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An Oil Pipeline Catastrophic Failure: Accident Scenario Modelling and Emergency Response Development

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In spite of advanced technologies, inherent safety and safety management system, pipeline loss of containments and large-scale releases of hazardous substances are still common accidents leading to severe consequences for human health, environment and assets, both in Europe and in developing Countries. This paper presents a detailed analysis of the catastrophic failure of a pipeline connecting the port oil terminal with a downstream oil plant, in the North part of Italy, causing a major oil spill into a river and subsequently into the Genoa harbor (Italy). Firstly, the impact of atmospheric dispersion is evaluated then, assuming oil containment failure, the hydrodynamic dispersion of the spill into the sea is studied. By means of numerical methods, we performed a consequence-based assessment incorporating the effects, the hazardous distance and the reaction time scale, related to oil spill. Results are focused on the atmospheric dispersion of the “key” oil volatile fractions and the propagation in the sea of the medium-heavy fractions, both performed by Lagrangian simulations.

1. Introduction

Large-scale pipeline release of hazardous materials can give rise to severe accident scenarios and environmental degradation, with transboundary effects in case of watercourses, or international seas. Hazardous pipelines are not covered by a comprehensive EU pipeline safety legislation and the national regulations of several Member States regulate the construction and operation without any detailed emphasis on complete risk assessment or safety implications. In fact, considering the recent SEVESO III Directive, only the inventory of a pipeline within the boundary of an establishment must be included in the calculation to determine application of the Regulations, while it is assumed that Member States are extending the scope of the Directive in their national laws, or by taking appropriate separate initiatives. It is amply recognized that the main difference between pipeline risk and other plant risk is connected to its character as a line source rather than a series of point sources of risk. Additionally, is difficult to establish threshold criteria for pipelines as the quantity of a hazardous substance that can be released in case of an accident is not readily available, depends both upon the inventory of an isolatable pipeline segment and the assumptions of the time required to shut-down the pipeline and isolate the affected pipeline stretch. A peculiar concern regards existing pipelines, in some cases in use for a time span approaching or exceeding their service life, frequently crossing a “changing environment”, because of both anthropogenic and natural causes. In fact, in relative terms, the problem of HazMat pipeline risk assessment does not come with hazard analysis, or the estimation of failure frequency, but with the calculation of the consequences (Palazzi et al., 2014). Starting from Concawe data (2015), it is possible calculating over a timespan of twenty years, a total release frequency of $2x10^{-4}$/y and average rupture plus spill frequency of $7x10^{-7}$/y per km pipeline. It should be remarked that several uncertainty factors affect both the frequency and consequence assessment in pipework risk assessment and proper

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approach should be applied for the incorporation of uncertainty assessments of unknown quantities, using knowledge-based (subjective) probabilities (Milazzo and Aven, 2012). An additional issue is posed by the correct management of risk arising from plants and pipeline ageing in chemical industry, possibly faced by adopting Risk-Based Inspection (RBI) standards (ASME, API or RIMAP), based on the use of subjective compensatory factors (Bragatto and Milazzo, 2016). We discuss a recent pipeline accident highlighting possible failing elements, related to supervising and managerial issues and enabling the accident to occur. In section 3 we present an overview of the modeling framework developed to provide an effective response to the pipeline spill and the management of the emergency, thus reducing the effects to the environment and people. We present and discuss the results of the applied methods in section 4, followed by overall conclusions of the work.

2.The event

On April 17th, 2016 at 8 p.m. ca. 16” off-ground pipeline crossing varied rural and urban terrain ruptured and spilled approximately 600 m^3 of crude oil firstly into the “Fegino rio” a small tributary river then in “Polcevera river” for a length of about 4.5 km of waterway. The pipeline connecting the port oil terminal of Genoa with a downstream oil refinery and an oil storage area, located in the inner part of Liguria has an overall length of 22 km and an initial diameter of 28” (700 mm); the delivery pressure of the pump station is nearly 70 ate, in correspondence to 350 m height difference. The leak of the transported crude oil Nigeria River Brass occurred in one of the two final pipe runs, did not ignite and there were no casualties. The original construction of the pipeline dates back to the Sixties and the high oil volume spilt is connected to the catastrophic failure and to the distance from the first interception valve for emergency shut-down procedure, located nearly 5 km downstream the rupture point, so that the overall inventory of the given pipeline segment was released. The accident confirms that although pipeline transport is one of the safest means for transporting oil and petroleum products it poses a major hazard to the environment due to the large volumes of hazardous liquids that can be released when a rupture occurs. As an immediate consequence the refinery activity was shut-down and the oil pipeline start-up again only on 24^{th} October 2016, after replacement of 16”- pipe segment of nearly 30 m. Technical investigations on immediate and root causes are currently carried on and consequently they are reportedly locked. Some common identified cause recognized in various pipeline loss of containment (LOC) include, as a not limitative overview: construction defect, erosion/corrosion internal, corrosion external, overpressure due to process control error; external interference; ground destabilization by earthworks or other natural events (accidental chemical releases triggered by natural hazards referred to as NaTechs); base destabilization by overload (ice, snow); intentional act. Safety management elements representing lines of defence against these LOC include (European Commission, 2011):

a. Organization and personnel requirements (roles, responsibilities, education and training,)
b. Hazard identification and risk assessment
c. Inspection and maintenance plans
d. Surveillance of the pipeline route
e. Emergency planning, including training and drills
f. Management and control of changes
g. Program for improvement

In the considered event, it should be evidenced that prior intelligent pig inspection activities (item c), carefully carried out in the year 2013, revealed the existence of nearly 20 critical points, such as early staged of corrosion and pipe thickness reduction, which were partially still under revision and maintenance (item g) (Filetto, 2016). In the literature, it is acknowledged that the minimum retirement thickness represents a critical point in calculating remaining safe life and should be accurately calculated using methods conforming to good industry practice. Following the accident (item e), all relevant emergency activities were carried out, i.e., collecting and analyzing representative water samples; barriers arrangement along the Polcevera river to prevent the oil from flowing into the sea; advanced modelling simulations, to determine the atmospheric concentration of volatile fractions and to estimate the eventual propagation into the sea and trajectories, in case of ineffectiveness of the barriers placed along the river.

3. Modelling framework for emergency response

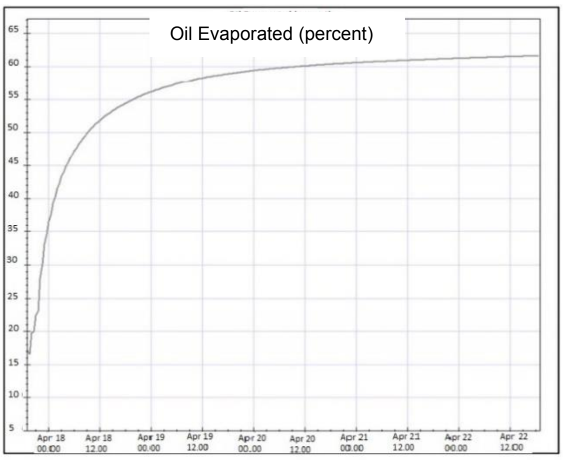
An effective response to a pipeline accident with potential transboundary effects requires adequate response system, well-trained staff and adequate description of the measures needed to limit the consequences for human health and environment, based upon a proper modelling framework. This framework needed for drawing-up contingency plans and laying down operative procedures is developed at two time scales: short-time evolution of the cloud of hydrocarbon vapours, connected to potential toxic effects and flame development; short/medium-time study of the evolution of the drift of oil spills under the influence of wind and tide estimation of the ‘characteristic spreading time” (Palazzi et al., 2004). In this chapter, we describe the development of the external emergency planning according to two subsequent steps, based on different “key oil components”, namely: source modeling, atmospheric dispersion impact of the light HC fractions and modelling by a Lagrangian approach of the hydrodynamic dispersion of the spill, considering the scenario of downstream flow of the oil slick into the sea, due to emergency containment failure.

3.1 Oil spill in water

Crude oil is a complex colloidal mixture with a large number of hydrocarbon and non-hydrocarbon compounds in very variable percentages classified according to their weight into three broad categories: lightweight components, medium and heavy. Light components represent 95% of the soluble fraction and are constituted by aliphatic hydrocarbons - up to 10 C atoms (alkanes and cycloalkane) with low water solubility (few mg/L) and by mono-hydrocarbons (benzene, toluene and xylene) with higher solubility. Globally, the maximum boiling point is 150 °C, while their evaporation approximately ends within 24 hours. The medium components are aliphatic hydrocarbons containing from 11 to 22 carbon atoms (easily biodegradable alkanes, whose concentration in time is a measure of the degradation of oil spilled), diaromatics (i.e. naphthalene) and polyaromatic (i.e., phenanthrene, anthracene, etc.). They are characterized by average boiling point between 150 and 400 ° C, low water solubility and evaporation rate. The heavier components are hydrocarbons with 23 or more carbon atoms in addition to waxes, asphaltenes, polar compounds; they are characterized by minimum water solubility and evaporation rate; long-term persistence in the environment mainly in sediments in the form of lumps, tar or asphalt floors. The herds are composed of hydrocarbons, belonging to the three mentioned categories, in widely differing proportions. When comparing different types of crude oil, an estimate of the environmental persistence may be useful; the flocks mainly made of medium and high molecular weight hydrocarbons are the most persistent in the environment; so they have more opportunity to affect the aquatic organisms, while the flocks made of low molecular weight hydrocarbons are not persistent. Most crude oil constituents are not very soluble in water and the dissolved concentration of water soluble compounds (e.g., benzene) is not controlled by the amount of oil in contact with the water, but by the concentration of the specific constituent in the oil (Charbeneau, 2003). Due to concentration variability, the extent and magnitude of the long-term effects of spills on a given ecosystem is a hard task to be achieved. In assessing the short-term behavior of crude oil spilled into the environment, main physical characteristics to be considered for proper modeling are specific gravity, volatility, viscosity and pour point. Usually, the volatile compounds (low and medium molecular weight) rapidly evaporate, dependently on pressure and mass transport conditions, including wind speed, solar radiation, ambient temperature, size of the slick etc.

3.2 Source and atmospheric dispersion

As previously stated, due to low volatility of crude oil the explosion potential after a pipeline LOC is considered limited while hazard assessment usually implies flash and pool fire scenarios, where the evolution is strictly connected to oxygen and HC depletion (Palazzi and Fabiano, 2012), the level of confinement/congestion and formation of hazardous gaseous buid-up (Palazzi et al., 2013) as well as possible flame impingement (Palazzi et al., 2005). Evaporation of an un-burning oil slick is a rather slow phenomenon unlikely involving flammable cloud formation. Given the catastrophic characteristics of the pipeline failure, unable to generate fine droplets in a spray up in the air, considering as well the atmospheric conditions and the presence of the river, we firstly evaluated the amount of evaporated crude.



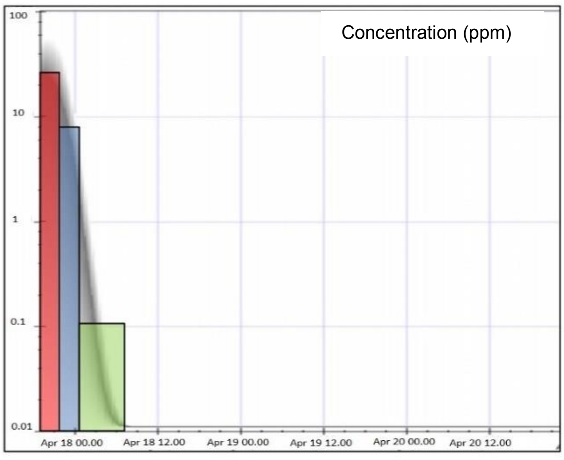


Figure 1: Nigeria River Brass crude oil evaporation. *Figure 2: Airborne benzene concentration (ppm) vs time.*

We took into proper account characteristics of the spilled oil, a sweet medium light crude from Nigeria: API density= 42.7 °API and pour point = - 9 °C. The meteorological data are as follows: wind speed 2 m/s; ambient temperature 18°C; water temperature 18°C; amount released 300 m^3; average river stream velocity 0.1 m/s. As an illustrative example Figures 1 depicts the airborne fractions of the spilled oil mainly consisting of lighter HC components and completing in few days. As a relevant component of the evaporation, the trend of benzene was estimated at the actual weather conditions, under simplifying but conservative hypothesis of no terrain/water absorption. Figure 2 evidences that the concentration remains for several hours above the olfactory threshold (12 ppm), while it exceeds the occupational exposure limit connected to inhalation hazard for operating personnel, which is considered only as a scale reference (TLV-STEL=2.5 ppm). Exposition to benzene concentration in excess of IDLH = 500 ppm can lead to unconsciousness and even to death, while for protecting aquatic biota, the lowest acute toxicity threshold protective of is set at 7.4 ppm (USEPA, 2001). Following the evaporation estimate, the iso-concentration curves along the river were evaluated. Simulation runs were accurately performed according to a modeling approach previously developed and relying on ADMS model (Vairo et al., 2014). The simulation referred to benzene emission and dispersion along the waterways is depicted in Figure 3 showing the time evolution of the mean hazardous compound concentration under SSW wind speed equal to 2 m/s. The emission curve was divided into three time intervals from time 0 corresponding to the accident: 0-3 h (red area), characterized by an average benzene concentration of 20 ppm; 4-6 h (blue area), characterized by an average concentration of 8 ppm; 7-15 h (green area), with an average emission value of 0.1 ppm, until time 15 h corresponding to negligible benzene concentration. We assumed a linear source along the path of Polcevera river, from the point of release until the sea, represented by poly-line indicated in Figure 4. On this basis, according to temporal concentration distribution, the emission values are respectively from release to L8: 20 ppm; from L8 to L11: 8 ppm; from points L11 to L13-C: 0.1 ppm.

3.3. Oil spill spreading

Following the accident, and the spill into the river, a certain amount of oil reached the mouth of the stream, creating a buffer zone, curbed by the containment barriers. In order to assess the potential impact of an eventual release into the sea, we performed several simulation runs of the oil spill spreading, according to the modeling framework described in Vairo et al., (2016). We adopted a numerical finite volume discretization method of the flow and transport equations in the horizontal dimension, with a non-structured triangular mesh having a variable resolution from offshore and towards the coast, utilizing a Ligurian sea model with a resolution up to 50 m along the coast. Simulations were performed assuming the cautious hypothesis of complete and continuous release from the barriers, while on sea observations demonstrated that only slight occasional slicks occurred. Several modelling runs were performed from April 18th to April 22nd 2016 to assess pollution evolving scenarios; results were compared with direct observations and sampling in the interested sea area. A summary of the results obtained following the medium term evolution of the oil slick is given hereinafter, in form of graphs of immediate readability. Figure 5 provides information on oil spill spreading referred to local time 9 p.m., the day after the event, i.e. nearly 25 hours following the LOC. The simulation evidences how the spill for most of the time is contained within stains inside the dam of the harbor where the river ends, with occasional spills from the eastern mouth of the dam, especially in the evening, as a consequence of the dominant North wind characterizing the weather conditions in the given day. Figure 6 allows visualizing at local time 12 a.m. the location of the particles that left the river mouth the day before, allowing the particles to drift off. The presence of a narrow band outside the east mouth of the dam agrees with direct observations in the sea of iridescent sheens on 19th April 2016.

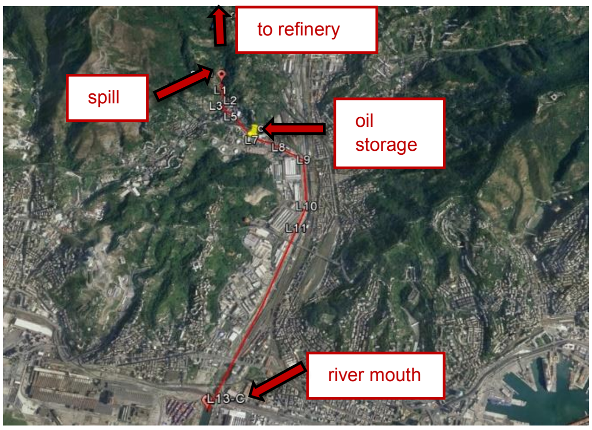


Figure 3: Linear emission source along the river.

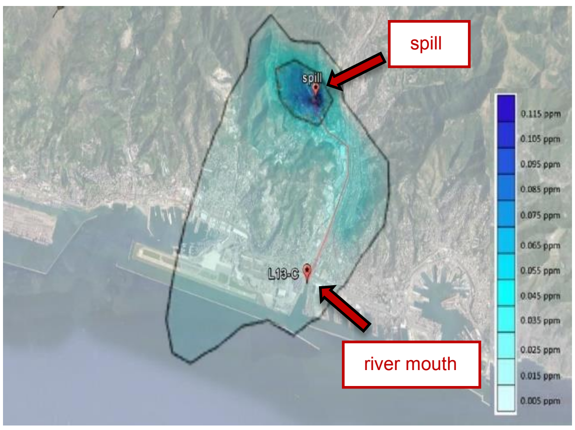


Figure 4: Isoplteh airborne concentration (0- 15 hours).

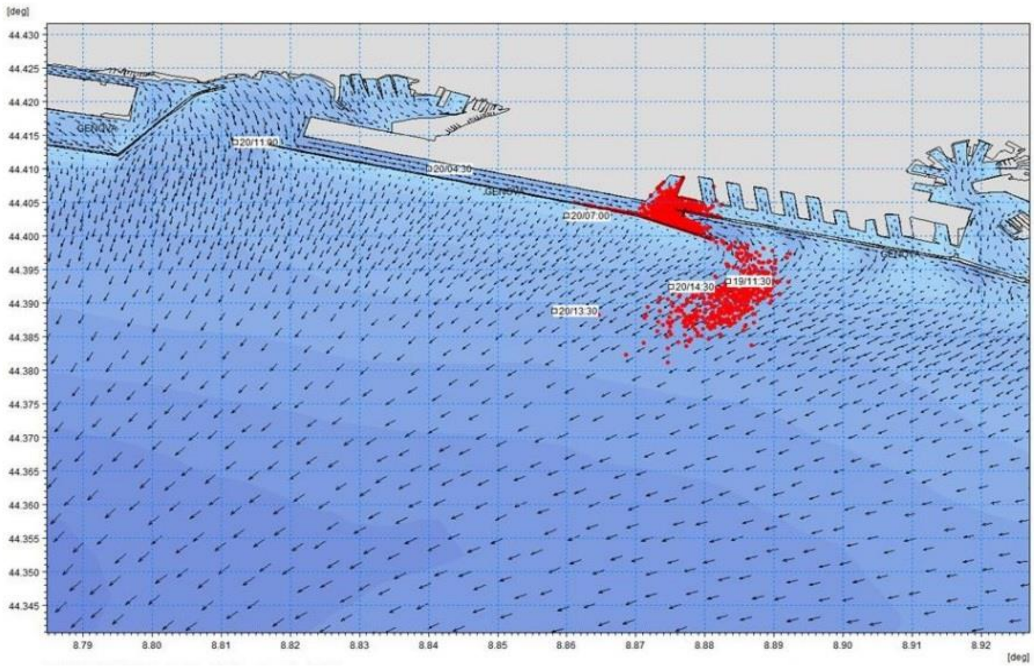


Figure 5: Oil spill trajectory and spreading for the day 18th April 2016 in the worst scenario assumption.

Figure 7 depicting the simulation of 21st April 2016 local time 10 a.m. evidences that the slick particles from the western entrance (yellow) and the ones from eastern inlet (green) are pushed towards open sea and spread out along the direction NE-SW, due to the combined effects of wind and dominant current. The agreement with observations at sea in the morning of the same (white areas) is rather remarkable. Clearly, the simulated oil particles are not quantitatively correlated with the oil mass, but provide the most significant statistical areas covered by the spill under the effects of spreading and weathering processes. Interestingly, modelling was applied while implementing a decision support system, after the partial collapse of the containment on Polcevera, due to hard weather conditions and rain, occurred on 23rd April. The modelization of relevant sea areas possibly affected following the river mouth containment outflow, proved effective assistance with mitigation actions and international resources coordination with France authorities too.

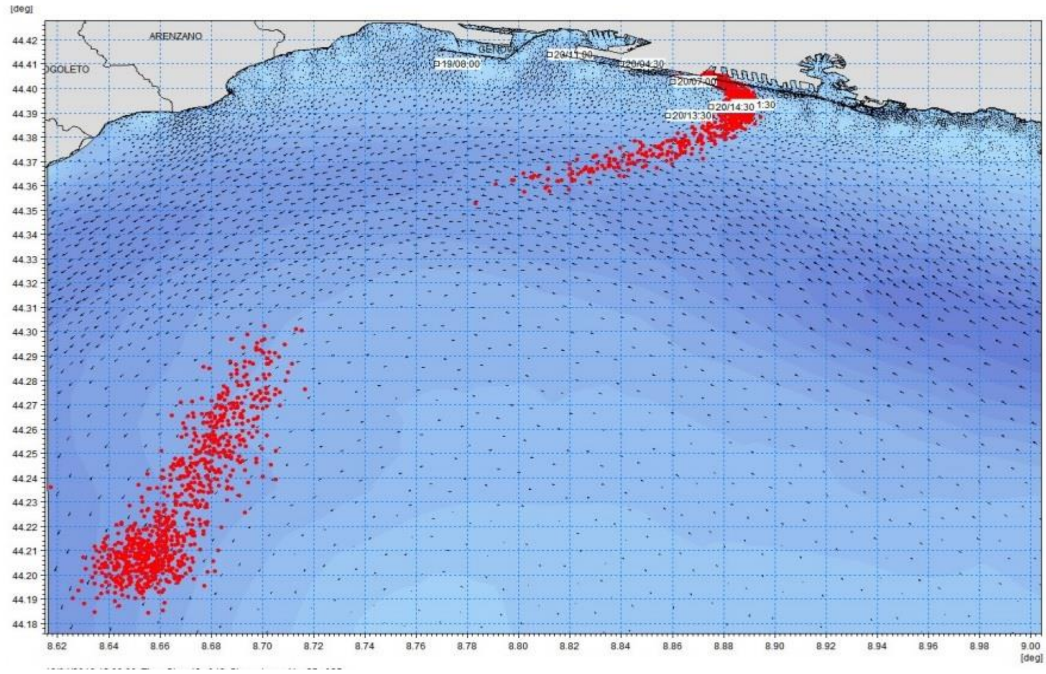


Figure 6: Oil spill trajectory and spreading for the day 19th April 2016 in the worst scenario assumption.

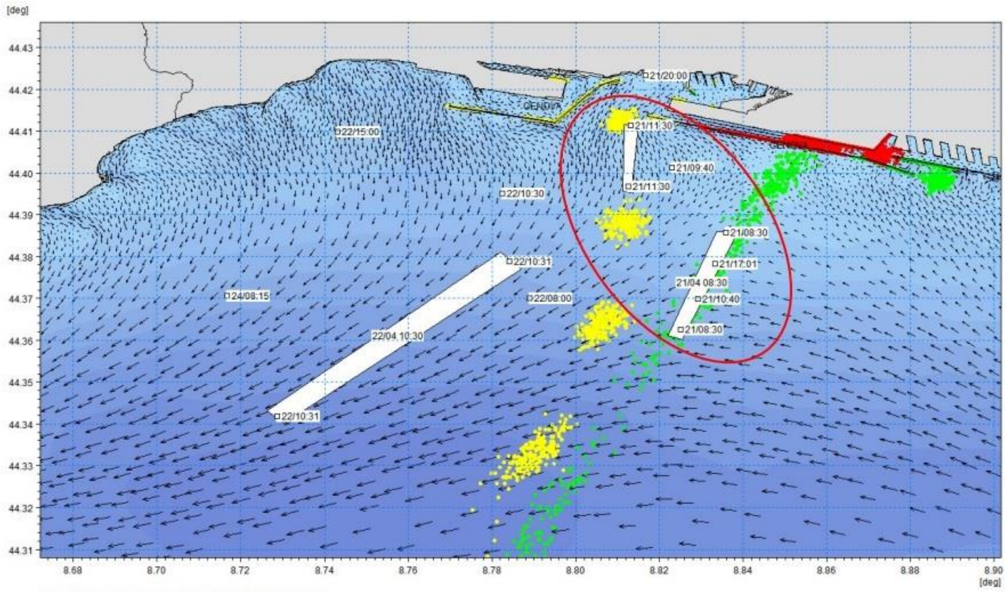


Figure 7: Oil spill trajectory and spreading for the day 21st April 2016 in the worst scenario assumption.

4. Conclusions

Downstream oil companies need to perform proper hazard identification on pipeline systems irrespective of whether these hazards are anthropogenic or natural and they must manage their risks using appropriate technologies: many old pipelines can suffer deterioration due to ageing, aggressive environmental factors, land-use modification and improper protection/maintenance. Both the results of atmospheric dispersion and oil spill spreading evidenced remarkable agreement with field observations and measurements. Two-time-scale modelling may give technical and managerial insights into the different dimensions of accident prevention and proved effective assistance with mitigation actions and international resources management and coordination.

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