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Review of Integrated Response Timing in Post-Monitoring Complex Dangerous Cargo

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In an interconnected world dominated by global trade and intricate supply chain management, the transportation and management of dangerous cargo such as flammable liquids, toxic chemicals and radioactive materials, present multifaceted challenges. These hazardous substances pose significant environmental and health risks, necessitating rigorous safety measures and regulatory oversight. This comprehensive overview examines the various types of dangerous cargo, their environmental implications and notable case studies, highlighting the critical importance of international cooperation and stringent regulations. It delves into the regulatory frameworks governing the transport of hazardous materials by rail, sea, air and land, emphasizing the pivotal role of institutions like the International Maritime Dangerous Goods Code and the Environmental Protection Agency. Analysis indicates a need for improved response times in monitoring programs, necessitating adaptability to diverse environments and specific circumstances. Monitoring and impact assessment programs within emergency response frameworks differ from those aimed at detecting long-term trends in physical, biological and chemical variables.

1. Introduction

In an era marked by global trade, industrial advancements and intricate supply chains, the transportation and management of hazardous materials (Kerroum et al., 2023) has become a pivotal yet intricate endeavor. The handling of dangerous cargo (Taubert et al., 2023) ranging from flammable liquids to radioactive materials, demands rigorous adherence to safety protocols, environmental considerations and regulatory frameworks. As these substances traverse borders and cross oceans, the complexities multiply, emphasizing the need for a holistic understanding and strategic approach. As per Figure 1, maritime freight accounted for 68 % of cargo transportation in the European Union (EU) in the year 2021. Roads are another popular choice which makes up 25 % of the transportation. Carrying volatile cargo by any means of transportation involves the troubling issue of the safety of people and the environment, not to mention the commercial loss and disruption of reputation. The database of dangerous goods contains 26,500 cases of accidents, with the USA, Netherlands, Australia, Germany and Great Britain at the top (Smiljanić et al., 2024). Figure 2 shows the number of marine causalities from 2014-2021. In 2021, an EU member state was identified as the coastal state with 74.8 % of the documented marine casualties and incidents (EMSA, 2022). Transportation by sea is considered the safest mode of transportation although accidents involving the Sea Elegance, Hyundai Fortune, Zim Hanifa and others stand out of this nomenclature (Ellis, 2011). The consequence of any spillage from dangerous goods is vigorous. When in terms of carrying different kinds of cargo in the same transportation mode, it is possible that there is a chance of mixing of cargos of different categories. The statistics show that in about 21 % of the incidents recorded, there was a mixture of different grades of dangerous cargo (Cunha et al., 2015). Different categories

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of dangerous cargo contain different ways to impact humans and the environment. The molecules of sunflower oil undergo polymerization due to wave action. This can take place in both seawater and the intertidal areas, leading to the creation of comparatively durable substances. Most of the research regarding post incident monitoring is conducted well after any incident. This comprehensive overview delves deep into the multifaceted realm of dangerous cargo. It is especially important that the response time of monitoring programs after any incident must be shortened. This study aims to underscore the imperative of safeguarding both human populations and our precious planet.

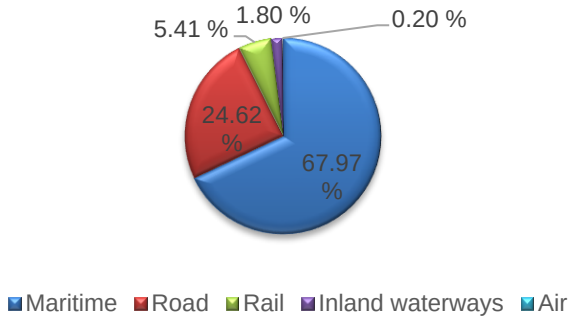

Figure 1: Modal split of freight transport, 2021 (Europa, 2023)

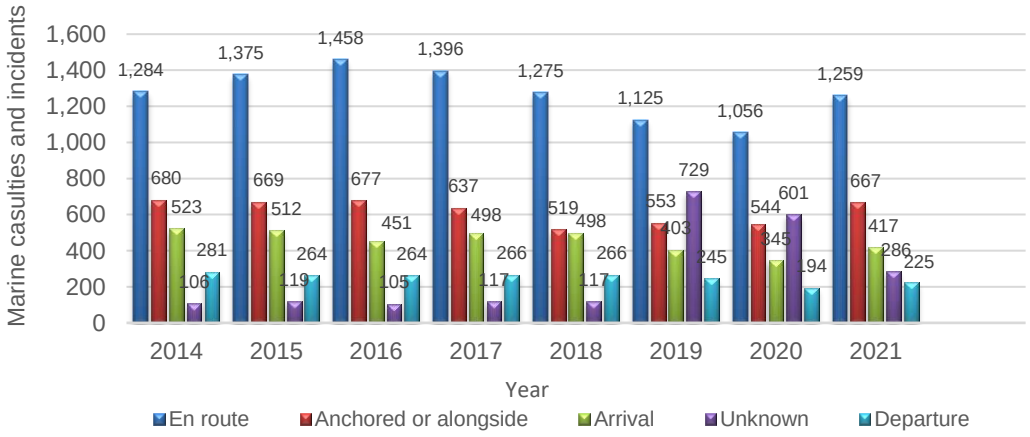

Figure 2: Evolution of number of marine casualties and incidents, organized by voyage segment (EMSA, 2022)

2. Types of dangerous cargo

In the realm of hazardous materials management, various substances present distinct challenges, each with its own set of implications for environmental and human health. Flammable liquids, characterized by their propensity to ignite quickly, carry the risk of both soil contamination upon spillage and immediate fire hazards. Toxic chemicals introduce a different dimension of concern in their potential to pollute water sources which can disrupt aquatic ecosystems and pose significant health risks to humans. The complexities surrounding radioactive materials are particularly pronounced. Any mishandling or improper containment will not only result in immediate health hazards but also lead to enduring environmental contamination, with ramifications that span generations. Every year, a bulk amount of dangerous goods are transported throughout the entire world. The category of goods, distance needed to travel, cost, condition of the transported area and so on determine the mode of transportation. Table 1 portrays the percentage of cargo transported in different modes of transportation in 2022 across the EU. Flammable liquids, including gasoline and solvents can ignite easily due to their low flash points (<60° C), posing storage and transportation challenges (Paraian and Radu, 2024). Industrial precautions include specialized containers and fire safety systems while transportation mandates strict packaging and routing guidelines (Du et al., 2018). Environmental risks i.e. soil and water contamination from spills, emphasize the need for rigorous safety and clean-up measures, highlighting the balance between their utility and the imperative for safety and environmental protection (Kátai-Urbán et al., 2023). Toxic chemicals,

including heavy metals and pesticides, can harm human health and ecosystems even at minimal exposures (Pannala and Wallqvist, 2023). Their diverse toxicological effects require strict regulations throughout their lifecycle, from production to disposal.

Table 1: Mode of transport vs dangerous goods in the EU in 2022

Type of dangerous goods	Mode of transportation (in %)	
	Road (Europa, 2022)	Inland water (Europa, 2024)
Flammable liquids	50.0	52.9
Gases, compressed, liquified dissolved under pressure	13.7	2.6
Corrosives	12.5	2.1
Miscellaneous dangerous substances	11.2	14.0
Oxidizing substances	4.0	0.1
Other	8.6	28.3

Industrial handling demands specialized equipment to minimize risks, while transportation requires stringent protocols to prevent environmental contamination (Yu et al., 2022). Given their persistence and potential to accumulate in the food chain, comprehensive management, encompassing safety measures and environmental oversight is essential for safeguarding human and ecological health (Candra Nugraha Deni and Shabirah, 2022). Radioactive materials emit ionizing radiation, posing significant health and environmental risks (Rusin and Stolecka-Antczak, 2023). Used in diverse sectors like medicine and industry, radioactive materials demand strict regulation throughout their lifecycle, from production to disposal (Talafha et al., 2023). Specialized facilities employ safety measures like shielding and monitoring to protect against radiation exposure (Tyupina et al., 2023). Transport regulations mandate secure packaging and routing.

3. Environmental risks

Hazardous substances like heavy metals and pesticides alter soil properties, reducing fertility, harming plant growth and aquatic ecosystems. Direct human exposure to tainted soil or food grown in polluted areas can lead to health issues, including respiratory and neurological disorders (du Preez et al., 2023). Addressing soil contamination requires a blend of technology, regulations and community involvement, emphasizing the need for immediate action to protect ecosystems and human well-being. Pollutants, ranging from chemicals to pathogens, disrupt aquatic ecosystems, leading to species decline and harmful algal blooms. Polluted water sources can spread diseases and cause chronic health issues like respiratory problems and cancer (Wu et al., 2023). Tackling water pollution requires comprehensive strategies, including strict regulations, technology advancements, community involvement and sustainable practices, emphasizing the intertwined nature of environmental protection, public health and sustainable growth. Air pollution, primarily from human activities like industry and transportation, poses significant threats to ecosystems, human health and global climate (He et al., 2021). This pollution introduces harmful substances into the atmosphere, leading to direct and secondary negative effects on air quality and ecological balance. Ground-level ozone, formed from certain pollutants, further jeopardizes both land and water life. For humans, air pollution is linked to a range of health issues, from respiratory ailments to premature death, while also playing a role in global climate change due to greenhouse gas emissions (Mendieta, 2023). Figure 3 shows premature death tolls which are caused by different methods of pollution.

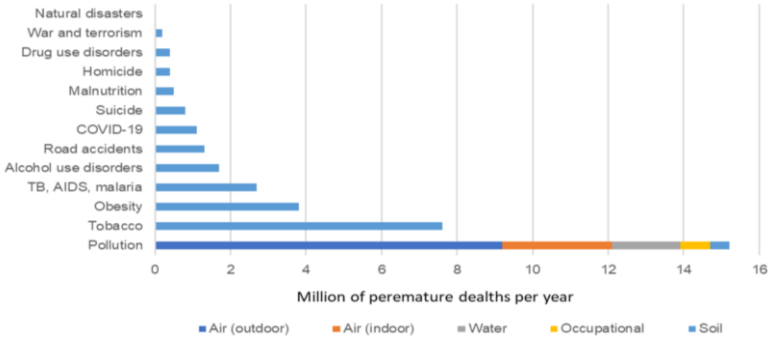

Figure 3: Estimates of premature death (Errigo et al., 2020)

4. Case studies

The Deepwater Horizon oil spill, a tragic event in April 2010, stands as a stark testament to the devastating environmental and socio-economic impacts that can arise from industrial mishaps (Dorr et al., 2019). Operating in the Macondo Prospect of the Gulf of Mexico, shown in Figure 4a, the BP-operated Deepwater Horizon drilling rig experienced a catastrophic blowout, leading to an explosion that claimed 11 lives and culminated in the rig's sinking (Omene, 2019). Over the ensuing 87 days, an estimated 499 x 10^3 t of crude oil gushed into the Gulf, tarnishing marine ecosystems, decimating wildlife populations and imperiling the livelihoods of countless individuals reliant on the region's fisheries and tourism (Makocha et al., 2019). Root causes of this disaster were manifold, encompassing technical deficiencies, inadequate risk evaluations and human errors, including a flawed cement seal and malfunctioning blowout preventer (Murawski et al., 2023). BP's response—marked by extensive clean-up operations and a 20 x 10^9 USD compensation fund—drew widespread scrutiny and intensified calls for stringent safety measures and regulatory reforms in offshore drilling activities (Bonnington et al., 2021). The incident's enduring legacy resides not merely in its environmental toll but also in the pivotal lessons it imparted, catalyzing a re-evaluation of industry practices, regulatory frameworks and the intrinsic value of environmental stewardship and sustainable resource management. The Bhopal chemical disaster of December 2-3, 1984, at the Union Carbide pesticide plant in India, shown in Figure 4b, remains a stark symbol of industrial neglect (Park et al., 2023). The release of methyl isocyanate gas, initiated by a water-induced reaction, claimed thousands of lives and inflicted long-term health issues on survivors, including respiratory ailments and birth defects (Antonova et al., 2022). Investigations revealed significant safety lapses at the plant, sparking debates on corporate responsibility. Union Carbide's 1989 settlement with the Indian government, valued at 470 x 10^6 USD, drew criticism for inadequacy (Roy, 2022). This tragedy emphasized the need for stringent safety measures, corporate accountability and global chemical safety standards to prevent similar catastrophes.

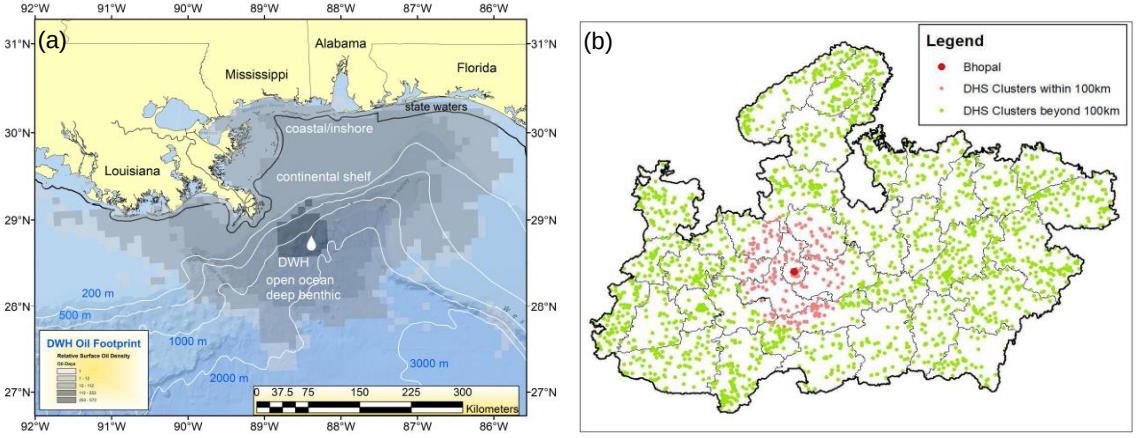

Figure 4: (a) DWH footprint and (b) Bhopal area (Makocha et al., 2019 for a; McCord et al., 2023 for b)

5. Response time vs monitoring program

These two components are complementary rather than mutually exclusive, as effective monitoring can contribute to shorter response times by enabling early detection of anomalies or hazards, thereby enhancing overall incident preparedness and response capabilities. Integrating response time optimization and robust monitoring programs are essential for comprehensive accident management strategies in the maritime sector, promoting safety, environmental protection and sustainable maritime operations. From the analysis of Table 2 it is evident that the response time of the monitoring program is elongated. Monitoring programs designed to evaluate the impact following an incident might require adaptability to diverse environments and consideration of highly specific circumstances. For instance, they may entail analysing chemicals for which standard procedures are lacking or sampling localized species and biological communities. Monitoring and impact assessment programs within an emergency response framework differ from those tailored to detect long-term trends in physical, biological and chemical variables.

Table 2: Year of accident vs year of research (Ellis, 2011)

Spill accidents	Year of accident	Year of research (most recent)
Kota Pahlawan	2006	2007
Horizon Producer	2006	2009
Hanjin London	2006	2007
Bermuda Islander	2006	2008
Star Fuji	2006	2006
MOL Renaissance	2006	2006
Hyundai Fortune	2006	2010
APL Chile	2007	2007
CMA-CGM Fidelio	2007	2008
Zim Hanifa	2007	2007
OOCL Keelung	2007	2008

6. Conclusion

The article discusses the handling and transporting of hazardous goods, emphasizing the importance of strict laws, rigorous monitoring procedures and continuous innovations to mitigate risks to public health and the environment. Key findings underscore the need for improved response times in monitoring systems and adaptability to various environmental contexts. Integrating long-term environmental impact assessments with short-term emergency response frameworks is crucial for addressing both immediate risks and long-term consequences. While regulatory frameworks like the International Maritime Dangerous Goods Code are essential, they require regular updates to remain effective. The paper advocates prioritizing environmental stewardship through preventive measures and regulatory compliance to protect ecosystems and communities. In conclusion, the research focuses on enhancing monitoring technologies, resilient regulatory frameworks and global cooperation to address the complexities of monitoring dangerous cargo while safeguarding the environment and communities.

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