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ENVIRONMENTAL CONSEQUENCES OF FUEL OIL TANKER DISASTERS: RISKS, ECOSYSTEM IMPACTS, AND MITIGATION MEASURES

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Purpose: To analyze the environmental consequences of heavy fuel oil tanker disasters in the Black Sea, identify their impact on the ecosystem, and propose mitigation measures and recommendations for future crisis responses.
Design/methodology/approach: The research employed comprehensive analysis of pollution, integrating meteorological data and dispersion modeling. A mathematical model was developed to predict the degradation dynamics of fuel oil components over one year. The study also reviewed literature and international legal instruments.
Findings: Fuel oil spills cause irreparable damage to marine flora and fauna (dolphins, seabirds) through toxicity and oxygen depletion. Modeling indicates a prolonged negative impact (asphaltenes stable for up to 19 years). The disaster was exacerbated by the use of outdated tankers, linked to military expenditures.
Research limitations/implications: Major limitations include restricted access to the affected area. Future research should focus on developing less toxic pollution control methods and advanced digital technologies for real-time monitoring.
Practical implications: The findings enable authorities to assess ecological risks and develop effective, coordinated international response measures and minimize damage. This supports the necessity of deploying environmentally safe sorbents and mobile monitoring systems.
Social implications: The study highlights the need to enhance international maritime law for regulating hazardous transport and strengthen vessel monitoring. It emphasizes holding perpetrators accountable and initiating measures to restore the Black Sea ecosystem.
Originality/value: The paper provides a comprehensive analysis of spills in the Black Sea, directly linking accidents to the geopolitical context and lack of vessel modernization funding. It presents an original mathematical model for degradation dynamics and an integrated mitigation approach. Valuable for policymakers and researchers.
Keywords: environmental disaster, fuel oil, Black Sea, marine ecosystems, oil spill.
Category of the paper: Research paper.

1. Introduction

Russia has caused significant damage to Ukraine's environment (Shevchenko, 2024). This complicates Ukraine's and the EU's efforts to achieve climate neutrality. The issue of environmental crimes should remain in the focus of national and global media attention. The war in Ukraine, initiated by the Russian Federation, has caused not only a large-scale humanitarian crisis, but also serious environmental consequences (Khrushch, 2023), affecting various components of the environment (Shekhunova et al., 2023; Levchenko et al., 2023). We have previously studied environmental pollution by heavy metals in the war zones (Krainiuk et al., 2023). The war has serious negative consequences for both the Ukrainian people and the rest of the world (Khrushch et al., 2023).

The armed invasion of Ukraine has created significant threats to the Black Sea environment, with oil spills posing particular dangers. For instance, in 2022, Russian forces attacked an abandoned tanker containing 600 tons of diesel fuel, leading to large-scale sea contamination (Astashieva, Cheban, 2023). These incidents have had a significant impact on biodiversity, harmed marine ecosystems, and created long-term risks for the natural environment (Malovanyy, Bohach, 2021).

The constant threat of shelling increases the risk of human-made disasters with transboundary effects (Ivaniuta, 2022). Some researchers (Kharytonov et al., 2024) emphasize the need to recognize environmental crimes during the war as a component of genocide or as a separate international crime.

A particularly critical incident was the catastrophe involving tankers carrying fuel oil. On December 15, 2024, in the Kerch Strait, two Russian tankers, "Volgoneft-212" and "Volgoneft-239", transporting fuel oil, were severely damaged by a storm. This led to a massive spill of petroleum products into the Black Sea. Estimates suggest that 3000 to 4000 tons of fuel oil were released, causing severe pollution of the coastal areas and water resources.

Another oil spill occurred on December 7, 2024, when the Russian oil tanker 'Volgoneft-109' was involved in an accident in the Black Sea. This was the third such event within a short period, highlighting the growing environmental risks of transporting oil products in the region.

Similar incidents have occurred in the past, such as the 2007 accident in the Kerch Strait, during which 1300 tons of fuel oil were spilled into the sea. The toxic substances released into the water posed a serious threat to marine flora and fauna, particularly dolphins and birds, and had a long-lasting negative impact on the ecosystem.

Maritime disasters significantly impact the marine environment. Maritime transport and related accidents contribute to the emission of harmful gases and water pollution, disrupting underwater food chains and altering hydrographic conditions. Studies (Klenkin, Agapov, 2011) indicate that, following accidents in the Kerch Strait, changes in oil pollutant concentrations have been observed in the aquatic ecosystem (Nedelcu, Rusu, 2022). Long-term monitoring starting in 2011 revealed differences in the concentrations and distribution of petroleum hydrocarbons in the Azov and Black Seas after oil spills. During regular oil spill monitoring in the eastern part of the Black Sea in 2011 and 2012, unprecedentedly large oil slicks of marine origin were detected. These oil slicks were primarily observed in the Russian sector of the sea. The presence of large oil slicks was confirmed through optical satellite imagery, suggesting tanker washing operations and illegal discharges of oil products (Ivanov, Kucheiko, 2014). In the Ukrainian coastal area of the Black Sea, pollution levels were significantly lower, pointing to a cleaner environment. This was the case before Russia's occupation of Crimea and the full-scale war beginning in 2022.

To assess the consequences of oil and chemical spill disasters, various models such as GNOME and PISCES-II are used. These models help identify accident 'hot spots' and evaluate the toxic effects of pollutants (Aşan et al., 2020; Yıldız, 2021).

Considering that the environmental impact during armed conflicts is almost always transboundary in nature. Kozmuliak (2022) analyzed the provisions of international instruments regulating this issue. These include the 1972 Stockholm Declaration, the World Charter for Nature, the 1992 Rio de Janeiro Declaration on Environment and Development, the Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques, the Additional Protocol to the Geneva Conventions of August 12, 1949, concerning the protection of victims of international armed conflicts, and the Convention on the Prohibition of the Development, Production, Stockpiling, and Use of Chemical Weapons and Their Destruction. It has been established that all of these documents call on the international community to take measures to prevent or minimize the destructive impact on the environment during military operations.

The aim of this study is to analyze the environmental consequences of this catastrophe, particularly its impact on the Black Sea ecosystems, as well as to identify ways to mitigate the damage and develop recommendations for improving responses to similar crises in the future.

The fuel oil spill created a large slick that spread due to currents and wind, contaminating significant areas of the sea and coastline. The oil film disrupted the oxygen balance in the water, threatening marine life, particularly dolphins. The contamination of the seabed and soil endangers spawning areas and salt marshes, causing long-term toxic effects.

The tanker accident is not directly related to military actions; however, due to Russia's expenditures on the war against Ukraine, funds for vessel modernization are lacking. Outdated tankers, some as old as 50 years, unsuitable for stormy seas, are being used, which led to this disaster. The deployment of such vessels in stormy conditions without proper modernization and permits violates safety regulations and could have been a cause of the accidents.

After the incident, the fuel oil spread along the coastline of the Taman Peninsula and later, due to a change in wind direction, moved towards the Crimean Peninsula (Fig. 1). By January 15, 2025, the pollution had spread not only to the Crimean coast but also to the Odesa region. Maps of the pollution's spread reflect the dynamics of the process and wind directions that contributed to the substance's transport. These data are crucial for risk assessment and for planning mitigation measures. However, the fact that the fuel oil reached Ukrainian territories confirms the need for immediate action.

In the first days following the accident, the pollution spread along the Taman Peninsula coastline under the influence of prevailing northern and northwestern winds. However, by December 21, 2024, maps indicate a change in wind direction, shifting towards the Crimean Peninsula. This immediately resulted in the transfer of fuel oil remnants southeastward, creating a risk of contamination along the Crimean coastline.

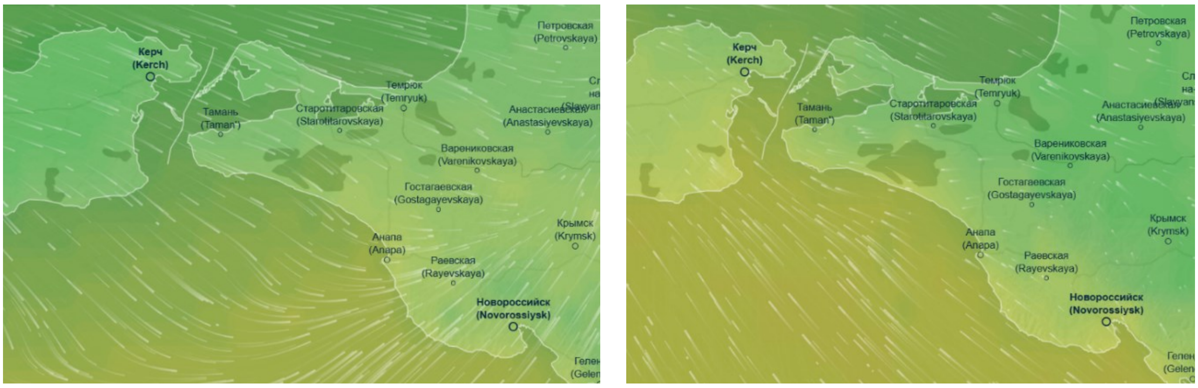

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Figure 1. Dynamics of fuel oil pollution spread along the Black Sea coastline depending on the wind direction (15-21 December 2024).

The fuel oil spill contaminated approximately 50 kilometers of the Black Sea coastline, including the beaches of Anapa (Fig. 1). Since late December 2024, pollution has been recorded along the Crimean coast (Kerch, Yevpatoria), and by mid-January 2025, even in the Odesa region. The accumulation of petroleum products on the shores poses a serious threat to the regional ecosystem.

2. Materials and Methods

The research methods applied in this study are based on a comprehensive analysis of the Black Sea pollution processes caused by fuel oil spills from tanker accidents. The study considered the specifics of the regional ecosystem, utilized meteorological observation data, and modeled pollution dispersion depending on weather conditions. Additionally, a review of literature sources was conducted to assess the impact of toxic substances on marine life and their persistence in the ecosystem. This approach allowed the development of recommendations for minimizing environmental risks and improving response measures.

3. Data analysis

Fuel oil is a residual product of oil distillation with a complex chemical composition and belongs to the group of heavy organic substances. Its chemical composition is determined by the source crude oil and processing conditions. From a chemical perspective, fuel oil contains the following components (Table 1).

Table 1.
Main groups of chemical substances in the composition of fuel oil

Category	Subcategory	Examples of substances	Chemical formula
	Aromatic	Naphthalene	$C_{10}H_8$
		Phenanthrene	$C_{14}H_{10}$
	Saturated	Docosane	$C_{22}H_{46}$
		Hexacosane	$C_{26}H_{54}$
	Cycloalkanes	Cyclopentane	C_5H_{10}
		Decalin	$C_{10}H_{18}$
Heteroatomic compounds	Sulfur	Thiophene	C_4H_4S
		Benzothiophene	C_8H_6S
	Nitrogen	Quinoline	C_9H_7N
		Indole	C_8H_7N
	Oxygen	Phenol	C_6H_5OH
Asphaltenes and resins	Asphaltenes	High-molecular compounds	$C_{40}H_{50}O_4S$
	Resins	Intermediate components	$C_{20}H_{30}O_2$
Metals	Metalloporphyrins	Vanadyl porphyrin	$C_{30}H_{36}N_4O_4V$
		Nickel complex	[Ni- complex]
Residues	Minerals	Chlorides	$NaCl$, $MgCl_2$
	Water	Free and emulsified	H_2O

Diagram 2 describes the main processes of oil spills: light components rise to the surface, forming a film, while heavy ones settle to the bottom, harming bottom-dwelling organisms. Evaporation, oxidation, and emulsion formation occur, with oil interacting with water particles, promoting settling. Light fractions partially decompose, but asphaltenes remain stable for years. Currents and storms increase the area of contamination, creating a complex environmental issue that requires specialized cleaning methods. These aspects complicate the cleanup and demand specialized approaches for neutralizing oil spills in water. The entry of oil into the water leads to a series of chemical reactions that can be predicted based on the composition of the oil and environmental conditions (salinity, temperature, oxygen availability, sunlight). Toxic substances are formed, contaminating water, soils, and affecting the marine ecosystem. The consequences of chemical reactions of oil in seawater can be catastrophic for the ecosystem and the environment (Table 2).

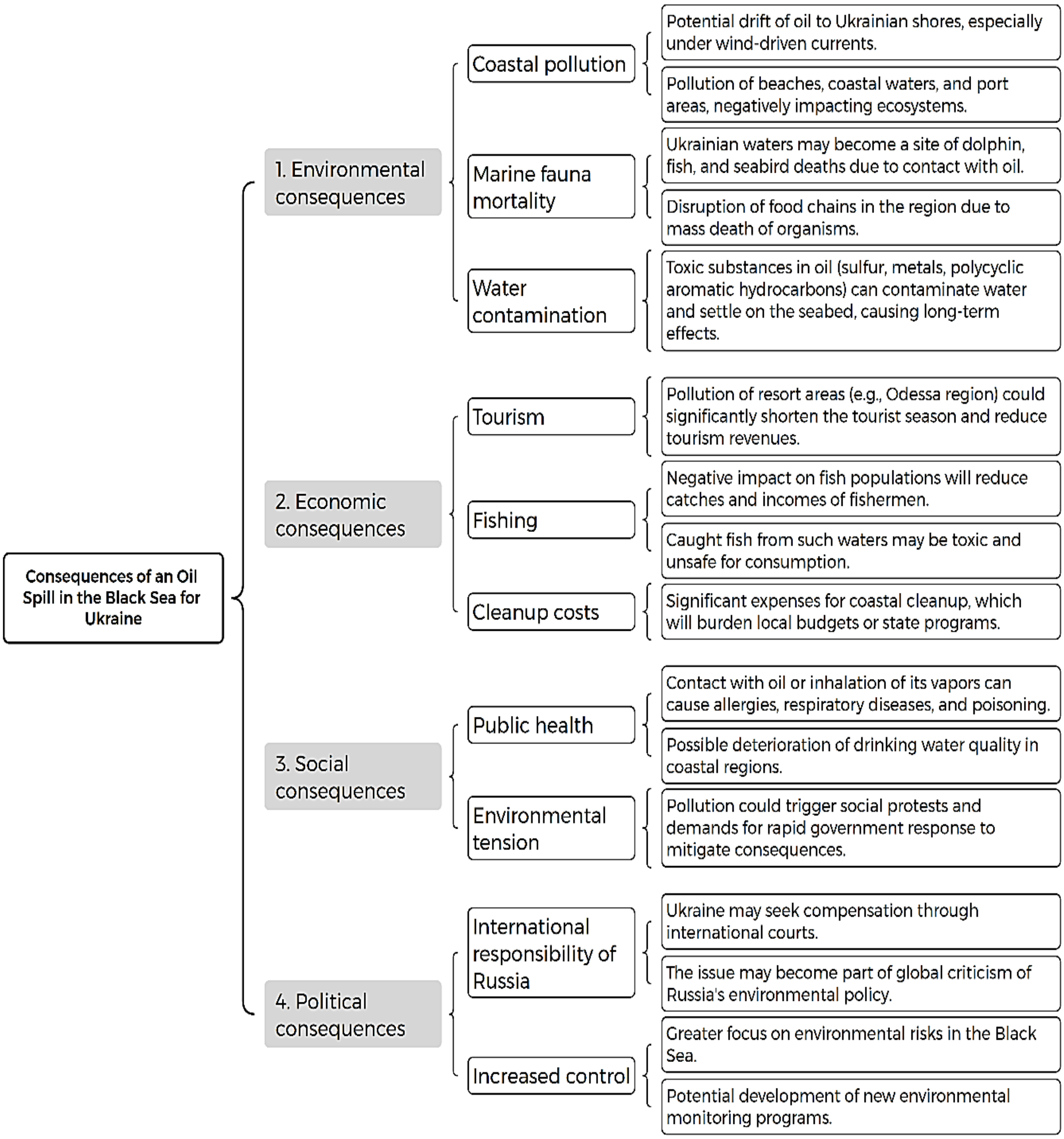

Figure 2. Stages of fuel oil pollution spread.

Table 2.
Consequences of chemical reactions of fuel oil in seawater

Aspect	Process	Consequences
Water Pollution	- Physical pollution: formation of an oil film on the water surface, reducing oxygen and light penetration, disrupting photosynthesis. - Chemical pollution: formation of toxic substances (hydrogen sulfide, organic acids, oxygenated compounds).	- Mass death of fish, molluscs, and plankton due to oxygen deficiency. - Disruption of food chains in the marine ecosystem.
Formation of Toxic Substances	- Hydrogen sulfide (H_2S): high concentration is dangerous for aquatic organisms, pollutes the atmosphere. - Surfactants (PAHs): carcinogenic substances accumulate in living organisms.	- Toxicity for fauna, bioaccumulation. - Harm to humans consuming seafood.

Ecosystem Destruction	- Polymerization of asphaltenes and resins: formation of sediments that cover marine ecosystems. - Hydrolysis and oxidation of organic substances, creating acidic environments.	- Destruction of biocenoses. - Reduction of biodiversity.
Deposition of Heavy Metals	Vanadium, nickel: settle in water or accumulate in bottom sediments.	- Long-term pollution of benthic ecosystems. - Toxic effect on organisms in contact with the bottom.
Interaction with Seawater Salt	Formation of emulsions that impair the water's self-purification ability.	- Prolonged duration of pollution. - Deterioration of living conditions in the affected region.
Impact on the Coastline	Oil causes soil erosion and poisons vegetation.	- Destruction of coastal ecosystems. - Reduction in the population of birds and animals that come into contact with contaminated surfaces.
Socio-economic Consequences	Contamination of fish and seafood, reduction of fishing potential. - Polluted beaches and deterioration of tourist attractiveness.	- Financial losses for local populations. - Deterioration of human health due to contact with toxic substances.

Accidents involving the spill of fuel oil into the marine environment have long-term and multi-dimensional consequences that affect not only the ecosystem but also human health and the economy. The marine environment is chemically aggressive and can accelerate certain chemical reactions (Table 3).

Table 3.
Reaction Rates in the Marine Environment

Process	Mechanism and Conditions	Reaction Rate
Oxidation of hydrocarbons	Occurs in the presence of oxygen. In surface layers with access to air, the reaction occurs faster. In the deep zones of the Black Sea, where oxygen may be deficient, the rate significantly decreases.	Surface layers: from months to a year; deep zones: decades.
Photo-oxidation	Under the influence of UV rays, polycyclic aromatic hydrocarbons (PAHs) are broken down in the surface layers. The efficiency depends on the water transparency and light penetration depth.	Several days to months in surface layers; practically absent in deep layers.
Hydrolysis	Breakdown of organic compounds by water. Formation of secondary toxic substances such as organic acids, hydrogen sulfide. For large molecules of fuel oil, the process is very slow.	Simple compounds: from weeks to months; large molecules (asphaltenes): years.
Biodegradation	Microorganisms break down organic compounds. The influence of seasonal temperature and salinity: activity is higher in summer. Lighter fractions degrade faster than heavier ones.	Light alkanes: a few weeks; heavy fractions (resins, asphaltenes): decades.
Formation of emulsions	Fuel oil mixes with water, forming water-organic emulsions. These "black ice" can persist for years and slow down other degradation processes.	Formation of emulsions: days; stability of emulsions: years.
Formation of solid deposits	Polymerization of heavy hydrocarbons (asphaltenes, resins), which then settle at the bottom. This process is active in areas with low water dynamics (deep zones).	Months to years.
Sedimentation of heavy metals	Reactions of heavy metals in fuel oil with salts of seawater (chlorides, sulfates). Sedimentation is more active in coastal areas with high salt and organic concentrations.	A few days to weeks.
Formation of hydrogen sulfide (H_2S)	Decomposition of sulfur compounds in fuel oil under anaerobic conditions. In the Black Sea, this process is active in deep layers, contributing to water contamination with hydrogen sulfide.	From a few weeks to months.

To estimate the total degradation time of fuel oil in the Black Sea, the main processes considered are evaporation, oxidation, degradation, and sedimentation. Each process influences the overall dynamics. For calculation, we use exponential dependence laws:

$$M(t) = \mathrm{M}_0 \cdot e^{-k \cdot t} \quad (1)$$

where:

M(t) – the mass of the component at time t;

M_0 – the initial mass of the component (total fuel oil 4000 tons);

k – the rate constant of the process (depends on temperature and type of process);

t – time.

Let's determine the degradation time for each component. Based on the calculations, we obtain the degradation time for the components (Table 4).

Table 4.

Table 4 Degradation time of fuel oil components

Components	Half-life, days	Time for complete degradation (until 1% of initial mass remains), days
Oxidation of alkanes (C_{10}-C_{40})	≈70	460 (≈1,5 years)
Degradation of aromatic compounds (benzene, naphthalene, PAHs)	≈140	1380 (about 4 years)
Polymerization of resins and asphaltenes	670 (about 2 years)	6900 (19 years)
Sulfide (H_2 S) release	230 (8 months)	1535 (4-4,5 years)

Let's try to build a system of differential equations that describe the degradation of fuel oil components in the Black Sea:

1. Evaporation of volatile components:

$$\frac{dM_{let}(t)}{dt} = -k_{let} M_{let}(t) \quad (2)$$

2. Oxidation of alkanes:

$$\frac{dM_{alk}(t)}{dt} = -k_{alk} M_{alk}(t) \quad (3)$$

3. Degradation of polycyclic aromatic hydrocarbons (PAHs):

$$\frac{dM_{PAV}(t)}{dt} = -k_{PAV} M_{PAV}(t) \quad (4)$$

4. Formation of Asphaltenes:

$$\frac{dM_{asf}(t)}{dt} = k_{alk} M_{alk}(t) + k_{PAV} M_{PAV}(t) - k_{asf} M_{asf}(t) \quad (5)$$

where k_{asf}– rate constant of asphaltene sedimentation.

5. Sedimentation to the bottom:

$$\frac{dM_{don}(t)}{dt} = -k_{don} M_{don}(t) \quad (6)$$

Numerical methods can be used to solve this system of equations (for example, the Runge-Kutta method). The model allows for predicting the dynamics of oil degradation by calculating the mass of remaining components over time.

The model built using Python shows the following results (Fig. 3): the reaction rates are extremely low in winter at a water temperature of 7°C. The fastest process remains the evaporation of volatile components, but even it proceeds very slowly. Other reactions practically stop, as the low temperature significantly slows the chemical transformations.

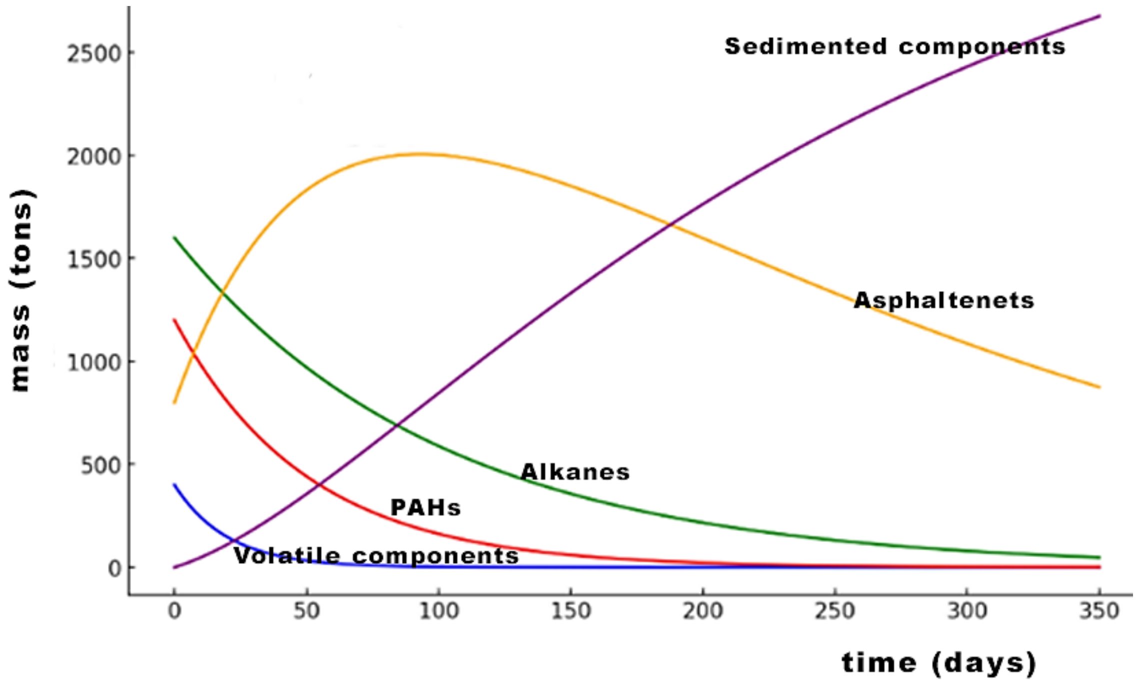

Figure 3. Dynamics of oil degradation in the Black Sea considering different components.

4. Results

In Figure 3, the forecast of the changes in the mass of components of the crude oil in the Black Sea over the course of one year is presented:

- Volatile components (blue line) quickly evaporate during the first weeks. They decrease rapidly within the first 50 days due to evaporation. This is a natural process, as the light fractions of crude oil have a low boiling point and gradually evaporate even at low temperatures.
- Alkanes (green line) degrade slowly due to the low oxidation rate. They gradually decrease over time through oxidation, but the process is quite slow due to the low reaction rate under cold conditions.
- Polycyclic Aromatic Hydrocarbons (PAHs, red line) degrade even more slowly, remaining active pollutants. They increase for a certain period because they are formed as a result of chemical reactions, but over time their quantity starts to decrease due to degradation.

- Asphaltenes (orange line) gradually increase due to the transformation of alkanes and PAHs, but later part of them settles. They are formed as a secondary product, and their amount grows gradually, but insignificantly.
- Sedimented components (purple line) accumulate on the seabed, forming a long-term source of pollution. They continuously increase, which corresponds to the formation of heavy components and their settling to the sea floor.

Thus, the overall forecast:

- Initial consequences (1-3 months): Degradation of light alkanes, partial formation of resins, and a decrease in oxygen levels can be expected.
- Medium-term consequences (1-2 years): These will be associated with the prolonged toxic impact of PAHs and the accumulation of H_2 S in the bottom layers.
- Long-term consequences (10 years): These will be related to the settling of heavy fractions (asphaltenes) to the seabed and ecosystem changes due to the reduction of oxygen.

The spill has affected numerous marine inhabitants (Figure 2). Toxic oil has covered the water's surface and settled on the seabed, causing harm to fish, mollusks, dolphins, and waterfowl. Birds, in particular, have proven to be especially vulnerable: the oil covering their feathers prevents them from flying, regulating their body temperature, and foraging for food, which inevitably leads to death.

Limited access to the affected area significantly complicates an objective assessment of the scale of the environmental disaster. Currently, only Russian organizations have direct access to the site, raising concerns about the reliability of available data. The critical situation is further exacerbated by adverse weather conditions, which hinder satellite imagery analysis. Nonetheless, available video evidence confirms the severe ecological impact – including an extensive oil slick near the Anapa coastline, an event unprecedented in the history of the Black Sea.

5. Discussion

Marine organisms, especially dolphins, suffer significantly from the consequences of oil and fuel pollution, which forms a toxic film on the water's surface and contaminates coastal areas. These effects are multifaceted, impacting both the physiological condition of the animals and the ecosystem as a whole, including:

1. Physical contact with fuel oil causes skin and mucous membrane injuries in dolphins. The acute chemical components of oil cause burns, eye irritation, and respiratory organ issues. This impairs their ability to swim, hunt, and breathe normally.

2. Disruption of respiratory function is related to dolphins' breathing by surfacing. Toxic fumes from oil and dispersants that form above the water surface can damage their lungs, leading to difficulty breathing and even suffocation.
3. Poisoning from consuming food. Dolphins, being at the top of the food chain, consume fish and other marine creatures that accumulate toxins from the water. This can lead to chronic poisoning and liver, kidney, and nervous system damage.
4. Pollution affects social behaviour, including communication and navigation. Noise from rescue operations and chemical pollution interfere with their ability to use echolocation, which is critical for hunting and communication within the group.
5. Reduction in reproductive potential. Prolonged exposure to toxic substances disrupts hormones, affecting reproductive capabilities. Pollution can cause miscarriages in pregnant females or the birth of non-viable offspring.

The oil spill significantly impacts the marine ecosystem, particularly by depleting the food supply. The death of small organisms, such as plankton, which are the primary food source for many fish and dolphins, leads to a food shortage. This triggers a chain reaction of hunger at all levels of the food chain. Moreover, pollution alters the chemical composition of the water, which becomes incompatible with the life of many marine organisms. These changes cause chronic stress for dolphins, forcing them to adapt to unfavorable conditions in their natural habitat.

Dolphins are not only key species in marine ecosystems but also demonstrate a high level of intelligence and social organization. Their health serves as an indicator of the overall condition of marine ecosystems. Protecting dolphins is not only an ethical imperative but also crucial for maintaining the integrity and biodiversity of the world's oceans.

Thus, any water and shoreline cleaning measures should aim to minimize harm to marine life, particularly by developing less toxic pollution control methods.

Another highly vulnerable group is seabirds. Their reliance on the aquatic environment for feeding, resting, and migration makes them particularly sensitive to toxic substances. Oil pollution presents multiple threats to the physiology, survival, and behavior of birds:

1. *Damage to feathers by oil* disrupts the natural water-repellent structure of the feathers, which is crucial for thermoregulation. Contaminated feathers become matted, losing their ability to retain heat, leading to hypothermia in birds, even in relatively warm waters.
2. *Difficulty flying and swimming due to matted feathers*, which increase the bird’s weight and impair aerodynamics, making flight more difficult. On the water, these birds become less maneuverable, making them easy prey for predators.
3. *Ingesting oil* while attempting to clean their plumage leads to damage to the digestive system, kidneys, and liver. Even small amounts of oil can be lethal due to its chemical toxicity and the resulting dehydration.

4. *Starvation due to the destruction of the food base.* Oil contaminates bodies of water where fish, mollusks, and other organisms that birds feed on are found. Polluted food becomes dangerous, and often inaccessible, leading to starvation.
5. *Pollution affects bird reproduction*. Toxins can reduce egg quality, decreasing the likelihood of viable offspring hatching. In some cases, contaminated areas become unsuitable for nesting.
6. *Oil-contaminated birds spend most of their time cleaning themselves* instead of searching for food, nesting, or caring for their offspring. This significantly reduces their chances of survival.

The 2010 oil spill in the Gulf of Mexico caused the mass death of species such as shearwaters, pelicans, and terns. After the disaster, high mortality rates were observed even in birds that appeared externally healthy, as prolonged contact with toxins caused internal damage.

Protecting birds requires swift responses to ecological threats, particularly to mitigate the harm caused by oil spills. To achieve this, implementing environmentally safe sorbents is crucial, as they allow for the effective and rapid collection of pollutants and the development of specialized bird rehabilitation programs, including the establishment of cleaning and treatment centres. A key priority is developing monitoring systems and rapid response mechanisms to prevent spills. The preservation of seabirds is of great importance not only from an ethical standpoint but also from an ecological perspective.

To correct the current dire environmental situation, it is essential to develop and implement urgent legal and political measures aimed at minimizing the harmful impact on the environment. In particular, it is necessary to continuously record all environmental crimes committed on the territory of Ukraine and document the damage caused (Kopytsia, Semenchenko, 2022). Furthermore, special attention should be given to developing a reconstruction plan for Ukraine that includes measures for environmental restoration and conservation.

Addressing oil spills in the Black Sea resulting from the Russian invasion requires leveraging international expertise and advanced technologies from the United States and other countries. Addressing this challenge necessitates a combination of regulatory frameworks, technological advancements, and coordinated international efforts.

The Convention on the Protection of the Black Sea Against Pollution, signed in 1992, was designed to promote sustainable marine management. However, its effectiveness has been undermined by geopolitical instability and ongoing conflict (Astasheva, Cheban, 2023). In parallel, the International Environmental Information Center for the Black and Caspian Seas (BCSEIC) serves as a critical platform for the exchange of expertise and strategies related to the prevention and mitigation of oil spills.

Technological advancements play a significant role in responding to oil spills. Numerical modeling has proven to be a valuable tool for predicting the movement and environmental impact of oil pollution, enhancing preparedness and response measures (Korotenko, 2018).

Additionally, satellite monitoring enables real-time detection and analysis of spills, improving risk assessment and facilitating timely interventions (Mityagina, 2019).

The United States' experience offers valuable insights into effective oil spill management. The U.S. oil spill response system integrates federal, state, and local agencies to ensure a coordinated and rapid reaction to pollution incidents (Astasheva, Cheban, 2023). The case of the Exxon Valdez disaster has further underscored the necessity of comprehensive response strategies, many of which could be adapted for Ukraine's specific needs.

Effective oil spill remediation requires a combination of mechanical, physicochemical, and biological methods, each aiding in the efficient removal of oil contamination from marine environments. The implementation of modern digital technologies for automated environmental monitoring in the Black Sea can enhance response efforts by providing real-time oil spill data. This facilitates prompt decision-making and enables proactive measures to minimize ecological damage (Gavardashvili et al., 2024).

6. Conclusion

Oil spills caused by tanker accidents in the Black Sea, resulting from Russia's military aggression, have created serious ecological threats to the regional ecosystem. The analysis showed that pollution causes irreparable damage to marine flora and fauna, particularly dolphins and seabirds, due to the toxicity of oil, which disrupts the oxygen balance in the water and alters the chemical composition of the environment. It was found that effective response requires a comprehensive approach, including the implementation of innovative cleaning methods, enhanced safety measures for the transportation of hazardous goods, and the improvement of international maritime law.

Reducing ecological risks further requires developing and utilizing mobile monitoring systems, deploying environmentally safe sorbents, and strengthening international cooperation to address environmental challenges. A key priority is holding perpetrators accountable under international law and initiating measures to restore the Black Sea ecosystem.

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