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Dedicated to Professor Liviu Literat, at his 80th anniversary

CHEMICAL RISK AREA ESTIMATION AS A TOOL FOR EFFICIENT EMERGENCY PLANNING

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ABSTRACT. Chemical disaster management has two essential components: Chemical Risk Management (CRM) and Emergency Situations Management (ESM). The connection between these two major elements is represented by the risk area estimations. Risk area estimations are an important tool in the process of Risk Assessment. It provides the authorities responsible with intervention in case of a major chemical accident, accurate and detailed information on the site, weather conditions, hazardous chemicals involved, and their dispersion patterns aiding in the development of Emergency Response Plans. The paper presents an overview of the Chemical Disaster Management process and a comparative case study of a possible chemical accident involving chlorine.

Keywords: *chemical risk assessment, risk analysis, consequence maps, chlorine*

INTRODUCTION

The technological processes that involve dangerous substances are known to have high risk levels, due to their capability to produce major accidents. These accidents can occur during the process, storage and transportation, releasing a large quantity of energy or substance which can harm humans or the environment, and lead to technological disasters.

Therefore the need for strict regulations arises, in order to prevent these disasters form occurring with the active participation of the industry, the authorities and the general public. The regulatory organism in the field of major industrial accidents involving dangerous substances is the European Union by the 2003/105/CE Directive, also called the Seveso III Directive [1].

Chemical disaster management has two essential components: Chemical Risk Management (CRM) and Emergency Situations Management (ESM), Figure 1.

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CRM can be considered as a combination of all the processes necessary to control chemical risk: risk analysis, risk evaluation, cost-benefit analysis, and change management. On the other hand ESM focuses on managing these events once they have occurred. ESM includes: internal and external emergency plans, emergency response, and post-emergency recovery.

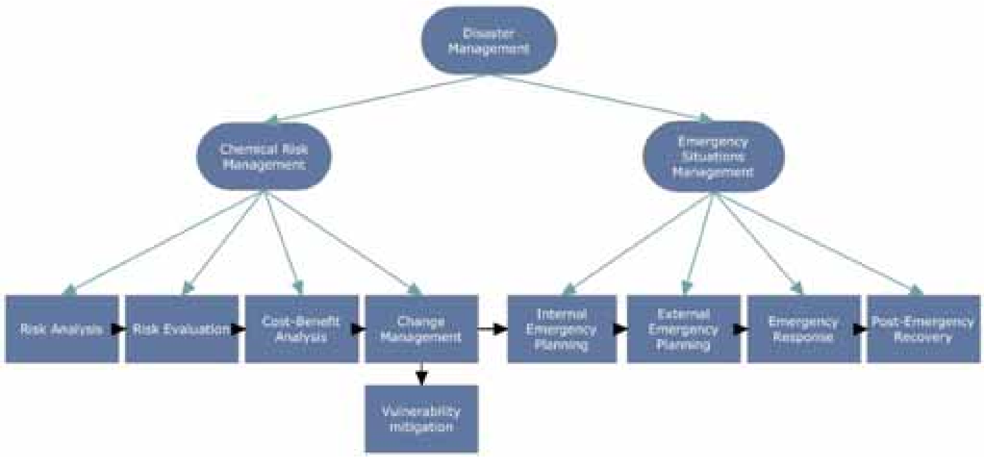


Figure 1. Disaster Management Scheme.

Risk analysis starts with the identification of the hazards present or likely to be formed in the process, dangerous conditions that are present or could be generated failures of certain parts of the process or process control system, and human errors. After the identification of the hazards and estimation of the likelihood of these hazardous events and an evaluation of the effects and possible consequences to humans, environment and for structures is needed.

In risk analysis certain questions need to be addressed:

- What weaknesses could occur in the security management system?
- What preventive measures can be taken in order to control the risk factor?
- How are these actions monitored?

The qualitative part of risk analysis focuses on identifying the risks, possible failure cases, using methods like:

- Preliminary Hazard Analysis (PHA), was developed according to military standards in this field, and can be applied in the preliminary project phases. It focuses on the main areas that might contain dangerous substances, and on the main equipments, and monitors the possible failure points where dangerous substances or energies could be released.

- "What If?" method, poses a series of questions in order to determine unexpected events in the system.
- Checklists identify known and predictable risks using standards. Some of the more relevant techniques are: DSF – Diagnosis Safety Form, DCT – Diagnostique et Conditions de Travail, SDQ – Safety Diagnosis Questionnaire.
- Hazard and Operability studies (HAZOP), is designed to identify safety and operability problems using a systematic and structured approach by a multidisciplinary team. Using brainstorming and certain keywords deviations in the process from the normal functioning are identified, their causes and consequences on the process, humans and environment are evaluated qualitatively. HAZOP is one of the most used methods in technological hazard evaluation.
- Failure Modes and Effects Analysis (FMEA) determines how the failures of certain system components affect the optimum system performance. This ensures that proper safety measures are taken and safety systems are installed. The FMEA is a complementary analysis of Layer Of Protection Analysis (LOPA).

The qualitative methods focus mainly on identifying the possible hazards and are usually followed by a more thorough quantitative analysis (QRA).

In order to quantify the risk historical data or mathematical algorithms can be used to estimate probabilities of failures and frequencies of accidental scenarios. Proper safety measures can be applied efficiently only after a thorough quantitative risk analysis. QRA is the starting point for more complex processes like Land-use Planning, and Emergency Planning. High quality data also provides decision-makers with accurate information about the situation.

Vulnerability (V [-]) should be introduced in the risk formula shown below:

$$R = F \times C \times V \text{ [loss/year]}$$

where F [event/year] is the frequency of the event and C [loss/event] represents the magnitude of the consequences [2].

Consequence analysis relies on theoretical models to simulate events like release, dispersion, fire and explosion of different hazardous materials. Generally, risk assessment methods begin with the identification of hazards and vulnerabilities. Consequence based risk analysis has an approach that starts with the identification of the major consequences by analyzing the potential accident scenarios and the effects of the accidents upon the environment, human factor and structures. Then the process searches for combinations of hazard and vulnerability that could result in the most serious consequences.

The advantage of the consequence based risk analysis is that it will show how qualitative threat, vulnerability and consequence information can be combined to derive a qualitative value for risk and offer an easy-to-understand graphical way to present risk assessment results [3].

Assessment of vulnerability

Vulnerability can be defined as the proneness to experience adverse impacts or failures, or as the characteristics of a person or a group to anticipate, cope, resist and recover after a hazardous impact. Vulnerability involves a combination of factors which determine the level of the hazard for health, life, and damage of property following an incident.

Quantitatively the vulnerability can be expressed as a number between 0-1 or 0%-100%.

The vulnerability depends on the infrastructure and socio-economical conditions of the area. With reducing the hazards we are reducing the vulnerability, too. In many cases the increased number of victims is not due to bigger hazards, but the amplification of vulnerability of population. Some social groups are more vulnerable than others, in function of sex, age, corporeal condition etc.

A major component of a risk assessment is assessing the area's vulnerability to hazards. Regional vulnerability is determined by evaluating hazard exposure and coping capacity. For determining the vulnerability it can be selected a set of indicators. In case of technological disasters these indicators can differ from one case to another, depending on the possible accident consequences [4].

Mitigation of vulnerability is strongly correlated with socioeconomic development, and with social stability. Therefore it can be used to reduce the causes of environmental vulnerability, not only the consequences in terms of disastrous casualties and losses [5].

The modeling and simulation of chemical accidents

In general, models can be used to measure and represent; describe structure, behavior and pattern; reconstruct past or predict future behavior; generate and test theories and hypotheses [6].

Consequence assessment and modeling is based on models for source-term definition, dispersion calculations, fire and explosion, and finally vulnerability estimation of health effects [1].

The most important issue in simulation of chemical accidents is to find the right model which fits to the purpose of the study. For example, different models should be used in case of a toxic dispersion simulation for flat and complex terrain. Two dimensional models can be applied for short distances where the topography of the terrain is not significant. 3D dispersion models are very useful for major releases above complex topography terrain. One of these 3D modeling systems is the SEVEX (SEVeso EXPert) system, which is built from three different parts:

- The *SEVEX-Meso* is a complex 3D terrain and meteorological model which solves the Navier-Stokes equations, considering the terrain roughness (the topography of the terrain), the land use of the terrain (five categories: water, forest, urban, grass-land and the mixture of the previous four) and the solar radiation and heat transfer between the ground and the atmosphere.
- The *SEVEX-Toxic* module is a Lagrangian 3D dispersion model that simulates the passive transport and dispersion of toxic and flammable material.
- The *SEVEX-Source* module simulates different types of releases and the effects of accidents. These three modules combined in SEVEX View software compute the worst-case realistic conditions of an accident. SEVEX View is the only software that considers both the SEVESO directives of the European Commission, and U.S. EPA guidelines. The software was built to simulate major industrial accidents, so the model is designed for impact zones from 1 to 18 km. The software was developed by the *Lakes Environmental Software* from Canada, in collaboration with ATM-Pro, Belgium [7].

A very popular model is the SLAB atmospheric dispersion model for denser-then-air releases over flat terrain. This model does not calculate source emission rates. It assumes that all source input conditions have been determined before. The current version of the *SLAB* model treats the following situations: instantaneous releases, finite and continuous releases from different sources like evaporating pools on land, horizontal or vertical jets, and instantaneous or short-duration evaporating pool on ground level.

The atmospheric dispersion of the released gas is calculated by solving the mass, heat and momentum flux conservation equations. The mathematical model is based on the theory of the superficial layer. The description of the variation that occurs in the gas plume is given by a differential equation system based on the total mass conservation and for the components, on the heat and impulse conservation for the three directions. The model is completed with the equations which describe the shape of the vapor cloud and physical equations [8]. The SLAB View software is the windows interface for the SLAB model and it was created by the Lakes Environmental Software in Canada.

Comparative analysis of a possible accident

In the followings are presented simulations of a chemical accident involving major liquefied chlorine release from storage vessel, a comparison between results obtained with 2D SLAB dispersion model and 3D SEVEX model.

The selected site is located at a height of 150 m above sea level, at 10 km from the city of Ramnicu-Valcea, Romania, on the right side of the Olt River on an alluvial terrace 7 meters above Govora Lake. The facility is 2 km long and 1,5 km wide. The site is surrounded by hills with a maximum altitude of 450 m, and the mean absolute altitude is 150 m.

With the building of the dams on the Olt valley, the surface covered by water increased, resulting in an increase of the relative humidity in the site's area, with a mean of 76%. The total annual precipitation in the area is 710,5 mm.

The wind circulation, both direction and speed, are influenced by the area's landscape. The Olt Valley has an obvious funneling effect, the highest wind frequencies occurring from the North (10,2%) and South (13%). The atmospheric calm situation has the highest occurrence rate (37,4%). The mean wind speed varies between 0.8 and 2 m/s. The dominant atmospheric stability conditions are class D (neutral), E (slightly stable) and F (stable) [9].

Simulations of the accident have been performed considering the meteorological "worst case scenario", for daytime, with a complete cloud cover, a 70% relative humidity, stability class D, ambient temperature of 20^{o}C, and for nighttime with no cloud cover, a 90% relative humidity, stability class F, ambient temperature of 10^{o}C.

The storage vessel has the following technical characteristics: length, L = 11 m, diameter d = 3 m, maximum capacity of storage equal to 90 tons of chlorine at 20^{o}C storage temperature, 80% filling level at 10 bar service pressure.

The SEVEX simulation considers the complex topography (GTOPO 30 database) and the land use of the terrain (CORIN database), calculating the wind direction and velocity for every 1 km x 1 km square using a 2 m/s synoptic wind [7]. The wind speeds for 36 directions were computed, for every multiples of 10^o, from 0^o to 350^o. For this reason, the overall area of danger is estimated based on a discrete set of results, generating the so called plume fingers.

RESULTS AND DISCUSSION

In the followings are presented the consequence maps obtained from SEVEX and SLAB simulations, for the daytime scenario considering the wind direction form S-SW and for the nighttime scenario from N-NE. These wind directions can be found most frequently in the area.

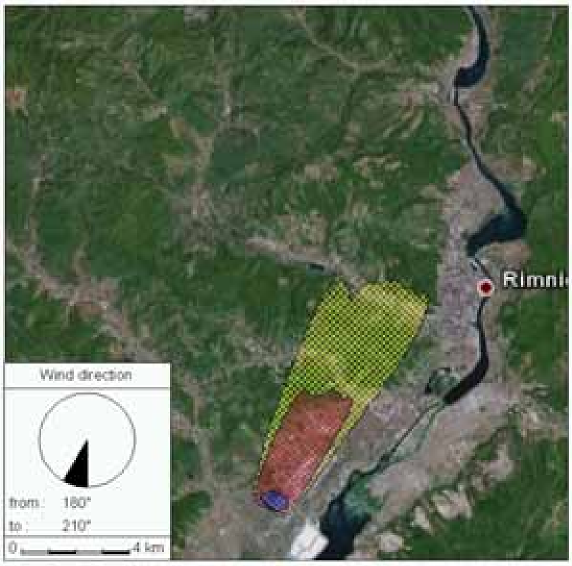
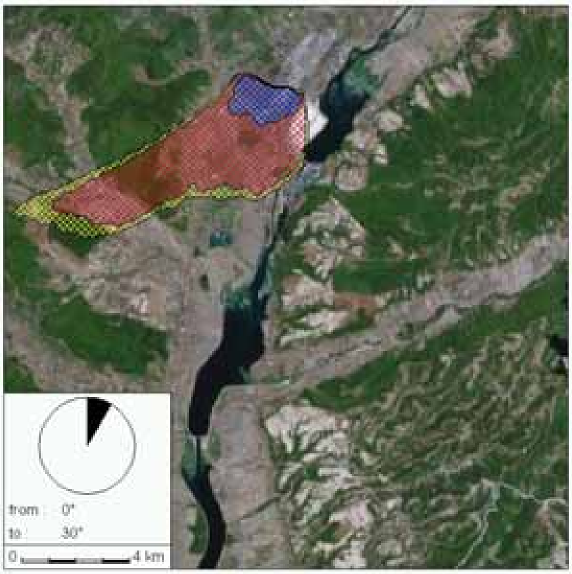


Figure 2. SEVEX View simulation for daytime scenario.



Risk	Orders	Criteria
None	No change in behaviour	C < 3,0 ppm p < 20 mbar
Temporary diseases Superficial injuries	Avoiding exposure advised	3,0 < C < 10,0 ppm 20 < p < 45 mbar
Permanent injuries out door	Self-confinement exclusion	10,0 < C < 293,0 ppm 45 < p < 100 mbar
Danger indoor	Evacuation	293,0 < C ppm 100 < p mbar

Figure 3. SEVEX View simulation for nighttime scenario.

In the SLAB View simulations we used the source emission rates calculated by the SEVEX model.

The distances obtained for the following typical concentration levels after one hour exposure: LC50 (Lethal Concentration 50%) = 293 ppm, IDLH (Immediately Dangerous to Life or Health concentration) = 10 pmm and EEGL (Emergency and Continuous Exposure Guidance Level) [10], are presented in Table 1:

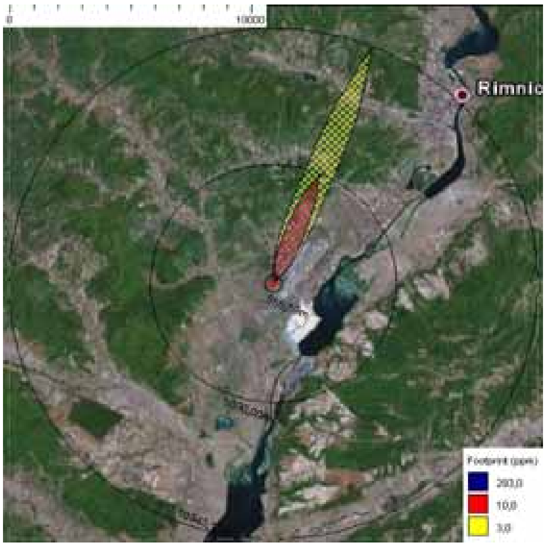


Figure 4. SLAB View simulation for daytime scenario.

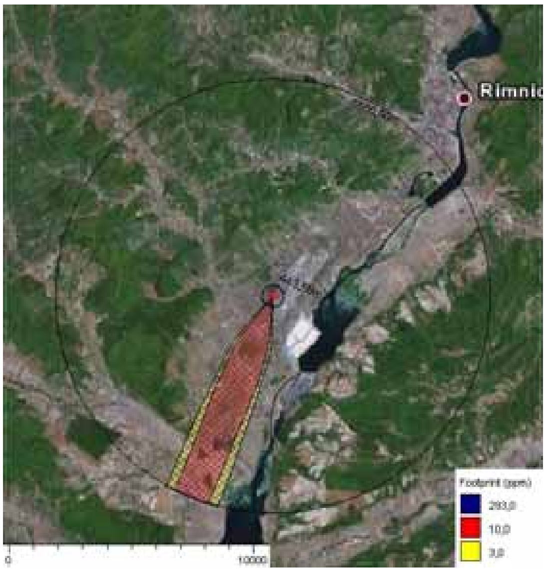


Figure 5. SLAB View simulation for nighttime scenario.

Table 1. Distances for the concentration levels of concern

SEVEX	**Concentration level**	**Daytime scenario**	**Nighttime scenario**
	LC50	651,9 m	1632,5 m
	IDLH	5042,3 m	6630,6 m
	EEGL	9780,8 m	9527,1 m
SLAB	**Concentration level**	**Daytime scenario**	**Nighttime scenario**
	LC50	357 m	443 m
	IDLH	5000 m	8880 m
	EEGL	10943 m	> 15000 m

The SEVEX model considers a possible fluctuation of 30 degrees in the wind direction and the results are presented considering this wind sector. The distances obtained in SEVEX, shown in Table 1, are the highest values from this 30 degrees wind sector. The SLAB simulation considers only one wind direction.

As seen, the daytime simulation results regarding the maximum distances are showing pretty close values in both cases. There are major differences in the nighttime simulation results; the distances obtained with the SLAB model are overestimated. The SLAB model does not take into account the topography of the terrain; it assumes that the dispersion is over a flat terrain with a specific roughness. This can lead to over or underestimation of danger zones for major releases, where the dispersion process can reach large distances.

CONCLUSIONS

The Chemical Risk Assessment is an important tool in the development of Safety Reports and Emergency Plans. The combination of qualitative and quantitative analysis methods can offer a good solution for the estimation of risk zones.

The aim of the Risk Analysis process is to reduce uncertainties by increasing safety levels by developing more efficient Emergency Plans for the restriction of insulation perimeters, offering immediate decisions, detailed, accurate and steady instructions.

Simulations of a possible chemical accident involving liquefied chlorine at a large storage facility have been preformed, and obtained dispersion results using two commercial software packages, SLAB View and SEVEX View.

The simulations show that the situation could become extremely dangerous to the nearby inhabitants, therefore an efficient external emergency plan must be developed and according to the Seveso III directive, the population should be informed about the hazards involved, emergency individual and collective measures, warning and evacuation plans.

In order to achieve this, high quality data is required, following the principle: “good quality data leads to good decisions”. With the use of high performance software like SEVEX, we can aid the Romanian stakeholders and decision makers with information in order to develop efficient plans and policies.

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