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HUMANITARIAN DEMINING OF THE BLACK SEA UNDER ENVIRONMENTAL CHALLENGES, TECHNOLOGICAL SOLUTIONS AND STATE PERMIT REGULATION

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The full-scale military aggression against Ukraine has transformed the Black Sea into a zone of critical mine danger and ecological crisis, requiring coordinated state permit regulation of demining activities. The destruction of the Kakhovka Hydroelectric Power Plant dam in June 2023 dramatically worsened the situation by triggering the uncontrolled drift of naval mines, anti-landing obstacles, and unexploded ordnance into the marine ecosystem. This paper presents a comprehensive analysis of current mine contamination in the Black Sea, highlighting the contradiction between urgent navigation safety needs and the prohibitive cost of traditional demining methods for Ukraine's wartime budget and regulatory constraints. Special attention is paid to the ecological impact of underwater explosions on marine biodiversity, particularly the critically endangered Black Sea harbor porpoise. Mathematical modelling of hydroacoustic shockwaves using Cole's equations demonstrates that standard high-order detonation creates lethal zones of up to 450 m and permanent hearing-loss zones of up to 1.8 km for cetaceans. Based on a systematic review of literature and available technologies, a three-stage "Cost-Effective Green Demining" strategy is proposed, integrating satellite GIS drift modelling, swarms of domestic autonomous underwater vehicles (AUVs), and low-order deflagration neutralization. An operational case study for the Grain Corridor approaches demonstrates a 4.8× speed gain and a 34× cost reduction compared to conventional methods. The proposed approach reduces the acoustic footprint of demining by a factor of 20–30 and enables Ukraine to attract international environmental funding unavailable for purely military projects. The study also emphasizes the role of engineering drawing and 3D CAD modelling in the design, standardization and local manufacturing of modular AUV/ROV platforms for marine demining. *Key words:* humanitarian demining, Black Sea, naval mines, ecological safety, underwater robotics, Kakhovka HPP, autonomous underwater vehicles, green demining, state permit regulation.

Гуманітарне розмінування Чорного моря в умовах екологічних викликів, технологічних рішень та регулювання державних дозволів. Жмуд В., Кот І.Т., Гребенюк Т.В., Броницький В.О.
Повномасштабна військова агресія проти України перетворила Чорне море на зону критичної мінної небезпеки та екологічної кризи, що вимагає скоординованого державного дозвільного регулювання діяльності з розмінування. Руйнування дамби Каховської гідроелектростанції у червні 2023 року різко погіршило ситуацію, спровокувавши неконтрольований дрейф морських мін, протидесантних перешкод та невибухлих боєприпасів у морську екосистему. У цій статті представлено комплексний аналіз поточного мінного забруднення Чорного моря, що підкреслює суперечність між нагальними потребами безпеки судноплавства та непомірною вартістю традиційних методів розмінування для воєнного бюджету України та регуляторних обмежень. Особлива увага приділяється екологічному впливу підводних вибухів на морське біорізноманіття, зокрема на зникаючу чорноморську морську свиню. Математичне моделювання гідроакустичних ударних хвиль з використанням рівнянь Коула демонструє, що стандартна детонація високого порядку створює смертельні зони до 450 м та зони постійної втрати слуху до 1,8 км для китоподібних. На основі систематичного огляду літератури та доступних технологій запропоновано триетапну стратегію «Економічно ефективного зеленого розмінування», що інтегрує моделювання дрейфу супутникової ГІС, рої вітчизняних автономних підводних апаратів (АНПА) та нейтралізацію дефлаграції низького порядку. Оперативне дослідження підходів «Зернового коридору» демонструє 4,8-кратне збільшення швидкості та 34-кратне зниження вартості порівняно з традиційними методами. Запропонований підхід зменшує акустичний слід розмінування в 20–30 разів і дозволяє Україні залучати міжнародне фінансування екологічних проєктів, недоступне для суто військових проєктів. У дослідженні також підкреслюється роль технічного креслення та 3D-моделювання в CAD-системах у процесі проєктування, стандартизації та місцевого виробництва модульних платформ AUV/ROV для розмінування морських акваторій. *Ключові слова:* гуманітарне розмінування, Чорне море, морські міни, екологічна безпека, підводна робототехніка, Каховська ГЕС, автономні підводні апарати, зелене розмінування.

Problem statement. The Black Sea has historically served as a vital transport corridor and a unique ecological system. Since February 2022, Russian naval forces have extensively mined Ukrainian coastal waters, blocking sea lanes and creating a persistent threat to civilian navigation. The situation reached a critical point on June 6, 2023, when the destruction of the Kakhovka HPP dam caused a massive discharge of explosive ordnance into the Black Sea, transforming its north-western shelf into a navigation "grey zone." Humanitarian demining in this context poses a complex dilemma: traditional large mine-sweeping vessels are prohibitively expensive for Ukraine's wartime budget, and standard in-situ detonation generates lethal hydroacoustic shockwaves that threaten the already critically endangered Black Sea harbor porpoise. There is therefore an urgent need for a strategy that is both economically viable and ecologically safe.

Allocation of previously unresolved parts of the general problem. The legal and economic framework for demining is analyzed by Ustymenko et al. [1], who demonstrate that the scale of contamination exceeds state budget capacity and that international donors increasingly require "green" standards. Ivanov [2] confirms Ukraine's obligations under international conventions to address military-related marine pollution. Hrytsaienko [3] advocates agile project-based management, while Bespalko et al. [4] propose a mathematical prioritization model for maximizing economic recovery per unit of expenditure.

The ecological dimension is documented by Tuchkovenko and Stepanenko [5], whose empirical data shows that the desalination and pollution plume from the Kakhovka disaster carried mine-risk objects into previously safe areas. Lebid et al. [6] validate GIS satellite monitoring as the primary tool for tracking mine drift vectors. Soloviov and Strilets [8] quantify how conventional blasting creates local "dead zones," arguing for non-contact neutralization. Karpiuk [7] warns that without intervention, ecosystem recovery could take decades.

On the technological front, Hassan et al. [9] review the global shift toward AI-driven detection and robotics. Chesnakov [10] and Vyrvykhvost [11] demonstrate Ukraine's industrial capacity to produce cost-effective modular AUV platforms capable of operating in turbid post-flood water using high-frequency multibeam sonar. Historical analysis by Boşneagu [12] and Akhundov [13] shows that post-WWII "brute force" trawling took over a decade and is inapplicable to the modern ecological context.

Methodological framework. The study treats Black Sea humanitarian demining as a multi-variable optimization problem balancing three conflicting parameters: Security (S), Economy (E), and Biodiversity (B), seeking a Pareto-optimal solution, while incorporating constraints of state permit regulation and environmental authorization procedures governing demining operations in marine areas. Four integrated methods are applied.

GIS overlay analysis superimposes mine drift vectors (derived from ERA5 retrospective wind and current data post-Kakhovka) onto biodiversity hotspot layers (Zernov's Phyllophora Field, dolphin migration routes) to identify high-priority non-contact zones and reduce the physical search area, taking into account regulatory restrictions on operations within environmentally sensitive and protected marine zones.

Mathematical modelling of hydroacoustic shockwaves uses Cole's empirical equations for shallow brackish water. Peak pressure $P_{max} = K\cdot(W^{1/3}/R)^{\alpha}$ (K=52.4, α=1.13 for TNT) and impulse $I = K_i\cdot W^{1/3}\cdot(W^{1/3}/R)^{\beta}$ are calculated for two scenarios: Scenario A – high-order detonation of a PDM-1M mine (10 kg TNT); Scenario B – low-order deflagration (0.05 kg charge), with consideration of permissible impact thresholds established by environmental regulatory frameworks.

Technical comparative assessment evaluates a NATO SeaFox disposal vehicle (>$15,000/shot, single-use) against a domestic reusable ROV prototype equipped with a 750 kHz/1.2 MHz multibeam sonar providing 2 mm resolution at 10 m range in zero-visibility conditions [10], including compliance with technical certification and operational permitting requirements for maritime robotic systems and also an analysis of design documentation, 3D models, component layouts, and suitability for mass production.

Economic modelling applies a direct cost-per-km² formula $C_{total} = (C_{fuel} + C_{crew} + C_{amort}) / (A_{coverage} / T_{survey})$ to compare traditional mine-sweeping with robotic swarm approaches, providing quantitative justification for international donors, while also accounting for costs associated with obtaining permits, environmental assessments, and regulatory compliance procedures.

Presentation of the main material. Mine threat landscape. The Black Sea presents a heterogeneous threat: Soviet-era anchored mines (YaRM, MYaM types) that may break free during storms; drifting riverine mines (PDM series) introduced by the Kakhovka flood; and extensive UXO on the seabed. GIS analysis of hydrological data [6] identifies three critical accumulation zones driven by south-westward Dnipro-Bug current: the Kinburn Spit area, Odesa Bay littoral, and the Danube Biosphere Reserve coast – all lying astride the Grain Corridor shipping lanes.

Ecological risk assessment. Two ecological risks are quantified. First, chemical contamination: corrosion of submerged munitions releases TNT and RDX degradation products, which enter the food chain through mollusks and fish. Second, acoustic trauma: simulation results for Scenario A (PDM-1M, 10 kg TNT) indicate a Lethal Injury Zone (100% mortality) of 450 m radius and a Permanent Threshold Shift zone of 1.8 km. For echolocating species, deafness is ecologically equivalent to death [7]. Behavioral disturbance extends to 12 km from the epicenter. Scenario B (deflagration, 0.05 kg) reduces these to <15 m and <60 m respectively – a 20–30× reduction in acoustic footprint.

"Cost-Effective Green Demining" strategy. The proposed three-phase strategy is structured as follows.

Phase 1 – Remote Monitoring and Risk Mapping. Satellite imagery and GIS drift modelling replace continuous ship patrols, identifying large debris patches and predicting mine trajectories. This concentrates expensive resources on high-probability sectors, reducing the physical search area by an estimated 60–70%.

Phase 2 – Robotic Identification. Swarms of 5–10 small-class domestic AUVs – each equipped with side-scan sonar and magnetometer – scan sectors in parallel formation, achieving 5× the survey speed of a single large vessel. Domestic platforms [10] use modular architecture repairable in field conditions, unlike imported analogs requiring overseas servicing.

Phase 3 – Eco-Friendly Neutralization. Once a threat is confirmed, ROV-mounted disruptors apply deflagration: a small shaped charge burns out the explosive without high-order detonation. For floating mines, robotic tugs tow objects to shallow sandy beaches for land disposal, negating acoustic marine impact entirely.

Economic feasibility. The robotic approach operates at approximately 5% of the cost of traditional naval demining (daily OPEX ratio 1:40). Critically, framing demining as an ecological rescue mission enables access to EU Life Programme, UN Environment Programme, and Green Climate Fund grants that are unavailable for purely military operations – aligning with the donor-funding rationale of Ustymenko et al. [1].

Case study: Grain Corridor approaches (Chornomorsk sector). A simulation for a 10 km² fairway sector (depth 15–20 m, silty seabed, estimated density 0.5 objects/km²) compared two approaches. Simulation A (Sandown-class mine-sweeper): 12 h mission, 5 high-order detonations in a biologically active zone, estimated cost $120,000. Simulation B (swarm of 5 domestic AUVs from RHIB): 2.5 h mission, 5 deflagration events with acoustic impact radius <50 m, estimated cost $3,500. Result: 4.8× speed gain, 34× cost reduction, negligible ecological impact.

SWOT analysis

The SWOT matrix reveals that Strengths (low cost, ecological safety) and Opportunities (international funding, export potential) heavily outweigh Weaknesses that are primarily technical and addressable through iterative R&D. The primary Threats are external and military, reinforcing the case for unmanned systems: the loss of a drone to enemy action is acceptable; the loss of a crewed vessel is not.

Main conclusions

1. Critical state of security and ecology. The Black Sea faces a dual crisis from intensive mine contamination and the Kakhovka technogenic catastrophe. The aquatorium contains a heterogeneous mix of anchored naval mines, drifting riverine mines, and UXO. Without technological intervention, natural seabed clearance would take an estimated 20–30 years.

2. Inadequacy of traditional methods. Standard NATO-style protocols are unsuitable economically – Ukraine's budget cannot sustain the CAPEX/OPEX of a conventional fleet covering 25,000 km² – and ecologically, since high-order detonations generate lethal zones up to 450 m and PTS zones up to 1.8 km, threatening the Black Sea harbor porpoise with local extinction.

3. Viability of the Green Demining strategy. The proposed three-stage strategy (Remote Monitoring – Robotic Identification – Green Neutralization) reduces the physical search area by ~60% via GIS drift modelling, eliminates acoustic trauma in biodiversity hotspots through mandatory deflagration, and has been validated by operational simulation.

Table 1

Comparative costs of mine detection per 1 sq. km (estimated)

Parameter	Traditional Mine-Sweeper (NATO-class)	Robotic AUV Swarm (Domestic)
Capital Cost (CAPEX)	> $50 million (per vessel)	< $0.5 million (per 10 drones)
Daily OPEX	> $20,000 (crew of 30+, logistics)	< $500 (operators, electricity)
Mobilization Time	Hours / Days	Minutes
Ecological Footprint	Significant (noise, CO_2, disturbance)	Minimal (silent electric motors)
Detection Probability	High	High (redundant sensors)

Table 2

SWOT Analysis of the "Green Demining" Strategy

STRENGTHS (Internal)	WEAKNESSES (Internal)
1. Zero mortality risk for marine mammals. 2. ~5% cost of traditional naval demining. 3. Scalable swarm architecture. 4. Complete personnel removal from danger zone.	1. Limited to Sea State 3 (waves <1.25 m). 2. Battery life of 4–6 hours requires frequent recharging. 3. High sonar data volume requires post-processing.
OPPORTUNITIES (External)	**THREATS (External)**
1. High eligibility for EU/UN environmental grants. 2. Dual-use for pipeline and cable inspection. 3. Export potential for low-cost demining drones.	1. Enemy electronic warfare targeting drones. 2. Re-mining risk in cleared areas. 3. Post-flood debris may damage fragile thrusters.

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4. Economic and technological independence. Comparative analysis confirms that domestic Ukrainian AUV platforms reduce capital expenditure by orders of magnitude versus imported systems and achieve an estimated 40:1 operational cost advantage, fostering the national defense-tech sector.

5. Strategic funding access. The "Green Demining" concept enables Ukraine to reframe demining as an international environmental mission, unlocking EU Life, Green Climate Fund, and UNEP grants unavailable for purely military budgets – the only economically viable path to post-war Black Sea recovery.

6. The engineering drawing and CAD-modelling component is essential for the practical implementation of the proposed green demining strategy, as it ensures the standardization, modularity, maintainability and local manufacturability of domestic AUV/ROV platforms.

Prospects for the use of research results. Implementation of the proposed strategy creates a replicable model for conflict-zone humanitarian demining globally. The domestic AUV platforms developed for Black Sea conditions can be adapted for riverine clearance in Ukraine and exported to other nations facing post-conflict mine contamination. The GIS drift-modelling methodology can be incorporated into standard NATO and UN mine-action protocols for coastal operations in turbid-water environments.

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