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Black Sea SIERRA

Project 101124670 – Black Sea SIERRA
Guide for specific remedial measures for armed conflict pollution

ISBN 979-12-81956-60-5



DOCUMENT DETAILS

Project acronym	Black Sea SIERRA
Project title	Harnessing complementary curricular preparedness via sustainable management in response to civil and military pollution on the coastline, tributaries and lagoons in Black Sea's North, West, South zone
Grant agreement number	101124670
Consortium coordinator	National Institute for Research and development in Environmental Protection Bucharest (INCDPM)
Project duration	36 months (01.10.2023 – 30.09.2026)
Granting authority	European Climate, Infrastructure and Environment Executive Agency (CINEA)
Programme	European Maritime, Fisheries and Aquaculture Fund (EMFAF)
Call	EMFAF-2023-PIA-FLAGSHIP - Regional flagships projects supporting sustainable blue economy in EU sea basins
Topic	EMFAF-2023-PIA-FLAGSHIP-2-BLACK - Harnessing preparedness and response to marine pollution in the Black Sea
Deliverable number	D1
Work Package	WP6
Dissemination level	PU - Public
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List of Acronyms

Acronym	Full Term	Description
HMX	High Melting Explosive	High-energy explosive compound (octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine) used in military applications due to its high detonation performance and stability.
ICZM	Integrated Coastal Zone Management	An interdisciplinary approach for the sustainable management of coastal areas, integrating environmental, economic, and social considerations.
LDPE	Low-Density Polyethylene	A widely used plastic polymer characterized by low density and flexibility, frequently detected as a marine litter contaminant.
RDX	Research Department Explosive	High-energy explosive compound (cyclotrimethylenetrinitramine) commonly used in military explosives and ammunition.
SAR	Synthetic Aperture Radar	Remote sensing radar technology used for monitoring land and marine environments, including the detection of surface changes and pollution-related events.
TNT	Trinitrotoluene	High-energy explosive compound widely used in military applications and recognized as a potential environmental contaminant.
UDMH	Unsymmetrical Dimethylhydrazine	Highly toxic and reactive rocket propellant fuel used mainly in aerospace and military applications.

Introduction

Marine and coastal ecosystems are increasingly recognized as critical components of environmental security, providing essential ecosystem services, biodiversity conservation functions, climate regulation mechanisms, and socio-economic benefits to coastal communities worldwide [6,11,12]. However, these ecosystems are exceptionally vulnerable to the impacts of armed conflicts, which generate complex and often long-lasting pollution pathways capable of compromising ecological integrity at regional and transboundary scales [2,3,4]. Conflict-induced marine pollution differs substantially from conventional anthropogenic contamination because it is characterized by sudden releases of multiple contaminant classes, limited site accessibility, damaged environmental governance systems, and severe constraints on monitoring and remediation activities [2,4,5]. Military operations can introduce petroleum hydrocarbons, heavy metals, unexploded ordnance residues, persistent organic pollutants, plastics, hazardous industrial chemicals, radioactive materials, and untreated municipal waste into marine environments simultaneously, creating cumulative ecological pressures that frequently persist for decades after hostilities have ceased [2,3,15,16].

Recent assessments of the Russia–Ukraine conflict have highlighted the scale of environmental degradation that may occur when military activities affect densely industrialized coastal regions and strategically important maritime corridors [3,8,15]. In the Black Sea basin, environmental impacts have included oil and fuel releases from damaged vessels and port infrastructure, contamination associated with attacks on industrial facilities, disruption of wastewater treatment systems, accumulation of military debris, destruction of marine habitats, and increased risks of hazardous substance releases into coastal waters [3,15]. These pressures threaten biodiversity conservation objectives, fisheries productivity, ecosystem services, public health, and regional economic stability [15,16].

The protection of marine ecosystems during and after armed conflicts is supported by an evolving framework of international environmental law, international humanitarian law, and regional environmental governance mechanisms. Key legal instruments include the United Nations Convention on the Law of the Sea, the Geneva Conventions and their Additional Protocols, the International Law Commission Draft Principles on the Protection of the Environment in Relation to Armed Conflicts, and regional agreements such as the Convention on the Protection of the Black Sea Against Pollution [5,6,7,13]. Together, these instruments establish obligations to prevent, minimize, assess, and remediate environmental damage arising from military activities. Scientific evidence demonstrates that no single remediation technology is capable of

addressing the diversity of contaminants generated by modern warfare [1]. Effective environmental recovery therefore requires integrated remediation frameworks combining emergency containment measures, advanced monitoring technologies, physical removal techniques, chemical stabilization processes, biological treatment systems, phytoremediation approaches, and long-term ecosystem restoration strategies [1,28]. The selection of appropriate remedial actions must be guided by risk-based assessments that consider contaminant characteristics, ecological sensitivity, exposure pathways, technical feasibility, and long-term sustainability objectives [9,10,22].

Building upon the evidence compiled within the State-of-the-Art Remedial Solutions Database [1], this guidance document provides a comprehensive framework for the assessment, prioritization, remediation, and restoration of marine and coastal environments affected by armed conflict pollution. The document integrates international legal obligations, European environmental policy objectives, and state-of-the-art remediation technologies to support environmental authorities, policymakers, engineers, port administrations, and international organizations involved in post-conflict environmental recovery. Its ultimate objective is to facilitate scientifically robust, operationally feasible, and environmentally sustainable interventions capable of restoring ecological integrity and strengthening the resilience of conflict-affected marine ecosystems [1,3,5].

Chapter 1: Policy Frameworks and Guiding Principles for Marine Remediation

1.1 International Legal Instruments and Conventions

The prevention and mitigation of marine pollution resulting from armed conflicts are governed by a multilayered framework of international environmental law, international humanitarian law, and customary legal principles. Together, these instruments establish obligations for States and conflict parties to prevent environmental damage, minimize ecological harm during military operations, and support post-conflict restoration [2,4,5].

The primary legal foundation for marine environmental protection is the United Nations Convention on the Law of the Sea (UNCLOS), adopted in 1982 [6]. Articles 192 and 194 establish the obligation of States to protect and preserve the marine environment and to prevent, reduce, and control pollution from all sources, including activities with potential military relevance. These obligations are complemented by Articles 204–206, which require environmental monitoring, impact assessment, and information exchange in cases of significant environmental risk [6].

International Humanitarian Law further strengthens environmental protection during armed conflict. Additional Protocol I to the Geneva Conventions prohibits warfare methods expected to cause widespread, long-term, and severe damage to the natural environment and requires the protection of civilian environments, including ecological systems. Although not originally designed with marine ecosystems in mind, these provisions are now widely interpreted as applicable to naval operations, coastal strikes, and industrial targeting affecting marine environments [7].

The Hague Regulations of 1907 remain relevant through their principles of military necessity and proportionality, which modern legal interpretation increasingly extends to environmental protection [2,4]. Excessive or avoidable environmental destruction is now generally considered incompatible with these principles.

A significant development is represented by the International Law Commission's Draft Principles on the Protection of the Environment in Relation to Armed Conflicts (2022), which consolidate existing legal norms across pre-conflict, conflict, and post-conflict phases [5]. These principles emphasize environmental integration into military planning, prohibit severe environmental harm, and encourage cooperation, monitoring, and post-conflict remediation.

Customary International Law reinforces these treaty obligations through the “no-harm principle”, requiring States to prevent transboundary environmental damage caused by activities under their jurisdiction [2,4]. This principle is particularly relevant in semi-enclosed seas such as the Black Sea, where pollution can rapidly spread across national boundaries [6,13].

Operational guidance is further developed by the International Committee of the Red Cross, which highlights the need for environmental risk assessment, precautionary measures, protection of sensitive ecosystems, and post-conflict restoration responsibilities [4]. These guidelines also recognize the long-term humanitarian consequences of environmental degradation, including impacts on water quality, food security, and ecosystem-dependent livelihoods.

Recent assessments by the United Nations Environment Programme confirm that environmental damage from modern warfare extends far beyond immediate combat zones, affecting river basins, coastal systems, and marine ecosystems at regional scale [2,3]. As a result, environmental protection in armed conflict is increasingly recognized as an issue of international security requiring coordinated legal, institutional, and scientific responses [3].

1.2 European Union Directives and Regional Governance Initiatives

Within the European Union, marine environmental protection is governed by an integrated policy framework aimed at ensuring long-term ecological sustainability, while supporting economic development and environmental resilience [11,12]. These instruments provide a relevant reference model for post-conflict environmental restoration in European marine regions, including the Black Sea. The Water Framework Directive (2000/60/EC) establishes the objective of achieving good ecological and chemical status for all water bodies through a river basin management approach [12]. This integrated perspective is particularly relevant in conflict-affected areas, where pollution often originates from damaged infrastructure and is transported from inland systems to coastal and marine environments.

Complementing this, the Marine Strategy Framework Directive (2008/56/EC) aims to achieve Good Environmental Status in European marine waters through eleven environmental descriptors, including biodiversity, contaminants, marine litter, underwater noise, and ecosystem integrity [11]. Many of these pressures are directly influenced by military activities, making the Directive highly relevant for assessing conflict-related marine degradation.

It is worth noting that none of the instruments referenced above — nor other European or international environmental regulations currently in force — establish specific environmental quality standards for contaminants directly associated with armed conflict, such as TNT, RDX, and other explosive residues, rocket propellants (e.g., unsymmetrical dimethylhydrazine, UDMH), or heavy metals of military origin. Existing threshold values under the Water Framework Directive and related legislation were developed primarily for industrial and agricultural pollutants, leaving a regulatory gap that constrains the definition of clear, legally binding remediation targets for conflict-affected marine environments.

The European Green Deal and the Zero Pollution Action Plan further reinforce these objectives by prioritizing pollution prevention, ecosystem restoration, circular economy principles, and sustainable resource management [11]. In this context, environmental protection is increasingly recognized as more effective and cost-efficient when integrated early into reconstruction and development planning. At the implementation level, the EU Mission “Restore Our Ocean and Waters” promotes science-based solutions for marine restoration, pollution monitoring, and ecosystem resilience through innovation and stakeholder cooperation [11]. At the regional scale, the governance of the Black Sea is primarily structured through the Bucharest Convention on the Protection of the Black Sea Against Pollution [13]. This legally binding framework addresses pollution from land-based sources, maritime activities, dumping, and emergency situations.

The Convention is implemented through the Black Sea Commission, which coordinates environmental monitoring and promotes harmonized management practices among coastal States [13]. Its work is supported by the Strategic Action Plan for the Rehabilitation and Protection of the Black Sea, which focuses on pollution reduction, biodiversity conservation, sustainable fisheries, and regional cooperation [14]. Following the environmental impacts of the Russia–Ukraine conflict, the importance of coordinated regional governance has increased significantly, highlighting the vulnerability of marine ecosystems to geopolitical instability [3,15]. Because marine pollution spreads across national boundaries through hydrodynamic processes, effective remediation in the Black Sea requires integrated implementation of EU policies, international conventions, and regional agreements [3,13,15].

1.3 Core Environmental Management Principles

Effective remediation of conflict-related marine pollution requires robust environmental management principles capable of guiding decision-making under

uncertainty, ecological complexity, and operational constraints [1,2]. These principles form the conceptual basis for integrating legal obligations, technical interventions, and long-term restoration strategies.

The precautionary principle is central to environmental governance, requiring preventive action in cases of potential serious or irreversible environmental harm, even when scientific certainty is incomplete [11,12]. In post-conflict settings, where access and data are often limited, this principle is essential to reduce further ecological damage [4,5].

Closely related, the prevention principle emphasizes avoiding pollution at its source, as prevention is generally more effective and less costly than remediation. This requires integrating pollution control and sustainable design into reconstruction and industrial planning from the outset [1,11]. The polluter pays principle reinforces environmental accountability by requiring those responsible for environmental damage to bear the costs of monitoring, remediation, and restoration. Despite enforcement challenges in conflict contexts, it remains a key element of deterrence and environmental governance [5,11,12].

Integrated Coastal Zone Management (ICZM) provides a framework for coordinating land–sea interactions and balancing environmental, social, and economic objectives, supporting coherent remediation across administrative and ecological boundaries [11]. Sustainable waste management and circular economy approaches are particularly relevant in post-conflict environments with large volumes of debris and contaminated materials. Resource recovery and minimization of secondary pollution are essential to reduce long-term environmental impacts [1,11,22].

Ecosystem-based management complements this approach by focusing on ecological interactions, habitat connectivity, and cumulative impacts rather than individual contaminants. This is especially important in conflict scenarios where multiple stressors act simultaneously on marine systems [1,11,16]. Nature-based solutions such as bioremediation, phytoremediation, habitat restoration, and ecological engineering further enhance resilience and cost-effectiveness [1,18,20,23].

Finally, adaptive management is essential due to uncertainty in contamination patterns and ecosystem responses. Continuous monitoring and iterative adjustments ensure that remediation strategies remain effective over time [1,9,10]. Together, these principles provide the operational foundation for all assessment, remediation, monitoring, and restoration activities described in this guidance, ensuring a coherent and sustainable approach to marine ecosystem recovery in post-conflict contexts.

Chapter 2: Technical Decontamination Methodologies for Marine Contaminants

2.1 Integrated Remediation Framework and Technology Selection Criteria

Marine pollution generated by armed conflicts presents unique technical challenges due to the simultaneous presence of multiple contaminant classes, damaged infrastructure, limited site accessibility, and elevated environmental risks [1,3,15]. Unlike conventional pollution events, conflict-related contamination often involves the concurrent release of petroleum hydrocarbons, heavy metals, plastics, unexploded ordnance residues, hazardous industrial chemicals, untreated wastewater, and military debris, resulting in highly complex environmental scenarios that require integrated remediation strategies [1,31].

Scientific evidence indicates that no single remediation technology is capable of effectively addressing the full spectrum of contaminants generated during military operations [1]. Consequently, contemporary remediation frameworks increasingly adopt a risk-based approach in which physical, chemical, biological, and nature-based solutions are combined according to site-specific conditions and environmental objectives [1,2]. The selection of appropriate technologies should consider contaminant characteristics, concentration levels, environmental sensitivity, hydrodynamic conditions, operational feasibility, security constraints, and long-term sustainability requirements [9,10,35].

Effective remediation programs generally follow a sequential framework beginning with emergency containment measures aimed at limiting contaminant dispersion. These actions are subsequently complemented by active remediation technologies designed to reduce contaminant concentrations, followed by ecological restoration interventions intended to recover ecosystem functionality. Long-term environmental monitoring and adaptive management remain essential components throughout the entire remediation process, ensuring that restoration objectives are achieved and maintained over time [3,9,10].

2.2 Mechanical, Chemical, and Biological Remediation of Oil Spills

Petroleum contamination represents one of the most severe environmental consequences associated with maritime warfare and attacks on coastal infrastructure. Large-scale oil releases can rapidly spread across marine environments, affecting coastal habitats, fisheries resources, marine biodiversity, and

ecosystem services while generating both acute and chronic toxicological effects [29,30,31].

Mechanical containment and recovery technologies constitute the preferred first response option because they physically remove contaminants from the environment without introducing additional chemical agents. Floating containment booms are commonly deployed to restrict the horizontal dispersion of oil slicks, while skimmers and vacuum recovery systems are used to collect floating hydrocarbons from the water surface. Under favorable weather and sea-state conditions, these technologies can achieve significant recovery efficiencies and reduce the risk of contamination reaching environmentally sensitive areas such as estuaries, wetlands, seagrass meadows, and coastal lagoons [8,29,30].

When mechanical recovery alone is insufficient, chemical response technologies may be employed to accelerate the natural degradation of hydrocarbons. Chemical dispersants reduce the interfacial tension between oil and water, promoting the formation of smaller droplets that become more accessible to microbial degradation processes [32]. Although dispersants can significantly reduce shoreline contamination risks, their use remains subject to scientific debate due to concerns regarding potential toxicological impacts on marine organisms and increased contaminant exposure within the water column. Consequently, dispersant application should only be considered following comprehensive environmental risk assessments and under appropriate regulatory oversight [32].

Bioremediation has emerged as one of the most promising long-term approaches for the treatment of hydrocarbon contamination in marine environments [18,19]. This strategy exploits the metabolic capabilities of naturally occurring or introduced microorganisms capable of degrading petroleum compounds into less harmful substances. Biostimulation techniques involve enhancing the activity of indigenous microbial communities through nutrient supplementation, whereas bioaugmentation relies on the introduction of specialized hydrocarbon-degrading microorganisms [18]. Numerous studies have demonstrated the effectiveness of bacterial consortia containing species such as *Pseudomonas aeruginosa* and *Rhodococcus erythropolis* in accelerating hydrocarbon degradation under marine conditions [19]. Nevertheless, biological treatment efficiency remains strongly dependent on environmental parameters including temperature, oxygen availability, nutrient concentrations, and contaminant composition.

2.3 Advanced Technologies for Marine Plastic and Debris Removal

Marine plastic pollution has become a major environmental concern due to its persistence, widespread distribution, and adverse ecological effects [26,27,33]. Armed conflicts contribute significantly to this problem through the destruction of infrastructure, military equipment, packaging materials, synthetic components, and debris generated by military operations. Once introduced into the marine environment, these materials may undergo fragmentation processes that lead to the formation of microplastics and nanoplastics capable of entering aquatic food webs [26].

Physical removal remains the most effective approach for managing large plastic debris and floating waste. Floating barriers, passive interception systems, autonomous collection vessels, and shoreline cleanup operations have demonstrated substantial effectiveness in reducing macroplastic accumulation in coastal and marine environments [34]. However, successful implementation requires continuous maintenance, proper waste handling infrastructure, and coordinated management efforts involving environmental authorities and local stakeholders.



Figure 1: Plastic waste and debris polluting a body of water, highlighting the issue of marine litter. Source: Pexels

To maximize resource recovery and minimize secondary environmental impacts, collected plastic waste should be incorporated into circular economy frameworks whenever feasible [11]. Advanced thermal and chemical recycling technologies, including pyrolysis and catalytic depolymerization processes, enable the conversion of plastic materials into fuels, chemical feedstocks, and reusable industrial products [27,33]. Such approaches contribute not only to pollution reduction but also to resource conservation and waste minimization objectives.

Biological degradation technologies have attracted growing scientific interest as sustainable alternatives for plastic waste management [28]. Certain bacterial and fungal species possess enzymatic systems capable of degrading polymer structures under specific environmental conditions. Marine fungi belonging to the *Aspergillus* genus, for example, have demonstrated promising degradation efficiencies for polyethylene and related polymers through the production of hydrolytic enzymes that facilitate polymer breakdown [28]. Certain bacterial and fungal species possess enzymatic systems capable of degrading polymer structures under specific environmental conditions. Marine fungi belonging to the *Aspergillus* genus, for example, have demonstrated promising degradation efficiencies for polyethylene and related polymers through the production of hydrolytic enzymes that facilitate polymer breakdown [17,48]. Although these technologies remain largely experimental at large operational scales, they represent a promising area of future research and innovation.

2.4 Remediation of Eutrophication and Nutrient Pollution

The destruction of wastewater treatment facilities, sewage networks, and industrial infrastructure during armed conflicts often results in substantial nutrient discharges into coastal and marine environments [15]. Elevated concentrations of nitrogen and phosphorus stimulate excessive algal growth, leading to eutrophication processes characterized by oxygen depletion, biodiversity loss, fish mortality events, and deterioration of water quality [20].

Physical remediation measures are commonly implemented to restore dissolved oxygen concentrations and improve water circulation within affected water bodies. Technologies such as artificial aeration and hypolimnetic oxygenation increase oxygen availability and mitigate hypoxic conditions, thereby supporting ecosystem recovery [20]. In some situations, sediment dredging may also be employed to remove nutrient-rich sediments that act as long-term internal nutrient sources.

Chemical treatment approaches focus on reducing nutrient bioavailability through precipitation and adsorption processes. Various coagulants and flocculants can bind phosphorus and other nutrients into insoluble compounds that are subsequently removed from the aquatic environment. Although these methods can achieve rapid reductions in nutrient concentrations, careful management is required to avoid unintended ecological consequences associated with chemical additions [20].

Biological and nature-based solutions increasingly represent preferred remediation strategies due to their ability to provide multiple environmental benefits simultaneously. Constructed wetlands, macroalgae cultivation systems, seagrass restoration projects, and ecological engineering interventions can effectively remove excess nutrients while supporting habitat recovery, biodiversity conservation, and carbon sequestration objectives [20]. The integration of these approaches within broader ecosystem restoration programs contributes significantly to long-term environmental resilience.

2.5 Physical, Chemical, Biological, and Nanotechnology-Based Remediation of Heavy Metals

Heavy metal contamination constitutes one of the most persistent environmental challenges associated with armed conflicts because metals do not degrade naturally and may remain environmentally available for extended periods. Military activities can introduce substantial quantities of lead, cadmium, chromium, mercury, copper, nickel, and zinc into marine ecosystems through munitions residues, damaged infrastructure, industrial accidents, and military debris [24].

Among physical remediation technologies, sediment dredging remains one of the most widely applied methods for removing heavily contaminated materials [22,35]. This approach can rapidly reduce contaminant inventories within affected areas and significantly decrease environmental risks. Nevertheless, dredging operations must be carefully managed to prevent sediment resuspension and secondary contaminant dispersion. Moreover, the long-term management and disposal of contaminated sediments often represent major logistical and economic challenges [22].

Chemical remediation technologies seek to reduce contaminant mobility and bioavailability through stabilization and immobilization processes. Techniques such as phosphate stabilization, electrocoagulation, reactive capping, and solidification treatments can effectively convert dissolved metal species into more stable and less bioavailable forms [21]. These approaches are par-

ticularly advantageous in environmentally sensitive areas where large-scale sediment removal may not be feasible.

Biological remediation methods have gained considerable attention because of their relatively low environmental impact and long-term sustainability [18]. Biostimulation and bioaugmentation strategies utilize microbial communities capable of transforming, immobilizing, or accumulating heavy metals under controlled conditions. Similarly, phytoremediation approaches use aquatic, coastal, and salt marsh vegetation to absorb contaminants through their root systems or to stabilize contaminated sediments in high-salinity environments. Halophytic species such as *Spartina alterniflora* (salt marsh grass) [38] and marine submerged macrophytes such as *Zostera marina* (eelgrass) [38,46] have demonstrated significant phytoextraction and rhizofiltration capabilities for removing cadmium, lead, chromium, and other hazardous metals from estuaries and coastal marine ecosystem [36].

Recent advances in nanotechnology have further expanded remediation possibilities. Nanoscale zero-valent iron particles, carbon nanotubes, graphene-based composites, and engineered nanomaterials exhibit exceptionally high reactivity and adsorption capacities, enabling the efficient removal of both inorganic and organic contaminants [23,25]. Although their large-scale implementation remains under evaluation, these technologies offer considerable potential for future remediation applications in complex conflict-related contamination scenarios.



Figure 2: Leaching mechanism of shoreline debris. Continuous wave action erodes industrial/military waste, releasing heavy metals directly into the marine water column. Source: Pexels

2.6 Emerging Contaminants, Explosive Residues, and Radiological Hazards

Modern armed conflicts generate contaminant classes that are frequently overlooked within conventional marine remediation frameworks [3,37]. Explosive residues derived from military ordnance, including compounds such as TNT, RDX, and HMX, may persist within marine sediments and pose long-term ecological risks. Similarly, propellant chemicals, combustion by-products, lubricants, and military-specific industrial compounds can contribute to complex contamination profiles requiring specialized assessment and remediation approaches [3]. Field assessments along the Romanian Black Sea coast confirm that ammunition and explosives are a significant source of heavy metals such as lead, copper, zinc, and cadmium, with quantitative mass-balance models proposed to support the preliminary evaluation of pollutant loads in conflict-affected coastal waters [50].

Additional concerns arise from the potential release of radioactive materials following attacks on nuclear facilities, industrial installations, or radioactive waste storage infrastructure [37]. Such contamination scenarios require highly specialized monitoring programs, radiological assessments, containment measures, and long-term environmental surveillance. Because contaminant behavior, toxicity, and environmental persistence vary substantially among these substances, remediation strategies must be developed on a case-by-case basis and supported by multidisciplinary expertise [5,37].

2.7 Long-Term Monitoring and Performance Verification

The effectiveness of remediation programs ultimately depends on the implementation of robust monitoring systems capable of verifying environmental recovery and identifying residual contamination risks [9,10]. Long-term monitoring should encompass physical, chemical, and biological indicators, including water quality parameters, sediment chemistry, contaminant bioavailability, ecological status indicators, and biodiversity assessments [24]. Hydrographic monitoring using CTD/SVP profiling has further shown that strong seasonal stratification in Black Sea coastal waters, such as at the Constanța Port roadstead, can substantially reduce vertical mixing and increase surface-layer contaminant retention time, underscoring the importance of accounting for water-column stratification when interpreting long-term monitoring data [51].

Technological advances have significantly improved monitoring capabilities through the integration of satellite observations, autonomous sensor networks,

remote sensing platforms, and real-time environmental data systems [10]. These technologies facilitate continuous environmental surveillance and enable rapid detection of emerging contamination events.

Performance evaluation should be linked to clearly defined ecological restoration objectives and measurable environmental indicators. Adaptive management frameworks allow remediation strategies to be modified in response to monitoring results, ensuring continuous improvement and maximizing the probability of achieving long-term environmental recovery goals [1,9]. Consequently, monitoring should not be regarded as the final stage of remediation but rather as an integral component of an ongoing environmental management process supporting sustainable ecosystem restoration.

Chapter 3: Strategic Assessment and Emergency Response for Armed Conflict Pollution

3.1 Analysis of Conflict-Driven Pollution Vectors in the Black Sea

The ongoing Russia–Ukraine conflict has generated a major environmental crisis affecting marine ecosystems in the Black Sea, with impacts that extend far beyond immediate humanitarian consequences. Military activities introduce multiple, interacting pathways of environmental degradation that threaten the ecological integrity of the basin over long time scales [3,15,39,40]. Unlike conventional pollution sources, conflict-related contamination is characterized by the simultaneous release of physical, chemical, and biological stressors across wide spatial scales and under highly dynamic conditions [16].

The Black Sea is particularly vulnerable due to its semi-enclosed morphology, limited water exchange, and pre-existing environmental pressures such as eutrophication and industrial pollution [14,42]. These characteristics favor the persistence and accumulation of contaminants, which can propagate beyond national boundaries and produce long-term cumulative effects [13,42].

Military operations contribute directly to marine pollution through the release of debris, fuel residues, heavy metals, explosive remnants, and synthetic materials. Naval engagements, vessel sinkings, and underwater detonations also generate acoustic pollution, which can disrupt marine fauna and ecosystem processes [15,41]. In addition, sunken military materials may become long-term secondary pollution sources through corrosion and gradual contaminant release.

Damage to industrial and energy infrastructure represents another critical pathway of contamination. The destruction of refineries, storage facilities,

chemical plants, and transport networks can release hydrocarbons, solvents, heavy metals, and combustion by-products into riverine and coastal systems [3,39]. These substances may accumulate in sediments and enter marine food webs through bioaccumulation processes [24].

Similarly, the disruption of wastewater treatment and urban drainage systems increases the discharge of untreated effluents into aquatic environments, leading to nutrient enrichment, pathogen spread, hypoxic conditions, and further ecological degradation [15,20]. The conflict has also disrupted fisheries and maritime activities across the region, altering access to fishing grounds, damaging port infrastructure, and increasing navigational risks due to military hazards [43]. These disruptions affect not only economic stability but also ecosystem dynamics through changes in fishing pressure and resource distribution. Overall, the combined effect of these pollution vectors highlights the need for integrated environmental assessment frameworks capable of addressing multiple stressors simultaneously. Effective management must therefore move beyond single-pollutant approaches and focus on the cumulative and interacting impacts of conflict-driven ecosystem degradation [3,15,40].

3.2 Environmental Risk Assessment and Pollution Hotspot Prioritization

Given the scale and complexity of environmental damage associated with armed conflicts, remediation resources must be allocated according to scientifically justified prioritization criteria [9,10,35]. Environmental risk assessment therefore represents the cornerstone of all post-conflict remediation planning activities.

The primary objective of environmental risk assessment is to identify locations where contamination poses the greatest threat to human health, ecological integrity, economic activities, and environmental security [10,35]. This process requires the integration of contaminant monitoring data, ecological sensitivity assessments, exposure pathway analyses, and socioeconomic considerations. Initial site characterization should focus on identifying contaminant sources, pollutant types, affected environmental compartments, and potential exposure routes. Water quality analyses, sediment investigations, habitat assessments, and contaminant transport modeling should be conducted whenever security conditions permit field operations [10,35]. In situations where direct access remains restricted, remote sensing technologies and autonomous monitoring systems can provide valuable preliminary information regarding environmental conditions [9].

Particular attention should be given to environmentally sensitive areas including wetlands, estuaries, spawning grounds, marine protected areas, seagrass meadows, and biodiversity hotspots [41,42]. Contamination occurring within such environments may generate disproportionately severe ecological consequences and therefore requires higher remediation priority. Risk ranking frameworks should evaluate contamination severity according to multiple criteria, including contaminant toxicity, persistence, mobility, ecological sensitivity, population exposure, and potential for transboundary impacts [10,35]. Areas exhibiting high contaminant concentrations, extensive habitat degradation, and significant human exposure pathways should be classified as critical intervention zones requiring immediate response measures.

The use of Geographic Information Systems, environmental sensitivity mapping, and multi-criteria decision analysis tools can substantially improve prioritization processes by integrating environmental, social, economic, and operational variables within a unified assessment framework [10,41]. Such approaches facilitate transparent decision-making and support the efficient allocation of limited remediation resources. Environmental risk assessment should not be considered a one-time exercise but rather an iterative process continuously updated through monitoring data and scientific investigations. This adaptive approach allows authorities to modify priorities as environmental conditions evolve and new information becomes available [1].

3.3 Emergency Monitoring and Remote Response Protocols

Active conflict zones present significant challenges for environmental monitoring and remediation activities due to security constraints, limited accessibility, and rapidly changing operational conditions [3,39]. Consequently, emergency response systems must increasingly rely on remote monitoring technologies and autonomous response capabilities.

The deployment of integrated monitoring networks constitutes a critical component of environmental emergency management. Modern monitoring systems combine satellite observations, aerial surveillance platforms, autonomous surface vehicles, underwater drones, sensor-equipped buoys, and real-time data transmission technologies to provide continuous environmental information [9,10]. These systems enable the rapid identification of pollution hotspots, contaminant transport pathways, and emerging environmental threats.

Satellite-based monitoring has proven particularly valuable for detecting oil spills, suspended sediment plumes, algal blooms, thermal anomalies, and infra-

structure damage over large geographic areas [10]. Advances in synthetic aperture radar (SAR) and multispectral imaging technologies allow environmental authorities to monitor marine pollution events even under adverse weather conditions or in areas inaccessible to field personnel. Autonomous and remotely operated technologies play an increasingly important role in post-conflict environmental management. Unmanned surface vehicles and remotely operated underwater vehicles can collect environmental samples, inspect submerged infrastructure, identify military debris, and assess contaminant distributions without exposing personnel to unacceptable risks [9]. These technologies are particularly valuable in areas affected by naval mines, unexploded ordnance, or ongoing military activity.

Emergency response protocols should prioritize actions aimed at preventing contaminant dispersion and reducing immediate ecological damage. Rapid deployment of containment barriers, temporary storage systems, floating recovery equipment, and emergency wastewater treatment units can substantially reduce environmental impacts during the initial stages of contamination events [8,29]. Early intervention is especially important in coastal environments where contaminant transport processes may rapidly affect sensitive habitats and populated areas. The effectiveness of emergency response operations depends heavily on communication and coordination among environmental agencies, emergency management authorities, military organizations, scientific institutions, and international partners [3,40]. Establishing interoperable monitoring platforms and standardized reporting procedures can significantly improve response efficiency and facilitate information sharing across jurisdictions.



Figure 3: Field monitoring and water sampling. An environmental engineer logs real-time data while analyzing a water sample from a stagnant, eutrophic water body. Source: Pexels

3.4 Post-War Sustainable Reconstruction and Ecosystem Restoration

As active hostilities decline, environmental priorities shift from emergency response toward long-term recovery and sustainable reconstruction [3,8]. The post-conflict phase offers a critical opportunity to rebuild damaged infrastructure while improving environmental performance, climate resilience, and ecosystem protection. Reconstruction should follow a “build back better” approach, integrating environmental sustainability into all planning and design processes [8]. Coastal infrastructure, ports, wastewater systems, industrial facilities, and transport networks should be redesigned according to modern environmental standards that reduce future pollution risks and enhance resilience to environmental stressors.

Environmental restoration must extend beyond contaminant removal to include the recovery of ecosystem structure and function. Habitat restoration in wetlands, seagrass meadows, coastal lagoons, estuaries, and spawning areas can accelerate ecological recovery while supporting biodiversity and ecosystem services such as carbon sequestration, shoreline stabilization, and fisheries enhancement [1,41].

Nature-based solutions should be prioritized where feasible. Approaches such as bioremediation, phytoremediation, ecological engineering, and living shorelines offer cost-effective and resilient alternatives or complements to conventional engineering solutions [1,20,23]. Their integration with technical remediation methods is increasingly considered best practice in degraded coastal systems.

Socioeconomic dimensions are also essential. Sustainable fisheries management, environmental education, stakeholder engagement, and community-based monitoring help strengthen governance systems and improve the long-term sustainability of restoration efforts [43]. Ultimately, effective post-conflict recovery depends on the implementation of international legal frameworks and regional cooperation mechanisms [5,6,13]. Given the trans-boundary nature of marine pollution in the Black Sea, coordinated policies, shared monitoring systems, and sustained scientific and institutional collaboration are essential to prevent recontamination and ensure lasting environmental recovery. Overall, successful restoration of conflict-affected marine environments requires not only technical remediation, but also strong governance, international cooperation, and long-term institutional commitment to environmental sustainability.

Chapter 4: Risk Prioritization and Decision-Making Framework for Conflict-Related Marine Pollution

4.1 Site Characterization and Environmental Baseline Assessment

The effectiveness of any remediation program depends on a robust initial environmental assessment. Before selecting technologies or allocating resources, authorities must develop a clear understanding of site conditions, contaminant distribution, ecological sensitivity, and exposure pathways [44,45]. In conflict-affected marine environments, where multiple pollution sources act simultaneously across large and heterogeneous areas, a multidisciplinary approach integrating physical, chemical, biological, and socioeconomic data is essential [3,15,39].

Site characterization begins with the identification of contamination sources and pollutant types, including damaged industrial facilities, military infrastructure, sunken vessels, fuel depots, wastewater systems, transport networks, and debris fields [3,15]. Particular attention should be given to high-risk sites containing hazardous materials with long-term environmental persistence. Environmental investigations should then quantify contaminant levels in water, sediments, and biota, distinguishing between primary impact zones and areas affected through hydrodynamic transport processes [10,35]. In contexts with limited field access, remote sensing and predictive modelling provide essential support for preliminary assessments [9].

Ecological baseline conditions must also be evaluated to determine ecosystem vulnerability and recovery potential. Habitat mapping, biodiversity assessments, fisheries data, and ecosystem service analyses help clarify the broader consequences of environmental degradation, particularly where conflict impacts overlap with pre-existing pressures [41,42]. Integrating environmental and socioeconomic data enables the identification of areas where contamination may have significant implications for public health, food security, and economic stability. This ensures that remediation planning supports both ecological recovery and long-term regional resilience [43,49].

4.2 Environmental Risk Classification and Priority Ranking

Given the limited financial, technical, and operational resources typically available during post-conflict recovery, environmental interventions must be prioritized according to objective and transparent criteria [44,45]. Risk-based prioritization provides a systematic mechanism for directing resource-

es toward areas where remediation activities will generate the greatest environmental and societal benefits. Environmental risk should be evaluated as a function of contaminant hazard, exposure probability, ecological sensitivity, and potential consequences [44]. Highly toxic and persistent contaminants such as heavy metals, petroleum hydrocarbons, explosive residues, and radioactive substances generally require elevated priority due to their long-term environmental persistence and capacity for bioaccumulation [24,31,37].

Ecological sensitivity represents a second critical component of risk evaluation. Contamination occurring within wetlands, estuaries, marine protected areas, seagrass meadows, spawning grounds, or biodiversity hotspots should receive higher priority than impacts affecting less sensitive environments [41,42]. Damage to such habitats frequently results in cascading ecological effects extending well beyond the immediate area of contamination. Human exposure pathways must also be considered. Areas where contamination threatens drinking water supplies, fisheries resources, recreational activities, or coastal communities may require urgent intervention even when ecological impacts remain relatively localized [44,49]. This approach recognizes the strong interdependence between environmental quality and human well-being.

To facilitate operational decision-making, contaminated sites may be classified into four priority categories. Critical-risk sites include locations where contamination poses immediate threats to human health, environmental security, or ecosystem survival. High-risk sites are characterized by severe contamination levels and substantial ecological impacts but may not require immediate emergency intervention. Moderate-risk sites exhibit measurable environmental degradation that can be managed through planned remediation programs, while low-risk sites generally remain suitable for monitoring-based management approaches emphasizing natural recovery processes [44,45]. The use of standardized risk classification systems improves transparency, supports resource allocation decisions, and facilitates communication among governmental agencies, international organizations, and technical stakeholders [47].

4.3 Decision-Support Framework for Remediation Technology Selection

Following risk classification, decision-makers must identify remediation technologies capable of achieving environmental objectives while remaining technically feasible and economically sustainable [1,35]. Because conflict-related

contamination typically involves multiple pollutants and environmental compartments, technology selection should follow a structured decision-support framework rather than relying on individual expert judgment alone. The first decision point concerns whether immediate intervention is required. Sites exhibiting acute contamination risks, active pollutant releases, or significant exposure pathways generally require emergency containment measures aimed at preventing contaminant dispersion [8,29]. Typical interventions may include containment booms, temporary barriers, wastewater diversion systems, and emergency recovery operations.

Table 1: Comparative Overview of Remediation Technologies for Conflict-Related Marine Contaminants.

Technology	Primary Target	Relative Cost	Typical Timeframe
Mechanical containment & recovery (booms, skimmers)	Oil / hydrocarbons	Low–Moderate	Immediate (hours–days)
Chemical dispersants	Oil / hydrocarbons	Low	Immediate (hours)
Bioremediation (biostimulation / bioaugmentation)	Hydrocarbons; some metals	Low–Moderate	Medium–long (weeks–months+)
Sediment dredging	Heavy metals; legacy sediment	High	Short–medium (weeks–months)
Chemical stabilization / reactive capping	Heavy metals	Moderate–High	Medium (months)
Phytoremediation	Heavy metals (via vegetation)	Low	Long (months–years)
Nanotechnology-based remediation	Heavy metals & organics	High (currently)	Emerging / experimental
Physical removal & barriers	Marine plastics / debris	Low–Moderate	Immediate–ongoing
Constructed wetlands / nature-based systems	Nutrients / eutrophication	Low–Moderate	Medium–long (months–years to mature)

**Table 1: Indicative comparison of principal remediation technology families was discussed in Chapter 2. Cost, timeframe, and maturity ratings are qualitative and relative, intended to support initial screening; site-specific feasibility studies remain necessary for project-level decisions.*

Once immediate risks have been stabilized, authorities must determine whether active remediation or monitored natural recovery represents the most appropriate management strategy. Active remediation is generally justified when contaminant concentrations exceed regulatory thresholds, ecological damage is severe, or natural attenuation processes are unlikely to achieve acceptable recovery within reasonable timeframes [35]. The selection of specific remediation technologies should consider contaminant characteristics, environmental conditions, operational constraints, technology maturity, and long-term sustainability objectives (see Table 1) [1]. Physical technologies may be preferred where rapid contaminant removal is required, whereas biological and nature-based approaches may offer greater sustainability for long-term restoration efforts. In many situations, hybrid remediation systems combining multiple technologies provide the most effective solution [1,23].

	Technical Maturity	Key Advantage	Key Limitation
	High – established	No added chemicals; safe first response	Weather/sea-state dependent; misses dissolved fraction
	High, but regulated	Fast reduction of shoreline risk	Ecotoxicological debate; moves contaminant into water column
	High for oil; lower for metals	Low secondary impact; sustainable	Slow; highly dependent on temperature, oxygen, nutrients
	High – widely applied	Rapid removal of contaminant inventory	Resuspension risk; costly disposal/ logistics
	Established; growing use	In-situ; avoids large-scale excavation	Contaminant not removed; needs long-term monitoring
	Proven mainly freshwater/ estuarine	Low cost; habitat co-benefits	Slow; limited scale; salinity tolerance constraints
	Low–Moderate – mostly pilot scale	Very high reactivity/ adsorption capacity	Limited large-scale validation; cost; unknown ecological effects
	High	Direct removal; prevents fragmentation	Requires continuous maintenance & waste infrastructure
	Established for wastewater; growing for coastal	Multiple co-benefits: habitat, carbon, biodiversity	Space/land requirements; slower than chemical treatment

Cost-benefit analyses should be incorporated into technology evaluations whenever possible. Although environmental protection remains the primary objective, decision-makers must ensure that remediation investments generate measurable environmental improvements relative to implementation costs [47]. This consideration becomes particularly important during large-scale post-conflict recovery programs where financial resources may be limited.

Adaptive management principles should remain central throughout the technology selection process. Remediation strategies should be viewed as dynamic systems capable of evolving in response to monitoring data, technological advances, and changing environmental conditions [1].

4.4 Environmental Monitoring, Performance Indicators, and Adaptive Management

Environmental monitoring provides the evidence base required to evaluate remediation effectiveness and support adaptive decision-making throughout the recovery process [9,10]. Without robust monitoring programs, authorities cannot determine whether restoration objectives are being achieved or identify emerging environmental risks requiring additional intervention. Monitoring programs should be designed according to clearly defined objectives and measurable environmental indicators. Water quality parameters, sediment chemistry, contaminant bioavailability, habitat condition, biodiversity status, and ecosystem functionality represent key components of comprehensive monitoring frameworks [24,41]. Monitoring frequency should reflect contaminant characteristics, ecological sensitivity, and management objectives.

Recent technological advances have significantly expanded environmental monitoring capabilities. Satellite observations, autonomous sensor networks, remote sensing platforms, unmanned vehicles, and real-time data transmission systems enable continuous surveillance across large geographic areas while reducing operational costs and personnel exposure risks [9,10]. These technologies are particularly valuable within conflict-affected regions where conventional monitoring approaches may be constrained by accessibility and security limitations. Performance evaluation should be linked to predefined environmental objectives established during project planning. Indicators may include reductions in contaminant concentrations, improvements in biodiversity metrics, habitat recovery rates, ecosystem service restoration, and reductions in human exposure risks [1,41]. The use of quantitative performance indicators enhances accountability and facilitates comparison among different remediation programs.

Monitoring results should feed directly into adaptive management processes. If performance targets are not achieved, remediation strategies may require modification through additional interventions, alternative technologies, or revised management objectives [45,46]. This iterative process allows environmental authorities to respond effectively to uncertainty while continuously improving restoration outcomes.

4.5 Institutional Coordination and Governance Mechanisms

The complexity of conflict-related marine pollution requires extensive coordination among multiple institutions operating at local, national, regional, and international levels [3,5,49]. Environmental recovery programs frequently involve environmental agencies, maritime authorities, emergency management organizations, scientific institutions, military stakeholders, international organizations, and local communities. Effective governance frameworks should establish clear roles and responsibilities for all participating entities. Coordination mechanisms must facilitate information exchange, technical cooperation, financial resource allocation, and harmonized decision-making processes [13,49]. Failure to establish such mechanisms often results in duplicated efforts, inefficient resource utilization, and reduced remediation effectiveness.

Regional cooperation assumes particular importance within semi-enclosed marine systems such as the Black Sea. Because contaminants can easily cross political boundaries through hydrodynamic processes, isolated national interventions are unlikely to achieve long-term environmental recovery [13,42]. Shared monitoring programs, joint environmental assessments, and coordinated remediation strategies therefore represent essential components of effective regional governance. International organizations can provide valuable technical expertise, financial assistance, and institutional support during post-conflict recovery processes [2,3,49]. Organizations such as UNEP, UNDP, the European Commission, the World Bank, and the Black Sea Commission possess extensive experience in environmental assessment, remediation planning, and ecosystem restoration, making them important partners for national authorities.

Ultimately, successful environmental recovery depends not only on technological solutions but also on institutional capacity, political commitment, stakeholder engagement, and long-term governance stability. These factors collectively determine whether remediation efforts produce lasting environmental improvements or merely temporary reductions in contamination levels [45,49].

4.6 Operational Roadmap for Post-Conflict Marine Recovery

The framework proposed within this guidance document culminates in a six-stage operational roadmap designed to support environmental authorities throughout the post-conflict recovery process (see table 2).

The first stage involves rapid environmental screening aimed at identifying major contamination sources, ecological risks, and priority intervention areas. The second stage focuses on detailed environmental assessment and risk classification, generating the technical information required for evidence-based decision-making. The third stage encompasses emergency containment measures intended to stabilize contamination and prevent further environmental degradation. The fourth stage involves the implementation of active remediation technologies selected according to site-specific conditions and restoration objectives. The fifth stage focuses on habitat restoration and ecosystem recovery, integrating nature-based solutions and long-term sustainability principles. Finally, the sixth stage consists of continuous monitoring, adaptive management, and institutional strengthening activities designed to ensure the durability of environmental recovery outcomes [1,44,49].

Table 2. Operational Roadmap for Post-Conflict Marine Recovery

Stage	Name	Objective / Key Actions
1	Rapid Environmental Screening	Identify major contamination sources, ecological risks, and priority intervention areas.
2	Detailed Environmental Assessment and Risk Classification	Generate the technical information required for evidence-based decision-making (site characterization, contaminant data, risk ranking).
3	Emergency Containment Measures	Stabilize contamination and prevent further environmental degradation (booms, barriers, wastewater diversion, emergency recovery).
4	Active Remediation Technologies	Implement remediation technologies selected according to site-specific conditions and restoration objectives (physical, chemical, biological, hybrid).
5	Habitat Restoration and Ecosystem Recovery	Restore habitat structure and function, integrating nature-based solutions and long-term sustainability principles.
6	Continuous Monitoring, Adaptive Management, and Institutional Strengthening	Ensure the durability of environmental recovery outcomes through ongoing monitoring, adaptive management, and governance capacity-building.

This roadmap establishes a structured and scientifically robust pathway linking environmental assessment, remediation, restoration, and governance within a unified framework. Its implementation can support the recovery of conflict-affected marine ecosystems while simultaneously strengthening environmental resilience, regional cooperation, and long-term ecological security.

Conclusions

The environmental impacts of armed conflicts represent a highly complex form of marine pollution, characterized by the simultaneous release of multiple contaminant types, widespread habitat disruption, and severely constrained monitoring and remediation conditions. These factors generate long-term and often transboundary ecological consequences that may persist well beyond the cessation of hostilities [2,3,15,42].

This guidance document demonstrates that effective remediation cannot rely on single technologies or isolated interventions. Instead, successful recovery of conflict-affected marine environments requires the integration of international legal frameworks, risk-based assessment methodologies, multi-technology remediation approaches, and long-term ecosystem restoration strategies within a unified operational structure [1,5,6]. The analysis of the Black Sea case highlights the vulnerability of semi-enclosed marine systems to cumulative pollution pressures arising from military activity, industrial damage, and infrastructure collapse [3,15,42]. These conditions underscore the importance of coordinated transboundary governance and shared monitoring systems to address environmental risks that extend beyond national boundaries.

The decision-making framework presented in this document provides a structured approach for prioritizing interventions, selecting appropriate remediation technologies, and ensuring adaptive management based on monitoring data and environmental performance indicators [44,45,49]. This risk-based approach enables more efficient allocation of resources while improving the effectiveness and transparency of restoration efforts.

Looking forward, strengthening integrated environmental monitoring systems, improving understanding of complex contaminant mixtures, and advancing remediation technologies for emerging pollutants remain key priorities. Particular attention should be given to explosive residues, microplastics, and other persistent contaminants associated with modern warfare [23,37].

Ultimately, the recovery of conflict-affected marine ecosystems requires more than technical remediation. It demands sustained institutional cooperation, long-term governance commitment, and the incorporation of environmental protection into broader security and reconstruction policies. The framework presented in this document offers a transferable model for supporting ecological restoration in marine regions affected by armed conflict and contributes to strengthening global approaches to environmental security [4,49].

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