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Risk analysis of technological hazards: simulation of scenarios and application of a local vulnerability index

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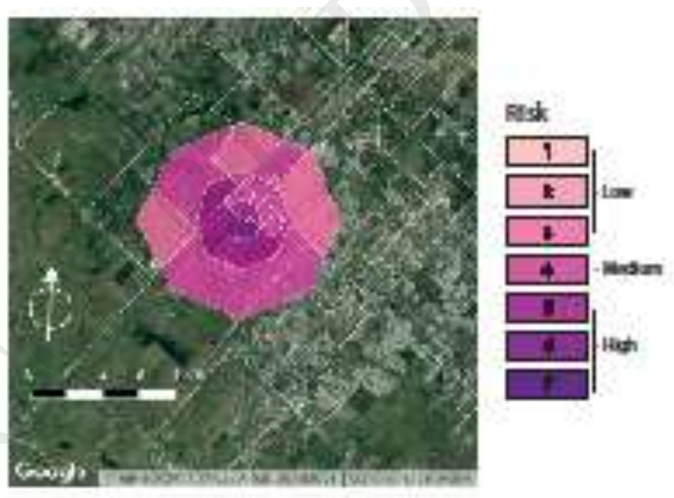
Graphical abstract



Highlights

- A methodology for estimating the risk of accidental leakage is proposed.
- This systemic approach based on the available information is methodologically flexible.
- This methodology optimizes the processing of the input data and its calculation.
- The use of a social vulnerability index could help to address the pressing priorities.

Abstract

The potential impact of a technological accident can be assessed by risk estimation. Taking this into account, the latent or potential condition can be warned and mitigated. In this work we propose a methodology to estimate risk of technological hazards, focused on two components. The first one is the processing of meteorological databases to define the most probably and conservative scenario of study, and the second one, is the application of a local social vulnerability index to classify the population. In this case of study, the risk was estimated for a hypothetical release of liquefied ammonia in a meat-packing industry in the city of La Plata, Argentina. The method consists in integrating the simulated toxic threat zone with ALOHA software, and the layer of sociodemographic classification of the affected population. The results show the areas associated with higher risks of exposure to ammonia, which are worth being addressed for the prevention of disasters in the region. Advantageously, this systemic approach is methodologically flexible as it provides the possibility of being applied in various scenarios based on the available information of both, the exposed population and its meteorology. Furthermore, this methodology optimizes the processing of the input data and its calculation.

Keywords: Social vulnerability, technological incident, worst- case scenario, ALOHA, INDEC

1. Introduction

Cities in which the fabrication, processing and storage sites of hazardous materials (HAZMAT) are located have a risk of HAZMAT events [1]. Particularly, many cities in Latin America have industrial facilities close to an urban area. The absence of territorial planning projects exposes the population to potential technological incidents [2]. These disasters often result in an unexpected and uncontrolled release of HAZMAT [3].

Risk is defined as the relationship between hazard and vulnerability. The risk value determinates the consequence degree in an economic, social and environmental level for a specific site and time.

This variable does not attempt to identify causal mechanisms to prevent or predict future occurrences of undesirable events; however it offers enough information to identify the areas that need to be taken care of.

This effort to reduce the impact of disasters requires risk analysis and risk reduction. Clearly, risks can never be completely eliminated. However, an understanding of its nature and extent can provide a basis for the development of land use strategies and controls that will ensure the appropriate management. In the same way, the literature offers several methodologies to estimate the risk based on different approaches such as sensor placement, hazard identification and land-use planning [4-8].

The tools required to estimate the consequences of accidental release are mathematical models, to predict accidental effects, and vulnerability models. The ultimate aim of risk assessment for a given case is to calculate the distribution of risk over the affected area by estimating the existing hazards and the consequences of the different accident scenarios [9].

The basic industrial safety and security idea is to protect assets from hazards and threats by creating safe conditions. Industrial safety is considered a transdisciplinary field because it must be built as a combination of risk-based and precautionary management strategies [10].

Various publications provide information about different methodologies to estimate the risk posed by a given system in terms of human loss or, in some cases, economic [11-13]. However, many of them consider the number of affected people but do not focus on the particular characteristics of the affected population. Additionally, the risk assessment methods use sophisticated tools and perform very meticulous analysis. These methods require very detailed information (for example, records from previous incidents, including historical data), which is not always available [14-15].

Considering that risk is a latent condition and can be mitigated, in this work we propose a methodology to estimate the risk of technological hazards, focused on two components. The first one is the processing of meteorological databases to define the most probable and conservative scenario of study and the second one is the application of a local social vulnerability index to classify the population.

In order to determine population at risk, in this work the proposed methodology takes into account the following key elements:

- *risk*, defined as the interaction of a toxic cloud and vulnerability of the exposed population,

- *matrix of atmospheric stability*, specifying probabilities for 'wind speed - atmospheric stability' pairs which are derived from historical meteorological data and used to represent atmospheric conditions at a site,
- *atmospheric concentrations of pollutants* to assess the exposure of the population are computed for each wind direction, and
- *Local Social Vulnerability Index* that characterizes the exposed population.

1.1. Technological Hazards

Technological hazards, which can affect localized or widespread areas, can cause loss of life and property damage, and can also significantly affect infrastructure [1]. The consequences of the accidents are taken into consideration quantitatively by estimating the distance in which the physical magnitude (e.g. toxic concentration) reaches a threshold value corresponding to the beginning of the undesired effect (e.g. fatality). The dimensions of the worst accident footprint are calculated using the appropriate model: fire, explosion or toxic gas dispersion [16-19].

Consequence-based methods seek to represent the worst-case scenario conceivable under the premise that if there are enough measures to protect the population from the worst conceivable accident, enough protection will also be provided for any accident of lesser proportions [14]. The proposed method evaluates only the extent of the accident based on the most likely scenario and the most conservative scenario from a meteorological point of view, and not the probability of its occurrence. In that regard, the consequences associated to the worst-case scenario are described in terms of the most probable weather conditions for the region, represented by an atmospheric stability matrix [15-16].

The meteorological factors that we wish to address in this work directly infer in the dispersion of the pollutants. Consequently, these factors influence the determination of the dimension and characterization of the risk and threat zone. When contaminants are not readily dispersed, they tend to increase their concentration. The speed of the wind plays a fundamental role in its dilution, determining how quickly the contaminants mix with the surrounding air. This implies that light winds do not favor the dispersion of pollutants. On the other hand, the type of atmospheric stability may favor or limit the upward vertical motions. Particularly, the pollutants emitted in a stable atmosphere tend to spread horizontally, rather than vertically.

Although the type of atmospheric stability and the wind speed are two notable factors, we must not forget that they depend on other factors such as temperature, air pressure, radiation and cloud cover. More information can be found in Miñarro [16] and Ahrens [20].

1.2. Social Vulnerability

Competition in global markets, rapid economic growth and industrialization processes exposes the environment, the community and workers to technological hazards. These conditions increase the vulnerability of social groups such as workers and people with lower income.

Social vulnerability taps on a broad range of susceptibilities at the individual and community level: lack of access to resources and lifelines, insufficient information and well-being, and certain beliefs and customs [21-23]. The underlying causes of social vulnerability are economic, demographic and political processes that affect the allocation and distribution of resources among different social groups, and which reflect the power relations that are generated between them [24].

Some aspects of social vulnerability which contribute to the severity of risk are presented below:

- The limited access to economic and cultural resources produces an unequal development of the social group capacities. At the same time, the conditions of poverty restrict people to access communication technologies. Consequently, individuals are not well prepared to respond to an emergency, both in terms of financial and communication means.

- The limited access to basic services (education, public health, potable water) increases the vulnerability of the population, both in previous instances and after a possible release. Although these characteristics do not cause this kind of unfortunate event, they condition the response of the population, the management system and the subsequent recovery. Additionally, building infrastructure quality and overcrowding are key factors in response decisions.

- Individuals who need care and attention, such as children and elders, increase the level of vulnerability of the population. In the same way, the high diversity of minority social identities is exposed to social and economic marginality. Finally, it should be noted that the degree of gender violence and unequal access to economic, cultural, social and political resources generate greater vulnerability to women over men.

The most common indices that have a significant association to social vulnerability from industrial hazards in developing countries attempt to represent these conditions [25]. The use of a social vulnerability index could help address the pressing priorities in disaster management programs [26].

Although there are different indicators of social vulnerability in the literature [27-30], it is not yet defined what indicators should be used in specific contexts to guide mitigation tools to reduce the harmful consequences of natural or man-made disasters. In that sense, to assess vulnerability indices and their validity for contributing to policy making is a pending subject [31].

In this context, this paper aims to quantify the impact of industrial facilities that handle HAZMAT on their urbanized environment. Thus, a methodology for estimating the risk of accidental leakage on the neighboring community is proposed. Finally, a risk mapping is presented.

2. Methods

As stated above, the accidental release simulation of the HAZMAT and the estimation of social vulnerability are necessary to determine the risk. Because of that, communities should recognize that past experiences with threats may differ from the future threat and hazard environment. Factors such as demographics, climate, and the built environment are subject to change. Communities should consider these factors when developing threat and hazard context descriptions [32]. In this sense, the proposed methodology considers the factors mentioned.

2.1 Hazard: Construction of scenarios

Following the release of a HAZMAT, the accidental sequence can follow diverse paths according to the release characteristics (pipeline or tank rupture, a hole, etc.), the material properties (flammability, toxicity and volatility), the meteorological conditions and the environmental circumstances (urban, rural) [8].

According to the criteria proposed by FEMA [32] and Miñarro [16], the methodology presented in this paper aims to identify the most likely and conservative scenarios, by simplifying the available information.

To develop threat context descriptions, communities should take into account the time, place, and conditions in which threats might occur: What time of day and what season would be most likely or have the greatest impacts and which locations would be most likely or have the greatest impacts?

In this work, a methodology for the construction of scenarios, based on the processing of available meteorological data is presented. To limit the calculation time for the quantitative risk analysis, usually, stability class and wind velocity data are grouped in a reduced number of representative sets [9].

During this development, the following aspects have been taken into account:

1- *Multiple atmospheric stability data were replaced by a single value, taking the more stable category of them.* For example, B instead A-B.
2- *Data are classified according to eight wind directions for the study period.*
3- *The stability matrix is calculated for each direction of the wind:* The knowledge of both the magnitude and the direction of the winds, as well as the classes of atmospheric stability of a given region, allows to elaborate so-called stability matrices referenced to a period of interest, which explain the frequency of the variables in question. For example: Frequency at which any combination of stability class-wind velocity is verified, frequency of each stability class and of each speed range, and combinations not possible.

The decisions tree in Fig. 1 shows a simplified scheme of databases processing, which is developed below.

First, we must select one of the wind directions to study. We must go through the tree as many times as classes of directions have been defined to cover the 360°. In addition, each of the wind directions may be associated with ground roughness (Z_0) which will give account of the characteristics of the terrain to leeward.

We propose the analysis of two types of potential scenarios for each of the wind directions: the most likely (MLS) and the most conservative (MCS). The first one is defined from as a consequence of the results of the stability matrix, while for the second one is obtained from the classes of magnitude more likely of the wind for the class of stability more stable (F).

To define MLS and MCS, we must have additional information, such as more frequent months and times in which the most likely and most conservative stability class is presented. In this sense, a processing of meteorological databases is necessary. The goal is to discriminate the most likely values. In terms of cloud cover, air temperature and humidity, the monthly values are averaged for the months defined in the previous step.

It is likely that the previous processing will return more than one scenario for each wind direction. In this case, all of the resulting scenarios must be studied for each of the wind directions. This step involves simulation with appropriate software (for example ALOHA [33], PHAST [34]) for the accidental release of the HAZMAT. Next, the one that offers the greatest range of threat zones will be selected and this will be defined as the worst-case scenario in the studied direction.

Based on the above, the information associated with the MLS and the MCS will be available in each of the wind directions.

Finally, an iso-threat curve connects all of the geographical locations around a hazardous activity with an equal threat. These contours can be circular if the impacts of the accidents spread uniformly in all directions or more irregular if the intensity of the effects differs according to the direction. As a result, a threat map is obtained.

2.2. Vulnerability: Social vulnerability index application

Vulnerability status can be estimated through a social vulnerability index. This index can be constructed from a database with the socioeconomic characteristics of the community. In this work, a database was summarized through a principal components analysis (PCA) in an index called *Local Social Vulnerability Index* (LSVI).

LSVI quantifies the deprivation status and relies on sixteen characteristics available at the neighborhood level based on the Argentinian Cense [35]. The variables cover various socioeconomic characteristics such as the proportion of overcrowded homes, the gender, the occupational class, employment status or basic amenities absence.

For the application of the PCA, it was necessary to normalize the data, for which a z-score of the variables was performed. Then, to reduce the number of variables the most used statistical technique is the PCA. This technique finds a set of linear combinations among the introduced variables with the purpose of simplifying the structure of the data in main components [26, 36].

To determine the degree of reliability among the normalized parameters, the parameter Alpha Cronbach was calculated. Then, the collinearity between the variables was evaluated with the Pearson correlation coefficient, discarding the variables with a correlation lower than 0.3 for some of the variables (with $p < 0.001$). For the diagnosis of multicollinearity, the Kaiser-Meyer-Olkin test (KMO) was used.

To define the number of principal components, a sedimentation graph was generated and the explained variance was analyzed. In the bibliography, it is considered necessary a greater explanation to 70% for social studies. To select a rotation method, the ability to explain the variance of the data was evaluated. The main components obtained were added to generate the LSVI. Table 1 shows the weight factors used to construct the LSVI.

Finally, to facilitate the interpretation of the outputs, a rescaling of the index was performed. LSVI values were categorized into 5 levels (very low, low, medium, high and very high).

For the construction of LSVI for Argentina, 19 variables were included:

- Number of people in the household most frequently.
- Proportion of housing occupied by loan, work or other temporary situation.
- Proportion of population under 14 relative to the population aged 15-64.
- Proportion of population over 65 relative to population aged 15-64.
- Proportion of women over total population.
- Proportion of immigrants over the total population.
- Proportion of population that never attended a formal educational establishment.
- Proportion of the population over 14 who does not read or write.
- Proportion of population in street situation.
- Proportion of the unemployed population over the active population.
- Proportion of population with some basic unsatisfied need.
- Proportion of dwelling with precarious materials.
- Proportion of dwelling with two or more households in the same dwelling.
- Proportion of dwelling without telephone.
- Proportion of dwelling without refrigerator.
- Proportion of dwellings with water outside the dwelling or land.
- Proportion of dwellings using firewood, coal or other alternative fuel for cooking.
- Proportion of dwellings without drains to public network, septic tank or blind well.
- Proportion of dwellings without internal bath.

After collinearity tests, the variables "Immigrants", "Shared housing" and "People in a street situation" were excluded from the indicators. After normalizing the data and performing the ACP, the index explained 77% of the variance data with 4 main components.
Data management and analysis were performed with R software. QGis software was used for spatial operations and cartography [37].

2.3. Risk Analysis and Mapping

In order to estimate the risk according to its definition, it is necessary to take into account the characteristics of the population in terms of their ability to anticipate, confront, resist and recover from the impact of a hazard [38]. Similarly, it is important to define a finite number of scenarios which represent the characteristics of the hazard and the study region. In this sense, the procedures proposed above allow to organize and analyze basic and available information for disaster preparedness.

A risk matrix allows quantifying the overall risk (7 levels) like the result of the threats of the accidental releases and the vulnerability of the potentially affected population. In this work, the direct sum of the variables was chosen because the risk matrix is rectangular (5 levels of vulnerability and 3 levels of threat), thus obtaining the matrix shown in Figure 2.

Finally, a chromatic classification on census areas represents the levels of risk around the industrial facility analyzed. In order to estimate these levels it is necessary to characterize the vulnerability of the surrounding population and calculate the respective contributions of different accident scenarios (each one has its own probability governed by regional meteorology).

3. Application case: Hypothetical release of liquefied ammonia in a meat-packing industry in the city of La Plata, Argentina

In Argentina, the Centre of Chemical Information for Emergencies (CIQUIME) has the function of providing useful information about actions as a response to chemical emergencies. A statistic report about accidents with HAZMAT published by CIQUIME, conclude the following facts [39]:

- Chemical accidents occur mostly in fixed installations (mainly factories and storerooms), during workdays and from 8 am to 5 pm.
- Liquids are of the most incidences, but the gaseous products are the most dangerous because they can disperse quickly occupying large surfaces and this makes them difficultly controllable.
- Inhalation is the main route of exposure. The majority of victims get intoxicated by gaseous substances.
- The most frequently substance involved is the ammonia.

The ammonia was the first refrigerant used in plants of refrigeration. The economic advantages and its good capacity of heat absorption position it as the refrigerant most chosen by cold storage and food processing facilities [40].

Due to the importance of the meat industry in Argentina, the wide use of ammonia as a refrigerant and the antecedents of undesirable events, it is our interest to estimate the risk for a hypothetical release of liquefied ammonia in a meat-packing industry (34°59'27.83"S, 58° 5'37.93"W) in the city of La Plata, Argentina. Figure 3.a shows the location of the meat-packing industry in the residential and urban context. The studied industry is located on an access road to the city of La Plata, with high vehicular traffic (520 Avenue), in a scenario composed of low building and cultivated land. At 14.8 km towards the east-northeast (ENE) is the geographical center of the urban area of the city of La Plata (yellow point). At 5.5 km towards the northeast (NE), the Interzonal Hospital Specialized in Acute and Chronic Neuropsychiatric "Dr. Alejandro Korn" is placed (red point). 2 km towards the south-west (SW) is the intersection of 520 Avenue with a highway known as provincial route 2, (light blue point). This highway is one of the routes with major traffic flows of the Province of Buenos Aires.

3.1. Vulnerability

Areas surrounding the meat industry have had sustained the growth of urbanization. While the 2010 census, 3489 inhabitants were recorded in the vicinity (4 km to the round), lending policies in recent years in Argentina, have led the real estate market to occupy new spaces. The application of the LSVI allowed categorizing the census areas of the study region. 8 census areas with medium vulnerability (level 3) and 5 areas high (level 4) were detected within the 4 km round (Fig. 3.b).

3.2. Hazard

In this work a leakage from a hole of 2 cm diameter in a receiver tank was modeled with ALOHA software. This tank is the component of the system that stores the largest volume of ammonia. Based on the operational conditions of the plant, the following assumptions were considered when modeling the emission source: Horizontal cylinder (Volume: 2800 L. Length: 5.30 m); pressure of work: 12.75 bar; the tank contains liquefied ammonia and it is filled in 85 %.

The meteorological data for the period 2014-2016 was provided by the SMN and its processing shows frequencies of 23.66, 21.70, 17.70, 10.01, 9.93, 6.67, 6.01 and 4.54 % for the winds N, E, S, W, NE, SE, SW and NW, respectively.

The stability matrix derived for each wind direction shows a class of atmospheric stability C and wind speeds lesser than 2 m s^{-1} as the predominant conditions of the region, in the 8 selected directions (Figure 4). As an example of this construction, Table 2 shows the stability matrix corresponding to the Eastern direction.

Also, a complementary analysis (Fig. 5) is necessary to reduce the number of scenarios to be simulated, focusing the study on MLS (associated with stability class C) and MCS (associated with stability class F). Based on this result, 4 MLS were defined for a given wind direction, according to the most frequent times and months of stability class C (Table 3). Finally, the worst-case scenario of these 4 was represented in the remaining directions, with the proviso that the Ground Roughness was estimated for each scenario [41]. A similar analysis was carried out for MCS.

The threat zone of the potential release was represented by the interpolation of the distances corresponding to each of the threat zones represented by ALOHA (Fig. 6). In this case, AEGL was used as a toxic level of concern.

Even though the toxic cloud will be transported in the direction of the wind, this direction cannot be accurately predicted with the presented emergency planning approach. The authors decided to screen the 360 degrees (analyzing 8 directions in our study case) to overcome this difficulty, offering a circular area of risk as a result. Although the escape will affect only a portion of the estimated circular area, the proposed methodology offers to the risk manager a complete description of the study scenario and environment, for any probable wind direction. This approach is conservative but avoids falling into underestimated results.

The MLS threat map, compared to the MCS map, does not have a perfectly circular shape and this is basically due to some differences between the values defined by the decision tree in the different directions of the wind.

Figure 7 shows the risk levels estimated from the risk matrix in Figure 2. For both MLS and MCS outputs, the high threat zone involves fractions of four census areas. This fraction is greater for the MCS as expected. However, the census area that is located southwest of the source of liberation presents, for MLS and MCS, the highest level of risk of the map (level 6) due to its high vulnerability in comparison to the other three census areas (level 5) of the high threat zone. Similarly, the medium-threat zone presents fractions of 3 high-level census area (level 5) and 7 middle-level census area (level 4). While the low-threat zone has fractions of 4 (MLS) and 5 (MCS) census area with medium risk (level 4) and fractions of 4 with low risk (level 3).

As a base layer, Fig 6 and 7 use a "zoom in" of the satellite image of Figure 3.a. The figures show the Interzonal Hospital Specialized in Acute and Chronic Neuropsychiatric "Dr. Alejandro Korn" (red point) as a point of geographic reference.

4. Discussion

The indicators of the social vulnerability in disasters can help the government officials to establish the appropriate programs to decrease the harmful consequences of disasters. Effective hazard mitigation and emergency response must begin with an understanding of the complex ways in which social, economic and political organization of a society create substantial differences in the vulnerability of those who are meant to protect. This paper attempts to explore those manifested needs in our society with the use of indicators of social vulnerability in man-made disasters, such as chemical release.

In this paper we seek to assess the social variables that have a significant weight against an accidental release. Such is the case of the "overcrowding", "children and elderly in charge of a responsible adult" condition, which directly affect the possibility of quickly escaping the threat zone. Similarly, "precarious constructions" that invalidate the possibility of protecting the population at home against the passage of a toxic cloud. Likewise, the "levels of illiteracy" that compel decision makers to evaluate and consider alternative channels of communication. In addition, Sphere Handbook [42] establishes that the safety and security of people in situations of disaster is of particular humanitarian concern. Some people may be particularly vulnerable to abuse and adverse discrimination due to their status (such as age, gender or race), and may require special measures of protection and assistance.

On the other hand, critical infrastructures are vital to both disaster response and to the overall safety of the affected population. Critical infrastructure problems must be addressed in the short term, while the disaster response operation is ongoing. Examples of critical infrastructure components include: transportation systems, communication, electricity, gas and oil storage and transportation, water supply systems, sanitation, emergency services, public health and continuity of government [43]. Some of these components have not been considered in the construction of LSVI as such information is not fully available in our country. This suggests the possibility of projection of risk management system in order to strengthen the characterization of risks in Argentina.

Coppola [43] says that looting is one of the most common security problems that follow major disruptive disasters. The threat of looting has been found to be a major factor contributing to the failure of some evacuation attempts. Therefore, a stimulus to know the representative risk of the study scenarios is the need to have the response capabilities to prevent an emergency from becoming a disaster. In this sense, the processing of the meteorological databases through the decision tree, allow finding scenarios representatives to the region.

As a final result, the risk map generated allowed us to visualize and detect those census areas that warrant primary care for risk mitigation.

In this paper, the concept of risk for the emergencies and disasters management is pondered. Although threat maps are a useful and simple tool for emergency response, risk estimation is a very useful resource for the preparation stage. The comparison of the MCS of Figures 6 and 7 shows an example of this: the zone of the higher risk represents 60% of the area of high threat (0.52 km^2). Therefore, the risk map makes it possible to optimize the available resources by directing them to the areas of the highest risk when facing the same threat as the other areas.

The risk in terms of safe distance can be quantified using Dow's Chemical Exposure Index or other toxic dispersion models available in the literature. Many of those consider fixed values (by default) of meteorological parameters, such as wind speed and stability class, but do not characterize the population that will be potentially affected. Afterwards an incomplete description of the study scenario may expose the risk manager to a non-representative scene.

Finally, risk managers can acquire tools for mitigation if they know the characteristics of the population that would potentially be affected by an accidental release. For example, a nonstructural mitigation involves modification of human behavior such as regulatory measures, community awareness and education, etc. If the inhabitants have concerns of another hierarchy, such as lack of work and food, they probably will not be motivated to participate in a training course. Their basic needs would be unsatisfied and nothing would be more important than attending to them.

5. Conclusions

Technological hazards can affect localized or widespread areas. These can cause property damage and loss of life, and can significantly affect infrastructure. Efforts to reduce the impact of disasters require analysis and reduction risk. Likewise, effective mitigation requires that we all understand local risks, address the hard choices and invest in long-term community well-being. In that sense, the proposed methodology optimizes the processing of the inputs (sociodemographic and meteorological data) for estimating the risk. Also, this methodology considers the social variables that have a significant weight against an accidental release.

The risk maps generated allowed us to visualize and detect those census areas that warrant primary care for risk mitigation. In the same sense, this map makes it possible to optimize the available resources by directing them to the areas of highest risk when facing the same threat as the other areas.

While this paper shows an application case in Argentina, the framework we describe has applications to risk estimation in other countries and for a wide variety of HAZMAT. It is only necessary to have reliable information on the sociodemographic characteristics of the study population and on the regional meteorology, as well as to know the processes of the industrial facility and the characteristics of emission source.

Proposed qualitative model over already available quantitative models presents remarkable advantages which have been discussed in this work. It is relatively simple, descriptive and uses affordable information. The coupling of two methodologies provides a detailed description of the study scenarios. This detail is very useful for mitigation tasks: community awareness and education, optimization of the available resources, etc. The use of numerical models to simulate the impacts of the threat, as well as the incorporation into the LSVI of components that account for critical infrastructure promise a more representative result of the risk scenarios.

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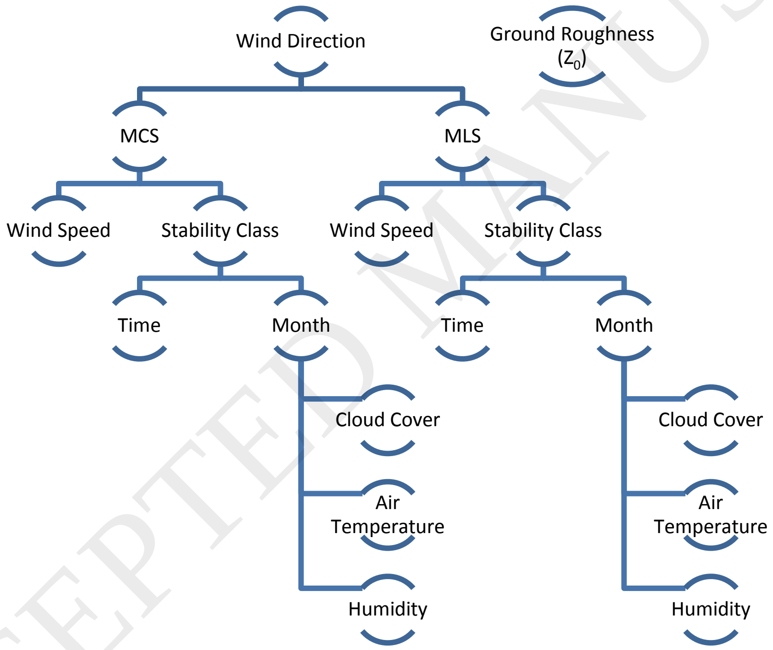

Figure 1. Tree of decisions based pre-*processing* operations of meteorological databases. MLS: most likely scenario; MCS: the most conservative scenario.

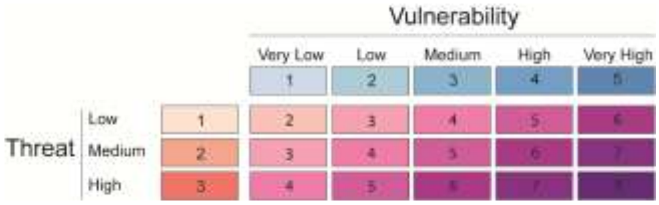

Figure 2. Risk matrix defined like the result of threats of an accidental release and the vulnerability of the potentially affected population. The matrix shows 7 levels of risk where 2 corresponding with low risk and 8 corresponding with high risk.

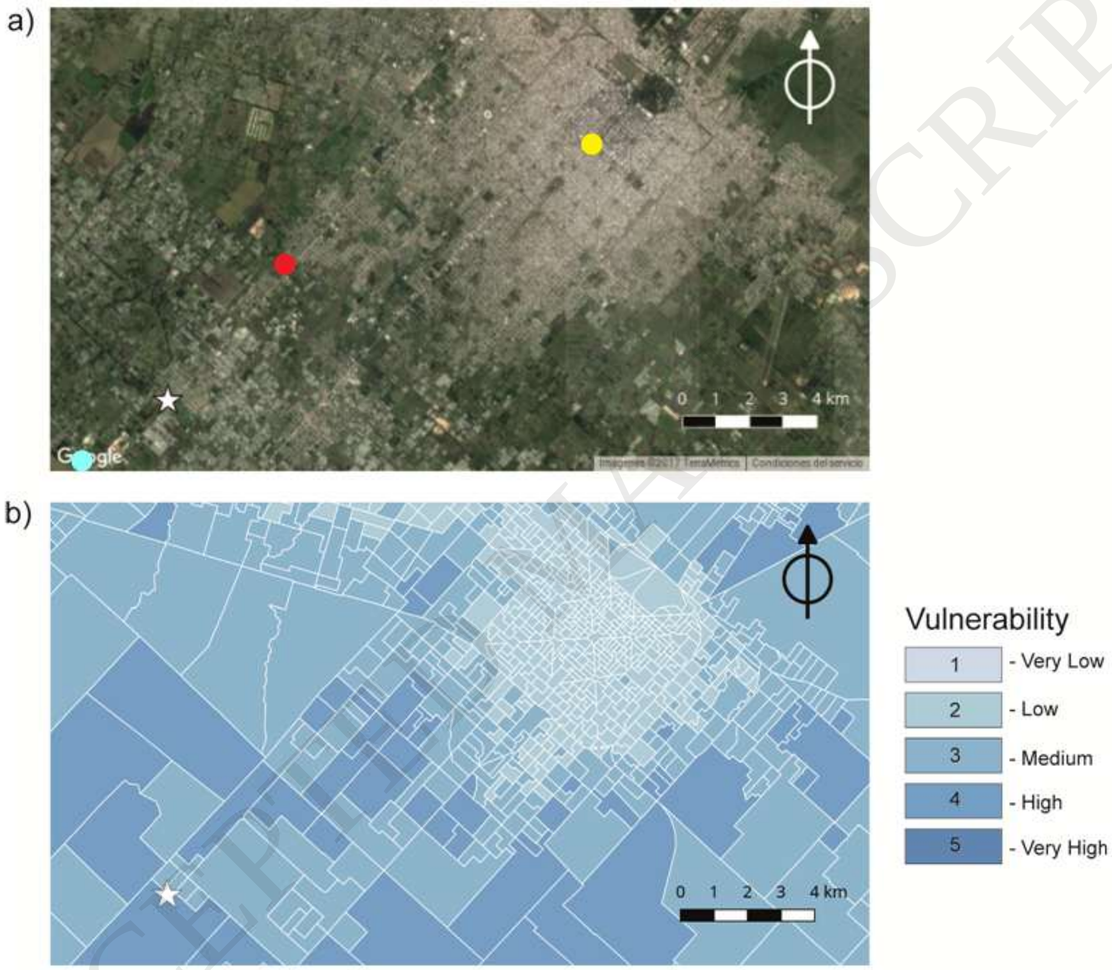

Figure 3. a) Satellite image of the study area. The star represents the meat-packing industry (34°59'27.83"S, 58° 5'37.93"W) in the city of La Plata, Argentina. Yellow point: center of the urban area of the city of La Plata (14.8 km towards the Northwest); Red point: Interzonal Hospital Specialized in Acute and Chronic Neuropsychiatric "Dr. Alejandro Korn" (5.5 km towards the northeast); Light blue point: intersection of 520 Avenue with a highway known as provincial route 2, 2 km towards the southwest. b) Classification of the census radios according to their vulnerability through the LSVI.

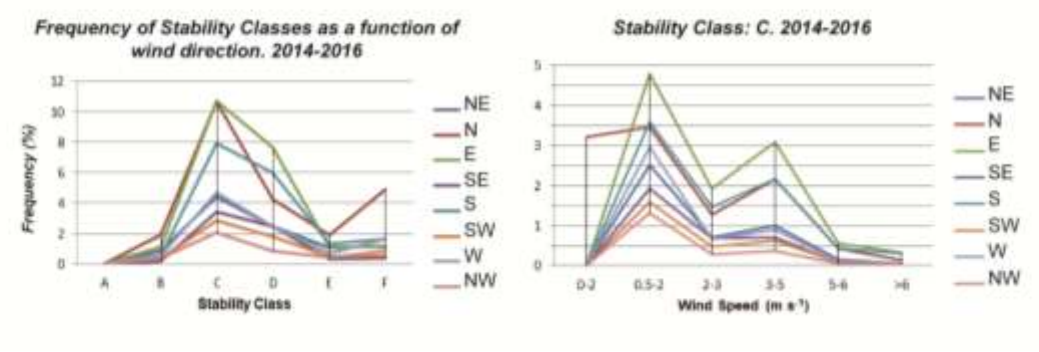

Figure 4. On the left, the graph shows the frequency of stability classes as a function of wind direction for the period 2014-2016. On the right, the graph shows the frequency of stability class C as a function of wind speed for the same period.

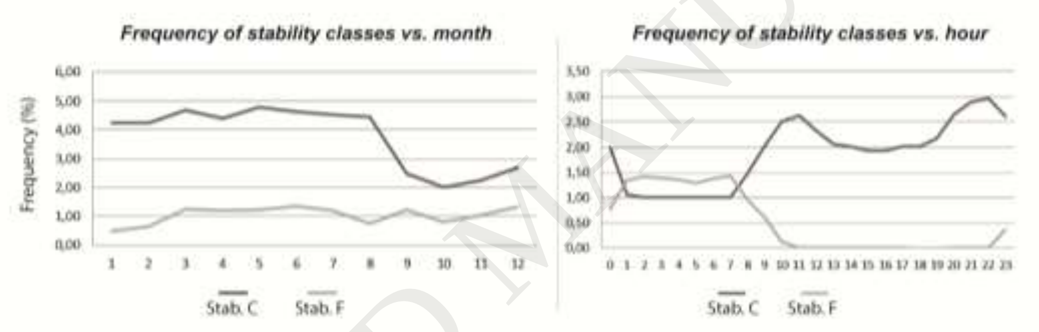

Figure 5. On the left, the graph shows the frequency of C and F stability classes as a function of the month for the period 2014-2016. On the right, the graph shows the frequency of C and F stability class as a function of the hour for the same period.

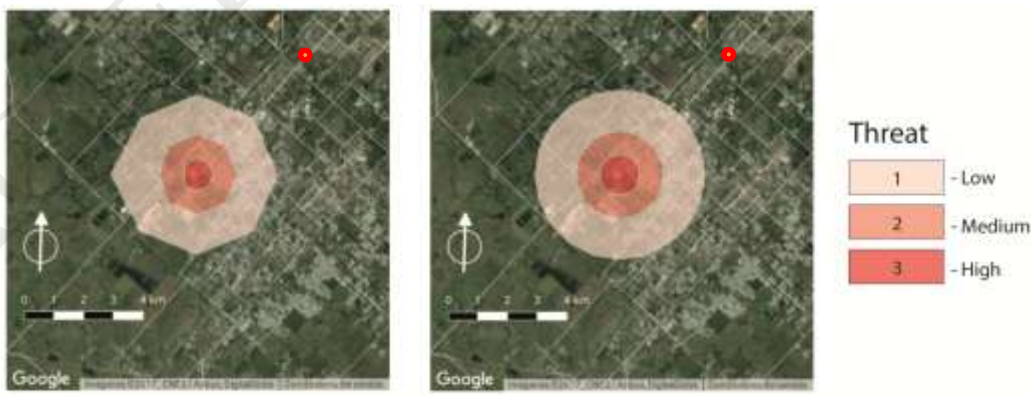

Figure 6. Toxic threat zones constructed with QGis from the graphical outputs of ALOHA (composition of 8 directions). On the left, the toxic threat zone of MLS. On the right, the toxic threat zone of MCS. Red point: Interzonal Hospital Specialized in Acute and Chronic Neuropsychiatric "Dr. Alejandro Korn".

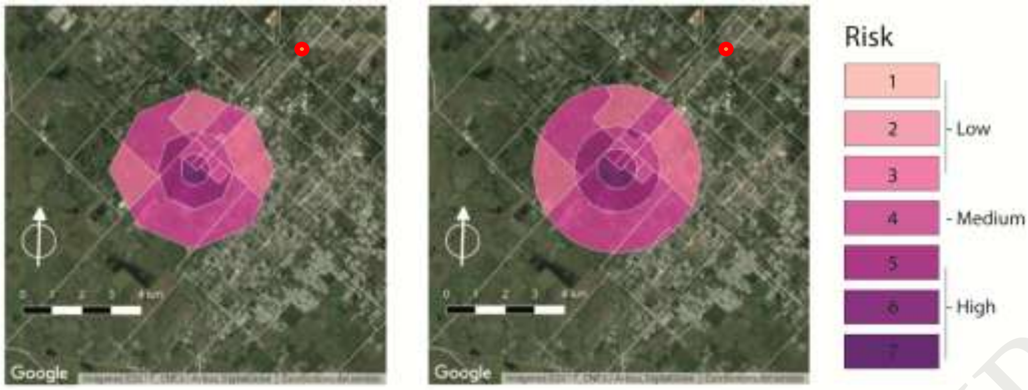

Figure 7. Levels of risk constructed with QGis from the crossing of the threat and vulnerability layer. Red point: Interzonal Hospital Specialized in Acute and Chronic Neuropsychiatric "Dr. Alejandro Korn".

Table 1. Weighting factors used to construct the LSVI by principal components analysis.

Variable	PC 1	PC 2	PC 3	PC 4
Number of people in the household most frequently	-0.080	-0.168	0.020	0.764
Proportion of housing occupied by loan, work or other temporary situation.	0.073	0.878	-0.035	-0.056
Proportion of population under 14 relative to the population aged 15-64.	0.279	0.163	0.629	0.528
Proportion of population over 65 relative to population aged 15-64.	-0.093	-0.227	0.025	-0.777
Proportion of women over total population.	-0.316	-0.711	0.375	-0.068
Proportion of population that never attended a formal educational establishment.	0.579	0.326	0.321	0.156
Proportion of the population over 14 who does not read or write.	0.562	0.289	0.490	0.345
Proportion of the unemployed population over the active population.	0.278	-0.158	0.776	-0.146
Proportion of population with some basic unsatisfied need.	0.815	0.134	0.125	0.277
Proportion of dwelling with precarious materials.	0.835	0.117	0.242	-0.048
Proportion of dwelling without telephone.	0.419	0.675	0.374	0.189
Proportion of dwelling without refrigerator.	0.857	0.268	0.158	-0.016
Proportion of dwellings with water outside the dwelling or land.	0.807	0.305	0.300	0.062

Proportion of dwellings using firewood, coal or other alternative fuel for cooking.	0.820	0.206	0.179	-0.148
Proportion of dwellings without drains to public network, septic tank or blind well.	0.469	0.595	0.328	0.096
Proportion of dwellings without internal bath.	0.872	0.071	-0.025	0.050

Table 2. Matrix of stability generated for the Eastern direction of the wind.

Wind Velocity ($m\ s^{-1}$)	Frequency of stability Classes (%)						
	A	B	C	D	E	F	Σ Classes
[0,0 ; 0,5)	0,0	0,0	0,0	0,0	0,0	0,0	***0,0***
[0,5 ; 2,0)	0,0	0,4	4,8	1,2	0,4	0,8	***7,6***
[2,0 ; 3,0)	0,0	0,2	1,9	0,8	0,2	0,1	***3,2***
[3,0 ; 5,0)	0,0	0,5	3,1	2,9	0,4	0,1	***7,0***
[5,0 ; 6,0)	0,0	0,1	0,6	1,3	0,0	0,0	***2,0***
≥ 6,0	0,0	0,0	0,3	1,5	0,0	0,0	***1,9***
Σ v	***0,0***	***1,1***	***10,7***	***7,7***	***1,1***	***1,1***	**21,70**

Table 3. Scenarios defined through operations of processing meteorological databases.

Id.	***Wind Direction***	***Scenario***	***Stability Class***	***Wind Speed ($m\ s^{-1}$)***	***Time (h)***	***Month***	***Z_o (m)***	***Cloud Cover (Tenths)***	***T_a (°C)***	***Humidity (%)***
1	N			1.3	11	3	0.3	3	21	70
2	N			1.3	11	5	0.3	4	15	80
3	N			1.3	21	3	0.3	3	21	70
4	N			1.3	21	5	0.3	4	15	80
5	NE			1.3	21	3	0.1	3	21	70
6	E			1.3	21	3	0.3	3	21	70
7	SE	MLS	C	1.3	21	3	0.3	3	21	70
8	S			1.3	21	3	1	3	21	70
9	SO			1.3	21	3	1	3	21	70
10	O			1.3	21	3	1	3	21	70
11	NO			1.3	21	3	0.3	3	21	70
12	E			4	21	3	0.3	3	21	70
13	N			1.3	2	6	0.3	4	11	80
14	N			1.3	2	12	0.3	3	23	70
15	N	MCS	F	1.3	7	6	0.3	4	11	80
16	N			1.3	7	12	0.3	3	23	70
17	NE			1.3	2	12	0.1	3	23	70
18	E			1.3	2	12	0.3	3	23	70

19	SE		1.3	2	12	0.3	3	23	70
20	S		1.3	2	12	1	3	23	70
21	SO		1.3	2	12	1	3	23	70
22	O		1.3	2	12	1	3	23	70
23	NO		1.3	2	12	0.3	3	23	70