A risk management framework for NaTech scenarios caused by flooding

Gabriele Landucci, Associate Professor,[1,2]

Giacomo Antonioni, Assistant Professor,[3]

Valerio Cozzani, Full Professor, [3]

[1] Institute of Security and Global Affairs, Faculty of Governance and Global Affairs, Leiden University, Wijnhaven Turfmarkt 99 2511 DP Den Haag (the Nethelands)

[2] Civil and Industrial Engineering Department, University of Pisa, Largo Lucio Lazzarino 2, 56126, Pisa (Italy)

[3] Department of Civil, Chemical, Environmental and Materials Engineering – University of Bologna, Via Terracini 28, 40131 Bologna (Italy)

Natural events such as severe floods may impact on industrial facilities leading to major accidents (fires, explosions, toxic dispersion or environment contamination), following damages to structures and equipment. This type of accident is indicated as a "natural-technological" (NaTech) event and often occurred in the past. The present study is aimed at exploring the risk management implications related NaTech events caused by floods impacting on industrial facilities, to support the straightforward identification of critical units and to quantify the effect of safety barriers. A previously developed risk assessment methodology constitutes the basis for the estimation of the risk contribution due to NaTech scenarios induced by severe flooding in industrial areas. The role of flooding protection measures (e.g., attaching vessels to concrete slabs or ground anchors, curbs, embankments, etc.) is discussed with an example of risk-informed decision making, also providing relevant criteria for the appropriate plant design to limit the potential impact of floods on process and storage equipment vulnerability.

Keywords: NaTech scenarios; major accident hazard; hazardous materials release; quantitative risk assessment; flood; equipment vulnerability models, safety barriers.

1. Introduction

Natural events may impact on industrial facilities leading to major accidents (fires, explosions, toxic dispersion or environment contamination), following damages to structures and equipment (Rasmussen 1995, Young et al. 2004). This type of accident is indicated as a "natural-technological" (NaTech) event and occurred in the past, often leading to severe accidental scenarios (Cozzani et al. 2010, Krausmann et al. 2011). Therefore, considering NaTech scenarios in the framework of Quantitative Risk Assessment (QRA) is a critical task (Antonioni et al. 2007, 2009). In fact, the correct assessment of risk associated to site operation and effective emergency planning in adjacent residential areas is a crucial safety aspect (Cruz & Okada 2008).

However, NaTech implementation in conventional QRA studies cannot be easily carried out, mainly due to the relevant uncertainties associated with frequency assessment of accidents triggered by natural events. On one side, the analysis of natural events characteristics and the evaluation of equipment resistance to natural event (vulnerability) require detailed information and dedicated multidisciplinary studies (Salzano et al. 2003, 2009, Necci et al. 2014). On the other, QRA studies usually require the assessment of a high number of scenarios and adopt simplifying assumptions for estimating accidental frequencies (Landucci et al. 2009).

Considering NaTech scenarios triggered by floods, recent studies allowed determining specific fragility models for both atmospheric and pressurized equipment, considering different types of geometries and flooding conditions (Landucci et al. 2012, 2014). These models, based on simplified correlations derived from the application of rigorous mechanical models, allow for a straightforward assessment of equipment damage probability given a flooding scenario and may support the accident frequency estimation.

The present study is aimed at exploring the risk management implications related to the risk caused by floods impacting on industrial facilities, to support the straightforward identification of critical units and to quantify the effect of safety barriers. The previously developed risk assessment methodology constitutes the basis for the estimation of the risk contribution due to NaTech scenarios induced by severe flooding in industrial areas.

The methodology is improved by discussing the role of flooding protection measures (e.g., attaching vessels to concrete slabs or ground anchors, curbs, embankments, etc.) in the final risk evaluation. A reference case study is analysed, based on an actual industrial layout considering different flooding conditions, and discussing the eventual effect of flooding protections.

2. Methodology

2.1 Overview and approach

The methodology for the introduction of NaTech scenarios in Quantitative Risk Assessment was developed in previous studies (Antonioni et al. 2007, 2009) and is summarized in Figure 1. The recent updates to the methodology are briefly discussed in the following.

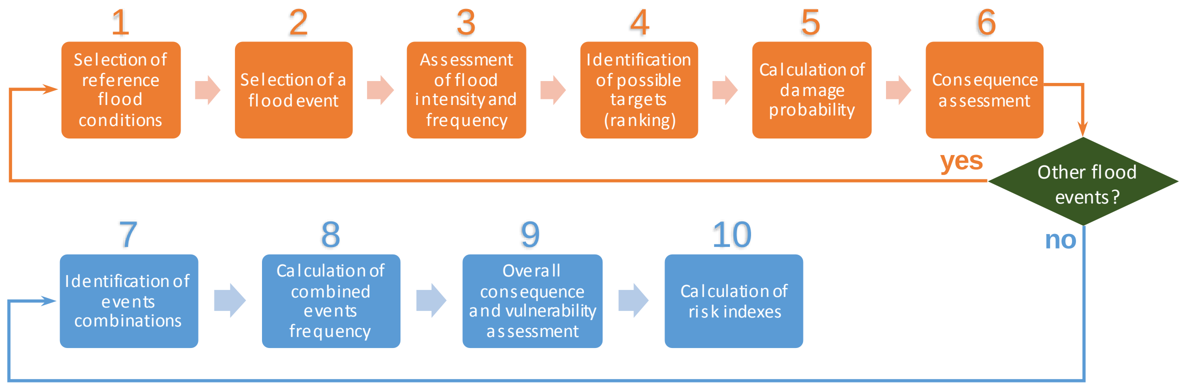

Figure 1. Overview of the methodology adopted for the QRA of NaTech scenarios caused by flood. Adapted from (Antonioni et al. 2007, 2009).

The starting point of the methodology is the identification of reference flood conditions, thus determining the reference scenarios to be considered in the QRA. Each flood event needs to be characterized in terms of frequency and of severity by a sufficiently simple approach, suitable for the use in a risk assessment framework (step 3).

The standard parameter for flood frequency evaluation is the return period (τ), that is given by hydrological studies and is usually available from local competent authorities. The flooding frequency (f_i) can thus be estimated as follows:

$$f_i = \left(\beta_{i+1} - \beta_i\right) / \tau \tag{1}$$

where the β_i represents the probability of having conditions exceeding the β-th percentile of the possible flooding conditions.

Next, an impact vector, whose elements represent the severity of the flood scenario, needs to be defined for each of the reference scenarios selected. Flood severity can be quantified by two parameters (Cruz et al. 2006): water effective depth (h_w) and water speed (v_w). The effective depth should account for the possible effect of protection measures, such as concrete supports higher than the ground level to which the vessel saddles are fixed. Simplified hazard ranking criteria based on inventory and physical state of hazardous substances may be used to identify critical equipment items that should be included in the analysis (step 4) (Antonioni et al. 2009).

The application of equipment vulnerability models is then needed to assess the equipment damage probability (step 5). These models are discussed in the Section 2.2. Consequence assessment of the single scenarios triggered by the natural event (step 6) may be carried out by using conventional models (Van DenBosh & Weterings 2005).

2.2 Equipment and utility vulnerability models

Data on equipment failure as a consequence of floods are scarce in the literature. Antonioni et al. (2009) report a general correlation that allows for a rough estimate of the failure probability. More recently, Landucci et al. have developed a simplified approach to evaluate the failure probability of vertical atmospheric tanks for liquid storage (Landucci et al. 2012) and of horizontal atmospheric or pressurized vessels (Landucci et al. 2014). The approach is based on the evaluation of vessel mechanical integrity under the action of the flood, which results in both a "static" external pressure component, due to the depth of the flooding (h_w), and in a "dynamic" external pressure component, due to the flood water velocity (v_w) and to the associated drag force. It is worth mentioning that the failure following the mechanical impact by objects transported in the water is not considered in the model.

In the case of atmospheric vertical vessels, it was evidenced that the vessel filling level is the more relevant parameter for the evaluation of the equipment integrity and of the failure probability. Thus, a critical filling level (CFL) was defined for each equipment item involved in a specified flooding event of given intensity (e.g., having assigned flood water speed and depth), as the liquid level below which the failure for instability is possible.

The CFL for atmospheric vertical vessel is evaluated as follows:

$$CFL = \left(\frac{\rho_w k_w}{2} v_w^2 + \rho_w g h_w - P_{cr} \right) \Big/ \rho_f g H \tag{2}$$

where ρ_w = flood water density (set equal to 1100 kg/m^3); k_w = hydrodynamic coefficient (1.8); g = gravity acceleration (9.81 m/s^2); ρ_f = stored liquid density (kg/m^3); and H = vessel height (m). P_{cr} is the instability critical pressure of the vessel and depends only on the vessel geometry and on the construction material; thus, it is independent from the loading conditions. P_{cr} may be calculated by the following rigorous expression (Timoshenko and Gere 1961):

$$P_{cr} = \frac{2\,E\,t}{D}\left\{\frac{1}{\left((q^2-1)\left[1+\left(\frac{2qH}{\pi D}\right)^2\right]^2\right)} + \frac{t^2}{3(1-\nu^2)D^2}\left[q^2-1+\frac{2q^2-1-\nu}{\left(\frac{2qH}{\pi D}\right)^2-1}\right]\right\}; \quad q \geq \left(\frac{\pi}{2}\right)\left(\frac{D}{H}\right) \quad q \geq 2 \tag{3}$$

in which E and ν are respectively the elastic modulus and Poisson's ratio of the construction material, t and D the vessel thickness and diameter and q is an integer number which minimizes P_{cr}.

In order to obtain a straightforward evaluation of the critical pressure, Landucci et al. (2012) developed a simplified correlation for the critical pressure for the typical atmospheric tanks adopted in refineries tank farms:

$$P_{cr} = J_1 C + J_2 \tag{4}$$

where C = vessel capacity (m^3); J_1 = -0.199 Pa/m^3; and J2 = 6950 Pa.

On the basis of the CFL, the vessels damage probability (Ψ) is derived by the ratio between the "unsafe" operative conditions with respect to all the possible operative conditions, represented by the filling level ϕ:

$$\Psi = (CFL - \phi_{\min})/(\phi_{\max} - \phi_{\min}) \tag{5}$$

In the present approach, for the sake of simplicity, a linear distribution of possible operative filling levels between ϕ_{min} (=1%) and ϕ_{max} (=75%) is assumed in the definition of Ψ for atmospheric vertical vessels. Nevertheless, more specific data, when available, may be introduced in Eq. (5) to obtain an equipment-specific vulnerability model.

This approach was extended by Landucci et al. (2014) in order to obtain the fragility model for horizontal cylindrical vessels, both atmospheric and pressurized. In this case, the possibility of having a rupture following the flood event is related to the resistance of the connection between the vessel framework and the ground. In order to estimate the failure probability of a horizontal vessel due to flood impact, two threshold parameters were used as a reference: the critical water velocity, $v_{w,c}$ and the CFL for horizontal vessels; the latter can be calculated with the following simplified correlation:

$$CFL = (\rho_{ref} \cdot A)/(\rho_l - \rho_v)\cdot(h_w - h_c) + (\rho_{ref} \cdot B - \rho_v)/(\rho_l - \rho_v) \tag{6}$$

where ρ_{ref} = 1000 kg/m^3, ρ_l and ρ_v are respectively the stored liquid and vapour densities, h_c is the height of concrete basement (= 0.25 m in the present study), A and B are parameters summarized in Table 1. Next, Eq. (5) is applied for the estimation of the vessel vulnerability adopting ϕ_{min} (=1%) and ϕ_{max} (=90%) in this case.

The parameter $v_{w,c}$ represents a threshold condition for velocity over which the drag force generated by flood water is sufficient to cause the failure of the bolt connection for a given floodwater height. The simplified correlations for the estimation of $v_{w,c}$ is reported below, in which the parameters, h_{min}, E and F are reported in Table 1:

$$v_{w,c} = E \cdot (h_w - h_c - h_{\min})^F \tag{7}$$

If flood water speed is higher than $v_{w,c}$, the failure probability is unitary (Ψ = 100%), without adopting the criterion based on the CFL (e.g. by applying Eq. (5)).

Table 1. Coefficients of the simplified correlation for the estimation of horizontal vessels critical filling level and water critical velocity. Adapted from (Landucci et al. 2014).

Correlation coefficient	**Equation**	**Definition**
A	6	A = 1.339×$D^{-0.989}$, D = tank diameter (m)
B	6	B = -1.2 $(W_t-374.4)^{-0.107}$, W_t = vessel tare weight (ton)
E	7	E = 5.497×$L^{-0.692}$, L = vessel length (m)
F	7	F = -0.06 ln(L/D)-0.375
h_{min}	7	Minimum flooding height able to wet the vessel surface; h_{min} = λ - D/2
λ	-	Saddle height parameter which indicates the vessel axis height respect to the ground anchorage point and function of the vessel capacity: λ = 0.98 m (Small capacity) = 0.98–1.38 m (Medium capacity) = 1.38-1.98 m (Large capacity)

2.3 Implementation of NaTech scenarios triggered by floods in QRA

2.3.1 Consequence analysis of credible scenarios

The main assumptions introduced for the consequence assessment of NaTech scenarios triggered by floods are summarized in the following.

For pressurized vessel, flooding may cause vessel displacement, while vessel rupture due the external pressure or wave impact is not credible due to the high thickness of vessel shell required to resist to the typical design pressures. Vessel displacement is likely to cause the rupture of pipe connections and nozzle flanges. Thus, the release event was selected as the more severe between: (1) the release of the entire content of the vessel considering a full-bore rupture of pipe connections; and (2) the release in 10 min of the entire inventory. Moreover, when a dispersion model is applied for the calculation of toxic effects or of flash-fire thresholds, values in the range of 0.1 to 1mm should be selected for the roughness length (Irwin 1967). These values are typical of sea surface (Chamberlain 1983) and are suitable for dispersions over the water surface in general.

For atmospheric tanks, a flood can affect the integrity of the tank shell due to its limited thickness. Hence, a catastrophic release can be assumed, and the resulting liquid pool can be considered unconfined. In fact, flood water level must be higher than a possible catch basin wall in order to affect the tank.

On the basis of the above defined release scenarios and source terms, Event Tree Analysis (ETA) was applied to determine the possible final outcomes according to conventional procedures as those of the "Purple Book" (Uijt de Haag & Ale 1999). Due to the nature of the substances released in the case-study, scenarios due to chemical interactions between the substance released and the flood water were not considered in the assessment. Physical effects associated to the final outcomes of the release scenarios were calculated by literature models (Van DenBosh & Weterings 2005).

2.3.2 Risk recomposition

Steps 7-10 were carried out following the NaTech risk assessment framework introduced in a previous study (Antonioni et al. 2009) based on the methodology developed by Cozzani et al. (2005, 2014) for domino effect risk assessment.

After the determination of equipment failure probabilities, the identification of credible combinations of events (step 7) and the evaluation of the resultant frequency (step 8) need to be carried out. The main is assumption is that, given a facility having n target equipment affected by a flooding scenario, the damage of any target is independent from a probabilistic point of view. Thus, the damage probability of a unit during the flooding event (namely Ψ and evaluated according to the methods described in Section 2.2) may be considered independent from the possible contemporary damage of n-1 other units. However, more than one unit may be damaged simultaneously during the flooding event. A single accidental scenario induced by flooding may thus be defined as an event involving the contemporary damage of k of n units resulting in k final outcomes, with k ranging between 1 and n.

The number of flooding induced scenarios involving k different final outcomes may be calculated as follows:

$$N_k = \begin{pmatrix} k \\ n \end{pmatrix} = \frac{n!}{(n-k)!k!} \qquad (8)$$

The total number of different overall scenarios that may be generated by a single flooding condition, N_f, may be calculated as follows:

$$N_f = \sum_{k=1}^{n} \begin{pmatrix} n \\ k \end{pmatrix} = 2^n - 1 \qquad (9)$$

If a numerical index (1 to n) is assigned to each of the n events that may be triggered by flooding, a single overall NaTech scenario may thus be identified as a vector ($\mathbf{J}^k{}_m = [\gamma_1, \gamma_k]$), whose elements ($\gamma_j$ ($j = 1, \ldots, k$)) are the indexes of the k rupture events that take place during the flooding scenario. The subscript m of vector **J** indicates that the overall NaTech scenario is the m-th ($m = 1,\ldots,N_k$) combination of k events.

The probability of a single overall NaTech scenario involving the contemporary damage of k units resulting in k events due to flooding, identified by the vector $\mathbf{J}^k{}_m$, may be calculated as follows:

$$P_f^{(k,m)} = \prod_{i=1}^{n} \left[1 - \psi + \delta\left(i, \mathbf{J}_m^k\right)(2\psi - 1)\right] \qquad (10)$$

where the function $\delta(i,\mathbf{J}^k{}_m)$ equals 1 if the i-th event triggered by flooding belongs to the vector $\mathbf{J}^k{}_m$, 0 if not. Eq. (10) is the algebraic expression obtained from the union of the probabilities of the k events belonging to the m-th combination, calculated considering as independent the flooding induced events. The expected frequency of the m-th overall flooding scenario involving k simultaneous equipment damages, $f_f^{(k,m)}$, may thus be calculated as:

$$f_f^{(k,m)} = f_i \cdot P_f^{(k,m)} \qquad (11)$$

where f_i is the overall expected frequency of the flooding scenario affecting the industrial facility, evaluated on the basis of Eq. (1).

In order to limit the number of combinations considered for the risk assessment, a frequency cut-off value was assumed. Combinations of events having frequency of occurrence lower than cut-off value of 10^{-10} 1/y were excluded from the analysis, since not credible.

The consequences of accident combinations triggered by flooding need then to be assessed (step 9 in Figure 1). The consequences of a generic (k,m) scenario triggered by flooding cannot be assessed directly using conventional models for consequence analysis, that assume single point-source scenarios. The same approach adopted for domino effect escalation scenarios was therefore applied (Cozzani et al. 2005). In particular, the overall consequences of global scenario triggered by flooding (e.g., due to the possible multiple failure of the equipment in the facility) is evaluated as the sum of the death probabilities due to all the scenarios involved in the flooding event, with an upper limit of 1:

$$V_f^{(k,m)} = \min\left[\sum_{i=1}^{m} V_{f,i};1\right] \qquad (12)$$

where $V_{f,i}$ are the vulnerabilities calculated for the (k,m) scenario triggered by the flooding conditions under analysis. The approach based on Eq. (12), tough simplified, was found to be acceptable and not over-conservative in the framework of domino effect implementation in QRA analysis (Cozzani et al. 2005, 2014).

Finally, step 10 of the methodology (see Figure 1) consists in the risk recomposition based on the obtained frequency and consequences results and was carried out according well-known procedures (Uijt de Haag & Ale 1999).

3. Definition of the case study

The case-study selected for the application of the methodology and especially of the new fragility correlations described in Section 2.2 was derived from an actual industrial site. The site is located in a flood-prone zone and for which a detailed flood risk assessment, previously performed, was used for the evaluation of the frequency and of the severity of the external flood events in the framework of a quantitative area risk assessment (QARA) project (CPA 2014).

The study allowed the estimation of the expected water height (h_w) and speed (v_w) distributions on a discrete grid over the site layout due to three reference flood hydrographs (namely the 30th, 60th and 90th percentile of the worst-case flood). An example of the results used in the presented study is reported in Figure 2, where the 90th percentile of the water height distribution (hence, $\beta=0.9$) over the area of interest is shown. Therefore, the values reported in the figure are expected to be exceeded with a probability of 0.1 (= 1- β).

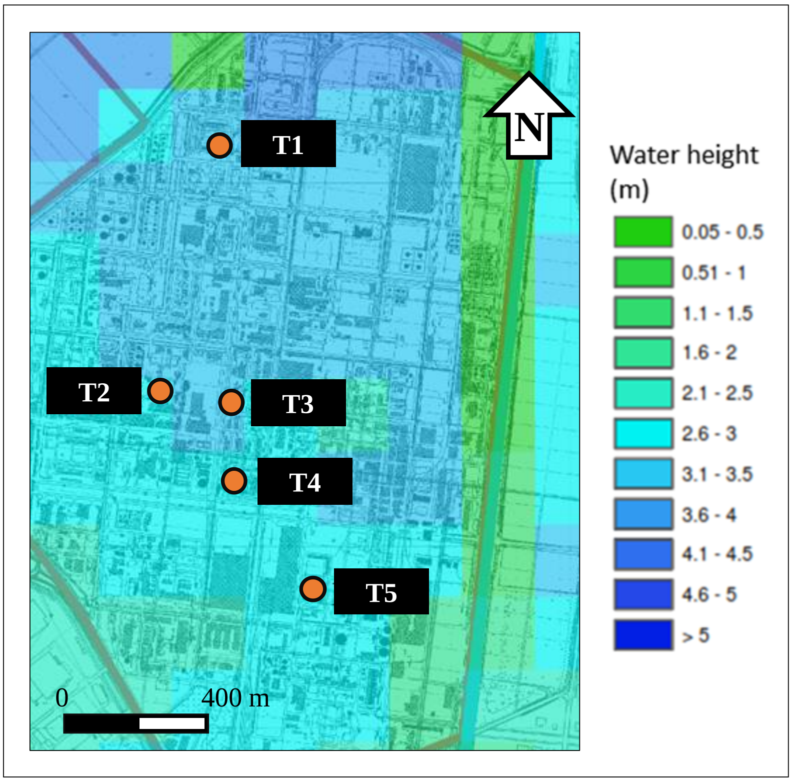

Figure 2. Example of the results of available hydrological study and location of the tanks within the industrial site.

The initiating flood wave in the river was assumed to have a return period $\tau = 200$ y, thus the simulated flooding events, considered as reference for the case study, have a frequency of 3.0×10^{-3}, 1.5×10^{-3} and 5.0×10^{-4} y^{-1} respectively for the 30th, 60th and 90th percentiles. It is worth to mention that a slight modification to Eq. (1) was introduced increasing the probability of 30th percentile conditions, in order to account for lower severity conditions.

Figure 2 also shows an overview of the industrial area, highlighting the position of five tanks selected for the case study definition. The tanks were selected in order to evaluate the effect of flooding conditions on different tanks typologies, featuring different stored substances. The main features of the selected tanks, which are required for the calculation of their damage probability and for assessing the consequences due to a loss of containment caused by the effects of flooding impact, are reported in Table 3.

Table 3. Main features of the tanks considered in the case study.

ID tank	**T1**	**T2**	**T3**	**T4**	**T5**
Type	Horizontal	Vertical	Vertical	Horizontal	Vertical[a]
Substance	Liquid fuels	LPG	Hexane	Hexane	Ammonia
P (kPag)	50	1550	0	50	0.9÷3.5
Tank features	Nitrogen blanketing	-	Nitrogen blanketing	Nitrogen blanketing	Double containment
L/ H (m)	13.6	4	9	10	22
D (m)	3.2	1.5	2	3	31
W_t *(kg)*	25700	3550	10650	17750	n.r.[a]
Φ *(mm)*	75	50	50	80	150

[a] not reported, not relevant for calculation of Ψ

For the calculation of societal risk, a uniform population density was assumed in the industrial area. In particular, according to the indications reported in the "Green Book" (Van Den Bosh et al. 1989), an average of 40 persons per hectare was assumed, since this is the typical value for industrial areas during working activities.

For the sake of comparison, the study was carried out also considering the presence of properly designed flooding protection measures, which may relevantly decrease the level of risk. A tank can be mounted on higher pedestals or providing curbs (e.g., increasing the term h_c in Table 1), or it can be anchored by attaching it to concrete slabs heavy enough to resist the force of flood waters or by running straps over it and attaching them to ground anchors (Kopytko & Perkins 2011).

In the present study, it is assumed that those measures provide a completely efficient protection and equipment are totally secured against flooding events. Thus, the same risk study was performed without NaTech scenarios, only assuming conventional process failures in the mitigated case. The same risk sources adopted in the NaTech case study were considered and results were obtained in the framework of a dedicated QRA project (CPA 2014).

4. Results

4.1 Frequency assessment

According to the methodology described in Section 2, the estimation of damage probability and frequency of flooding induced scenarios were the critical steps to support the risk assessment study. The flooding conditions from the QARA project (CPA 2014) were first adopted to determine the flooding parameters h_w and v_w for each tank and associated utilities, based on the location in the area. Table 4 summarizes the flooding parameters in correspondence of 30th, 60th and 90th percentile of the worst-case flood for each considered tank.

On the basis of the tanks and utilities features summarized in Table 3, the probability of failure Ψ was estimated for each (h_w,v_w) combination, according to the procedure described in Section 2.2. The results are reported in Table 4 together with an indication of the possible damage mode, e.g. due to slow submersion (S) or wave impact (I). In the first case, the hydrostatic load due to flood water depth prevails, while in the second case the drag effect associated to the wave impact is more relevant.

Then, from the single Ψ values, the probability of the relevant combinations of final outcomes were determined according to Eq. (10). The frequency values of the combinations were then obtained applying Eq. (11). In particular, 31 possible combinations were determined (i.e. 2^5 -1).

Table 5 reports the total frequency estimated for the most relevant combinations, for which an ID is associated, and the involved tanks are indicated.

Table 4. Determination of tanks probability of failure given the flooding conditions. S = Slow submersion; I = wave impact.

ID tank	Parameters	Results		
T1	*Percentile*	30th	60th	90th
	h_w *(m)*	1.8	2.8	3.3
	v_w *(m/s)*	0.25	0.75	1.3
	ψ *%*	23.2	100	100
	Damage mode	S	I	I
T2	*Percentile*	30th	60th	90th
	h_w *(m)*	1.8	1.8	2.8
	v_w *(m/s)*	0.25	0.75	1.3
	ψ *%*	13.3	26.0	33.3
	Damage mode	S	S	S
T3	*Percentile*	30th	60th	90th
	h_w *(m)*	2.3	2.8	3.3
	v_w *(m/s)*	0.25	0.75	1.3
	ψ *%*	33.4	44.4	56.6
	Damage mode	S	S	S
T4	*Percentile*	30th	60th	90th
	h_w *(m)*	1.8	1.8	2.8
	v_w *(m/s)*	0.75	1.3	1.3
	ψ *%*	63.6	100	100
	Damage mode	S	S	I
T5	*Percentile*	30th	60th	90th
	h_w *(m)*	1.8	1.8	2.8
	v_w *(m/s)*	0.75	0.75	1.3
	ψ *%*	2.20	2.20	6.58
	Damage mode	S	S	S

Table 5. Overall frequencies (f_f) of NaTech scenarios combinations.

ID combination	Damaged tanks	*Frequency* f_f (y^{-1})
A	T1, T4	9.89×10^{-4}
B	T4	8.28×10^{-4}
C	T1, T4, T3	7.84×10^{-4}
D	T4, T3	4.15×10^{-4}
E	T1, T2, T4	3.18×10^{-4}
F	T1, T2, T4, T3	2.77×10^{-4}
G	T3	2.38×10^{-4}
H	T1	1.43×10^{-4}
I	T2, T4	1.27×10^{-4}

4.2 Consequence and vulnerability assessment

The consequences of each final outcome due to the damage of each tank have been assessed by means of conventional models (Van Den Bosh & Weterings 2005). The reference incidental scenario considered, was the release from the largest connected pipe, whose diameter (namely, Φ) is reported in Table 3. The consequences of these scenarios were already assessed for the preparation of safety report of the industrial facility, as prescribed by SEVESO Directive 2012/18/EU (EU 2012). Thus, for the sake of comparison and for confidential reasons, the same scenarios were considered even in the assessment of risk induced by NaTech events. Finally, vulnerabilities (e.g., probability of death) due to single final scenarios were combined according to Eq. (12).

4.3 Risk assessment

In order to show and evaluate the risk contribution associated to NaTech scenarios, the Local Specific Individual Risk (LSIR) was calculated for the area of interest in the case study. Figure 3 shows the LSIR evaluated on the basis of the same consequences and adopting the frequencies evaluated in Section 4.1 for the 31 overall NaTech scenarios.

As shown in Figure 3, a relevant risk profile is obtained for the industrial facility by introducing the contribution of NaTech scenarios. The average LSIR value over the area is about 1.4×10^{-5} y^{-1} and, depending on the location, LSIR is between 10^{-4} and 10^{-3} y^{-1}, especially close to the location of tank T1.

When introducing flooding protection measures, the maximum risk reduction that can be achieved was evaluated performing a conventional QRA study, e.g. without introducing NaTech scenarios and assuming ideal flooding protection measures. The result of conventional QRA are shown in Figure 4.

In the case of mitigated scenarios, the average risk profile of the facility is reduced by at least one order of magnitude (e.g., from 1.4×10^{-5} to 4.3×10^{-6} y^{-1}) and, depending on different locations, it can be reduced by a factor 1000. In particular, for tank T5 the peak risk is reduced from about 1×10^{-6} to 1×10^{-9} y^{-1}.

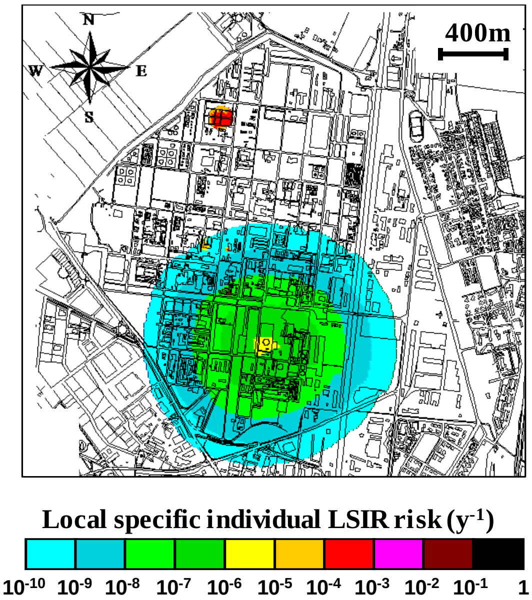

Figure 3. LSIR distribution in the industrial site considering NaTech scenarios caused by flooding.

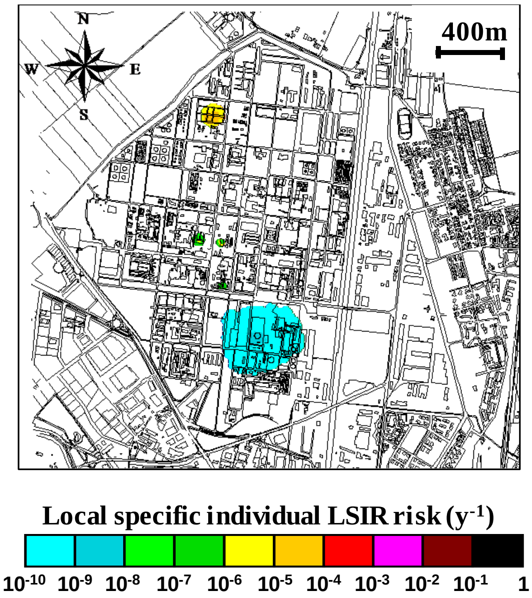

Figure 4. LSIR distribution in the industrial site without considering NaTech scenarios: effect of flooding protection systems.

Moreover, also impact areas (i.e., areas where LSIR is larger than a threshold value) are relevantly increased introducing NaTech scenarios, as can be seen from the comparison of Figure 3 and 4.

The same risk decrement achievable with effective flooding protection systems was also quantified in terms of societal risk results. Potential Life Loss (PLL) per thousand years (Lees 1996) decreases from 9.3 in case of NaTech scenarios consideration to 0.46, in case of conventional risk assessment. This is due to the effect of frequency decrement, since failure of equipment is only induced by random ruptures without NaTech events, but also due to the decrement in fatalities. In fact, NaTech events induce combinations of simultaneous scenarios leading to multiple fatalities.

5. Discussion

The analysis of the case study demonstrated that a high impact on the risk profile of industrial facilities storing and processing hazardous materials may be associated to NaTech scenarios caused by flood events. Since the industrial area is located in a flood prone area, the considered flooding conditions were of relevant severity. This resulted in high values of vessel failure probabilities, that were estimated through the use of novel fragility models (Landucci et al. 2012, 2014) as detailed in Section 4.1. Consequently, rather high values of accident frequencies were estimated, even due to the considered high return period for worst case flooding conditions (e.g., $\tau = 200$ y). This is due to the fact that, in flood-prone zones, flooding frequencies may reach values that are orders of magnitude higher with respect to those related to component failures due to internal causes (Uijt de Haag & Ale 1999), such as mechanical failure, corrosion, erosion, rupture induced by vibrations, etc.

It is worth to mention that the effect of utility malfunctions was not explicitly considered in the present study. However, lack of cooling water, inserting systems, instrument air, emergency generators, refrigeration units, may strongly affect the operation of the facility, leading to cascading events even if equipment are not directly damaged by the flooding.

A conventional procedure was adopted for the consequence assessment. However, the impact of scenarios induced by flooding may be different with respect to the one estimated in common QRA studies. In fact, pool spreading on water surface or possible interaction among water and released chemicals were neglected in the present sample application and may be a relevant issue to improve the risk assessment caused by NaTech triggered by flooding.

What clearly appears from the analysis of the case study is that risk assessment may drive the design of the facilities located in flood-prone areas. In fact, a risk-based approach might be suggested for the design of supports and anchorage of safety-critical units, as those storing or processing flammable or toxic liquefied gases under pressure to achieve relevant risk reduction, such as in the case study. However, a straightforward approach was adopted to consider safety barriers, thus with unitary availability and efficiency. In order to achieve a more detailed evaluation of risk, performance data of flooding protection measures should be analysed such as in the case of protection against cascading events triggered by fire and explosions (see (Landucci et al. 2015) for more details).

Finally, it is worth to remark that the protection design should take into account both parameters related to the credible flooding scenarios and the resistance of the vessel.

6. Conclusions

A methodology for the assessment of risk contribution associated to NaTech scenarios triggered by floods was presented. The methodology was based on the implementation of equipment vulnerability models to calculate the failure probability of vertical, horizontal cylindrical vessels and their utilities as a function of flood severity. The application to a case-study confirmed that NaTech scenarios caused by floods may have an important influence on industrial risk due to major accidents involving of hazardous substances. The methodology also allowed the quantitative assessment of mitigation barriers in the prevention of NaTech scenarios triggered by floods, indicating the importance of an appropriate design of the vessel supports and basements to limit the potential impact of floods on process and storage equipment.

7. References

Antonioni, G., Spadoni, G. & Cozzani, V. 2007. A methodology for the quantitative risk assessment of major accidents triggered by seismic events. *J. Hazardous Materials* 147:48–59.

Antonioni, G., Bonvicini, S., Spadoni, G. & Cozzani, V. 2009. Development of a framework for the risk assessment of Na-Tech accidental events. *Reliability Engineering and System Safety* 94:1442–1450.

Chamberlain, AC. 1983. Roughness length of sea, sand, and snow. *Boundary-Layer Meteorology* 25(4):405-409.

Cozzani, V., Gubinelli, G., Antonioni, G., Spadoni, G., Zanelli, S., 2005. The assessment of risk caused by domino effect in quantitative area risk analysis. *J. Hazardous Materials* 127:14-30.

Cozzani, V., Campedel, M., Renni, E. & Krausmann, E. 2010. Industrial accidents triggered by flood events: Analysis of past accidents. *J. Hazardous Materials* 175:501–509.

Cozzani, V., Antonioni, G., Landucci, G., Tugnoli, A., Bonvicini, S. & Spadoni, G. 2014. Quantitative assessment of domino and NaTech scenarios in complex industrial areas. *J. Loss Prevention in the Process Industries* 28:10-22.

CPA (Civil Protection Agency of Emilia-Romagna). 2014. *Studio di sicurezza integrato d'area del polo chimico di Ferrara.* Final report (classified). In Italian.

Cruz, A,M. & Okada N. 2008. Consideration of natural hazards in the design and risk management of industrial facilities. *Natural Hazards* 44:213–227.

EU (European Union). 2012. Council Directive 18/2012/EU of 4 of July 2012 on the control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC. OJ L 197/1.

Irwin, JS. 1967. A theoretical variation of the wind profile power-law exponent as a function of surface roughness and stability. *Atmospheric Environment* 13(1):191-194.

Kopytko, N. & Perkins, J. Climate change, nuclear power, and the adaptation–mitigation dilemma. *Energy Policy* 39(1):318-333.

Krausmann, E., Cozzani, V., Salzano, E. & Renni, E. 2011. Industrial accidents triggered by natural hazards: an emerging risk issue. *Natural Hazards Earth System Science* 11:921–929.

Landucci, G., Gubinelli, G., Antonioni, G., Cozzani, V. 2009. The assessment of the damage probability of storage tanks in domino events triggered by fire. *Accident Analysis and Prevention* 41:1206-1215.

Landucci, G., Antonioni, G., Tugnoli, A. & Cozzani, V. 2012. Release of hazardous substances in flood events: damage model for atmospheric storage tanks. *Reliability Engineering and System Safety* 106:200-216.

Landucci, G., Necci, A., Antonioni, G., Tugnoli, A. & Cozzani V. 2014. Release of hazardous substances in flood events: damage model for horizontal cylindrical vessels. *Reliability Engineering and System Safety* 132:125-145.

Landucci, G., Argenti, F., Tugnoli, A., Cozzani, V., 2015. Quantitative assessment of safety barrier performance in the prevention of domino scenarios triggered by fire. *Reliability Engineering and System Safety* 143, 30–43.

Lees, F.P. 1996. *Loss Prevention in the Process Industries*. Oxford (UK): Butterworth-Heinemann.

Necci, A., Argenti, F., Landucci, G. & Cozzani, V. 2014. Accident scenarios triggered by lightning strike on atmospheric storage tanks. *Reliability Engineering and System Safety* 127:30-46.

Rasmussen, K. 1995. Natural events and accidents with hazardous materials. *J. Hazardous Materials* 40:43–54.

Salzano, E., Iervolino, I. & Fabbrocino, G. 2003. Seismic risk of atmospheric storage tanks in the framework of quantitative risk analysis. . *Loss Prevention in the Process Industries* 16:403–409.

Salzano, E., Garcia Agreda, A., Di Carluccio, A. & Fabbrocino, G. 2009. Risk assessment and early warning systems for industrial facilities in seismic zones. *Reliability Engineering and System Safety* 94:1577–1584.

Timoshenko, S. & Gere, J. 1961. *Theory of elastic stability*. 2nd ed. New York: McGraw-Hill.

Uijt de Haag, P.A.M. & Ale, B.J.M. 1999. *Guidelines for quantitative risk assessment (Purple Book).* The Hague: Committee for the Prevention of Disasters.

Van Den Bosh, C.J.H. & Weterings, R.A.P.M. 2005. *Methods for the calculation of physical effects (Yellow Book)*, 3rd ed. The Hague (The Netherlands): Committee for the Prevention of Disasters.

Van Den Bosh, C.J.H., Merx, W.P.M., Jansen, C.M.A., De Weger, D., Reuzel, P.G.J., Leeuwen, D.V. & Blom-Bruggerman, J.M. 1989. *Methods for the calculation of possible damage (Green Book)*. The Hague (The Netherlands): Committee for the Prevention of Disasters.

Young, S., Balluz, L. & Malilay, J. 2004. Natural and technologic hazardous material releases during and after natural disasters: a review. *Science of the Total Environment* 322:3–320.