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Comprehensive approach to addressing oil spills from critical infrastructure accidents

Keywords

oil spills, stochastic modelling, critical infrastructure accidents, shipping critical infrastructure

Abstract

This chapter presents a general approach to analyzing oil spills, which are frequently caused by critical infrastructure accidents. The definitions of critical infrastructure and complex system are given and the main sectors significant to the safety of industry operations are listed. The chapter underlines the importance of properly maintaining and monitoring shipping critical infrastructure to respond to potential accidents and ensuring the security of the people and goods transported. There are also presented different categories of oil spills, which can help responders to understand the scope of the problem and mitigate the effects of environmental damage if the oil discharges reach sensitive ecosystems or accumulate in large quantities. The application of useful mathematical models is described to support decision-making in oil spill response. The main factors affecting oil spill movement are listed, including the effects of hydro-meteorological conditions on predicting oil spill trajectory. Moreover, the development steps of constructing and verifying a proper probabilistic model for oil spill management are given. The chapter concludes by highlighting the need for further research in this area to improve our understanding of the complexity of the oil spill issue at the considered area.

1. Introduction

Stochastic modelling is a type of mathematical modelling that is widely used to represent uncertain outcomes for complex systems (Asmussen & Glynn, 2010; Kołowrocki, 2014). This approach utilizes random variables and probabilities to capture the dynamics of a system, allowing for analysis of the behaviour of the system over time. Stochastic modelling has become a powerful tool in a wide range of fields, including weather forecasting, finance, and epidemiology, among others.

One area where stochastic modelling has proven to be particularly useful is in the field of environmental science. In particular, as the probabilistic models are used to make predictions and decisions in situations where the exact outcome is unknown or difficult to predict, they can be also applied to predict the behaviour of an oil spill over time in aquatic ecosystems (Dąbrowska, 2023).

In recent years, advances in computing power and data analysis techniques have led to significant improvements. This has allowed for the development of more accurate and efficient models, which have proven to be invaluable for mitigating the environmental impact of oil spills. These models are usually based on a combination of historical data, expert opinion, and physical / chemical properties of the oil. The simulation-based models can be used to assess the direction of an oil spill, the potential environmental impacts, and the effectiveness of different response strategies, such as containment and cleanup (Bogalecka & Kołowrocki, 2018a, 2018b; Dąbrowska & Kołowrocki, 2019b, 2020b; Fingas, 2013; French-McCay et al., 2005). Oil spills pose a significant threat to the environment, and accurately predicting the trajectory of spilled oil is essential for effective response efforts. The complexity of the problem

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makes it challenging to predict the exact spread of an oil spill, and simulation-based probabilistic modelling provides a useful framework for capturing this uncertainty.

However, the movement of oil spills is influenced by a variety of factors, including hydro-meteorological conditions like wind and current patterns (French-McCay et al., 2005; Ju et al., 2022; Kołowrocki & Kuligowska, 2018). Hydro-meteorological conditions refer to the combination of hydrological and meteorological conditions that affect a particular area. Wind speed and direction, currents, wave height, and air temperature can all affect the movement of the dispersed oil (Fingas, 2013). Wind can cause the oil to spread out in a thin layer and move, while water currents can carry the oil in a different direction. Faster currents will cause the oil to move more quickly. Wind can also increase the rate of evaporation of the oil: the greater the wind speed, the greater the potential evaporation rate (Yuriy & Dobrin, 2022). Evaporation of light oils, e.g. crude or refined products also leads to a significant reduction in total spill volume (Yuriy & Dobrin, 2022). Consequently, that can influence oil tendency to sink or spread. Waves mix the oil with the water, while air temperature can affect the viscosity of the oil and how quickly it moves and spreads. Waves can also impact the trajectory of an oil spill by creating turbulence in the water that can break up and disperse the oil. Larger waves can create more surface area for the oil to spread out, making it more difficult to contain. In addition, the presence of rain or snow can cause the oil to mix with the water, increasing the difficulty to cleanup. Rainfall can impact the trajectory of an oil spill by diluting the oil and making it more complicated to contain. For instance, heavy rain can cause the oil to spread more quickly and make it more difficult to skim. Besides, salinity can also affect the density and viscosity of the oil, which can impact how it moves in the water.

A semi-Markov model can be used to represent the process of changing hydro-meteorological conditions that impact the movement of spilled oil (Dąbrowska & Kołowrocki, 2019b; Kołowrocki, 2014). The stochastic model of hydro-meteorological conditions' involves a set of states representing different conditions, such as temperature, humidity, wind speed, and so on (Dąbrowska & Kołowrocki, 2020b). Each state has a set of transition probabilities associated with it. The probability of transitioning from one state to another is calculated on the basis of historical data. For instance, at a given area, the probability of transition from strong wind to calm breeze can be different than the probability of transition from a moderate wind to a storm, depending on how often the given transition occurred in the assumed time range in the past. The model also accounts for the sojourn times that take to transition between the states (Dąbrowska, 2021, 2022).

Understanding the hydro-meteorological conditions' impacts on oil spill trajectory is critical for estimating the possible size and length of the spill and creating efficient models. Identifying and modelling these conditions and their influence on the oil spill movement is important for developing effective response strategies.

The research question of the Chapter is as follows. What strategies and technologies can be utilized to effectively address and mitigate the environmental impact of oil spills caused by critical infrastructure accidents? Thus, the Chapter is divided into several sections, including an Introduction, Sections 1–4, and a Conclusion. This division ensures a logical flow of ideas and helps readers navigate through the Chapter effectively.

Section 2 introduces a general approach to analyzing oil spills caused by accidents of critical infrastructures, including shipping, and emphasizes the need for maintenance and emergency planning for prevention. Additionally, it presents different categories of oil spills, which can aid responders in understanding the scope of the problem and mitigating environmental damage caused by oil discharges that reach sensitive ecosystems or accumulate in large quantities. Finally, the section highlights the importance of mathematical modelling in analyzing and managing oil spills to support decision-making in oil spill response. These models can predict oil trajectory, assess potential impact, optimize response efforts, identify environmental risks, and communicate with stakeholders. The section also discusses the various physical, chemical, and biological processes that occur during an oil spill, such as dispersion, evaporation, biodegradation, and bioaccumulation, which can affect the fate of spill and can have long-term effects on marine ecosystems.

Section 3 describes the development of a proper model for oil spill management: model selection and formulation, simulation setup and parameters, as well as validation and sensitivity analysis.

In Section 4, the future research in the modelling of oil spills can improve the current state of the art by exploring new areas. These include improving data sources and availability, integrating machine learning and AI techniques, developing more realistic models, exploring the impact of emerging technologies, assessing the impacts of oil spills on marine ecosystems, and simulating cleanup strategies. By focusing on these areas, researchers can advance the field and provide more accurate and effective ways to predict and mitigate oil spills.

In conclusion, the summary emphasizes the importance of the prediction of the potential extent and duration of the oil spill. It highlights that the properly maintaining and monitoring critical infrastructures and having emergency plans in place to respond to potential accidents ensure the safety and security of the human beings.

2. General approach to analysis of oil spills caused by critical infrastructure accidents

2.1. Definitions

The phrase *critical infrastructure* (CI) initially emerged in the 1990s to refer to large electricity system failures that affected millions of people in the United States (Kendra & Wachtendorf, 2003). We associate the infrastructure to the electricity used in homes, the water consumed, the everyday journeys performed via buses and trains and the network offering the worldwide web for communication, information transmission, and data sharing. It is difficult to fathom how a big agglomeration would operate if its electricity source were cut off, even for a short period of time. Numerous additional devices and installations that, as a result of the advancement of civilization as a whole, simplify life and improve security could suffer as a consequence of power outages. When their correct operation is interrupted, it is possible to see just how dependent a person is on these structures and constructions.

These systems refer to banking and monetary systems, electric power, telecommunication and transportation systems (McCreight, 2023). The daily activities and goods of residents may be in peril if they are disrupted or rendered unavailable for an extended period of time (National Research Council, 2012). It is crucial to understand which infrastructure is a CI. We begin this theoretical background by fixing the terminology in order to assure consistency between this paper and any subsequent papers that address this topic. A system's fundamental impact on the safety and security of the nation and its inhabitants qualifies it as a critical infrastructure (DHS, 2015). The phrase "critical infrastructure" in this case mainly applies to a real, complex system or to a network of systems that function cooperatively and interdependently in its place of operation to ensure a constant flow of essential products and services (NIPP, 2013). It is an asset or system that is necessary for maintaining important public activities, according to the European Commission (EC, 2022).

CIs may suffer harm or destruction as the consequence of either natural disasters, age-driven failures or human-caused accidents (Goerlandt & Montewka, 2015; Karakoc et al., 2019). We should mainly focus on them due to their inside and outside dependencies, which could have a major impact on both the social or financial conditions of society as a consequence of CIs damage caused by natural catastrophes or other threats (terrorism, criminal acts, or harmful behaviour). When a system has many interconnected components, even a minor disturbance could have detrimental, rarely cascading effects and pose risks to people (DHS, 2015; Kołowrocki & Soszyńska-Budny, 2011).

Critical infrastructure's effectiveness is influenced by economic growth and technical advancement. It happens, for instance, in the transportation industry for systems that supply fluid fuel and in systems that provide energy to production plants (Kajitani & Sagai, 2009). The long-term problems in this field always have severe economic repercussions and immediately impact the human beings. Individuals may observe this in a decrease in the nations' ability to defend themselves, barriers to carrying out duties that are important to society, or in reduced financial income. As a result, such circumstances would directly affect both societal disorder and individual quality of living (Karakoc et al., 2019).

Very important is a concept of a complex system, which is defined as a set or group of interconnected, interdependent or interacting elements or their parts that are arranged and merged to form an organizational unity or an integrated whole in order to accomplish a common goal (Kołowrocki, 2014). This definition focuses on the interactions between a system's various components and its external environment in order to carry out a specific task or function related to their operation. We are able to investigate the demands (inputs) that the system will be subjected to, whether they are expected or unexpected, and establish whether the system possesses the necessary and sufficient resources to handle those demands. In addition, these might appear to be stresses. These stresses can be anticipated as a result of routine operations or unanticipated as a result of unexpected occurrences that cause unusual or abnormal behaviour (Kołowrocki, 2014).

In the next subsection, some common types of CIs, including energy and power grids, transportation networks, water, communications systems, financial systems, and other essential services will be presented. It also includes the personnel, facilities, and information technology that support these systems. The protection of them is essential to national security and public safety.

2.2. Types of critical infrastructures

Concerning the definition from Subsection 2.1., a critical Infrastructure refers to the essential physical and virtual systems that support the functioning of society and the economy. They are vital to the national security, public safety, and economic prosperity. Here are some examples of critical infrastructure sectors (International Energy Agency, 2019; ITU, 2008; Federal Communications Commission, 2023; Food and Agriculture Organization of the United Nations, 2023; U.S. Department of Homeland Security, 2023; U.S. Government Accountability Office, 2020; U.S. Department of the Treasury; U.S. Department of Transportation, 2017; WHO, 2022): energy, transportation, water, (tele)communications and information technology, finance, food and agriculture, emergency services, healthcare, government and defence. These are the main sectors that are critical to the safe and efficient operation of the industry, which is essential to global trade and commerce (Ganguly et. al., 2021). Among the common types of critical infrastructures, there can be also considered other sectors: shipping critical infrastructure, chemical, manufacturing, nuclear and commercial facilities (Alcaraz & Zeadally, 2015; Bogalecka, 2020).

Shipping is a critical infrastructure that plays a vital role in the global economy by transporting goods and people across the world's oceans, lakes, and rivers (Bogalecka & Kołowrocki, 2018a, 2018b; Noble, 2019). The shipping industry transports more than 80% of global trade by volume, making it an essential component of the global supply chain (Bogalecka, 2020; UNCTAD, 2022; WTO, 2020). Any disruption to this industry can have far-reaching consequences on the economy and public safety. For example, an attack on a major port or shipping channel could disrupt the flow of goods, leading to shortages of essential commodities, higher prices, and economic instability (UNCTAD, 2022). Maritime security also plays a crucial role in ensuring the safety and security of the crew, passengers and cargo aboard ships (UNCTAD, 2022). This includes protecting against criminal activities such as piracy and theft, as well as ensuring compliance with international maritime laws and regulations (IMO, 2010, 2023).

Here are some examples of the critical infrastructure' elements associated with shipping (Bogalecka, 2020; Munim & Schramm, 2018; Tubielewicz et. al., 2010).

- Ports and terminals: these facilities are responsible for the loading and unloading of cargo from ships, as well as the movement of containers and other equipment. They are often the primary interface between ships and the land-based transportation system.
- Shipping channels: these are the waterways that ships use to navigate from one port to another. They are critical to the movement of goods and people and must be maintained to ensure safe passage.
- Navigation systems: these include GPS and other technologies that enable ships to navigate accurately and safely.
- Shipping companies: these are the entities that own and operate the ships that transport goods and citizens around the world.
- Shipping registries and maritime security companies: these are the organizations that register ships and provide them with legal status and protection under international law from security threats such as piracy, terrorism, and cyber-attacks.
- Shipbuilding and repair facilities: these are the facilities that design, build, and repair ships.

All presented CIs in this subsection are the examples of the types of critical infrastructure that exist in modern societies (Council Directive, 2008; COM, 2005). The protection of the assets is essential to ensure the safety and security of the population.

2.3. Critical infrastructures accidents

Critical infrastructure accidents can include a variety of incidents, such as power outages, water contamination, and cyber-attacks (Bogalecka, 2020; Goerlandt & Montewka, 2015). These accidents can have a devastating impact on a community, as they can cause major disruptions to essential services, such as electricity, water, and communication.

In some cases, the accidents can even lead to fatalities. In order to prevent these accidents, it is important to ensure that critical infrastructure is properly maintained and monitored. Additionally, it is important to have emergency plans in place to respond to any potential accident (U.S. Department of Homeland Security, 2023; Goerlandt & Montewka, 2015).

Shipping accidents can refer to a wide range of incidents involving ships, such as collisions, groundings, fires, explosions, and sinkings (Bogalecka & Dąbrowska, 2023). These accidents can have various causes, including human error, equipment malfunction, hydro-meteorological conditions, and external factors such as piracy or terrorism. The use of probabilistic models can support decision-making in oil spill response (Barker et al., 2020).

Some notable shipping accidents in recent history include the sinking of the Titanic in 1912, the Exxon Valdez oil spill in 1989, the sinking of the Costa Concordia in 2012, and the grounding of the Ever Given in the Suez Canal in 2021 (Gualda, 2014). Efforts are continuously made to prevent and mitigate shipping accidents through improved technology, regulations, and training for ship crews (Bogalecka, 2020).

Shipping accidents can have significant environmental, economic, and human consequences. They can result in oil spills or other pollution that harms marine ecosystems and wildlife, disrupt trade and commerce, and cause loss of life and property damage. In the next subsection, there will be selected the main categories of oil spills.

2.4. Parameters determining effects of spills

The effects of oil spills can be classified into different categories based on various factors and criteria. The parameters determining these effects of spills include the type of oil spilled, the location of the spill, the cause or source of the spill, and the quantity and extent of damage caused by the spill (Fingas, 2016; NOAA, 2023; Tansel, 2014).

- Type of oil spilled: crude oil spills are more toxic and difficult to cleanup than refined oil spills. Heavy crude oil is thicker and more viscous than the light one as this type of oil can sink and adhere to surfaces, making it more difficult to recover.
- Location of the spill: oil spills can occur on land, in freshwater bodies such as rivers and lakes, or in marine environments such as oceans and seas:
  - land-based spills: these occur when oil is released onto land, such as from a pipeline, storage tank, or refinery,
  - marine spills: these occur when oil is released into the sea or ocean, such as from a tanker, offshore platform, or drilling rig,
  - airborne spills: these occur when oil is released into the atmosphere, such as from an aircraft or a refinery,
  - underground spills: these occur when oil is released into the ground, such as from a leaking underground storage tank or when a wellhead or drilling rig experiences a blowout.
- Cause of the spill: oil spills can be caused by natural disasters such as hurricanes and earthquakes, accidents such as oil tanker collisions and pipeline leaks, or intentional acts of sabotage and deliberate spills such as oil theft. Moreover, operational spills occur when oil is released during routine operations such as oil drilling, refining, or transportation and can be caused by human error, equipment failure, or inadequate safety measures.
- Extent of damage caused to the environment, wildlife, and human health: small spills may have minimal impact, while large spills can cause significant harm to ecosystems and local communities.
- Time of the cleanup: persistent oil spills occur when oil remains in the environment for a long time, often due to the oil's chemical composition or the conditions of the environment. For example, oil spills in cold or ice-covered environments may persist for longer periods, as the oil can be trapped in ice or snow. The chose of the appropriate methods used for cleanup is

also important for a quick response and matching the oil type, such as mechanical cleanup using booms and skimmers, chemical dispersants, or bioremediation using bacteria to break down the oil.

Understanding the above can help responders define the scope of the problem and mitigate the effects on environmental damage e.g. if the oil discharges reach sensitive ecosystems or accumulate in large quantities.

2.5. Approach to maritime oil spill management

The approach to an oil spill management may involve a coordinated effort to identify, contain, recover, and cleanup the spilled oil (Bogalecka & Dąbrowska, 2023; French-McCay et al., 2005; McCreight, 2023; Montewka et al., 2013).

- Identify the source of the oil spill: the first step in analyzing an oil spill caused e.g. by a critical infrastructure accident is to identify the source of the oil spill. This can be done by examining the infrastructure itself, as well as any other evidence that may be available, such as eyewitness accounts or satellite imagery. The initial response to an oil spill should be done as quickly as possible.
- Assess the extent of the spill: once the source of the spill has been identified, the next step is to assess the extent of the spill. This includes determining the size of the spill and the type of oil spilled.
- Apply an oil spill model and develop a response plan: once the extent of the spill has been determined, a response plan should be developed according to a specified model or considered approach.
- Action of mitigating the contamination effects and cleanup actions: once the spill has been contained, a thorough assessment of the spill site and surrounding area is conducted. This helps to determine the potential impact on the environment and wildlife, and the best course of action for cleanup the oil spill residue. It is important to recover as much of the spilled oil as possible. This is typically done using skimmers, vacuum trucks, and other specialized equipment that can separate the oil from the water. It can involve applying appropriate models to use the known techniques, such as using absorbent materials to soak up the oil, washing shorelines with high-pressure water, and using bioremediation techniques to break down the oil.
- Monitoring: throughout the cleanup process, the environment is monitored to ensure that the oil is being effectively removed and that there are no long-term impacts on the ecosystem. This is especially important for gathering the real-time data and adjusting the model on an ongoing basis.
- Restoration: once the cleanup is complete, efforts may be made to restore the affected ecosystem to its pre-spill state. This can involve reintroducing plant and animal species, rebuilding habitats, and implementing other measures to promote ecological recovery. There can be applied many types of models that are crucial for assessing the potential impact of an oil spill.

The general approach to an oil spill management involves a coordinated effort between government agencies, industry, and environmental organizations to minimize the impact of the spill and restore the affected ecosystems. It is a complex process that requires expertise, well-designed and effective model implementation, specialized equipment, and a commitment to protecting the environment.

2.6. Mathematical modelling

Mathematical models are particularly important for understanding the complex processes involved in oil spills and for simulating different scenarios to inform decision-making determining the most effective strategies for containing and cleanup the spill. They can be used for (Asmussen & Glynn 2010; Dąbrowska & Kołowrocki, 2020a; Fingas, 2016; Fingas & Brown 2014; French-McCay et al., 2005; Kołowrocki, 2014; Magryta & Kołowrocki, 2020; Magryta, 2020; Magryta-Mut, 2023; Montewka et al., 2013).

- Prediction of oil trajectory: analytical probabilistic models and stochastic simulation-based models can be used to accurately predict the trajectory of spilled oil and the rate of spread, allowing for more effective deployment of containment and recovery measures. The models can use e.g. historical hydro-meteorological data, as well as the real data reads e.g. from the ship's sensors.

Assessment of potential impact: models can be used to assess the potential environmental and economic impacts of an oil spill, helping to inform decisions about response efforts and mitigation strategies.

- Optimization of response efforts: numerical and stochastic models can be used to optimize response efforts by simulating different scenarios and evaluating the effectiveness of different containment and cleanup strategies. This can help responders to make informed decisions about which strategies are likely to be most effective in different situations.
- Identification of environmental risks: mathematical models can identify areas of high environmental risk, allowing responders to focus their efforts on protecting sensitive habitats and wildlife.
- Communication with stakeholders: models and various techniques can be used to communicate the potential impact of an oil spill to stakeholders, including local communities, regulators, and industry partners. This can help to facilitate more informed decision-making and collaboration.
- Post-spill assessment: models can be used to assess the effectiveness of cleanup efforts and evaluate the long-term impacts of the spill on the environment and local communities.

Overall, the application of models, especially mathematical ones, is a significant component of oil spill response and management, allowing for more informed decision-making, improved response efforts, and better communication with stakeholders.

2.7. Processes occurring during oil spill

Oil spills and chemicals in the marine environment can undergo various physical, chemical, and biological processes and transformations, including (Guo et al., 2022):

- dispersion: the mechanical breaking up of oil into small droplets by e.g. wind, waves, and turbulence,
- evaporation: the release of volatile components from the oil into the atmosphere,
- dissolution: the process of oil components dissolving in the water,
- biodegradation: the breakdown of oil components by microorganisms in the water,
- photo-oxidation: the breakdown of oil components by sunlight and oxygen,
- adsorption: the process of oil components attaching to suspended particles and sinking to the bottom of the water basin,
- emulsification: the mixing of oil and water to form an emulsion, which can be more difficult to cleanup,
- sedimentation: the settling of oil particles to the bottom of the sea/ocean,
- bioaccumulation: the accumulation of oil components in the tissues of marine organisms.

These processes can affect the fate and transport of oil spills and chemicals in the marine environment, and can have long-term effects on marine ecosystems and the organisms that live in them.

3. Probabilistic modelling approach

Stochastic modelling is an approach that takes into account the inherent randomness and variability of a system. In the context of oil spills, stochastic modelling involves developing models that simulate the movement and behaviour of oil spills e.g. under different hydro-meteorological conditions and other factors.

Stochastic modelling is important for several reasons. First, it can help account for the inherent variability and uncertainty in the system and critical infrastructure, such as the randomness in water currents or the unpredictability of weather patterns. Second, it can provide a more realistic and accurate representation of the system compared to deterministic models that assume fixed parameters and inputs. Third, stochastic modelling can help estimate the probability of different outcomes and assess the risk associated with oil spills under different scenarios.

There are several methods for developing models that uses probability theory for oil spill management (Dąbrowska & Kołowrocki, 2019b, 2020b; Liu et al., 2022; Qiu et al., 2021; Zhang, 2020). These include semi-Markov models, Monte Carlo simulation-based probabilistic models, particle models, stochastic cellular automata models, and simulation agent-based models, which are discussed in Subsection 3.1. Each of these methods has its own strengths and weaknesses, and the choice of method depends on the specific research question, computational resources and available data.

3.1. Model selection and formulation

Model selection and formulation are critical steps in developing a stochastic model useful for oil spill management. The following are some common models used in the literature (Bogalecka & Dąbrowska, 2023; Dąbrowska & Kołowrocki, 2019a, 2020a; Grabski, 2014; Liu et al., 2022; Qiu et al., 2021; Zhang, 2020).

- Markov models: Markov models are a type of stochastic models based on the assumption that the future state of the system depends only on the current state and not on the past history of the system. Moreover, it is assumed that the time spent in a particular state is exponentially distributed and independent of the previous duration of time spent in that state (sojourn time) or any other states.
- Semi-Markov models: a semi-Markov model relaxes the assumption of exponential distribution of time spent in a given state, and allows for a more comprehensive approach. In this model, the time spent in a state can follow any distribution, as long as it is independent of the previous time spent in that state. This means that the semi-Markov model considers the current state, the duration of time spent in that state (sojourn time), and the probabilities of transitioning to other states. Semi-Markov models can be used to model a wider range of systems where the time spent in a state is not necessarily exponential or memoryless. The model can be applied in estimating the movement of oil spills under e.g. different hydro-meteorological conditions.
- Monte Carlo simulation: Monte Carlo simulation is a method for modelling the uncertainty and randomness in a system by simulating multiple realizations of a variable using random input values. Monte Carlo simulation can be used to model the movement of oil spills and estimate the probability of different outcomes having regard different factors.
- Particle models: particle models that are based on stochastic processes simulate the movement of individual particles in a system. Particle models can be used to model the behaviour of oil droplets or slicks under different conditions and influencing factors.
- Cellular automata models: cellular automata models are a type of stochastic model that divide the system into discrete cells and simulate the movement of oil spills between cells. These models can be used to track the movement of oil spills and estimate the probability of different outcomes,
- Agent-based models: agent-based models are types of stochastic models used to simulate complex systems. They replicate the behaviour of individual agents, such as oil droplets or vessels (that could potentially be involved in the spill) in a system. These agents interact with each other and with their environment, based on a set of rules or behaviours. Each oil droplet or boat in the model would be considered an individual agent that interacts with one another. For example, in an Agent-based model of oil droplets, each droplet could have its own properties such as size, buoyancy, and adhesion to other surfaces. The droplets would interact with each other and with the environment, such as waves and currents, based on these properties and rules. The model could be used to simulate the movement and fate of the oil spill over time.

Overall, model selection and formulation are critical steps in developing a proper model for oil spills' management. The choice of model depends on the specific research question, available data, and computational resources. Markov models, Monte Carlo simulation, particle models, cellular automata models, and agent-based models are all useful tools for modelling oil spills and predicting their behaviour under varying conditions.

3.2. Simulation setup and parameters

Stochastic modelling of oil spills involves the use of random variables and probability distributions to represent uncertain inputs and model the variability and uncertainty associated with oil spill events.

To set up a simulation for stochastic modelling of oil spills, the following parameters need to be considered (Dąbrowska & Kołowrocki, 2019a, 2020a; IMO, 2010, 2023; Kim et al., 2013; Leigh & Bryant, 2015; Marseguerra & Zio 2002; Rao & Naikan, 2016).

- Spatial extent: the simulation domain needs to be defined by specifying the geographic area of interest and its boundaries. This could be a coastal region, a sea area, or a specific location like a port or an offshore drilling rig.

- Time frame: the simulation needs to be run for a specific period, typically ranging from a few days to several weeks or months. This time frame should be consistent with the duration of potential spills in the area of interest.
- Oil spill source: the type and location of the oil spill source need to be defined. This could be a pipeline, an oil tanker, an offshore drilling platform, or any other potential source.
- Oil properties: the physical and chemical properties of the spilled oil need to be specified. This includes density, viscosity, and volatility, which determine the behaviour and fate of the oil in the environment.
- Hydro-meteorological conditions: hydro-meteorological conditions, including wind speed and direction, wave height and direction, and current speed and direction, can significantly affect the behaviour and trajectory of oil spills. These parameters need to be specified using historical data and statistical distributions.
- Other model parameters: the model parameters, such as the diffusion coefficient and settling velocity of the oil, should be based on the best available data and calibrated against observations where possible. In some cases, it may be necessary to simulate multiple scenarios with different parameter values to assess the sensitivity of the results to these parameters.
- Response strategies (optional): the simulation can include the evaluation of different response strategies, such as the use of booms, dispersants, and skimmers, to mitigate the impact of the oil spill.
- Validation and sensitivity analysis: the simulation results should be validated against observations where possible and sensitivity analysis can be performed to assess the sensitivity of the results to the various parameters and inputs.

Once these parameters are defined, the simulation can be run using stochastic modelling techniques such as Monte Carlo simulation-based model or probabilistic risk assessments to estimate the likelihood and potential consequences of oil spill events. The simulation can also be used to assess the effectiveness of different response strategies and inform contingency planning efforts.

3.3. Validation and sensitivity analysis

Validation and sensitivity analysis are important steps in the stochastic modelling the behaviour of oil spills to ensure the accuracy and reliability of the model.

Validation involves comparing the model predictions with observed data to assess the performance of the model (Mitchell & Sheehy, 1997). This can involve comparing the predicted trajectory of an oil spill with observed trajectories, as well as comparing other variables such as oil thickness and concentration with observations. Validation can also involve assessing the ability of the model to predict the behaviour of oil spills under different factors, e.g. hydro-meteorological conditions.

Sensitivity analysis involves assessing the sensitivity of the model to different parameters and input variables. This can involve varying one parameter at a time while holding others constant, or performing more complex analyses to assess the joint sensitivity of multiple parameters (Drews et al., 2003; Harris & Van Horn, 1996). Sensitivity analysis can help identify which parameters and inputs have the greatest influence on the model predictions, and can help guide efforts to improve the accuracy and reliability of the model.

Both validation and sensitivity analysis are important steps in stochastic modelling of oil spills' behaviour. Validation helps to assess the performance of the model and its ability to predict the movement of oil spills under different conditions. Sensitivity analysis helps identify which parameters and inputs have the greatest influence on the model predictions.

3.4. Future research

Future research in the modelling of oil spills could focus on a number of areas, including the following items.

- Improved data sources and availability: there is always a need for better data sources and availability to improve the accuracy and reliability of models. This could involve the development of new sensors and observation techniques, as well as efforts to integrate and synthesize data from multiple sources or to gather more detailed data on the physical properties of oil and water.
- Integration of machine learning and AI techniques: machine learning and AI techniques have the potential to improve the efficiency of models, particularly in cases where large amounts of data are available to improve the predictive capabilities. This could involve us-

ing machine learning algorithms to analyze data on past oil spills and environmental conditions in order to better predict the behaviour of future spills,

- Development of more realistic models: many existing models of oil spills rely on simplifying assumptions about the behaviour of oil in the marine environment. Future research could focus on developing more realistic models that account for more complex processes such as biodegradation, wave-induced mixing, and interactions with sediments and benthic organisms, which are the living beings that exist on or near the bottom of a body of water. This might involve applying more advanced algorithms and computational methods with greater precision.
- Exploration of the impact of emerging technologies: emerging technologies such as autonomous vehicles and drones have the potential to revolutionize the monitoring and response to oil spills. Future research could explore the impact of these technologies on the modelling of oil spills' movement and how they could be incorporated into existing models to detect and track oil spills in real-time, allowing for faster and more effective response to mitigate the damage caused.
- Assessment of the impacts of oil spills on marine ecosystems: while models of oil spills often focus on the movement and fate of oil in the marine environment, there is also a need to assess the impacts of oil spills on marine ecosystems. Future research could explore the development of models that incorporate that influence, as well as efforts to improve our understanding of the long-term impacts of oil spills. This would allow for a more comprehensive approach.
- Simulation of cleanup strategies: another area of research could be to simulate different cleanup strategies for oil spills, in order to determine the most effective and efficient methods for minimizing the environmental impact. This might involve testing different types of dispersants, skimmers, and other cleanup technologies in a virtual environment before implementing them in the field.

4. Discussion

Critical infrastructure refers to the essential physical and virtual systems that support the functioning of society and the economy, and includes sectors such as energy, transportation, water, telecommunications, financial, food and agriculture, healthcare, as well as government and defence. Shipping is also considered as a critical infrastructure that plays a crucial role in the global economy, and includes elements such as ports and terminals, shipping channels, navigation systems, shipping companies and registries, and shipbuilding and repair facilities.

In order to effectively analyze oil spills caused by critical infrastructure accidents, it is essential to consider the unique characteristics and interconnectedness of critical infrastructure systems, as well as the potential impacts of oil spills on the environment, economy, and society. This requires interdisciplinary collaboration, incorporating expertise from various fields such as engineering, environmental science, policy, and emergency management. Additionally, the use of probabilistic models can support decision-making in oil spill response, helping to inform effective strategies for prevention, preparedness, response, and recovery. Various factors including hydro-meteorological conditions can have a significant impact on the trajectory of oil spills and must be taken into account when designing spill response strategies and models. The movement of oil spills is largely driven by the movement of water currents, waves, wind, and other. Wind can affect the direction and speed of the oil spill by creating surface currents and waves that can push the oil in a particular direction.

By performing rigorous validation and sensitivity analysis, the model can provide more accurate and reliable predictions of the behaviour of oil spills under various factors affecting it e.g. different hydro-meteorological conditions.

Future directions for research in oil spill modelling include improving data sources and availability, integrating machine learning and AI techniques, developing more realistic models, exploring the impact of emerging technologies, and assessing the impacts of oil spills on marine ecosystems.

5. Conclusion

In conclusion, the analysis of oil spills caused by critical infrastructure accidents requires a comprehensive approach that considers the complex nature of critical infrastructure systems.

Accidents involving critical infrastructure can have severe consequences, including disruptions to essential services, environmental damage, economic losses, and threats to public safety. Therefore, it is important to properly maintain and monitor shipping critical infrastructure to prevent accidents, and have emergency plans in place to respond to any potential incidents.

Overall, a comprehensive and integrated approach is necessary to effectively analyze and address oil spills caused by critical infrastructure accidents, with the goal of minimizing their impacts and protecting the environment and society.

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