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Industrial accidents triggered by flood events: Analysis of past accidents

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ABSTRACT

Industrial accidents triggered by natural events (NaTech accidents) are a significant category of industrial accidents. Several specific elements that characterize NaTech events still need to be investigated. In particular, the damage mode of equipment and the specific final scenarios that may take place in NaTech accidents are key elements for the assessment of hazard and risk due to these events. In the present study, data on 272 NaTech events triggered by floods were retrieved from some of the major industrial accident databases. Data on final scenarios highlighted the presence of specific events, as those due to substances reacting with water, and the importance of scenarios involving consequences for the environment. This is mainly due to the contamination of floodwater with the hazardous substances released. The analysis of process equipment damage modes allowed the identification of the expected release extents due to different water impact types during floods. The results obtained were used to generate substance-specific event trees for the quantitative assessment of the consequences of accidents triggered by floods.

1. Introduction

In the usual approach to process safety, loss of containment events are mostly attributed to internal failure causes. However, the analysis of accident databases indicates that a limited but significant number of major accidents involving hazardous substances is due to external factors, such as domino effect, natural events or intentional acts [1]. While significant efforts were dedicated in the technical literature to the assessment of domino effect [2–4], less attention was devoted to the analysis of accidents triggered by natural events, which are also referred to as NaTech accidents (Natural events triggering Technological disasters).

NaTech accidents may be triggered by several different categories of natural events. Floods and lightning are among the most frequent natural hazards triggering technological accidents [5], although seismic events have caused the most severe NaTech events [6].

A preliminary survey of the impact of floods on process equipment indicated that structural damage (displacement, impact with floating objects, collapse) and failure of electrical equipment are the two main damage modes caused by floods [7]. Water dispersion and reactions of released chemicals with water are the main causes for the severe final consequences experienced in such accidents. Krausmann and Mushtaq [8] list a number of flood-triggered NaTech accidents including failure modes and consequences. An illustrative example is the release of toxic chlorine from a facility manufacturing synthetic fibers during the summer floods in the Czech Republic in 2002. Tanks containing liquid chlorine were lifted by the floodwaters due to buoyancy forces, thereby damaging pipe connections and releasing 80 tons of liquefied chlorine and 10 tons of chlorine gas. As a consequence crops and fields in the surroundings were damaged or destroyed, resulting in important economic losses. Another example is the release of over 30,000 m^3 of oil from tanks that floated off their foundations due to Hurricane Katrina and the accompanying flooding, leading to soil contamination in the affected areas. Fires and explosions occurred during the flooding of a refinery in Morocco when waste oil was lifted by the floodwaters from the internal drainage system, and ignited upon contact with hot equipment. Two people died in this accident. Reaction of chemicals with floodwaters that had penetrated an explosives factory and the subsequent formation of hydrogen led to an explosion that destroyed the entire building [8]. An accident triggered by the loss of utilities occurred in France in 2002 when a fluid catalytic unit was restarted after heavy flooding. A loss of electricity and the failure of electrical devices led to a fire [9].

The above examples indicate the potential for severe consequences in flood-triggered NaTech accidents. However, only recently the specific features of such accidents were recognized [8,10,11] and a formal approach to the quantitative assessment of the risk due to these events was introduced [12]. Nevertheless, a general awareness concerning the potential hazards of NaTech accidents is still missing, although there is evidence that about 2–4% of industrial accidents fall inside this category [8], as shown in Table 1. An example is the "Seveso-II" European Directive (Directive

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Table 1
% of NaTech events reported in some of the databases considered [12].

Databases	Total number of records	% NaTech events
ARIA	30,859	2
FACTS	22,214	2
MARS	602	4
MHIDAS	7000	2

96/82/EC) [13], that addresses in detail the control of major accident hazards, but that only indirectly mentions the possible hazard due to natural events in Section IV of Annex II, not introducing specific obligations. Moreover, several specific elements that characterize NaTech events still need to be investigated. In particular, the damage modes of equipment and the specific final scenarios that may take place in NaTech accidents are key elements for the assessment of hazard and risk due to these events.

Accident analysis is a powerful method to understand the potential hazards and the specific features of accidental events. Important lessons and models useful for risk assessment and control may be derived from the analysis of industrial accidents. In the present study, data on NaTech events triggered by floods were extracted by a systematic search of the major industrial accident databases. The accident files were analyzed in order to highlight two key issues: the damage modes of equipment items during floods, and the features of the final scenarios that took place after the release of hazardous substances due to the flood. The final aim was the development of systematic event chains to approach the quantitative assessment of the risk due to this category of accidents.

2. Methodology

2.1. Data sources consulted for the analysis

The data analysis was carried out through the consultation of databases reporting data on accidents that occurred in process plants. Data were retrieved from five European databases (ARIA, FACTS, MARS, MHIDAS, TAD), one U.S. (NRC) database and from the open literature [14,15]. Different keywords and approaches were used for the data search since each database presents distinctive characteristics in recording and organizing the data. Both categorical and numerical data were extracted from the databases and were subsequently analyzed. A brief outline of the main data sources is provided in the following.

The ARIA database (Analyse, Recherche et Information sur les Accidents) [16] is managed by the French Ministry of Ecology and Sustainable Development (ARIA 2006). 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. The information recorded in this database mainly comes from the French Department of Civil Protection and from the French Ministry of the Environment. The recorded events are 30,859 as of June 2009, of which 25,361 occurred in France in the period from 1900 to 2005.

The FACTS database (Failure and ACcidents Technical information System) [17] is managed by TNO Industrial and External Safety Department, and contains information on events which caused (accidents) or could cause (near misses) severe consequences. The information stored in FACTS is often obtained from professional sources, such as official accident reports or from publications in the technical literature, as well as from confidential sources. FACTS contains more than 21,600 records concerning industrial accidents involving hazardous materials.

The MARS (Major Accident Reporting System) [18] database is managed by the Major Accident Hazards Bureau at the European Commission Joint Research Centre in Ispra. The database was established to comply with the obligations of Article 19 of the "Seveso-II" Directive (Directive 96/82/EC) that requires the competent authorities for the application of the Directive to establish a database in order to record and exchange data on the accidents that occurred in the industrial sites falling under the obligations of the Directive. Thus, the database contains reports coming from the competent authorities describing accidents and near misses occurred in "Seveso" plants. Each record is divided in three sections: Report Profile, Short Report and Full Report. The Report Profile contains information to identify the event. In the other two sections, details are reported on the causes of the accidents, the circumstances, the evolution and the consequences, and the responses to major accidents. The Short Report is available to the public, and contains free text fields which allow the quick notification of available information concerning the accident. The Full Report is confidential and contains more detailed information about the accident. It is provided only after that the causes, the evolution and the consequences of the accident are fully understood.

MHIDAS (Major Hazard Incident DAta Service) [9] is a database managed by AEA Technology Ltd. (Warrington, UK) on behalf of the British Health and Safety Executive. The database contains information on more than 7000 accidents that occurred in industrial sites and during the transport of hazardous materials that actually or potentially had off-site impact. The stored data are based mainly on the information available from dailies and are very schematic, concise and organized through keywords. In MHIDAS it is possible to find records from 95 countries, although most of the information comes from USA, UK, Canada, France, Germany and India.

The IChemE database [19] is a product of the Institution of the Chemical Engineers, an international professional membership organization that promotes research activities and knowledge development in all the sectors of chemical engineering, including process safety. The IChemE database contains data from different sources, including the "Loss Prevention Bulletin". The data stored may be searched using specific keywords ("flood" was chosen in the present study). The information stored in the records of the database is often very concise and usually limited details are reported on the installation where the accident took place and on release mechanism and path. No details are reported on structural damage suffered by the units where loss of containment took place.

The NRC (National Response Center) [20] is the sole federal point of reference for reporting information on oil and chemical spills in the USA. The National Response Center receives reports about the release of hazardous substances such as chemical, radiological, biological and etiological discharges into the environment anywhere in the United States. The NRC database contains all the received records. Each file represents a calendar year and contains the data related to incidents which occurred during that year. In the NRC database it is possible to find summaries of the most significant industrial accidents. The data stored are usually short summaries of the event. Data may be accessed with ordinary non-specific software, but no itemized keywords are defined to ease data searching.

2.2. Data extraction

A limited but significant number of accidents reported in accident databases were triggered by natural events, as shown in Table 1 [12]. In the present study, only industrial accidents triggered by flood events are of interest. Thus, criteria were developed to extract data from the database searched. Although the specific features of each database consulted required the development of dedicated queries, some general features of the search performed need to be outlined.

The accidental events extracted from the accident databases consulted have the following features:

Table 2
Data retrieved from the interrogation of industrial accident databases.

Categories of data retrieved
Substances involved
Type of activity
Flood event: type, maximum water depth at site, maximum water velocity at site
Equipment involved: category, geometrical data
Damage: type and extension of damage of involved equipment
Loss of Containment: type, intensity, inventory involved
Accident scenario: events following release, final scenario
Safety barriers: safety barriers present, safety barriers effective
Consequences: extent of damage and life loss

1. A dangerous substance is involved.
2. An industrial activity having a relevant inventory of hazardous substances is involved.
3. The event generated or had the potential to generate an accidental event with off-site consequences (major accident).

In this context, the term dangerous substance refers to chemicals that are classified in and regulated by the European Dangerous Substances Directive (European Council Directive 67/548/EEC [21] and following amendments).

The following equipment items were considered:

- Storage: atmospheric or pressurized storage tanks, warehouses.
- Process: reactors, heat exchangers, columns, separators, others.
- Auxiliary: pipeworks, pumps and compressors.

The categories of equipment items considered were defined on the basis of the results of previous systematic studies concerning the taxonomy of process plants [22–24].

Accidents involving electricity transformers were not considered in the analysis, and neither were accidents related to the damage of single small storage items like drums in civil buildings. The data extraction from the databases aimed at the collection of the data listed in Table 2. As shown in the table, the data extracted and used in the analysis were mainly categorical data, although also numerical data, when available, were retrieved.

3. Results and discussion

3.1. Quality of data

The quality of the data reported in industrial accident databases is usually not homogeneous. In most cases, the difficulty to obtain detailed and clear information from qualified sources may result in an incomplete or not accurate description of the accident. Moreover, often the aim of the accident file is to report data on final consequences, thus neglecting data on structural damage or on the features of the natural event causing the final scenario. A reporting bias towards severe-consequence accidents was also observed in the analyzed databases.

In particular, the information about the type of flood and the water impact modes is frequently not available. In fact, only for a limited number of events the maximum water level and/or the water velocity were reported. With respect to the structural damage of process equipment caused by the flood, in most cases the reference to equipment damage is only expressed in general terms, without specifying which damage modes are leading to loss of containment (LOC). Moreover, the presence of a loss of containment is some times reported without indicating if the leakage is coming from a hole in a pipeline or from the failure in the shell of a storage tank. Consequently it is very difficult to understand the dynamics of the accidents and to assess the extent of the damage suffered by the equipment.

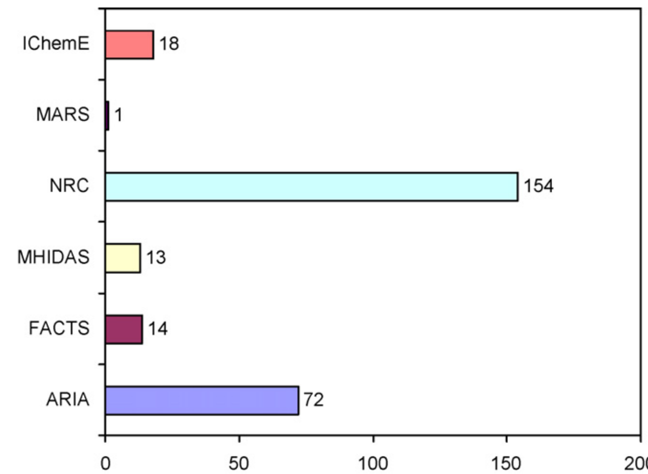

Fig. 1. Sources of the accidental events analyzed in the present study (272 records, 1960–2007).

The consistency and the level of detail of the available data concerning past accidents is an important problem, often hampering the possibility to learn from accidents. In the case of accidents caused by natural events, this issue is even more crucial, since industrial accident databases are often not designed to store and classify information on the natural event that triggered the accident. The development of a specific database for the systematic collection of detailed data on NaTech accidents would be an important step to enhance knowledge and awareness on this category of accidents [12].

3.2. Structural damage and damage modes of equipment items

The criteria defined in Section 2.2 led to the collection of 272 accident records. In the few cases where information on the same accident was available in more than one database, the more complete file was adopted as a reference, and was integrated, where possible, with data coming from the other databases. Fig. 1 shows the original or the main source of the accident data collected and analyzed. Due to the lack of detail in some accident files, sub-sets of accidents were used when necessary in the present analysis, in order to focus the attention on the accident files that report the information of interest.

The first aspect considered in the analysis was the characterization of the flood event that triggered the accident. Fig. 2 presents the data available concerning the severity of the flood event. The figure shows that only in 39 cases quantitative data for water

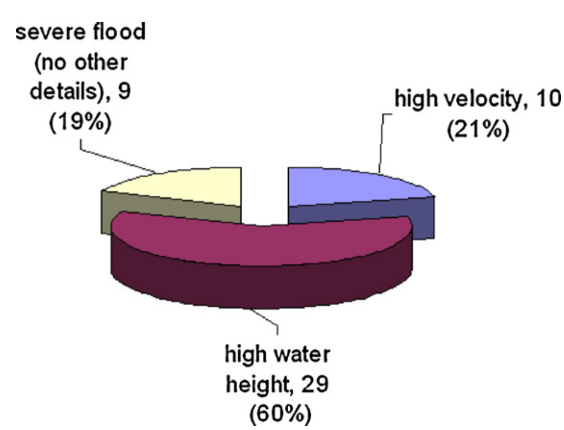

Fig. 2. Characterization of the flood severity based on 48 records with sufficient level of detail (number of events and % distribution).

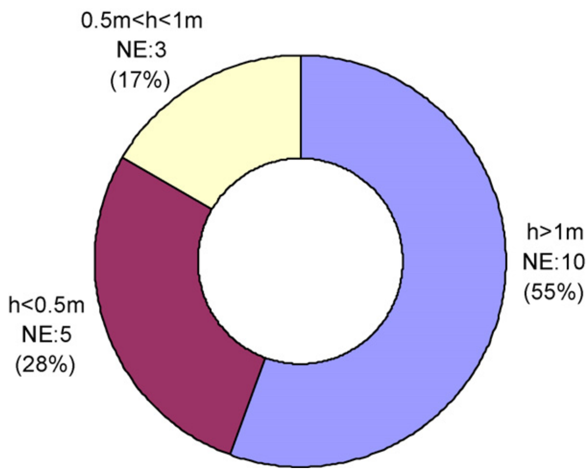

Fig. 3. Classification of 18 NaTech events triggered by floods based on the maximum water height (*h*: maximum water height, m; NE: number of events).

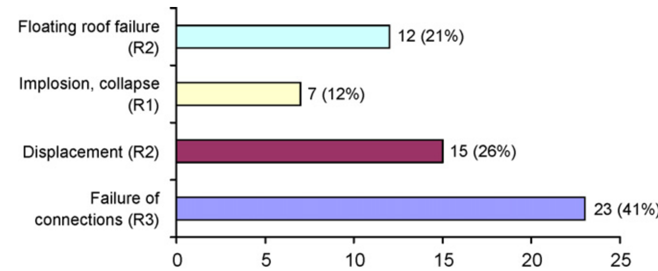

Fig. 5. Available data for categories of structural damage experienced by process equipment items during flood events and associated release category. Results obtained from the analysis of 57 events.

height or water velocity are reported to describe the flood, while for other 9 events only a generic definition ("major severity") is given, but there are no quantitative data that describe the severity of the flood in these events. Only for 18 events it was possible to obtain data on the water height, as shown in Fig. 3. The figure suggests that a water height in excess of 1 m was responsible for the equipment damage in more than 50% of the events considered.

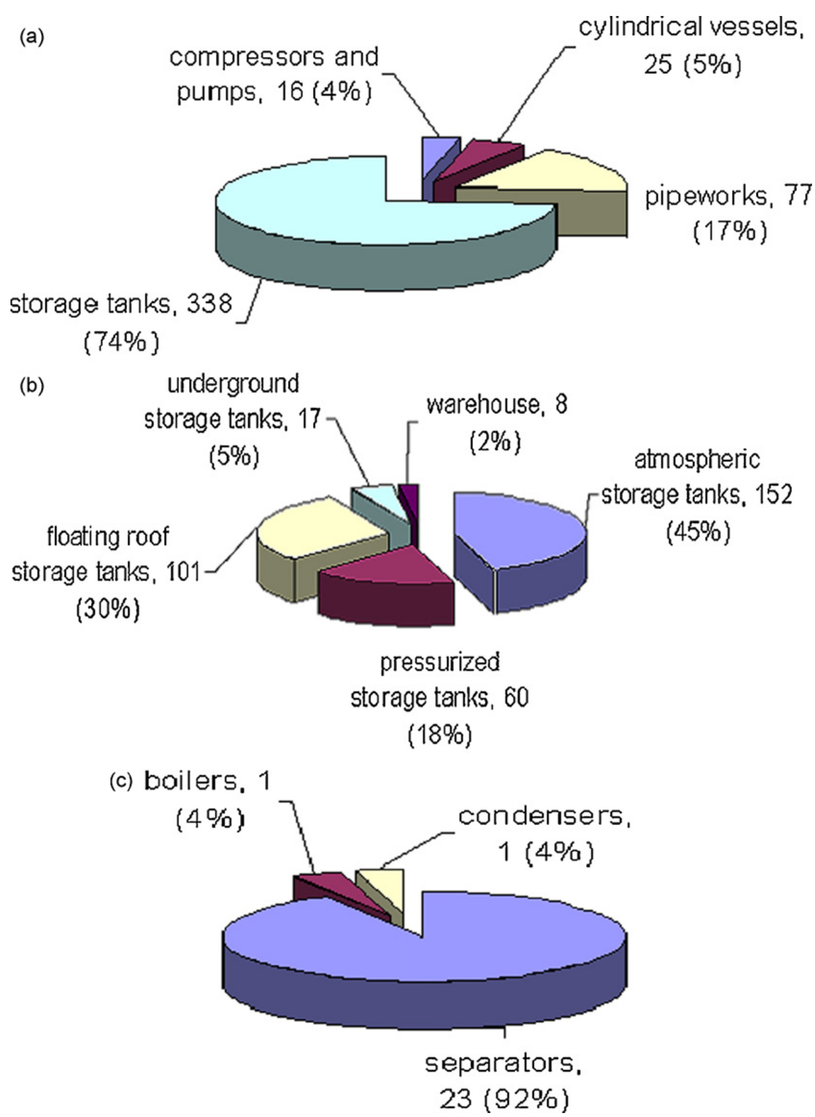

Fig. 4. Categories of equipment items mainly involved in the accidents triggered by flood events: (a) general categories; (b) detail of storage tanks; (c) detail of cylindrical process vessels.

Table 3
Description of structural damage modes experienced by tanks and process equipment during flood events. The release category associated to the damage is also estimated.

Modality of flood impact	Type of structural damage	Release category
Slow submersion	Collapse for instability (catastrophic failure)	R1
	Complete failure of connected piping	R2
	Failure of flanges and/or connections	R3
Moderate-speed wave	Failure of flanges and connections	R3
	Damage of connections due to floating objects	R3
High-speed wave	Impact with/of adjacent vessels	R1
	Roof failure and/or shell rupture	R2
	Complete failure of connected piping	R2
	Failure of flanges and connections	R3

A more detailed analysis of the accident files collected allowed the identification of the equipment categories that are most frequently damaged as a consequence of floods. Fig. 4 reports the results obtained through the statistical analysis of the 272 records available. As shown in Fig. 4(a), storage tanks and pipeworks are the equipment items that were most frequently damaged during flood events while cylindrical vessels, compressors and pumps resulted less affected. Fig. 4(b) which shows the storage-tank category in more detail indicates that atmospheric tanks are by far the tank category most frequently involved in events leading to loss of containment, due to their lower structural resistance. If cylindrical vessels are considered, separators are the equipment item mainly affected by such events (23 records), as shown in Fig. 4(c), while no damage was reported for some equipment categories (e.g. columns) in the analyzed accident files. The apparent high accident frequency involving separators in Fig. 4(c) is likely due to the generic classification adopted which includes in this equipment category a broad variety of equipment items present at a wide range of process plants.

Fig. 5 reports the data available on the damage experienced by equipment items in flood events. The figure indicates that item displacement due to water drag and/or to floating are among the principal causes for loss of containment. The failure of connections is also reported as a further cause for loss of containment. Possibly, also these events are caused by the flood-triggered displacement of plant items caused by the flood event, although no evidence is present in the accident files. Further important causes of loss of containment are the roof failure of floating roof tanks and the collapse of tanks due to water pressure and/or drag.

Although only scarce information is reported on structural damage of equipment items, the available data allow the identification of a limited number of damage modes. These are summarized in Table 3. The intensity and the extent of the release following the damage are seldom described, but sufficient data is available to identify three main release categories:

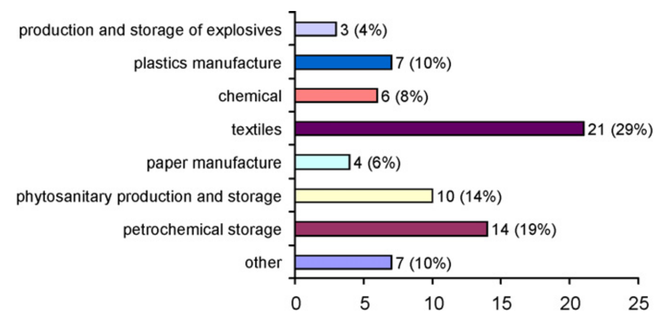

Fig. 6. Industrial activities involved in NaTech accidents triggered by floods based on 72 accident records.

- The instantaneous release of the complete inventory, defined as R1 release category.
- The continuous release of the complete inventory in a limited time lapse due to the full-bore rupture of large diameter connections or due to shell ruptures, defined as R2 release category.
- Minor leaks from the partial rupture of connections or from the full-bore rupture of small diameter pipes, defined as a R3 release category.

As shown in Table 3, the three release categories identified are a consequence of the different impact modes of the floodwaters.

3.3. Substances involved and final scenarios

A number of different industrial activities were involved in flood-triggered NaTech events, ranging from those of the conventional chemical and petrochemical sector to those of the manufacturing sector. Fig. 6 shows the industrial sectors that were affected by floods based on the collected data. According to the accident files analyzed, the chemical and petrochemical industry

Table 4
Dangerous substances and preparations involved in accidents triggered by floods and related hazards based on the general hazard classification defined by the European Directive on dangerous substances [21].

Category	Hazard	Number of accidents
Chlorine	Toxic, dangerous for the environment	3
Oil, diesel fuel and gasoline	Extremely flammable, dangerous for the environment	142
Cyanides	Toxic, dangerous for the environment	5
Propane, butane and LPG	Extremely flammable, dangerous for the environment	12
Explosives	Reacts violently with water	3
Fertilizers	Dangerous for the environment, toxic	11
Acid products	Toxic, dangerous for the environment	7
Calcium carbide	Contact with water liberates extremely flammable gases	3
Soap and detergents	Dangerous for environment	1
Liquid hydrocarbons	Extremely flammable, dangerous for the environment	8
Liquid aromatics	Extremely flammable, dangerous for the environment	8
Oxides	Explosive with or without contact with air, reacts violently with water	5
Ammonia	Toxic, dangerous for the environment	5

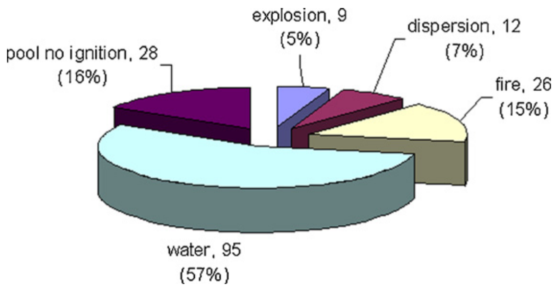

Fig. 7. Accident scenarios initiated by flood events based on 170 accident records.

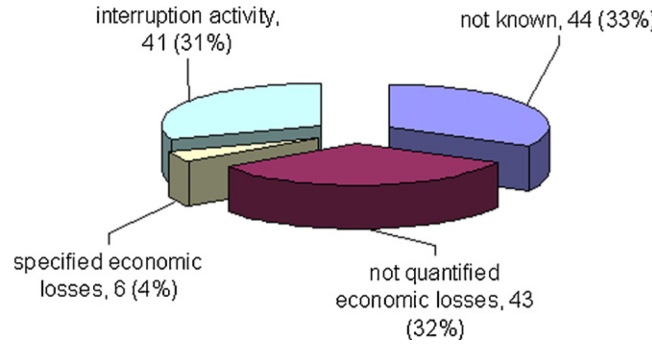

Fig. 8. Economic consequences of flood events based on 134 accident records.

(petrochemical storage, chemical industry, plastics manufacturing) is the most affected industrial sector where about 27% of analyzed accidents were reported, followed by the textile sector. It should be noted that these results are influenced by the number of sites worldwide where hazardous substances [21] are present, as well as by the site vulnerability to flood events.

The analysis of the accident files also allowed the extraction of information on the substance categories involved in the accidents and the related hazards. The results are reported in Table 4 which shows the category of the released substance, the related hazard (according to the classification of general substance hazards defined in the European Council Directive 67/548/EEC [21] and following amendments) and the number of associated accidents. These results are consistent with the conclusions from the previous section on the main equipment items affected by floods. With atmospheric storage tanks being one of the principal equipment items affected by floods, it is not surprising that the substances most frequently involved in such events are gasoline, oil and diesel fuel, which are usually stored in this type of vessels.

Having in mind the information presented in Table 4, it is interesting to analyze the data available on the final scenarios reported in Fig. 7, and those concerning the economic losses induced by the accident, reported in Fig. 8. The accident scenarios listed in Fig. 7 lead in most cases to an extended damage of process equipment that resulted in the disruption of the activity. However, only in six cases the economic losses due to the accidents were specified, thus no clear figure was obtained on this issue from past accident data analysis.

As shown in Fig. 7, the most recurrent final scenario is water contamination. In fact, in several events the released substances stratified on and were spread by the floodwaters, thereby contaminating them and possibly spreading the released materials over wider areas. Consequently, in such events, surface and ground water contamination can also occur.

The present study also indicated that in NaTech accidents triggered by floods the two scenarios typical of the process industry, fire and toxic dispersion, can have specific non-conventional causes due to the presence of wide amounts of water in flood events. If substances reacting with water are involved in an accident in a significant amount, it is possible that flammable or toxic gases are developed, generating fire or dispersion scenarios. Table 5 highlights this problem, reporting six examples of accidents due to the formation of hazardous substances after the reaction of released chemicals with water in warehouses or in storage tanks. As shown

Table 5
Examples of past accidents where violent reactions of chemicals with water took place.

No	Date	Flood target	Substances	Final scenarios
1	1998	Warehouse	Calcium carbide (acetylene after water contact)	Fire
2	04/01/1987	Atmospheric storage tanks	Nitric and sulphuric acids	Toxic gas cloud dispersion
3	25/11/1967	Warehouse	Phosphorus	Fire, Explosion Toxic gas cloud dispersion
4	27/06/1982	Warehouse	Oleum	Explosion, Toxic gas cloud dispersion
5	08/1984	Warehouse	Calcium carbide (acetylene after water contact)	Fire, Explosion
6	28/08/1983	Warehouse	Cyanide salts (hydrogen cyanide after water contact)	Toxic gas cloud dispersion

Table 6
Systematic description of the final scenarios experienced due to the release of hazardous substances in flood events involving industrial facilities (VCE: vapor cloud explosion; LEL: lower explosive limit; UEL: upper explosive limit).

Primary consequence of LOC	Final scenarios following the LOC
Water contamination with significant damage to environment	*Primary scenario*: contamination of floodwater and of surface water. The severity is depending on the quantity of the hazardous substance released, its solubility and its density *Secondary scenario*: contamination of the soil and of underground water due to contaminated floodwater
Fires and explosions	*Pool-fires*: usually due to the ignition of flammable substances spread by floodwaters *Flash-fires or VCE*: generated due to the ignition of released vapors
Toxic dispersion	*Toxic dispersion*: atmospheric dispersion of toxic substances due to a continuous or instantaneous release
Violent reactions with water and secondary scenarios	*Flash-fires and VCE*: when flammable vapors are generated due to reaction with water in a quantity sufficient to form a cloud within LEL and UEL limits *Toxic dispersion*: when relevant quantities of toxic vapors are generated due to reaction with water

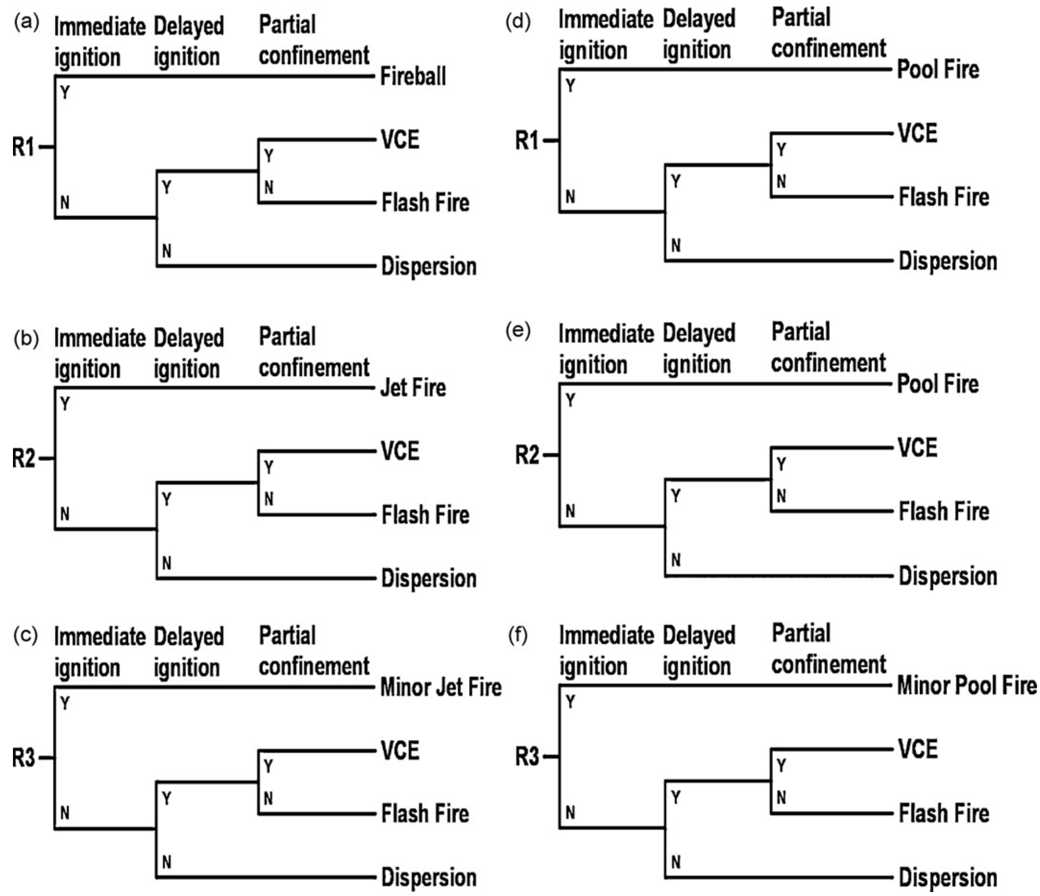

Fig. 9. Post-release event trees derived from past accident analysis for flammable substances and the three release categories defined in the present study. (a) R1, pressurized; (b) R2, pressurized; (c) R3, pressurized; (d) R1, non-pressurized; (e) R2, non-pressurized; (f) R3, non-pressurized. VCE: vapor cloud explosion.

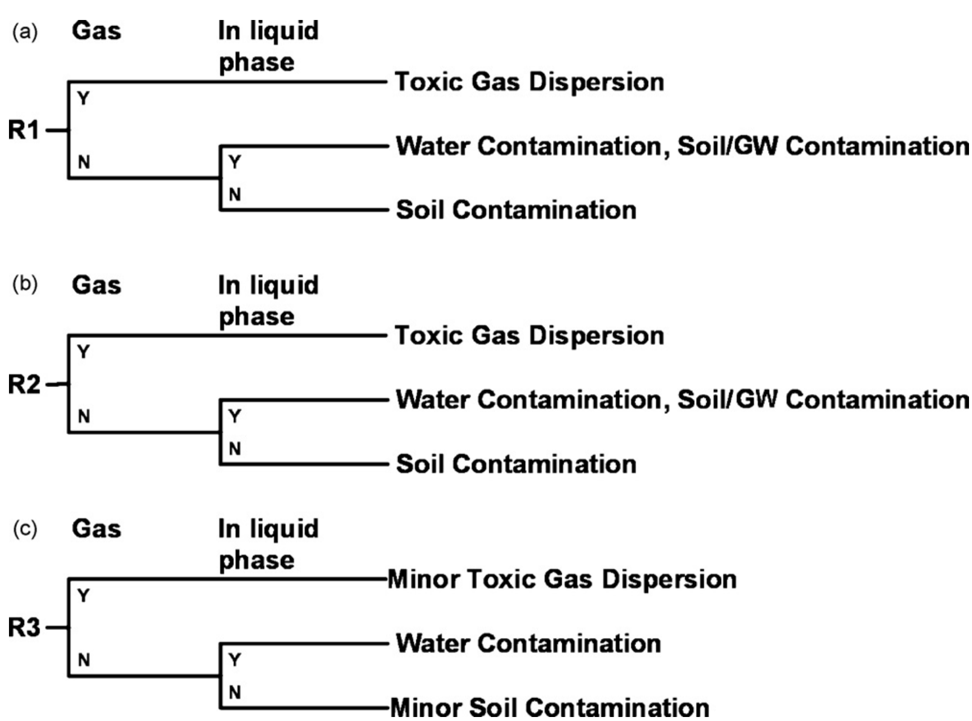

Fig. 10. Post-release event trees for toxic substances in NaTech accidents triggered by floods, built on the basis of past accident analysis. (a) R1 release category; (b) R2 release category; (c) R3 release category. VCE: vapor cloud explosion; In liquid phase: liquid or solid soluble in water; GW: groundwater.

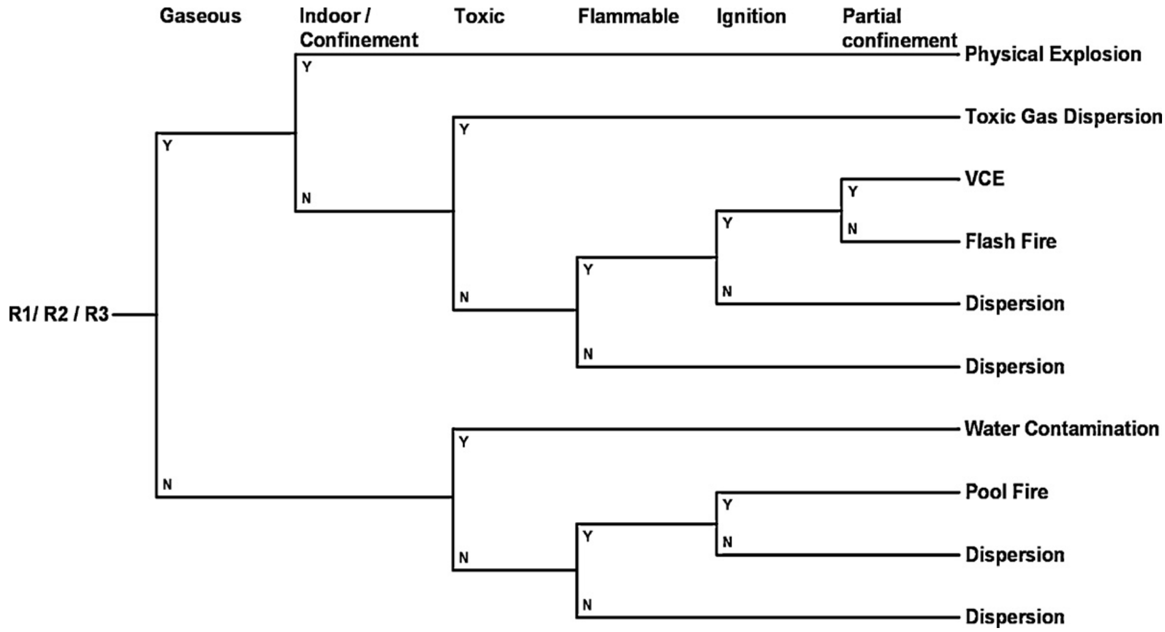

Fig. 11. Post-release event trees for substances reacting with water in NaTech accidents triggered by floods, defined on the basis of past accident analysis. VCE: vapor cloud explosion.

in the table, final consequences of such accidents may be affected by confinement. Despite involving the same substance, accidents 1 and 5 resulted in different final scenarios: an explosion occurred when the presence of confinement hampered the free expansion of the gaseous combustion products in one of the accidents (event 5).

Thus, the analysis of past accidents allowed the identification of the final accident scenarios that should be considered as possible in the case of floods. Table 6 summarizes the primary consequences recorded for LOCs following equipment damage and the final scenarios that may result depending on LOC conditions and substance hazard. As shown in the table, the primary consequences of a LOC are fires, explosions, toxic dispersion and the additional flood-related consequences: water contamination and formation of hazardous substances due to violent reactions of chemicals with water. The final scenarios that were experienced following the LOC are: (i) pool-fires due to the ignition of flammable substances spread by the floodwaters; (ii) flash-fires or VCEs due to the ignition of released vapors; or (iii) toxic dispersion due to a continuous or instantaneous release. When flammable vapors are generated due to reaction with water in a quantity sufficient to form a cloud within explosivity limits, flash-fires and VCEs may occur. A systematic analysis of data in Table 6 allowed the development of post-release event trees. It should be noted that no specific protection or mitigation barriers are present in industrial sites to manage the consequences of releases triggered by floods. On the contrary, flood events usually cause the failure of confinement barriers as catch basins, whose content may be washed out by floodwater. Common cause failures of active safety barriers as sprinklers and water curtains may as well be caused by flooding. Thus, general post-release event trees are mostly influenced by the characteristics of the substance released (physical state, hazard, etc.) and by the presence of ignition sources. Fig. 9 reports the results obtained for the loss of containment of flammable substances. As evident from the figure, post-release event trees are similar to those obtained as a consequence of internal failures, although it should be noted that the catch basin is not effective in preventing the spread of liquid hydrocarbon pools in the case of floods.

If toxic substances are considered, Fig. 10 shows that flood events may result in surface water contamination that may cause both soil and/or ground water contamination. The presence of floodwater has an important effect on the event tree, causing the displacement and the dispersion in the environment of the released substance. Finally, Fig. 11 shows the event tree following the release of substances reacting with water. The event tree shown in the figure is specific of releases triggered by flood events, as highlighted also by the events reported in Table 5.

4. Conclusions

The analysis of past accidents triggered by floods in industrial facilities was carried out. The limited number of available records and mainly the limited information present in the accident files reported in industrial databases hampered the collection of quantitative data on structural damage and on the intensity of loss of containment experienced by equipment items. However, the analysis of the data collected provided an insight into the damage and release modes of equipment items under flood conditions. The analysis of the damage modes allowed the identification of the expected release extent due to different floodwater impact modes. Data on final scenarios highlighted the presence of specific events, as those due to substances reacting with water, and the importance of scenarios involving consequences for the environment. The latter is mainly due to the contamination of the floodwaters with the hazardous substances released. The results obtained allowed the development of substance-specific post-release event trees that may be used in the quantitative assessment of the consequences of accidents triggered by floods.

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