity are identical due to their different sizes, ages, technology or processes employed.

5 Conclusions

This study demonstrated that floods have a potential for causing hazmat releases and other technological accidents. Consequently, floods should be considered explicitly as separate accident-triggering events in the planning, design and operation of industrial installations that process or store (eco-)toxic, flammable or explosive materials. Our analysis also confirmed a general lack of detailed information on Natech disasters, highlighting the necessity for standardised reporting of these events, and the need for systematic research in the field. The JRC has launched a Natech data-collection exercise and other activities in support of improving our understanding of the causes, the evolution and the potential consequences of Natech events.

The proposed Natech damage scale is a first attempt at linking flood-severity levels to technological damage or failure. It is largely based on the in-depth analysis of past Natech case histories and is therefore a function of the amount and the quality of the data available. While the collected material was sufficient for drawing general and qualitative conclusions on the potential link between floods and technological hazards, the quantification of the damage scale would depend on the existence of an exhaustive amount of quantitative data on both the natural-hazard severity and the triggered Natech. Upon availability of the required information an attempt can be undertaken to update the damage scale. Moreover, the study would benefit greatly from supplementary information from industrial risk analyses that try to identify the most probable flood-triggered hazmat release paths through a detailed systems analysis.

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