THE WAR IMPACT ON UKRAINE'S MARINE ENVIRONMENT

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The article is devoted to an overview of the impact of hostilities on Ukraine's marine environment. Marine ecosystems are highly vulnerable to anthropogenic factors, especially to pollution caused by hostilities, which leads to serious environmental, economic and social consequences. Ukraine, which has significant marine resources, faces the need to assess environmental risks and develop strategies to minimise them. Given the importance of marine areas for fisheries, tourism, transport and ecosystem services, a detailed study of the impact of military operations on the marine environment is crucial. Such a review will allow for the development of effective mechanisms to protect the marine environment, facilitate ecosystem restoration, and help reduce the negative impact on the economies of coastal regions. In this regard, studying the impact of military operations on the marine environment is essential for the future environmental security of Ukraine and the sustainability of its marine resources. The study aims to determine the impact of military operations on Ukraine's marine environment. It has been established that the extremely negative impact of military operations on the Black and Azov Seas is caused by the sinking of military equipment (ships, submarines, aircraft, unmanned aerial vehicles, etc.), which begins to corrode, releasing heavy metals (lead, copper, cadmium and mercury) into the water, as well as fuel materials containing oil and its derivatives. Oil forms a film on the sea surface, which harm photosynthetic organisms, disrupts gas exchange in the water, and can lead to mass mortality of fish and other aquatic organisms. This leads to the pollution of the aquatic environment, which can accumulate in marine life and affect the entire ecosystem. Another important example of the impact of military operations is the presence of explosive remnants in the Black and Azov Seas, such as mines and shells, which can remain dangerous for decades after the end of hostilities, posing threats to marine biota and human health. Military action will, therefore, have far-reaching consequences for the Black and Azov Seas, creating complex environmental, economic and social problems.

Keywords: *marine environment, military operations, war's impact on marine waters, Black Sea region*

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1. Introduction

Seawaters play an essential role in human life. They are a significant source of biodiversity and an important factor in economic development. It provides human civilization with food, energy, and raw materials and creates conditions for the development transport, tourism and recreation.

One of the strategically important aspects of marine waters is their ability to ensure food security. Fisheries are an important source of protein for more than 3 billion people worldwide. The oceans and seas provide around 80-200 million tonnes of fish yearly, making them a critical food source (Vianna et al., 2020; Ritchie and Roser, 2021).

In particular, before the full-scale Russian invasion of Ukraine, fish and seafood production reached 100,080 tonnes in 2021 (Fig. 1).

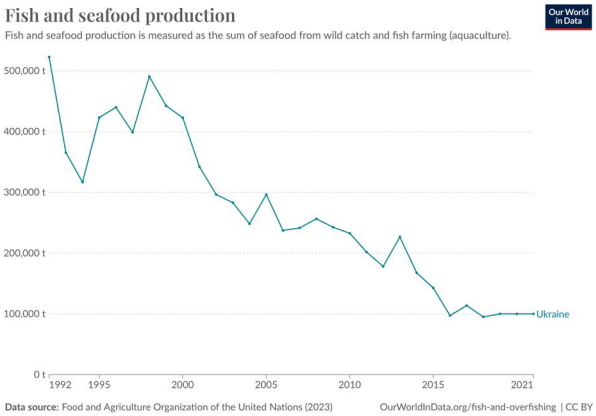

Fig. 1. *Fish and seafood production in 2021 in Ukraine (Ritchie and Roser, 2021)*

Seawater is also a source of desalination, which provides drinking water to millions of people in regions with a deficit of fresh water. This seawater utilization approach is also applicable in the southern regions of Ukraine, where there is a shortage of fresh water.

In addition, marine waters play an important role in the global energy sector. Offshore oil and gas fields account for a significant share of global energy production. Renewable energy sources, such as wind, wave, and tidal power, are becoming increasingly important as they harness the sea's potential. Installing offshore wind turbines and developing technologies for generating energy from waves and tides contribute to developing a green economy and reducing dependence on fossil fuels.

Another extremely important aspect is that sea routes are the main arteries of global trade, transporting more than 90% of all cargo. Freight transport by sea is cost-effective, especially for transporting large volumes of goods over long distances. As crucial transport hubs, ports provide jobs for millions of people and contribute to the development of coastal regions. In particular, in Ukraine, logistics of agricultural exports rely on maritime routes, which is critically important for the country.

Sea waters are also important for tourism and recreation. Coastal areas, beaches, and marine reserves are attractive to tourists from all over the world. Marine tourism provides significant revenues to countries' budgets, contributing to the development of local infrastructure and improving the economic situation of coastal communities. Therefore, ensuring safe access to clean marine waters in Ukraine is a significant challenge and an important task for the state.

Protection of the biodiversity of marine waters in Ukraine and globally is important not only from an ecological point of view but also for maintaining the stability of ecosystem services provided by marine ecosystems, including climate regulation, water purification and conservation of fish stocks, as well as ensuring the social stability of many coastal communities, and depends on the sustainable use of marine resources and maintaining the health of marine ecosystems.

Thus, marine waters are a vital human resource, providing food security, energy independence, economic development and social stability. Sustainable management of marine ecosystems is key to maintaining their ability to provide these essential services in the face of increasing man-made pressures, especially in times of war when the impact of military operations is catastrophic.

Thus, the study aims to determine the impact of military operations on Ukraine's marine environment.

2. Military operations and their impact on marine waters

Even in peace times, the marine environment is subject of significant negative impacts due to natural and anthropogenic pollution. In particular, marine waters can be contaminated with substances such as oil products (Chuah et al., 2022; Bani Hani et al., 2019), heavy metals (Trus et al., 2021; Ansari et al., 2003; Mahboob et al., 2022; Trus and Gomelya, 2021), antibiotics (Litynska et al., 2021; Dasí et al., 2024), pesticides and herbicides (Mercurio et al., 2015; Ojemaye et al., 2020), various organic pollutants (Litynska, 2024), microplastics (Kyrii et al., 2023; Alfaro-Núñez et al., 2021) etc. These pollutants pose a serious threat to ecosystems, biodiversity, fisheries and human health.

Past and present military operations have had a significant and often detrimental impact on marine waters and the entire ecosystems that inhabit them. The release of pollutants, physical disturbance and the long-term presence of military debris can cause serious and lasting damage to marine waters, affecting ecology and human health.

Hostilities inevitably cause mechanical and chemical pollution of all water bodies and seawaters. Massive flooding of military equipment and ammunition in the waters, leaks of oil products, rocket fuel and other chemical compounds as a result of missile strikes, and the destruction of large industrial enterprises or infrastructure facilities have an extremely negative impact (Litynska et al., 2024).

2.1 Submerged military equipment

Submerged military equipment (such as sunken ships, aircraft, submarines, drones etc) is a source of significant pollution of aquatic ecosystems with metal ions. The corrosion of large volumes of steel that enter water bodies, including seawater, results in the massive release of metal ions, leading to the oversaturation of the aquatic environment and threatening aquatic organisms. Metals, especially in their ionic form, can bind to the boundary epithelial structures of aquatic organisms, becoming bioavailable and easily penetrating cell membranes, which disrupts their normal function. The bioaccumulation of ferrous iron poses a serious environmental hazard, even with a slight increase in its concentration in water. This is because the biological functions of iron in aquatic organisms are carried out at low concentrations, and its excessive accumulation can lead to chronic or acute poisoning (Rabchenyuk et al., 2016).

The removal of such debris is often complex and costly, requiring careful consideration to avoid further environmental harm.

2.2 Ammunition

Various munitions pose a particular danger to marine waters. Once exposed to the marine environment, ammunition casings corrode and can leak.

Ammunition enters the seas and coastal zones during warfare through two main mechanisms. Firstly, munitions that have been fired but not exploded. It is estimated that approximately 20-30% of all projectiles fired during the world wars did not work as intended (A Guide to Survey and Clearance of Underwater Explosive Ordnance, 2016). Secondly, munitions on board ships and aircraft were destroyed as a result of enemy attacks or defensive manoeuvres, leading to their sinking along with military materials.

Ammunition contains a variety of chemical components, including conventional explosives and chemical warfare agents, which pose genotoxic, cytotoxic and carcinogenic risks to both humans and marine organisms (Strehse and Maser, 2020; Koske et al., 2019). However, the behaviour of these substances and their ultimate impact on the marine environment still need to be better understood. In general, explosives encompass a wide range of chemical groups, such as nitramines and nitroaromatic compounds, which can be transformed by various abiotic and biotic mechanisms (Beck et al., 2018).

Remnants of both conventional explosives and chemical warfare agents have been found in various types of marine ecosystems (Strehse and Maser, 2020). For example, trinitrotoluene was found in water samples, sediments and various marine organisms on the east coast of Vieques Island, Puerto Rico (Porter et al., 2011). Gledhill et al. (2019) also identified a variety of explosive chemicals in marine biota collected from a munitions dump site in the western Baltic Sea dating back to World War II (Gledhill et al., 2019).

2.3 Petroleum products

Submerged military equipment also poses a serious environmental threat due to significant volumes of petroleum products, such as diesel fuel, petrol, oils, greases, etc., used to operate it. Oil and its derivatives are complex mixtures of toxic hydrocarbons that can exist in various forms and undergo several stages of migration in the aquatic environment. Oil products in water can be subject to assimilation by aquatic organisms, sedimentation, emulsification, formation of oil aggregates, oxidation, dissolution or evaporation.

When oil products enter seawaters, they spread over the water surface, forming an oil film from which light fractions gradually evaporate (approximately 25% of the slick evaporates within a few days), while low-molecular-weight components partially dissolve in water. Oil products can concentrate other pollutants, such as heavy metals and pesticides, creating conditions for various chemical reactions. This is especially dangerous when oil films cover large areas of water (Boichenko et al., 2015).

The impact of oil products on living organisms is classified into five main categories (Boichenko et al., 2015):

1. Direct toxic poisoning, which can lead to the death of organisms;
2. Significant disruption of the physiological activity of organisms;
3. Negative effect of enveloping organisms with oil products, which leads to complications in their vital activity;
4. Painful changes caused by the penetration of hydrocarbons into the tissues of organisms;
5. Changes in the habitat's biological characteristics affect the biota's viability.

Thus, the presence of petroleum products in aquatic ecosystems seriously threatens aquatic organisms and ecosystems in general.

2.4 Bullets and ammunition fragments

Bullets and ammunition fragments, including shell casings, are often made of materials that can hurt the ecosystems they enter. Lead, one of the most common metals used in the production of bullets and shell casings, has a high toxic potential that can cause significant damage to various organ systems of vertebrates, including the nervous

system (Papanikolaou et al., 2005). In addition, some groups use depleted uranium ammunition and shell casings, which can lead to localised contamination of soil and bottom sediments, creating additional environmental risks (Briner, 2010).

Consequently, the combined impacts of pollution, physical disturbance, and military debris can have profound consequences for the marine environment, biodiversity, and ecosystems. In addition, the livelihoods of coastal communities that depend on a healthy marine environment for fishing, tourism, and other economic activities will also be negatively affected.

3. The impact of hostilities on the Black and Azov Seas

The main impacts of the armed conflict on coastal and marine ecosystems are chemical and acoustic pollution, physical damage to habitats, and reduced environmental protection measures. The hostilities have also complicated environmental monitoring and control of the Black and Azov Seas. Damage to industry and settlements can cause chemical pollution of the coastal and marine environment (Tahmid et al., 2023).

In addition to the obvious causes of the environmental disaster for Ukraine's marine waters (submerged military equipment, ammunition, petroleum products, bullets and ammunition fragments, etc.), it is possible to highlight the disruption of the operation of sewage treatment plants in coastal settlements (including through the destruction of energy facilities that power pumping stations and equipment) that treat municipal and industrial wastewater that can enter the sea. Mechanical and chemical pollution of marine waters due to hostilities, the effects of rocket attacks and the destruction of infrastructure, etc., also have extremely negative consequences.

For example, the lack of electricity supply and active hostilities in 2022 made it impossible to ensure the proper operation of local enterprises' treatment facilities and Mariupol's water and sewage system, which resulted in wastewater discharges into the Azov Sea (Anhurets et al., 2023). Also, in 2022, shelling was carried out on the sewage treatment plant in Mykolaiv, which serves a large population. This led to damage to the mechanical and biological wastewater treatment system. Another not obvious but significant factor in the disruption of the operation of treatment plants is the departure of specialists from the occupied territories who used to operate the treatment plants. The occupation and the loss of specialists critically exacerbate the water management problem (Anhurets et al., 2023).

According to the Ministry of Environmental Protection and Natural Resources of Ukraine, the full-scale war caused almost UAH 305 billion in damage to the Black Sea region. For example, one of the many environmental crimes committed by the Russians was the destruction of the Kakhovka hydroelectric power station dam in June 2023, which led to large amounts of fresh water and wastewater entering the Black Sea (Environmental Damage in the Black Sea Region Amounts to Almost UAH 305 Billion, 2023). The occupiers' explosion of the Kakhovka hydroelectric power station caused large-scale seawater salinity reduction and significant income of nutrients. According to large-scale research of marine ecosystems (Röthig et al., 2023), salinity is the most important factor affecting the composition and functionality of microorganisms in

marine ecosystems, and changes in salinity can lead to disruption in metabolic processes of microorganisms, phytoplankton, algae, fishes, mussels etc.

Over the past two years, a significant number of ships have sunk in the Black Sea and in the Sea of Azov, including cruiser "Moscow" (on April 14, 2022, between the Danube delta and the Crimea), the ship "Saratov" (on March 24, 2022, in the port of Berdyansk), etc., which led to the pollution of the marine environment with heavy metals, oil products and explosives (Serhii et al., 2022). Also, as a result of the fire at the drilling platforms (on June 20, 2022, in the Black Sea), oil and combustion products got into the water (Serhii et al., 2022).

Explosions, chemical and acoustic pollution have significantly reduced populations of different fish species, including whiting, thornback ray, spotted dogfish and turboton, which are in the red list and in danger of being extinct in Black Sea (Radulescu, 2023). The war led to an extremely sharp decline in the population of dolphins in the Black Sea (Safranov et al., 2024). Military operations also negatively affected the population of horse mackerel, which is the main fishing species in the Black Sea (its fishing is about 98.7 % of all fishing) (Radulescu, 2023).

Unfortunately, until the end of the war, it is impossible to estimate the total number of harmful leaks into Ukrainian marine waters and fully understand the horror of the negative consequences they can cause.

4. Possible measures to minimise the negative effects of the war on the marine environment of Ukraine

Military operations' impact on marine waters is a significant environmental problem that requires urgent attention.

Future studies should focus on understanding the full extent of all the negative impacts of military operations on Ukrainian marine waters, developing effective marine monitoring systems, and smart strategies to minimise the environmental footprint of these military operations in marine ecosystems.

In particular, it is crucial to monitor the state of marine waters, which requires measuring the level of pollution through regular analysis of water, sediments and marine organisms for toxic substances such as heavy metals (lead, nickel, cadmium, mercury), oil products, explosives, microplastics, etc. In particular, the development of indicator systems that would help to quickly and efficiently detect these pollutants in seawater is relevant in this case.

The next step, based on the monitoring data, is to develop measures to purify marine waters and rehabilitate and restore marine ecosystems.

The final stage is to prevent future threats by establishing systems for the proactive safeguarding of marine ecosystems. This will entail the formulation of contingency plans in the scenario of potential new conflicts.

Thus, the impact of military operations on the marine environment of Ukraine is a serious environmental problem that requires a comprehensive solution through a combination of scientific research, technical measures and international support.

5. Conclusions

The deployment of military operations in the territory of Ukraine, particularly in the

Black and Azov Seas, has resulted in a considerable negative impact on the marine environment. The primary sources of marine pollution attributable to hostilities include submerged warships, aircraft, UAVs and other equipment, emissions of oil products, heavy metals, remnants of mines and ammunition, and chemical contamination from explosives. All of these factors result in significant contamination of marine environments with a range of pollutants, including metals (iron, lead, cadmium, mercury, etc.), chemicals (explosives and their decomposition products, oil products), microplastics, etc. These pollutants enter the marine ecosystem through various pathways, including oil leaks from damaged equipment, corrosion of sunken objects, dispersal of explosive residues, chemical emissions from the destruction of ammunition, damage to coastal treatment systems, and destruction of critical infrastructure.

The environmental impact of these pollutants is evidenced by the disruption of cell membranes in marine organisms, the accumulation of toxic substances in the tissues of fish and other aquatic organisms, which leads to bioaccumulation. This can result in a precipitous decline in the number of certain species, disruption of ecosystem balance, damage to spawning grounds, and an elevated risk to human health from seafood consumption. Oil products that form a film on the water’s surface impede the process of photosynthesis, thereby reducing the productivity of ecosystems. Threats to marine ecosystems include loss of biodiversity, destruction of marine habitats, accumulation of hazardous chemicals in trophic chains, and the risk of environmental disasters.

To mitigate the negative impacts of the war on Ukraine's marine environment, it is essential to implement measures such as regular monitoring of pollution levels in seawater and bottom sediments, developing measures based on monitoring data for the rehabilitation and restoration of marine ecosystems, and creating systems for the preventive protection of marine ecosystems, including the preparation of action plans in the event of new conflicts.

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ВПЛИВ ВІЙНИ НА МОРСЬКЕ ДОВКІЛЛЯ УКРАЇНИ

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Стаття присвячена огляду впливу військових дій на морське середовище України. Морські екосистеми є надзвичайно вразливими до антропогенних факторів, особливо до забруднень, спричинених бойовими діями, які призводять до серйозних екологічних, економічних та соціальних наслідків. Україна, яка володіє значними морськими ресурсами, стикається з необхідністю оцінки екологічних ризиків та розробки стратегій для їх мінімізації. Враховуючи важливість морських акваторій для рибальства, туризму, транспорту та екосистемних послуг, детальне дослідження впливу військових дій на морське середовище є надзвичайно важливим. Такий огляд дозволить вподальшому розробити ефективні механізми захисту морського середовища, сприятиме відновленню екосистем та допоможе зменшити негативний вплив на економіку прибережних регіонів. У зв'язку з цим, дослідження впливу військових дій на морське середовище має вирішальне значення для майбутнього екологічної безпеки України та стійкості її морських ресурсів. Метою дослідження є визначення впливу військових дій на морське середовище України. Встановлено, що надзвичайно негативний вплив військових дій на Чорне та Азовське моря спричиняють затоплення військової техніки (кораблів, підводних човнів, літаків, безпілотних літальних апаратів тощо), які часом починають кородувати, вивільняючи у воду важкі метали (свинець, мідь, кадмій і ртуть), а також паливні матеріали, що містять нафту та її похідні. Нафта утворює плівку на поверхні моря, що негативно впливає на фотосинтезуючі організми, порушує газообмін у воді, та може призводити до масової загибелі риб і інших водних організмів. Це призводить до забруднення водного середовища, яке може накопичуватися в організмах морської фауни і впливати на всю екосистему. Іншим важливим прикладом впливу військових дій є наявність у Чорному та Азовському морях вибухонебезпечних залишків, таких як міни та снаряди, які можуть залишатися небезпечними протягом десятиліть після закінчення бойових дій, створюючи загрози для морської біоти та людського здоров'я. Отже, військові дії будуть мати далекосяжні наслідки для Чорного та Азовського морів, створюючи складні екологічні, економічні та соціальні проблеми.

Ключові слова: *морське середовище, військові дії, вплив війни на морські води, Чорноморський регіон*