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Black Sea SIERRA

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Introduction

Marine ecosystems represent one of the most complex and interconnected components of the Earth system, playing a fundamental role in climate regulation, biodiversity conservation, fisheries productivity, maritime transportation, and the provision of ecosystem services essential for coastal communities worldwide. Coastal and marine environments support economic sectors of strategic importance, including tourism, fisheries, aquaculture, shipping, and energy production, while simultaneously contributing to global biogeochemical cycles and climate stability. However, despite their ecological and socio-economic importance, marine ecosystems are increasingly exposed to cumulative anthropogenic pressures that compromise their ecological integrity and resilience [1].

Among these stressors, armed conflict represents a severe driver of environmental degradation. Warfare impacts extend beyond direct physical destruction and can generate long-term ecological consequences persisting for decades after hostilities cease [2]. Military operations, explosions, naval warfare, and destruction of industrial infrastructure can release hazardous substances into marine systems under conditions where monitoring is often limited. The environmental dimension of armed conflict is well documented historically, but contemporary warfare increasingly affects industrialized coastal regions and critical maritime infrastructure, amplifying environmental risks. In many cases, pollution originates not only from direct military actions but also from secondary disasters such as the destruction of fuel depots, ports, wastewater systems, and industrial facilities [3].

The Black Sea represents a particularly sensitive case study due to its semi-enclosed nature and limited water exchange, making it vulnerable to pollutant accumulation [4]. The ongoing Russia–Ukraine conflict has further intensified environmental pressures through oil spills, infrastructure destruction, and disruption of environmental governance systems [5]. These conditions highlight the limitations of conventional monitoring systems and the need for integrated frameworks combining field data, remote sensing, modelling, and autonomous technologies.

This guide, developed within the Black Sea SIERRA project, aims to provide a methodological framework for monitoring marine pollution associated with armed conflict, aligned with European directives such as the Marine Strategy Framework Directive (MSFD) and Water Framework Directive (WFD), as well as regional systems including BSIMAP and EMODnet.

1. Purpose and scope

The purpose of this guide is to establish a methodological and operational framework for monitoring marine pollution linked to armed conflict, with focus on the Black Sea region. It is intended for environmental authorities, research institutes, laboratories, and policy makers.

Conflict-related pollution presents challenges that differ from conventional monitoring due to its abrupt onset, uncertainty in pollutant composition, and operational constraints [6].

The framework adopts an adaptive, risk-based approach covering the full monitoring cycle: source identification, sampling design, laboratory analysis, data management, and reporting.

Alignment with EU and regional frameworks such as MSFD, WFD, BSIMAP, EMODnet Chemistry, and WISE Marine ensures interoperability of data and comparability of results [7].

The geographic scope includes coastal waters, estuaries, ports, offshore waters, and river-influenced marine areas affected directly or indirectly by conflict.

The temporal scope includes:

- emergency response (immediate incidents),
- short-term assessment (weeks to months),
- long-term monitoring (ecosystem recovery)

Due to the transboundary nature of marine pollution, regional cooperation is essential for effective assessment and management.

1.1 Armed conflict and marine environmental stressors

Armed conflict introduces a broad spectrum of environmental stressors into marine and coastal ecosystems, generating impacts that are often immediate, cumulative, transboundary, and long-lasting. Unlike conventional pollution sources, conflict-related environmental pressures are characterized by sudden onset, unpredictability, and a high degree of spatial and temporal variability. These characteristics complicate environmental assessment processes and significantly increase the operational challenges associated with monitoring and mitigation activities [8].

Military activities occurring in coastal and offshore environments can directly alter marine ecosystems through explosions, bombardments, underwa-

ter detonations, naval warfare, and mine deployment. Such activities generate intense physical disturbances capable of damaging benthic habitats, increasing sediment resuspension, altering turbidity regimes, and modifying ecological conditions over extensive marine areas. Underwater explosions may additionally generate acoustic disturbances affecting fish populations, marine mammals, and sensitive biological communities. One of the most significant environmental risks associated with warfare concerns the destruction of industrial and energy infrastructure located within coastal zones. Ports, oil terminals, fuel depots, petrochemical facilities, and industrial storage systems often represent strategic targets during military operations. Their destruction can result in the uncontrolled release of petroleum hydrocarbons, hazardous chemicals, heavy metals, combustion residues, and untreated industrial waste into surrounding marine environments. In many cases, such releases generate complex contaminant mixtures whose environmental behaviour and toxicological effects remain difficult to predict accurately [9].

Hydraulic infrastructure represents another critical vulnerability during armed conflicts. Damage to dams, pumping stations, reservoirs, wastewater treatment facilities, and water-distribution systems can profoundly modify hydrological regimes and water-quality conditions. The collapse of wastewater treatment capacity frequently results in the direct discharge of untreated municipal and industrial effluents into rivers and coastal waters, increasing nutrient loads, microbiological contamination, and chemical pollution. Simultaneously, the destruction of hydraulic structures may trigger extensive sediment transport processes capable of redistributing contaminants accumulated over decades within riverine and coastal sediments [10].

The environmental consequences of armed conflict are further amplified by disruptions affecting environmental governance systems and monitoring infrastructures. Environmental inspections, laboratory activities, field monitoring programmes, and data collection operations are often interrupted due to institutional instability, security restrictions, damaged infrastructure, and elevated risks for scientific personnel. These disruptions create substantial gaps in environmental information precisely when rapid environmental assessment and emergency-response capabilities are most needed. In the Black Sea region, these environmental pressures are intensified by the semi-enclosed nature of the basin and its limited water exchange with the Mediterranean Sea. Pollutants introduced into the marine environment may therefore persist for extended periods and accumulate within sediments, biota, and coastal habitats. Furthermore, major river systems such as the Danube, Dniro, and Dniester rivers facilitate the transport of contaminants originating from inland conflict-affected areas toward the marine environment [11].

In addition to chemical contamination, armed conflicts generate substantial quantities of debris and solid waste materials. Destroyed infrastructure, military equipment, shipwrecks, plastics, construction materials, and synthetic components contribute to increasing levels of marine litter and microplastics. These materials may cause direct physical damage to habitats and marine organisms while simultaneously acting as vectors for hazardous contaminants adsorbed onto their surfaces.



Photo 1: Polluted coastal water with visible floating waste and debris along the shoreline, illustrating anthropogenic contamination and environmental degradation in an aquatic ecosystem. Source: Pexels.

1.2 Conceptual framework for conflict-related marine pollution monitoring

The monitoring of marine pollution generated by armed conflict requires a conceptual framework capable of functioning under conditions of uncertainty, restricted access, rapidly evolving environmental risks, and severe operational limitations. Conventional environmental monitoring systems are generally designed to assess stable anthropogenic pressures within predictable regulatory and logistical conditions. Conflict-related pollution, however, introduces abrupt disturbances and non-linear environmental responses that require more flexible and adaptive monitoring approaches.

The conceptual framework proposed in this guide is based on the integration of risk-based environmental assessment, adaptive monitoring strategies, and multi-source data integration systems. The objective is to ensure that environmental monitoring activities remain scientifically robust while simultaneously maintaining operational feasibility under conflict conditions.

The first component of the framework concerns source identification and characterization. This stage involves the systematic assessment of potential pollution sources associated with military operations, damaged infrastructure, industrial facilities, and conflict-related accidents. Potential sources may include shipwrecks, fuel depots, naval operation zones, industrial plants, wastewater treatment facilities, damaged pipelines, military waste deposits, and contaminated river systems. Characterization of these sources also requires identification of potential pollutant types, release mechanisms, and environmental pathways.

The second component focuses on environmental pathway analysis. Once contaminants are introduced into marine environments, their transport and transformation are influenced by hydrodynamic, physicochemical, and biological processes. Ocean currents, waves, river discharges, sediment transport, salinity gradients, and meteorological conditions all contribute to determining contaminant dispersion patterns and environmental fate. Under conflict conditions, these pathways may evolve rapidly due to altered hydrological regimes, damaged infrastructure, or emergency-response interventions.

The third component involves receptor assessment and impact evaluation. This stage focuses on identifying ecosystems, habitats, species, and human activities potentially affected by contamination events. Marine protected areas, fisheries, aquaculture sites, shellfish harvesting zones, tourism areas, and drinking-water intakes may all represent priority receptors requiring enhanced monitoring attention [12]. Receptor assessment additionally considers ecological vulnerability, exposure duration, pollutant persistence, and potential bioaccumulation processes within marine food webs.

These three components are integrated within a dynamic monitoring cycle consisting of observation, analysis, interpretation, and adaptive feedback. Monitoring priorities should be continuously updated based on newly acquired information, evolving environmental conditions, and changing operational constraints. Such adaptive monitoring structures are particularly important in conflict scenarios, where environmental risks and accessibility conditions may change rapidly over time [13].

An important characteristic of the framework is the integration of multiple monitoring technologies and data sources. Field sampling, laboratory analyses, satellite remote sensing, autonomous systems, hydrodynamic modelling, and regional environmental databases all provide complementary information necessary for comprehensive environmental assessment. The combination of these approaches increases spatial coverage, improves temporal resolution, and reduces dependence on direct field access in hazardous areas [14].

2. Main conflict-related pressures and pollution pathways

Armed conflict generates numerous pathways through which pollutants may enter marine and coastal environments. These pathways involve both direct contamination mechanisms associated with military activities and indirect processes linked to infrastructure destruction, industrial disruption, and altered environmental-management conditions. Understanding these pathways is essential for identifying monitoring priorities and designing effective environmental assessment strategies.

Direct pollution pathways are primarily associated with military operations occurring within coastal and offshore environments. Naval combat activities, underwater detonations, shelling, missile strikes, mine explosions, and the sinking of vessels may release hazardous substances directly into seawater and sediments. Military equipment, ammunition residues, combustion products, and damaged infrastructure may all contribute to localized or widespread contamination events [15].

Shipwrecks represent particularly important long-term pollution sources within marine environments affected by conflict. Corrosion processes occurring over time may gradually release petroleum products, heavy metals, anti-fouling compounds, and hazardous cargo materials into surrounding ecosystems. In cases involving fuel tankers or industrial cargo vessels, contamination may persist for decades and progressively affect sediment quality, benthic habitats, and marine food webs [16].

Explosions and attacks occurring near industrial facilities may additionally trigger secondary contamination events involving hazardous chemicals, industrial waste deposits, fuel storage systems, and contaminated infrastructure materials. Fires associated with military attacks may also generate airborne contaminants capable of being transported atmospherically and deposited into marine environments through precipitation processes [17].

Riverine systems constitute another major pathway for conflict-related marine pollution. Rivers crossing conflict-affected territories may transport contaminated sediments, untreated wastewater, industrial chemicals, agricultural pollutants, and debris toward coastal waters. Major Black Sea river systems play a particularly significant role in redistributing contaminants originating from inland regions toward marine ecosystems [18].

Sediment transport processes are especially important in conflict-related environmental scenarios. Explosions, dredging activities, vessel movements, hydrodynamic alterations, and hydraulic infrastructure failures may resuspend contaminated sediments and increase contaminant bioavailability. Fine-grained sediments can adsorb hydrocarbons, metals, explosives, and persistent organic pollutants, acting both as temporary sinks and secondary contamination sources [19].

Marine debris generated during conflicts represents an additional and increasingly significant environmental pressure. Destroyed infrastructure, plastics, wreckage materials, synthetic fibres, and military equipment fragments may accumulate in coastal habitats and offshore areas. Beyond their direct physical impacts on marine organisms and habitats, debris materials may adsorb toxic substances and facilitate their transport within marine systems. Fragmentation processes additionally contribute to the generation of microplastics capable of entering marine food webs and transporting associated contaminants.

The interaction between these multiple contamination pathways creates highly heterogeneous environmental conditions characterized by significant spatial and temporal variability. Consequently, monitoring programmes must adopt integrated approaches capable of combining field observations, remote sensing technologies, hydrodynamic modelling, and environmental risk-assessment methodologies to adequately capture the complexity of conflict-related marine pollution dynamics.

2.1 Priority pollutants and chemical signatures of conflict

Conflict-related marine pollution is characterized by the release of a wide range of hazardous substances originating from military activities, damaged industrial infrastructure, combustion processes, and accidental chemical discharges. Unlike conventional marine pollution scenarios, warfare-related contamination often involves complex mixtures of pollutants introduced simultaneously into the environment under uncontrolled conditions. These

mixtures may exhibit cumulative, synergistic, or long-term ecological effects that complicate environmental assessment and remediation activities.

Among the most significant pollutants associated with armed conflict are petroleum hydrocarbons derived from damaged vessels, fuel depots, refineries, pipelines, and port infrastructure. Oil spills generated during military operations may rapidly spread across large marine areas, affecting water quality, sediments, coastal habitats, fisheries, and marine biodiversity [20]. In semi-enclosed basins such as the Black Sea, the persistence of hydrocarbons may be particularly prolonged due to limited water exchange and reduced dilution capacity.

Heavy metals also represent a major category of conflict-related pollutants. Military ammunition, explosives, destroyed industrial facilities, shipwrecks, and combustion residues may release substantial quantities of lead, mercury, cadmium, copper, zinc, chromium, nickel, and arsenic into marine ecosystems [21]. These contaminants may persist in sediments for extended periods and pose chronic ecological risks to benthic organisms, fish populations, and higher trophic levels.

Explosive compounds and energetic materials constitute another characteristic chemical signature of armed conflict. Substances such as TNT, RDX, HMX, perchlorates, and other military explosives may enter marine environments through unexploded ordnance, ammunition residues, underwater detonations, and military waste disposal [22]. Over time, corrosion processes affecting submerged munitions may gradually release these substances into surrounding waters and sediments, creating persistent contamination hot-spots.

Persistent organic pollutants (POPs) may additionally be mobilized during conflicts due to the destruction of industrial facilities, contaminated sites, transformers, and waste storage areas. Polychlorinated biphenyls (PCBs), dioxins, pesticides, and other persistent contaminants can remain in marine ecosystems for decades due to their resistance to environmental degradation [23]. Their high bioaccumulation potential increases risks for marine food webs and human health, particularly in regions dependent on fisheries and seafood consumption. Another emerging concern involves marine litter and microplastic contamination associated with warfare-related destruction. Damaged infrastructure, military equipment, synthetic materials, construction debris, and destroyed urban areas generate large quantities of waste materials capable of entering marine systems through riverine transport, coastal erosion, and direct deposition [24]. Fragmentation processes may subsequently generate microplastics that interact with other contaminants and facilitate their transport within marine food webs.

Nutrient pollution and microbiological contamination may also increase substantially during conflicts due to the collapse of wastewater treatment systems and disruptions affecting sanitation infrastructure. Untreated sewage discharges can elevate concentrations of nitrogen, phosphorus, pathogens, and antibiotic-resistant microorganisms within coastal waters, contributing to eutrophication processes and public-health risks [25].

Understanding the environmental behaviour of these pollutants is essential for designing effective monitoring strategies. Different contaminant groups exhibit varying degrees of persistence, mobility, toxicity, and bioavailability. Consequently, monitoring programmes must adopt multidisciplinary analytical approaches capable of addressing the complexity of warfare-related contamination scenarios.

2.2 Environmental matrices and monitoring domains

Effective monitoring of conflict-related marine pollution requires the investigation of multiple environmental matrices capable of providing complementary information regarding contaminant distribution, transport pathways, ecological exposure, and long-term environmental impacts. The selection of appropriate monitoring domains is fundamental for obtaining a comprehensive understanding of pollution dynamics within marine and coastal ecosystems. The water column represents one of the primary monitoring matrices for detecting acute pollution events and assessing contaminant dispersion processes. Monitoring activities within the water column are particularly important following oil spills, chemical discharges, explosions, or wastewater releases associated with military activities. Parameters commonly assessed include hydrocarbons, dissolved metals, nutrients, suspended particulate matter, dissolved oxygen, salinity, pH, turbidity, and microbiological indicators [26].

Surface waters frequently provide the first indication of ongoing contamination events, especially in cases involving petroleum spills or floating debris. However, subsurface and bottom-water monitoring may also be necessary because certain contaminants exhibit vertical transport and accumulation processes influenced by hydrodynamic conditions and sediment interactions. In stratified marine systems such as the Black Sea, vertical water-column structure may significantly affect contaminant behaviour and oxygen availability. Marine sediments constitute another critical environmental matrix because they act both as sinks and secondary sources of contamination. Fine-grained sediments can accumulate hydrocarbons, heavy metals, persistent

organic pollutants, explosive residues, and microplastics over extended periods of time. Sediment monitoring is therefore essential for identifying long-term contamination hotspots and assessing historical pollutant deposition associated with conflict-related activities.

Sediment analyses additionally provide important information regarding contaminant persistence, bioavailability, and potential remobilization processes. Disturbances generated by storms, dredging operations, vessel movements, or explosions may resuspend contaminated sediments and increase exposure risks for marine organisms. Consequently, sediment monitoring programmes should include both chemical analyses and physical characterization parameters such as grain-size distribution and organic matter content [27].

Biological monitoring represents a further essential component of environmental assessment frameworks. Marine organisms can accumulate contaminants within their tissues, providing valuable information regarding bioavailability, trophic transfer, and ecological exposure. Mussels, fish species, benthic invertebrates, and plankton communities are frequently used as bioindicators for assessing contamination trends and ecological effects [28]. Biomonitoring activities may additionally support the assessment of sublethal biological effects associated with warfare-related contamination, including genotoxicity, oxidative stress, reproductive impairment, and physiological alterations. Such approaches are particularly important for evaluating chronic environmental impacts that may not be immediately detectable through conventional chemical analyses alone.

Coastal habitats and ecosystems also require dedicated monitoring attention because they frequently represent areas of high ecological sensitivity and pollutant accumulation. Wetlands, lagoons, estuaries, seagrass meadows, and spawning grounds may be especially vulnerable to contamination associated with oil spills, sediment transport, and wastewater discharges [29]. Habitat monitoring should therefore include assessments of ecological integrity, biodiversity changes, habitat degradation, and ecosystem-function alterations. Marine litter and debris monitoring constitutes another increasingly important monitoring domain in conflict-affected environments. Large quantities of debris generated during warfare may accumulate along coastlines, within estuaries, and across offshore areas. Monitoring programmes should therefore evaluate debris abundance, composition, spatial distribution, and fragmentation processes contributing to microplastic generation [30].



Photo 2: Control room for environmental monitoring showing multiple real-time digital dashboards used for continuous monitoring and data integration. Source: Pexels.

Because conflict-related pollution affects multiple interconnected environmental compartments simultaneously, monitoring strategies should adopt integrated and multidisciplinary approaches. Combining observations across water, sediments, biota, habitats, and debris matrices allows for a more comprehensive understanding of contamination dynamics and improves the reliability of environmental assessments.

3. Monitoring Approaches and Methodologies

The design of monitoring networks for conflict-related marine pollution requires a strategic and risk-based approach capable of addressing highly heterogeneous environmental conditions and operational constraints. Unlike conventional environmental monitoring programmes, conflict-related monitoring networks must remain sufficiently flexible to adapt rapidly to evolving environmental risks, accessibility limitations, and emerging contamination hotspots [31].

Hotspot areas represent priority locations for monitoring activities due to their elevated probability of contamination and ecological impact. Such areas may include damaged ports, industrial coastal zones, oil terminals, naval operation areas, estuaries receiving contaminated river discharges, and locations affected by underwater explosions or shipwrecks. Monitoring stations located within these zones should support both emergency-response activities and

long-term environmental assessment objectives. In addition to hotspot stations, monitoring networks should include background or reference sites located outside the direct influence of conflict-related pollution sources. These reference stations are essential for distinguishing conflict-related contamination from pre-existing environmental conditions and broader anthropogenic pressures [32]. Background sites additionally support trend analysis and facilitate the interpretation of environmental changes over time.

Gradient stations positioned along contamination pathways may further improve understanding of pollutant transport and dispersion dynamics. Such stations are particularly useful near river mouths, coastal currents, wastewater discharge zones, and sediment transport corridors. Monitoring along spatial gradients allows assessment of contaminant dilution, transformation, and accumulation processes occurring within marine ecosystems.

Temporal considerations also play a critical role in monitoring network design. Emergency-response monitoring may require rapid deployment of temporary stations immediately following pollution incidents, while long-term assessment programmes may involve permanent or semi-permanent monitoring infrastructure [33]. Seasonal variability, hydrological cycles, storm events, and operational constraints should all be considered when defining sampling schedules and monitoring frequency.

Accessibility and safety constraints represent major operational challenges in conflict-affected regions. Certain marine or coastal areas may become inaccessible due to military activity, unexploded ordnance, damaged infrastructure, or security restrictions. Consequently, monitoring networks should integrate remote sensing technologies, autonomous monitoring platforms, and alternative observation methods capable of reducing dependence on direct field access.

The integration of fixed stations, mobile surveys, satellite observations, and autonomous systems provides greater operational resilience and improves spatial coverage under unstable conditions. Such integrated monitoring architectures are particularly important within the Black Sea region, where environmental conditions and operational accessibility may change rapidly over time. Monitoring network design should additionally ensure compatibility with existing European and regional marine monitoring frameworks. Alignment with MSFD descriptors, WFD assessment methodologies, BSIMAP structures, and EMODnet standards facilitates data interoperability and contributes to broader regional environmental assessment efforts [34].

Ultimately, effective monitoring networks must balance scientific robustness, operational feasibility, and adaptive capacity. The dynamic nature of conflict-related environmental risks requires monitoring systems capable not only of doc-

umenting contamination events but also of supporting rapid environmental decision-making, emergency response, and long-term ecosystem recovery.

3.1 Sampling strategies, frequency, and field operations

Sampling strategies should therefore be designed according to a risk-based framework that prioritizes areas characterized by elevated probabilities of contamination, ecological vulnerability, and potential impacts on human activities. Priority should generally be given to zones affected by oil spills, industrial accidents, wastewater releases, underwater explosions, shipwrecks, and contaminated river discharges [35]. At the same time, monitoring programmes should maintain sufficient spatial coverage to assess contaminant transport pathways and identify secondary contamination hotspots.

Emergency-response sampling constitutes one of the most critical components of conflict-related environmental monitoring. Immediately following pollution incidents, rapid environmental assessment is essential for identifying contaminant types, evaluating ecological risks, and supporting emergency-response decision-making processes. Emergency sampling campaigns should therefore prioritize rapid deployment capabilities and simplified operational procedures capable of generating reliable environmental information within limited timeframes. [36].

Temporal frequency represents another fundamental consideration in monitoring design. Acute pollution events may require intensive short-term sampling frequencies during the first hours or days following contamination incidents. Such high-frequency observations are particularly important for rapidly evolving phenomena such as oil spills, chemical releases, wastewater discharges, or sediment resuspension events. Over time, monitoring frequency may gradually transition toward medium- and long-term assessment schedules focused on contaminant persistence, ecological recovery, and chronic environmental impacts [37]. Seasonal variability should additionally be considered when designing monitoring programmes.

Sampling methodologies should remain consistent with internationally recognized standards whenever operationally feasible. Water-column sampling may involve surface, subsurface, and bottom-water collection depending on pollutant characteristics and environmental conditions. Sediment sampling should include both surface sediments and deeper sediment cores where long-term contamination assessment is required. Biota sampling may focus on bioindicator species capable of reflecting contaminant bioavailability and trophic transfer processes [38].

Field operations conducted within conflict-affected regions must place particular emphasis on personnel safety and operational preparedness. Environmental monitoring teams may face risks associated with unexploded ordnance, military activity, damaged infrastructure, chemical exposure, and restricted navigation areas. Consequently, field operations should be preceded by detailed risk assessments and coordinated with relevant authorities responsible for maritime safety and civil protection [39].

Remote and autonomous monitoring technologies may substantially improve operational safety and data continuity under hazardous conditions. Autonomous surface vehicles, underwater drones, remote sensing platforms, and satellite observations may support environmental assessment activities in areas where direct field access is limited or unsafe. These technologies additionally improve temporal coverage and allow near-real-time monitoring of rapidly evolving contamination events [40].

Quality assurance procedures should also remain integral to field operations conducted under emergency conditions. Even during rapid-response campaigns, standardized sampling protocols, chain-of-custody procedures, contamination prevention measures, and metadata recording remain essential for ensuring data reliability and comparability.

3.2 Analytical methods, laboratory procedures, and qa/qc

Analytical activities conducted within the framework of conflict-related marine pollution monitoring must ensure high standards of scientific reliability, comparability, and traceability despite the operational challenges associated with emergency-response conditions and damaged infrastructure.

Laboratory analyses represent a fundamental component of environmental assessment because they provide the quantitative information necessary for identifying contaminants, evaluating ecological risks, and supporting remediation and policy decisions. The selection of analytical methods should be guided by the characteristics of expected pollutants, monitoring objectives, available laboratory capacities, and applicable international standards. Given the complexity of warfare-related contamination scenarios, monitoring programmes frequently require multidisciplinary analytical approaches capable of addressing hydrocarbons, heavy metals, explosive compounds, persistent organic pollutants, nutrients, microbiological contaminants, and microplastics simultaneously [41].

Hydrocarbon analyses generally focus on total petroleum hydrocarbons (TPHs), polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), and oil-fingerprint characterization techniques capable of identifying

contamination sources. Gas chromatography coupled with mass spectrometry (GC-MS) remains one of the most widely applied analytical techniques for petroleum-related contaminants due to its sensitivity and specificity [42].

Heavy-metal assessment commonly includes the analysis of mercury, cadmium, lead, copper, zinc, chromium, nickel, and arsenic within water, sediments, and biological tissues. Inductively coupled plasma mass spectrometry (ICP-MS) and atomic absorption spectrometry (AAS) are frequently used for trace-metal determination because of their high analytical precision and low detection limits [43].

The analysis of explosive compounds and energetic materials requires specialized analytical procedures due to the physicochemical properties and environmental behaviour of these substances. High-performance liquid chromatography (HPLC), liquid chromatography–mass spectrometry (LC-MS), and related methods are commonly applied for detecting compounds such as TNT, RDX, HMX, and their degradation products within environmental matrices [44].

Microbiological analyses may also play a critical role in conflict-related monitoring, particularly in areas affected by wastewater releases or damaged sanitation infrastructure. Parameters commonly assessed include faecal indicator bacteria, pathogenic microorganisms, and antimicrobial resistance markers capable of representing public-health risks associated with untreated sewage discharges [45].

In addition to chemical analyses, biological-effect monitoring approaches may support the assessment of sublethal ecological impacts associated with warfare-related contamination. Biomarker analyses, ecotoxicological tests, genotoxicity assays, and physiological indicators can provide valuable information regarding pollutant bioavailability and biological stress responses that may not be detectable through chemical analyses alone [46].

Quality assurance and quality control (QA/QC) procedures are essential for ensuring the reliability and comparability of analytical results generated under conflict conditions. Standard operating procedures, calibration protocols, certified reference materials, laboratory intercalibration exercises, blank analyses, duplicate samples, and recovery assessments should all be incorporated into analytical workflows whenever feasible [47].

Chain-of-custody procedures and metadata documentation are equally important for maintaining traceability and supporting the legal and scientific credibility of monitoring results. In conflict-related scenarios, environmental data may additionally contribute to environmental accountability processes and post-conflict damage assessments, increasing the importance of transparent and well-documented analytical procedures.

Integrating microplastic monitoring into conflict-related environmental assessment programs substantially broadens the diagnostic scope of collected data. Reliable results require dedicated inert sampling equipment, sequential filtration (333 μm and 10 μm mesh), and for sediments, density separation followed by organic matter digestion. Polymer identification should be confirmed by FTIR or Raman spectroscopy, with reporting following MSFD TG-ML standards to ensure regional comparability. Where field conditions or access constraints limit laboratory capacity, portable FTIR spectrometers represent a valuable and deployable alternative [48].

3.3 Remote sensing, modelling, and autonomous systems

Remote sensing technologies, autonomous monitoring systems, and numerical modelling tools represent increasingly important components of environmental monitoring frameworks designed for conflict-affected marine environments. These technologies significantly enhance monitoring capacity under conditions where direct field access is restricted, hazardous, or operationally unfeasible.

Satellite remote sensing provides large-scale and near-real-time observations capable of supporting the detection and assessment of oil spills, suspended sediments, algal blooms, debris accumulation, coastal damage, and hydrodynamic changes. Optical and radar satellite systems are particularly valuable because they enable environmental observations across extensive marine regions while minimizing dependence on direct field operations [49].

Synthetic Aperture Radar (SAR) imagery has proven especially useful for detecting oil spills and marine surface anomalies under diverse meteorological conditions, including cloud-covered environments. SAR systems can identify oil slicks based on changes in sea-surface roughness and are therefore widely used within operational marine-pollution surveillance frameworks [50]. Optical satellite imagery additionally supports the assessment of turbidity, chlorophyll concentrations, sediment plumes, and coastal habitat changes associated with conflict-related environmental disturbances.

Remote sensing technologies may also support damage assessment activities following attacks on industrial facilities, ports, dams, and coastal infrastructure. High-resolution imagery can facilitate the identification of pollution sources, infrastructure destruction, shoreline changes, and debris distribution patterns, contributing valuable information for emergency-response coordination and environmental-risk assessment [51].

Autonomous monitoring platforms further improve operational flexibility and environmental coverage within hazardous or inaccessible areas. Autonomous surface vehicles (ASVs), autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs), and instrumented buoys can collect environmental data without exposing personnel to direct operational risks. These systems may support water-quality monitoring, seabed mapping, contaminant detection, and underwater infrastructure inspections [52]. Numerical modelling tools constitute another essential component of integrated monitoring frameworks. Hydrodynamic models, oil-spill trajectory models, sediment transport simulations, and contaminant dispersion models support the prediction of pollutant transport pathways and environmental exposure scenarios. These models are particularly important during emergency-response situations because they assist decision-makers in identifying potentially affected areas and prioritizing intervention measures [53].

Modelling approaches additionally support long-term environmental assessment by improving understanding of contaminant persistence, sediment accumulation processes, ecosystem recovery trajectories, and transboundary pollution dynamics within the Black Sea basin. The integration of modelling outputs with field observations and remote-sensing data substantially improves the reliability of environmental assessments and facilitates scenario analysis under uncertain conditions. Despite their significant advantages, remote sensing and modelling approaches should not be considered replacements for conventional field monitoring activities. Instead, these technologies should be integrated with broader multidisciplinary monitoring systems capable of combining direct observations, laboratory analyses, autonomous platforms, and predictive tools. Such integrated approaches provide the highest level of environmental assessment reliability and operational resilience under conflict conditions.

3.4 Data Management, integration, and reporting systems

Effective monitoring of conflict-related marine pollution requires robust data-management systems capable of ensuring data accessibility, interoperability, traceability, and long-term preservation. Environmental information generated during conflict situations often originates from multiple institutions, laboratories, monitoring platforms, and emergency-response activities. Consequently, harmonized data structures and standardized reporting procedures are essential for ensuring consistency and comparability between datasets. Data-management frameworks should support the integration of field observations, laboratory analyses, satellite products, modelling outputs, and auton-

omous monitoring systems within a common operational structure. Standardization of metadata, sampling methodologies, analytical units, and geospatial references is particularly important for facilitating regional cooperation and transboundary environmental assessment [54].

Compatibility with existing European and regional marine-data infrastructures should also be prioritized. Monitoring results generated within conflict-affected areas should remain interoperable with systems such as EMOD-net Chemistry, WISE Marine, and MSFD reporting platforms in order to support long-term environmental assessment and policy development [55].

Rapid information exchange mechanisms are equally important during emergency-response situations. Timely dissemination of environmental information may support pollution-response operations, navigation safety, public-health protection, and regional coordination activities. For this reason, monitoring systems should incorporate procedures for data validation, rapid reporting, and secure information sharing between relevant institutions.

4. Implementation, Governance and Applications

Environmental monitoring activities conducted within conflict-affected regions involve substantial operational, logistical, and ethical challenges. Safety considerations must remain the highest priority throughout all monitoring operations, particularly in areas affected by active military activities, unexploded ordnance, damaged infrastructure, or hazardous contamination sources [56]. Operational constraints may additionally include limited access to monitoring stations, damaged transportation infrastructure, interruptions in communication systems, and shortages of analytical equipment or laboratory reagents. Under such conditions, adaptive monitoring approaches and the use of remote technologies become essential for maintaining environmental-assessment capacity.

Ethical considerations also play an important role in conflict-related environmental monitoring. Monitoring activities should avoid increasing risks for local communities and should ensure responsible handling of sensitive environmental information. Transparency, scientific integrity, and respect for international environmental and humanitarian principles must remain central elements of all monitoring operations [57].

4.1 Risk-based prioritization and adaptive monitoring

Given the complexity and scale of environmental impacts associated with armed conflict, monitoring activities must be prioritized according to risk-based assessment principles. Not all contaminated areas can be monitored simultaneously, particularly under conditions of limited resources and restricted accessibility. Monitoring priorities should therefore focus on areas characterized by elevated ecological vulnerability, significant contamination risks, and potential impacts on human health and economic activities [58]. Risk assessments should consider multiple factors, including pollutant toxicity, persistence, transport potential, ecosystem sensitivity, exposure pathways, and the presence of critical habitats or socio-economic activities. Coastal wetlands, fisheries areas, marine protected areas, and densely populated coastal zones may require particular monitoring attention due to their ecological and socio-economic importance.

Adaptive monitoring represents another essential principle for conflict-related environmental assessment. Monitoring systems should remain sufficiently flexible to respond rapidly to changing environmental conditions, newly identified pollution sources, and evolving operational constraints [59]. This may involve modifying sampling frequencies, relocating monitoring stations, integrating additional technologies, or expanding analytical parameters according to emerging environmental risks. The integration of adaptive monitoring approaches improves the resilience and effectiveness of environmental-assessment frameworks under unstable conditions and contributes to more efficient allocation of monitoring resources.

4.2 Implementation roadmap

The implementation of a conflict-related marine pollution monitoring framework should follow a phased and operationally realistic approach capable of adapting to changing environmental and geopolitical conditions. Initial implementation phases should prioritize institutional coordination, emergency-response preparedness, and rapid environmental assessment capacity.

The first implementation stage should involve the establishment of coordination mechanisms between environmental authorities, research institutions, laboratories, maritime agencies, and regional organizations. This phase should additionally include the identification of priority pollution hotspots, existing monitoring capacities, available datasets, and operational constraints.

The second stage should focus on the deployment of core monitoring activities in high-priority areas. Initial monitoring networks may include a limited number of strategically selected stations combined with satellite observations and rapid-response sampling procedures. During this phase, harmonized methodologies and QA/QC procedures should be progressively implemented [60].

Subsequent implementation phases may involve expansion of monitoring networks, integration of autonomous technologies, enhancement of laboratory capacities, and increased interoperability with regional and European reporting systems. Long-term implementation should additionally support ecosystem-recovery assessment, policy development, and environmental governance processes. A phased implementation strategy improves operational feasibility while allowing monitoring systems to evolve progressively according to available resources, environmental priorities, and regional co-operation capacities.

4.3 Regional application: the Black Sea context

The Black Sea represents one of the most environmentally vulnerable regional seas in Europe and constitutes a particularly relevant case study for the application of conflict-related marine pollution monitoring frameworks. Its semi-enclosed configuration, limited water exchange with the Mediterranean Sea, extensive riverine inputs, and intense anthropogenic pressures make the basin highly sensitive to pollutant accumulation and ecosystem degradation [61]. The ongoing conflict involving Ukraine has generated multiple environmental pressures affecting the Black Sea marine environment. Oil spills, damaged industrial infrastructure, wastewater discharges, debris transport, and sediment redistribution processes have all contributed to increasing environmental uncertainty within the region. Additionally, the destruction of hydraulic infrastructure has altered riverine transport dynamics and may influence contaminant dispersion patterns within north-western Black Sea coastal waters [62].



Photo 3: The Black Sea following the destruction of the Kakhovka Hydroelectric Power Plant in June 2023. Source: Ivan Strakhov

The Black Sea additionally presents important transboundary environmental-management challenges. Pollutants introduced in one part of the basin may be transported across national boundaries through hydrodynamic circulation and riverine systems. Consequently, effective monitoring and environmental assessment require strong regional cooperation and harmonized methodologies between Black Sea countries and institutions [63].

Existing regional frameworks such as the Black Sea Integrated Monitoring and Assessment Programme (BSIMAP), together with European initiatives including EMODnet and Copernicus Marine Service, provide important foundations for the development of integrated conflict-related monitoring systems within the basin.

4.4 Integration with European and international frameworks

An essential objective of this guide is to ensure compatibility between conflict-related monitoring activities and existing European and international marine environmental-governance systems. Harmonization with established

frameworks improves data comparability, facilitates regional cooperation, and supports the integration of conflict-related environmental information into broader marine-assessment processes [64].

The Marine Strategy Framework Directive (MSFD) represents one of the principal European policy instruments relevant to marine environmental monitoring. The MSFD establishes a comprehensive framework for achieving Good Environmental Status (GES) across European marine waters and includes descriptors addressing contaminants, marine litter, biodiversity, eutrophication, and hydrographic alterations [65]. Many of these descriptors are directly relevant for assessing the environmental consequences of armed conflict.

The Water Framework Directive (WFD) additionally provides important methodological guidance for monitoring transitional and coastal waters, particularly regarding chemical status assessment, ecological indicators, and river-basin management approaches. Because many conflict-related contaminants are transported through river systems, integration with WFD structures is particularly important within the Black Sea basin. Regional monitoring frameworks such as BSIMAP, OSPAR methodologies, HELCOM guidance documents, and EMODnet data standards also provide valuable technical and operational references for harmonized environmental assessment [66]. Alignment with these systems facilitates interoperability and contributes to the development of coordinated transboundary monitoring strategies.

International organisations serve a dual function in the governance framework concerning conflict-related marine pollution monitoring: they act as normative authorities by formulating and implementing the aforementioned international legal instruments, while also serving as operational partners that offer technical guidance, satellite services, scientific coordination, and capacity-building assistance. The UNEP functions as the primary UN entity for post-conflict environmental evaluation and oversees the implementation of international environmental law in situations affected by conflict. The IMO oversees MARPOL and the London Protocol, both of which set forth binding technical norms directly relevant to pollution monitoring in conflict situations. The IOC-UNESCO offers oceanographic data infrastructure and scientific coordination vital for the Black Sea area. The European Environment Agency provides comparative environmental statistics and facilitates compliance with MSFD reporting requirements. It is imperative to effectively integrate the monitoring activities outlined in this guide with the mandates and technical resources of these organisations to ensure the scientific credibility and legal defensibility of environmental assessments conducted in conflict-affected marine environments.

The **United Nations Convention on the Law of the Sea** (UNCLOS, 1982) constitutes the principal international legal framework governing the protection of the marine environment and should be cited explicitly in any document addressing marine pollution. Articles 192–237 of UNCLOS establish binding obligations for all States to protect and preserve the marine environment, including during armed conflict, and provide the legal basis for enforcement jurisdiction over pollution events occurring in coastal waters, exclusive economic zones, and the high seas. In the Black Sea context, UNCLOS obligations apply to all riparian States and provide the overarching legal mandate within which regional monitoring and response frameworks operate [67].

The **International Convention for the Prevention of Pollution from Ships** (MARPOL 73/78) regulates operational and accidental discharges of oil, noxious substances, sewage, garbage, and air pollutants from vessels. Although Article 3(3) of MARPOL allows States to exempt warships and vessels on government service from its provisions, many NATO and EU member states voluntarily apply MARPOL standards to their naval fleets. In conflict-affected environments, MARPOL Annex I (oil) and Annex II (noxious liquid substances) provide the technical reference standards for classifying spill severity and selecting appropriate analytical monitoring parameters. The IMO's Manual on Oil Pollution (Section IV) [10] should be read in conjunction with MARPOL obligations.

International humanitarian law provides the most directly applicable legal framework for environmental protection during active armed conflict. Article 35(3) and Article 55 of Additional Protocol I to the Geneva Conventions (1977) prohibit methods or means of warfare that are intended, or may be expected, to cause widespread, long-term, and severe damage to the natural environment. These provisions are binding on States party to the Protocol and constitute customary international law applicable to all parties to an international armed conflict [68]. The ILC Principles on Protection of the Environment in Relation to Armed Conflicts (2022), adopted by the UN International Law Commission, further consolidate and develop these obligations, introducing principles applicable before, during, and after conflict, and specifically addressing marine and aquatic environments. Monitoring frameworks developed under this guide may generate environmental data directly relevant to assessments of compliance with these norms and should therefore be designed with evidential traceability in mind [69].

The **Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques** (ENMOD, 1976) prohibits the deliberate manipulation of natural processes (including hydrological systems) as a weapon of war. While the legal qualification of such events

falls outside the scope of this monitoring guide, awareness of ENMOD obligations is relevant for framing the governance and accountability dimensions of post-conflict environmental assessment discussed in Section 4.5 [70].

The **Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter** (London Convention, 1972) and its 1996 Protocol regulate the deliberate disposal of waste materials at sea, including munitions and military equipment. The Protocol's precautionary approach to the assessment of dumping permits is directly relevant to post-conflict management of submerged military wreckage, unexploded ordnance, and conflict debris accumulating in the Black Sea. Monitoring of dumped munitions and their chemical degradation products (TNT, RDX, HMX transformation derivatives) should be conducted in alignment with the London Protocol's waste assessment framework [71].

The **Convention on the Protection of the Black Sea Against Pollution** (Bucharest Convention, 1992) is the principal regional legal instrument governing marine environmental protection in the Black Sea. The Bucharest Convention and its three Protocols (covering land-based pollution sources, dumping, and biological diversity) are binding on all six Black Sea riparian States (Bulgaria, Georgia, Romania, Russia, Turkey, Ukraine) and establish the legal foundation for the regional monitoring frameworks referenced throughout this guide, including BSIMAP. The obligations established under the Bucharest Convention offer an important reference point for monitoring activities conducted in the Black Sea region, including those developed within the Black Sea SIERRA project. The Black Sea Commission (BSC), as the institutional body established under the Convention, plays a central role in transboundary data sharing and coordinated environmental assessment across the riparian States [72].

The **Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal** (1989) is applicable to the management of hazardous waste streams generated by the destruction of industrial facilities, chemical storage sites, and military installations during conflict. Conflict-related debris containing persistent organic pollutants, heavy metals, and reactive chemical residues may constitute hazardous waste under Basel Convention definitions, and cross-border transport of contaminated materials for treatment or disposal requires compliance with Basel notification and consent procedures. Monitoring programmes should therefore incorporate waste characterization components capable of supporting hazardous waste classification decisions under national and international law.

The **International Convention on Civil Liability for Oil Pollution Damage** (CLC, 1992) and the **Oil Pollution Compensation Fund** (IOPC Fund) offer an established framework for compensation in cases of oil pollution

from ships, including those damaged or lost during armed conflict. The environmental monitoring data generated under this guide (covering spill extent, volume, and ecological effects) may prove highly relevant in such processes, and consideration of CLC/IOPC evidentiary requirements when designing monitoring protocols could enhance the broader utility of the data collected.

4.5 Environmental recovery, accountability, and long-term governance

Environmental monitoring activities conducted during and after armed conflicts should not be limited solely to emergency-response objectives. Monitoring systems also play a fundamental role in supporting long-term ecosystem recovery, environmental governance, and environmental-accountability processes [73].

Environmental data may additionally contribute to legal and policy processes related to environmental accountability and damage assessment. Scientifically robust monitoring results can support environmental-impact evaluations, restoration planning, and international discussions concerning environmental protection during armed conflicts [74]. For this reason, monitoring activities should maintain high standards of transparency, methodological consistency, and data traceability. Strengthening environmental governance capacities is equally important for improving long-term environmental resilience within conflict-affected regions. Institutional cooperation, regional coordination mechanisms, scientific-data sharing, and harmonized monitoring standards all contribute to more effective marine-environmental management and preparedness for future environmental crises.

Ultimately, environmental recovery within the Black Sea region will depend not only on remediation activities but also on the establishment of integrated governance systems capable of supporting sustainable environmental protection and regional cooperation over the long term.

Conclusions

Marine pollution associated with armed conflict represents a complex and evolving environmental challenge requiring integrated, adaptive, and multidisciplinary monitoring approaches. The environmental consequences of warfare extend beyond immediate contamination events and may generate persistent ecological impacts affecting marine ecosystems, coastal communities, and regional environmental governance systems. The Black Sea region illustrates the importance of developing operational monitoring frameworks capable of functioning under conditions of uncertainty, restricted access, and rapidly changing environmental risks. Traditional environmental-monitoring systems alone are insufficient to address the complexity of conflict-related pollution scenarios. Instead, effective assessment frameworks must integrate field observations, laboratory analyses, satellite remote sensing, autonomous technologies, modelling tools, and interoperable data infrastructures [75].

This guide proposes a methodological framework designed to support environmental authorities, scientific institutions, and regional organizations involved in monitoring marine pollution generated by armed conflict. Particular emphasis has been placed on harmonization with existing European and regional monitoring frameworks, including the MSFD, WFD, BSIMAP, EMODnet, and WISE Marine systems [76]. Strengthening regional cooperation and transboundary coordination will remain essential for improving environmental assessment and response capacities within the Black Sea basin [77]. Shared monitoring methodologies, interoperable data systems, and coordinated scientific efforts can significantly enhance regional preparedness and environmental resilience.

Looking forward, continued technological development, expanded use of remote sensing and autonomous systems, and improved integration between environmental science and policy will play an increasingly important role in addressing conflict-related marine pollution. Long-term environmental protection within the Black Sea region will ultimately depend on the capacity of institutions and regional actors to develop adaptive governance systems capable of responding effectively to future environmental crises while supporting sustainable ecosystem recovery and environmental security [78].

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