CHEMICAL ENGINEERING TRANSACTIONS

VOL. 43, 2015

A publication of AIDIC

The Italian Association
of Chemical Engineering
Online at www.aidic.it/cet

Chief Editors: Sauro Pierucci, Jiří J. Klemeš

ISBN 978-88-95608-34-1; **ISSN** 2283-9216

DOI: 10.3303/CET1543324

An Approach to Risk Evaluation in Connection with Fire Scenarios from a Cruise Ship

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The main threat from ship accidents is connected to the transport of chemical/petrochemical products and possible environmental impact from leakages. However, in case of sensitive environmental targets, a serious threat can be represented by cruise ship too, as demonstrated by Costa Concordia, a perfect example of a modern cruise ship that capsized in 2012, under calm sea and clear visibility conditions near the shore of Giglio Isle, Italy. This paper approaches cruise risk assessment in a vulnerable area located about 25 km East of Genoa with 13 km of coastline into the Ligurian gulf. The framework allows the attainment of cautious values of the maximum affected and hazardous areas, in connection with fire scenarios and smoke spreading. The conservative results are to be considered in setting-up emergency planning with appropriate response equipment, fire-fighting and lightering resources and can be a powerful tool to design optimal ship route and temporary docking points for cruise tourism, thereby balancing economic issues and inherent safety criteria.

1. Introduction

Despite of all the scientific and technical advancement in marine technologies, which sharply contributed to improve the overall safety in shipping industry and related activities, accidents still do happen while the public tolerance level for acute and environmental risks remains low (De Rademaeker et al., 2014). Generally speaking, marine traffic risk is coupled with transport safety, shipping efficiency, distribution reliability and loss prevention, while risk management in maritime ports assumes high importance, as accidents at industrial ports can results in personnel injury or death, as well as in severe environmental damages (Fabiano et al., 2010). Discrete storage of hazardous chemicals or energetic materials in port areas, in transportable containers (Fabiano et al., 2013), or as open piles poses different hazards, as compared to conventional storage installations, requiring ad hoc solutions to reduce environmental impact (Fabiano et al., 2014) and rigorous safety standards. The main threat from ship accidents is connected to the transport of chemical/petrochemical products and possible environmental impact from leakages. The most effective protective actions, such as release containment and recovery, are mainly based on the knowledge of the long time evolution of the oil spot (Palazzi et al., 2004). By analysing statistics in this regard, it is noteworthy noting that few high profile spills are responsible for a large percentage of the oil spilt: e.g. in 1991 by ABT Summer – Angola incident ($2.6\cdot10^5$ Mg) and Haven – Genoa Italy ($1.44\cdot10^5$ t); in 1989 by Exxon Valdez – Alaska ($3.7\cdot10^4$ t) and Khark V-Atlantic coast of Marocco ($8\cdot10^4$ t) and Sea Empress - Galles UK ($7.2\cdot10^4$ t). However, in case of sensitive environmental targets, a serious threat can be represented by cruise ships too, as demonstrated by Costa Concordia, a perfect example of a modern cruise ship which was built in 2004/2005 by Fincantieri - Sestri Ponente, equipped with state-of-the-art electronic aids to navigation, security and resources management systems. The ship capsized in January 2012, causing 32 fatalities, under calm sea and clear visibility conditions, having struck a rock in the Tyrrhenian Sea, near the shore of Giglio Isle, on the West coast of Italy. Concordia accident provides an illuminating example of the types of human and organizational failures that can result in major accidents. The accident chances in modern cruise liners are very rare but if an accident

Please cite this article as: Vairo T., Pastorino R., Rehman A., Fabiano B., 2015, An approach to risk evaluation in connection with fire scenarios from a cruise ship, Chemical Engineering Transactions, 43, 1939-1944 DOI: 10.3303/CET1543324

happens, its consequences can be disastrous as they carry several thousands of people on board (Vanem et al., 2006). When Costa Concordia was struck into the sea, its tanks were full of 2,380 t of heavy diesel that could leak into the sea causing worst destruction of the ecosystem. Large and catastrophic spills belonging to the category of relatively rare events pose serious ecological risk and result in long-term environmental impact, depending upon the quality, chemistry and properties of oil and its sensitivity to biological resources impacted, as well as in economic loss to coastal infrastructure. Risk assessment of vulnerable coastlines and near shore waters is also an essential element of oil spill preparedness and can be done by evaluating ship traffic and likelihood of accidents along with likelihood of releases from fixed offshore installations and impact on the surrounding waters (Galt et al., 1999). Fire hazard to a cruise ship due to fuel leak, electrical cables malfunction, engine room troubles or caterings is considered to be the worst scenario in shipping industry because of life losses and its serious environmental consequences (smoke spreading and oil spill) on the surrounding environment and marine life (Wang et al., 2004). A striking example is provided by the Norman Atlantic ferry, a ro-ro vessel designed to carry wheeled cargo, such as automobiles, trucks, semi-trailer trucks, trailers, and railroad cars that are driven on and off the ship on their own wheels. The blaze is believed to have broken out early morning on 28th December 2014, in the lower deck garage of the vessel, the fire apparently quickly went out of control and the captain sent a distress signal when the Norman Atlantic was 35 nautical miles northwest from Corfu island, between Italy and Albania. A total of 503 passengers and crew members were on board and the long lasting fire resulted in more than 11 fatalities and nearly one hundreds injured people. The severity of this accident scenario was related to the exposure to a very broad range of toxic combustion products from truck/car fire in confined environment (Vianello et al., 2012) and to the extent of their duration and bio-persistence. In case of cruise liner fire, compounds such as carbon dioxide, methane, chlorofluorocarbons, aerosols, nitrogen oxides, sulphur oxides, carbon monoxide and particulate matter in the form of propagating smoke potentially affect visibility, human and environmental health. Numerical risk models are powerful tools for environmental risk assessment of fire scenario representing a proactive approach allowing determining the probability of such a situation to occur and the expected consequence of the incident (Vanem et al., 2006). In the present paper, a theoretical framework to assess environmental risk caused by fire from tank rupture, or catastrophic failure of a cruise ship is presented by utilizing numerical methods. Risk of the people onboard of the ship is outside the subject of the study. By a Risk Matrix Approach, the combination of frequency and severity rankings is used for the estimation of the "Risk Ranking Number" (RRN), categorizing risks according to their importance (Loughran et al., 2000).

2. Statistical overview on sea risk

The statistics about the frequency of casualties can provide the quantification of the real safety levels involved in the shipping activity, allowing as well an overall quantitative view on the main failure modes for different ship types. In order to establish the expected frequency for the considered events, various experts and data sources were used to ensure a solid foundation for the quantitative evaluations. Statistical data were used where available, other ship types, as such data can be transferred to cruise navigation without difficulties. Darbra and Casal (2004) showed a clear upward trend regarding the frequency of accident occurrence in port areas: starting from 471 accidents occurring in seaports in the years 1941-2002, they concluded that the trend is in part attributable to the increase in port activity and the growth in sea transport of hazardous substances. In the first step of this paper we considered, in detail, the analysis of accidents during HazMat sea transport, over the time span 2002-2013. A detailed database was elaborated starting from different sources and data banks, with a total accident number of 1673 and collecting information on the vessel involved, owner, nationality, dead weight tonnage, ship age, amount and immediate cause of oil spilt, location, event severity.

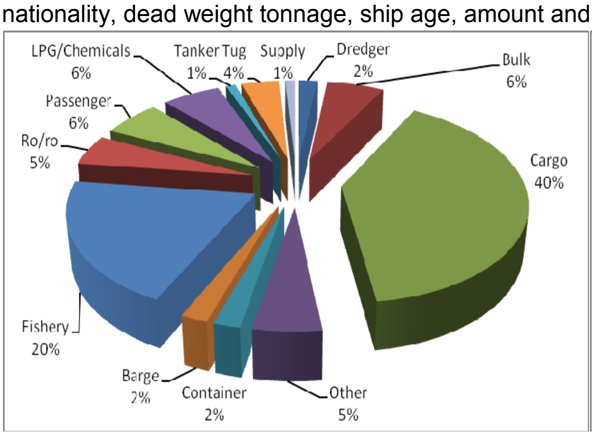

Figure 1: Ship accidents sorted by vessel type.

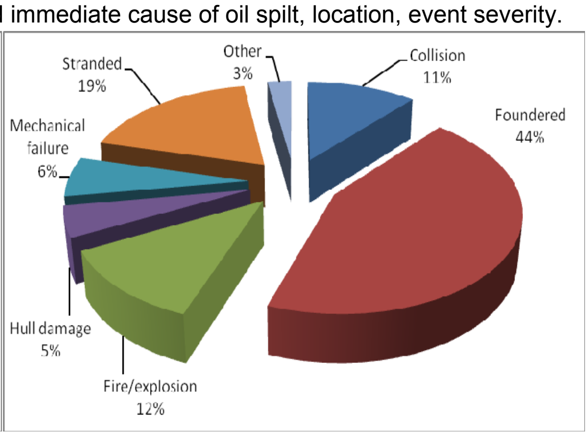

Figure 2: Immediate causes of ship accidents.

By analysing Figure 1, it can be noticed that, as expected, the main ship types involved in these accidents are cargo (40%), fishery (20%) and passengers (6%). From Figure 2, it can be argued that the three main causes of accidents are, respectively, foundering (44%), stranding (19%) and failures with fire/explosion (12%). These figures are obtained regardless to accident severity, so they include a striking percentage of accidents that resulted in low magnitude damages, often limited to the ship equipment. In this respect, it must be evidenced that according to a previous study covering the time span 1987-1998, when considering only major accidents, causing large spills and/or life losses, the immediate causes are mainly human errors, or severe atmospheric events, with other primary accident causes connected to on-board fires and explosion, followed by collision. These considerations highlight the importance of the navigational aids, of ship crew training as well as of technological equipment and ship structural reliability. An important role is played by human errors, to be considered in all phases of the process i.e. design, construction, operation and ship management. Concerns about the poor management standards, possible safety deficiencies and the contribution of the human error and management shortcomings on marine casualties have motivated the introduction of the International Safety Management (ISM), also given the major challenge offered by ad hoc safety management system for reducing the spill frequency due to failure (Milazzo et al., 2010). The high striking percentage of accidents caused by human errors is further confirmed by analysing statistics referred to the year 2013, evidencing three main headings as follows: foundering (72.5%), stranding (12%) and fire/explosion (12%).

3. Cruise liner environmental risk assessment

This paper approaches risk assessment in a vulnerable area represented by Portofino promontory, located about 25 km East of Genoa with 13 km of coastline into the Ligurian gulf. The peninsula has a rough coastline, steep seabed and high indices of biodiversity, both in its terrestrial and marine ecosystems. Since 1935, a terrestrial protected area known as Portofino Park was established and since 2001 the seaward area became a marine reserve. Nowadays, the whole area maintains the characteristics of an attractive tourist resort and its present economy almost exclusively relies on onshore and offshore tourism. As amply known, the release of oil in case of accident to a cruise ship is considered one of the most serious threats to coastal and marine environment exerting immediate and potential long term consequences. A modeling study was conducted, to assess possible environmental consequences along the coast of Portofino and Santa Margherita Ligure, and following objectives were considered as basis of the cruise environmental risk assessment study: to identify the possible causes of damage to the ship leading to loss of containment; to quantify the physical effects through fire consequence modeling, due to loss of containment in terms of radiation and toxic/flammable dispersion; to evaluate the unwanted event frequency, by using frequency obtained from historical data and, at last, to perform a qualitative risk assessment based on event frequency and consequence results.

3.1 Materials and methods

The field study was conducted in the area shown in Figure 3 showing Portofino promontory and coast.

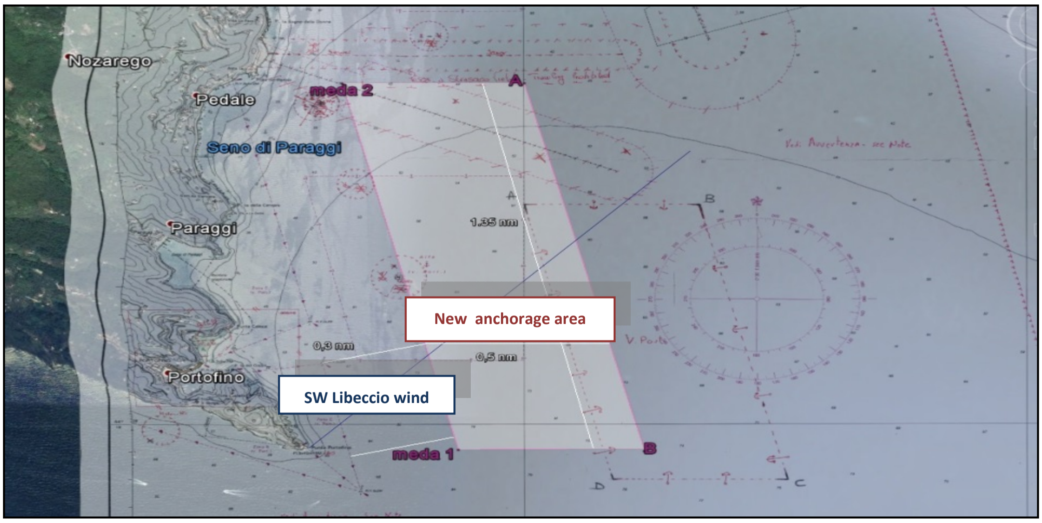

*Figure 3: Geographical study area and corresponding anchoring points identified by following coordinates DMS **A**: 44°19’ 13,95” N 9°13’ 59,04” E; **B**: 44°17’ 54,42” N 9°14’ 27,33” E; **MEDA1**: 44°17’ 54,70” N 9°13’ 43,47” E; **MEDA2**: 44° 19’ 13,82” N 9° 13’ 16,12” E.*

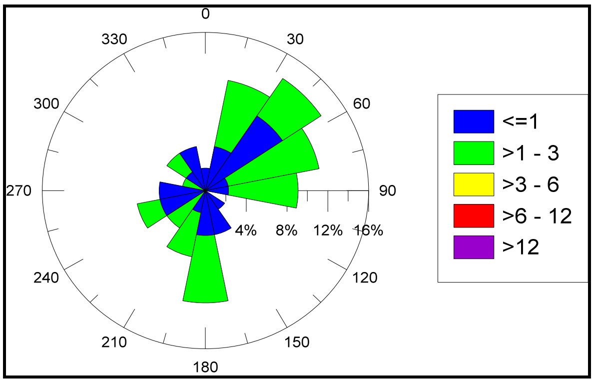

Figure 4: Portofino Mount wind rose (year 2014).

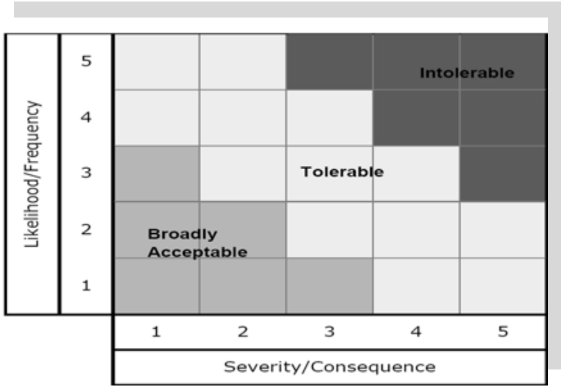

Figure 5 : Simplified environmental risk matrix.

The consequences evaluation arising from the development of a fire on board of a cruise ships was performed making reference to the source points corresponding to the identified temporary anchoring points of the cruise ships. These points were cautiously selected to protect vulnerable communities of designated marine features, with the aim of meeting both the environmental and safety goals. Figure 4 depicts the wind rose obtained from meteorological statistical observations over Portofino Mount and defining the long term probabilities of wind directions and speeds. The 2F weather stability class was adopted for the consequence modelling, considering worst-case consequence in connection with flammable gas dispersion. For the purpose of the present simplified evaluation we considered one event/scenario: the random rupture of ship fuel tank causing the release of a flammable and toxic substance. The fuel characteristics are as follows: flash point 325 K; LFL 1.3 % UFL 6%; vapour pressure 2.17 mm Hg at 294 K; specific gravity 0.841 at 289 K; boiling point 556-611 K at 760 mm Hg; H_2O solubility < 1 mg/mL at 294 K. Based on historical data, hole sizes corresponding to medium size leak and catastrophic failure were considered and a qualitative estimation of the frequency of each loss of containment event and associated scenarios was calculated using a combination of API 581 standard and event tree technique. In this respect, a peculiar uncertainty is related to ignition probability (Paci et al., 2011). The corresponding fire evolution scenarios at each point were evaluated considering as well the propagation of the combustion fumes resulting from fire. A multi-method approach to effect evaluation was performed utilizing standard software EFFECTS 5.5 (TNO), for the evaluation of the impact zones of a fire, ALOFT-FT 3.1 (A Large Outdoor Fire plume Trajectory) of NIST, for the propagation of smoke caused by the fire and at last ADMS 5 (CERC) for the atmospheric dispersion of the combustion gases. For the assessment of the acceptability criteria of environmental risk, we considered a simplified ALARP matrix (see Figure 5), based on the definition of risk as the relation between frequency and the number of people/environmental targets suffering from a specified level of harm in a given population from the realization of specified hazards.

4. Results and discussion

As amply reported, rate and amount of smoke produced during a fire scenario depend upon the type and quality of material involved in the fire, combustion rate and the rate at which air is entrained into the plume. Utilizing the numerical procedure previously outlined, the scenario corresponding to a medium size leakage and subsequent fire was based on a maximum release rate corresponding to 305 kg/min, a total released mass of 12,654 kg and a maximum pool diameter of 55 m.

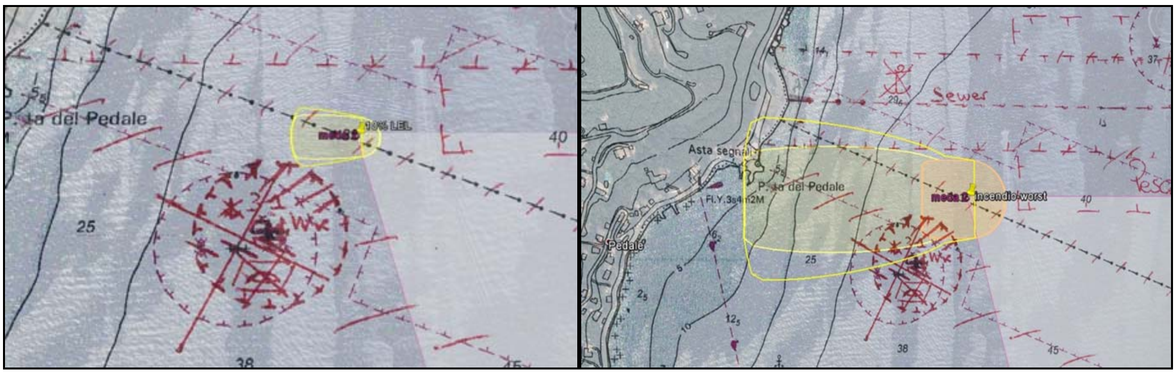

Figure 6 a, b: Extension of the hazardous area corresponding to 10% LFL East wind source at Meda 2 point, respectively considering medium size leakage (left-hand side) and catastrophic tank failure (right-hand side).

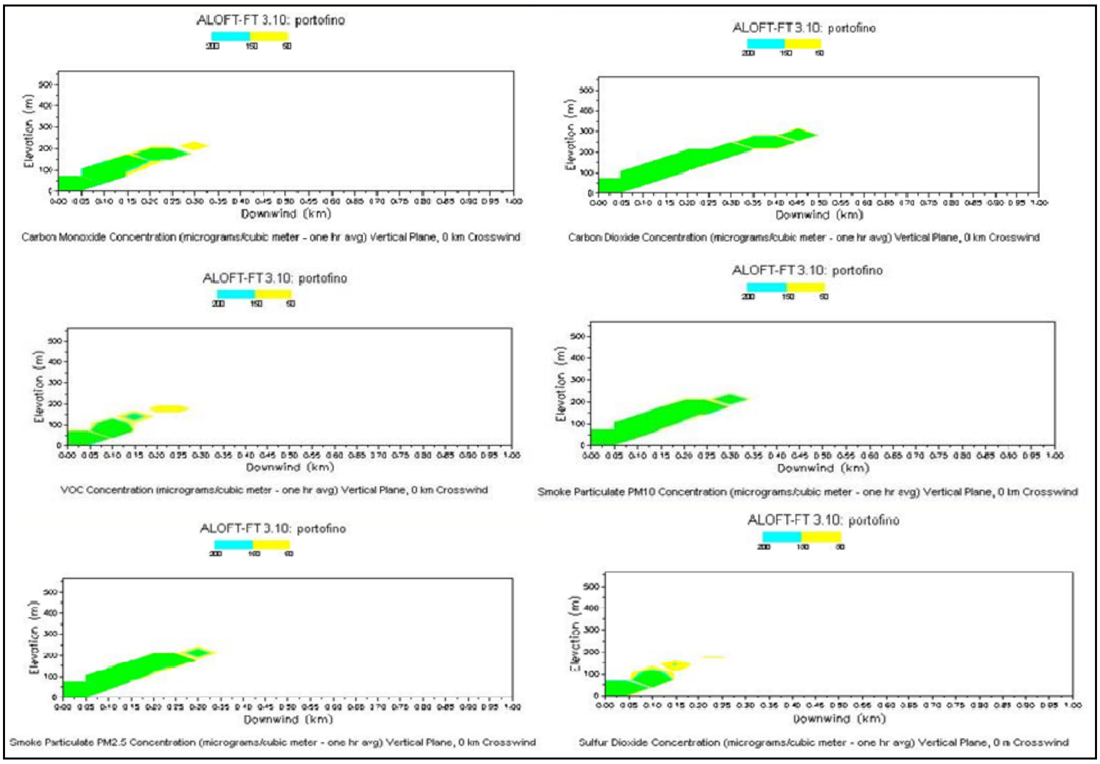

Figure 7: Downwind concentration profiles of main combustion products for catastrophic tank failure.

As clearly depicted in Figure 6a, the maximum downwind extension of the hazardous area at 10% Lower Flammable Limit (LFL) can be calculated as corresponding to 86 m in connection with the point Meda 2. The scenario corresponding to a catastrophic leakage and subsequent fire was based on a maximum release rate corresponding to 4,000 kg/min, a total released mass of 231,210 kg and a corresponding maximum pool diameter of ca. 200 m. From Figure 6b it can be argued that the maximum downwind extension of the hazardous area at 10% LFL is calculated as corresponding to 477 m, in connection with the point Meda 2 representing the most sensitive case. The whole numerical modelling study considered following combustion products on the basis of the utilized fuel: PM10; PM2.5; CO; CO_2; SO_2; VOC. As an illustrative example, the corresponding plume rise and extension concerning the combustion products referred to the worst case event, impacting the coast are reproduced in Figure 7. Considering the vulnerability of Portofino promontory, we performed a long-term evaluation of potential environmental damage considering the atmospheric dispersion of combustion gas in connection with the standard engine activity of the ship. To this end, we considered transit and temporary anchorage activities as resulting from statistics covering the yearly time span and frequency commonly dedicated to cruise in the Mediterranean area.

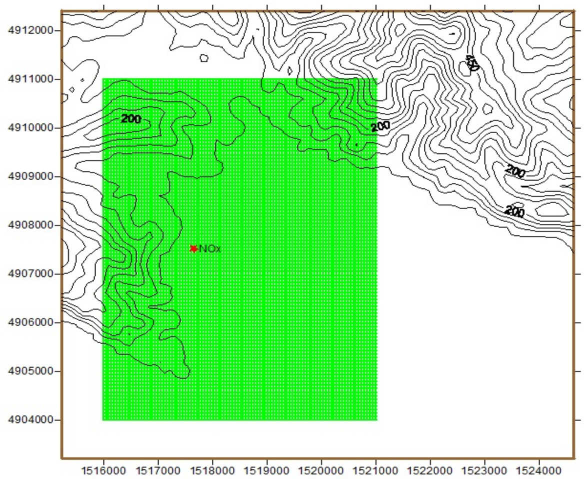

Figure 8: ADMS calculation domain and receptor grid.

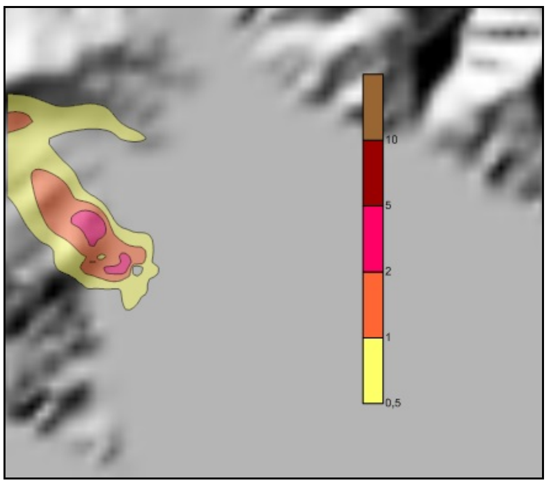

Figure 9: Long-term nitrogen oxide fallouts (µg /m³).

The effect distance is considered as the distance at which an observable adverse effect occurs to the biophysical environment. The dispersion path of the combustion products was cautiously evaluated making reference as emission source to the already mentioned anchoring point Meda2, by means of the ADMS 5 model coupled with the meteorological pre-processor FlowStar. Input data for the three-dimensional wind field elaboration were obtained from the statistical wind rose covering the period May-October 2014 (Figure 4). As a relevant illustrative example, Figures 8 and 9 depict respectively the calculation domain with the receptor grid and the immission isopleths referred to nitrogen oxides, well-known precursors for photochemical ozone formation characterized by critical level for all vegetation types corresponding to 30 μg/m^3.

5. Conclusions

The improvement of risk prevention in sensitive areas can be approached by carrying out an environmental risk analysis, in which the possibilities of both accidental and routine emissions are identified and analyzed considering the various effects. To this end, firstly a simplified framework to assess environmental risk from ship cruise in connection with fire scenarios was presented. For the purpose of this environmental risk analysis the focus was to estimate a reasonably conservative effect distance at which an observable effect could occur: the worst case was calculated under East wind condition and is referred to carbon dioxide with a distance of nearly 1 km, in connection with a maximum plume height of 250 m. The catastrophic failure of the tank at Meda2 is the only accidental scenario impacting environmental receptors on the promontory and is characterized by an expected frequency lower than 10^{-7} y^{-1}, even considering that the limitation of the estimate is within one order of magnitude. All the other accidental fire scenarios do not affect the coast environment. Likewise normal continuous emissions, well controlled in industrial operations, a further potential of environmental harm was evaluated as resulting from normal ship transit. The atmospheric dispersion map expressed in terms of hourly average over the cruise season, evidenced a maximum NOx corresponding to 10 μg/m^3. The knowledge of the ship cruise risk on sensitive environments due to the fire and the subsequent worst case evaluation allow concluding that the risk lies in the broad acceptable region. The simplified approach can be used to make comparative evaluations through relative ranking of risk reduction strategies (e.g. anchoring point selection, engine/ship management and operation etc.) and develop risk-based decision making. Additionally, it can build awareness on safety and emergency procedures, so as to reduce site vulnerability and increase the overall safety of the given vulnerable area.

References

Darbra R.M., Casal J., 2004, Historical analysis of accidents in seaports, Safety Science 42, 85-98.

De Rademaeker E., Suter G., Pasman H.J., Fabiano B., 2014. A review of the past, present and future of the European Loss Prevention and Safety Promotion in the Process Industries. Process Safety and Environmental Protection 92, 280-291.

Fabiano B., Currò F., Reverberi A.P., Pastorino R., 2010, Port safety and the container revolution: A statistical study on human factor and occupational accidents over the long period, Safety Science 48, 980-990.

Fabiano B., Currò F., Reverberi A.P., Palazzi E., 2014, Coal dust emissions: from environmental control to risk minimization by underground transport. An applicative case-study, Process Saf Environ 92, 150-159.

Fabiano B., Kersten R.J.A., Barbucci A., Boers M.N., 2013, Experimental and theoretical approach to the assessment of stability criteria for safe transport of ammonium nitrate based emulsions. Chem Biochem Eng Q 27(3), 307-317.

Galt J. A., Payton D.L., 1999, Development of quantitative methods for spill response planning: a trajectory analysis planner, Spill Sci Technol Bull 5, 17–28.

Loughran C., Pillay., Wang J., Wall A., Ruxton T., 2002, A preliminary study of fishing vessels, Journal of Risk Research 5, 3-21.

Milazzo M.F., Maschio G., Uguccioni G., 2010, The influence of risk prevention measures on the frequency of failure of piping, International Journal of Performability Engineering 6, 19-33.

Palazzi E., Currò F., Fabiano B., 2004, Simplified modelling for risk assessment of hydrocarbon spills in port area, Process Safety and Environmental Protection 82, 412-420.

Pesce M., Paci P., Garrone S., Pastorino R., Fabiano B., 2012, Modelling ignition probabilities within the framework of quantitative risk assessments, Chemical Engineering Transactions 26, 25-31.

Vanem E., Skjong R., 2006, Designing for safety in passenger ships utilizing advanced evacuation analyses. A risk based approach, Safety Science 44, 111–135.

Vianello C., Fabiano B., Palazzi E., Maschio G., 2012, Experimental study on thermal and toxic hazards connected to fire scenarios in road tunnels. J of Loss Prevention in the Process Industries 25, 718-729.

Wang J., Lois P., Wall A., Ruxton T., 2004, Formal safety assessment of cruise ships, Tour Mana 25, 93-109.