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Black Sea SIERRA

Project 101124670 – Black Sea SIERRA
Awareness Materials on Novel
Available Solutions for Marine Pollution
Decontamination Related to Armed Conflicts





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Project 101124670

Awareness materials on novel available solutions for marine pollution decontamination related to armed conflicts

Awareness manual for stakeholders, authorities, educators, researchers and coastal communities



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Prepared in English for multilingual adaptation

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Consortium members

Role	Institution	Country
Coordinator	INCDPM – National Institute for Research and Development in Environmental Protection Bucharest	Romania
P1	Institute of Oceanology BAS – IO-BAS	Bulgaria
P2	E.M. Associazione A.R.C.E.S. – ARCES	Italy
P3	Ordu Universitesi – ORDU	Türkiye
P4	Ukrainian Scientific Centre of Ecology of the Sea – UkrSCES	Ukraine
P5	Mircea cel Batran Naval Academy – MBNAR	Romania
P6	Gheorghe Asachi Technical University of Iasi – TUIASI	Romania



Project consortium visual identity. Source: Black Sea SIERRA project materials.

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Executive summary

This awareness manual presents novel and available solutions for decontaminating marine and coastal environments affected by armed-conflict-related pollution. It integrates the Black Sea SIERRA Guide for specific remedial measures for armed conflict pollution, which emphasizes that modern warfare can generate mixed, sudden, difficult-to-access and long-lasting contamination events. Damaged vessels, ports, fuel storage systems, wastewater infrastructure, munitions, debris fields and industrial sites may release hydrocarbons, heavy metals, nutrients, plastic debris, explosive residues, hazardous chemicals and, in exceptional scenarios, radiological contaminants.

The Black Sea is a particularly sensitive setting for such awareness work. The basin is semi-enclosed, influenced by large rivers and shared by several countries. Pollution may therefore move through river systems, coastal currents, sediment transport, floating debris and food webs. The project documentation and official project information underline the need for coordinated cross-border response capacity, methodological guidance, monitoring systems, remedial prototypes and complementary training materials.

The manual is not designed as a highly technical engineering specification. Its purpose is to translate scientific and operational knowledge into clear messages for authorities, decision-makers, emergency responders, researchers, educators, port and coastal infrastructure managers, NGOs and communities. It explains what remedial measures exist, when they may be useful, what limitations must be communicated and why long-term verification is necessary.

The main message is that no single technology can solve conflict-related marine pollution. Effective response requires a sequence of actions: safety screening, detection, field verification, containment, technology selection, active treatment, ecological restoration, monitoring, performance verification and adaptive management. The specific remedial measures guide strengthens this document by adding a clearer structure for oil spill response, plastic and debris removal, eutrophication control, heavy metal remediation, emerging contaminants, explosive residues, radiological hazards, risk prioritization and operational roadmapping.

A specific section is dedicated to geopolymer-based and waste-derived materials, because project research highlights their relevance as porous, low-carbon and potentially circular remediation materials. Geopolymer-zeolite composites can combine physical filtration, adsorption, ion exchange and immobilization in saline waters. Activated carbon can act as a finishing stage for residual organic contaminants, fine particles and turbidity. Nevertheless, the manual keeps a balanced tone: promising materials must be tested under realistic marine conditions, including salinity, competing ions, turbidity, pH variation, biofouling and long-term leaching risk.

Final awareness message: decontamination must not simply move pollutants from water to land. Remediation materials and spent filters must be designed, monitored and managed across their full life cycle.

INCDPM: Scientific Expertise and Research Capacity

As Coordinator of the Black Sea SIERRA project, the National Institute for Research and Development in Environmental Protection (INCDPM) brings together multidisciplinary expertise, specialised research teams and technical capabilities addressing a wide range of environmental challenges. INCDPM combines scientific research with laboratory analysis, field investigations, environmental monitoring and applied solutions, providing a strong knowledge base for collaborative environmental action.

This multidisciplinary capacity enables INCDPM to integrate complementary scientific perspectives within a coherent environmental framework. These capabilities directly support the project's approach to marine pollution preparedness and response, connecting environmental assessment, monitoring, modelling, technological innovation and ecosystem protection.



INCDPM MISSION



SCIENTIFIC PROJECTS



Environmental Factors Analysis



Biosafety Level II Laboratories



Environmental Quality Assessment and Impact



Waste Management and Circular Economy



Environmental Protection Engineering and In-situ Monitoring



Climate Change, Sustainable Development and Taxonomy



Advanced / Smart Materials for Environmental



Numerical Modeling, GIS and Hydromorphodynamic



Biodiversity and Ecosystem Dynamics



Renewable Energies and Hydrogen Valorization In Environmental Protection



Across its specialised departments, INCDPM brings together complementary areas of scientific and technical expertise. This organisational structure supports an integrated approach to environmental research, allowing knowledge, methods and technical resources to be combined across disciplines and applied to complex environmental challenges.

Through its coordinating role, INCDPM provides a framework for interdisciplinary collaboration and knowledge exchange among the project partners, contributing to the development and dissemination of practical, science-based approaches for addressing marine pollution and strengthening environmental resilience across the Black Sea region.

*Awareness materials on novel available solutions
for marine pollution decontamination related to armed conflicts*

Moreover, INCDPM has a broad and complementary portfolio of scientific expertise and technical capabilities. Its multidisciplinary teams combine research, monitoring, modelling and field-based experience across key environmental domains, providing a strong foundation for coordinating complex, multi-partner activities and translating scientific knowledge into practical solutions.

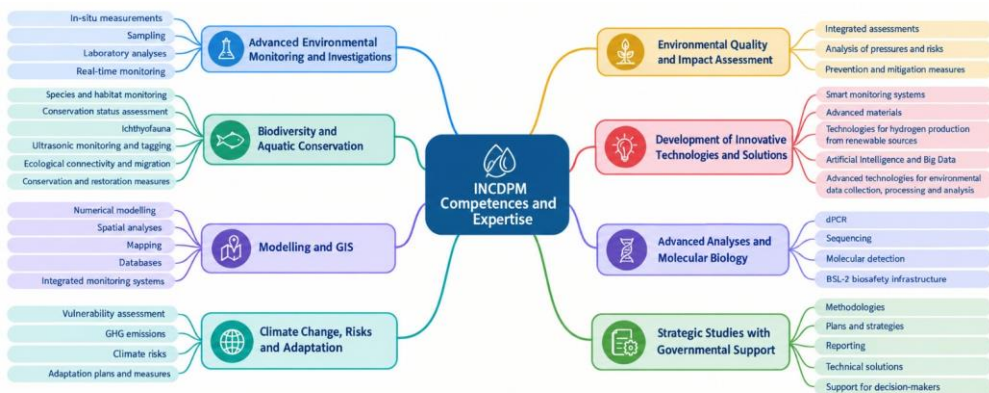


Figure 1. The scientific competencies and technical capabilities of INCDPM. Source: author-created.

Together, these competencies provide INCDPM with the capacity of studying ecosystems, generate and analyse high-quality data, develop innovative solutions and translate scientific knowledge into practical measures and decision-support tools.

This scientific capacity is underpinned by dedicated research infrastructure, specialised analytical and monitoring equipment, established methodological frameworks and accumulated institutional expertise.

These resources support the generation, validation and interpretation of environmental data across different spatial and temporal scales, while enabling the application of standardised and scientifically robust approaches.

1. Why this awareness material is needed

Figure 1 illustrates why visible shoreline debris should be treated as an initial warning sign, not as complete evidence of contamination.



*Figure 2. Shoreline debris and contaminated coastal water as visible signs of marine pollution.
Source: WHOI Sea Grant, Marine Debris regional resources.*

Marine pollution is usually presented through visible images: floating plastic, oil films, dirty beaches, dead organisms or colored water. In armed-conflict contexts, however, the most serious risks may remain hidden. Contaminants can be dissolved in water, bound to suspended matter, locked inside sediments, released slowly from corroding debris or accumulated in organisms.

This creates a communication challenge. Communities and local actors may see a beach that appears normal while sediments contain heavy metals, hydrocarbons or explosive residues. Conversely, visible litter can attract attention while less visible pollution from damaged wastewater systems, fuel depots or port infrastructure remains underreported. Awareness materials must therefore combine clear language with scientific caution.

The purpose of this document is to help non-specialists understand what kinds of remedial solutions are available and how they should be combined. It also helps specialists communicate their work without creating unrealistic expectations. A filtration unit, an oil boom, a satellite image, a wetland or a geopolymer material each solves only part of the problem. Real response requires an integrated system.

- Explain why armed conflicts can generate mixed and long-term marine pollution.
- Present available decontamination and mitigation solutions in a form understandable to non-specialists.
- Promote early detection, safe sampling, data sharing and rapid communication.
- Highlight advanced materials and digital tools without overstating their readiness.
- Encourage life-cycle thinking so that remediation does not create a new waste problem.
- Support multilingual dissemination, training courses, workshops and stakeholder dialogue.

For multilingual use, the document avoids unnecessary jargon and repeats key terms consistently. Short definitions and awareness messages are provided at the end so that partner institutions can adapt them into Romanian, Bulgarian, Turkish, Ukrainian and other relevant languages while preserving the same technical meaning.

2. Black Sea SIERRA context and target audiences

The Black Sea SIERRA project is an EMFAF-funded initiative dedicated to strengthening preparedness and response to civil and military marine pollution in the Black Sea region. Official project information describes its objective as preparing and adapting decision-makers' response capacity to current and emerging marine pollution through coordinated cross-border response to armed-conflict contamination [1]. Expected outputs include methodological guidance, pollution databases, modelling datasets, monitoring guidance, a remedial solution prototype, management planning, complementary curricula and training workshops [2]. Their main information needs and recommended uses are summarized in Table 1.

This document contributes to the communication and training dimension of that wider framework. It is intended to be useful during courses, workshops, stakeholder consultations, public communication campaigns, and institutional discussions on post-conflict environmental recovery. It should be read together with the monitoring guide, the complementary sustainable management plan, the remedial measures guide and the research outputs on innovative materials.

The target audiences are deliberately broad. Environmental authorities and decision-makers need concise, reliable explanations to support planning and coordination. Researchers and laboratories need a common vocabulary and an overview of applicable technologies. Emergency responders need to understand when specialist input is required and why access may be restricted. Ports, fisheries, coastal communities and tourism actors need practical reporting and risk communication messages. Educators and NGOs need accessible material that can be used in awareness activities.

Table 1. Target audiences and recommended uses of the awareness material.

Audience	What they need from this material	Recommended use
Authorities and policy makers	Clear link between pollution risks, response options and governance responsibilities.	Workshops, briefings, strategy documents and public communication.
Emergency responders	Simple understanding of safety restrictions, incident classification and first-response limits.	Training sessions, coordination exercises and operational checklists.
Researchers and laboratories	Shared terminology for pollutants, matrices, monitoring and remediation technologies.	Course support, project meetings and interdisciplinary collaboration.
Ports and coastal infrastructure managers	Practical awareness of oil spills, runoff, sediment disturbance and waste handling.	Internal environmental management and incident reporting.
Educators, NGOs and communities	Short messages on observation, reporting, avoidance of unsafe contact and long-term risks.	Posters, leaflets, social media and local awareness events.

Why multilingual? The Black Sea is a shared basin. If countries use similar messages and visual structures, communication during regional incidents becomes faster, clearer and easier to coordinate.

The main pollutant classes and awareness messages are summarized in Table 2.

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3. Armed-conflict pollution: sources, pathways and priority pollutants

Pollution related to armed conflicts differs from conventional marine pollution because it is often sudden, mixed, unsafe to access and difficult to characterize immediately. A single incident can include several contaminants at the same time: fuel, soot, metals, plastics, unexploded ordnance residues, untreated wastewater and disturbed sediments. These substances can then be transported by rivers, runoff, coastal currents, storms, floods or sediment resuspension. This source-to-sea movement from conflict-related sources to environmental compartments and risks is summarized in Figure 2.

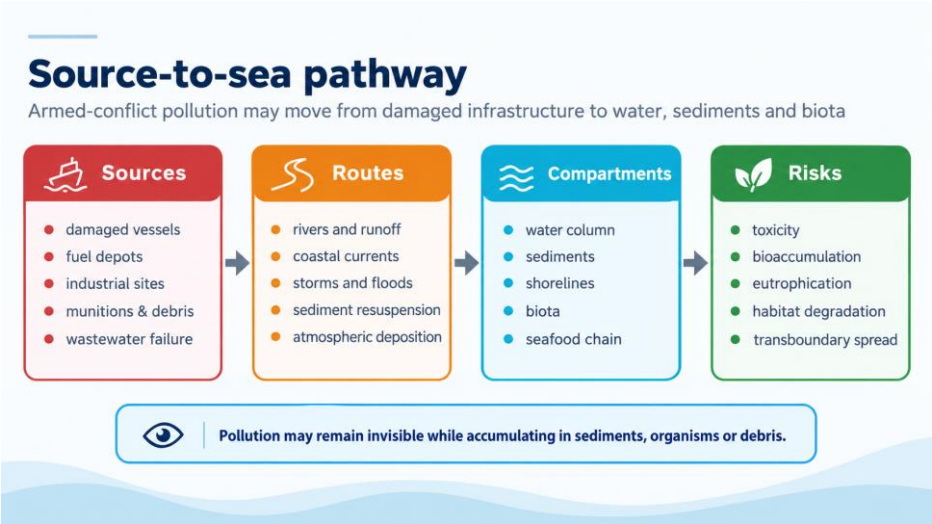


Figure 3. Source-to-sea pathway of armed-conflict pollution. Source: author-created diagram based on Black Sea SIERRA remedial and monitoring guidance.

In the Black Sea region, this mixed nature is especially important. The sea is semi-enclosed and receives substantial inputs from tributary rivers and coastal industrial areas. Conflict-affected river basins may transfer pollutants from inland sites to lagoons, ports and coastal waters. Sediments can act as both a sink and a secondary source, releasing contaminants again when disturbed by storms, dredging, explosions or changes in pH and oxygen conditions.

Table 2. Priority pollutant classes, typical conflict-related sources and awareness messages.

Pollutant class	Typical conflict-related sources	Main risk message for awareness
Petroleum hydrocarbons	Damaged ships, port infrastructure, fuel depots, vehicles, fires.	Oil may spread quickly, contaminate shorelines and remain in sediments after visible slicks disappear.

Pollutant class	Typical conflict-related sources	Main risk message for awareness
Heavy metals	Munitions, metal debris, ships, vehicles, industrial infrastructure and resuspended sediments.	Metals do not degrade and may accumulate in sediments and organisms.
Explosive residues	Unexploded ordnance, ammunition residues, military storage areas and underwater detonations.	TNT, RDX, HMX and related compounds require specialized safety and analytical protocols.
Persistent organic pollutants	Combustion products, industrial chemicals, PAHs, PCBs and remobilized legacy contamination.	Long-term toxicity and bioaccumulation may continue after the original event.
Nutrients and pathogens	Damaged wastewater treatment plants, sewer networks and flood-affected settlements.	Eutrophication, hypoxia, harmful algal blooms and health restrictions may follow.
Plastics and debris	Destroyed infrastructure, equipment, packaging, ropes, nets, synthetic materials and debris fields.	Macroplastic may fragment into microplastics and transport other contaminants.
Radiological hazards	Damage to nuclear or radioactive storage facilities; exceptional high-risk scenarios.	Requires specialized monitoring, containment and institutional coordination.

For awareness communication, a key rule is to distinguish between visible evidence and confirmed contamination. A photograph of an oil sheen, dead fish or debris field is important, but it does not identify all contaminants. Laboratory analysis, documented sampling, remote sensing and expert interpretation are necessary before final conclusions are communicated.

4. Guiding principles for remedial action

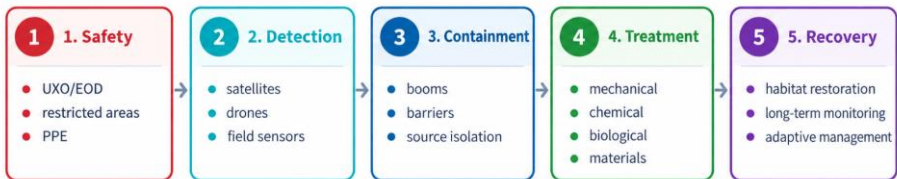
The remedial measures guide emphasizes that armed-conflict pollution must be addressed through a combination of legal, environmental and operational principles. These principles help authorities and technical teams act under uncertainty, where field access may be limited and risks may change quickly.

- Safety first: no environmental sampling or cleanup action should place personnel at risk from unexploded ordnance, damaged infrastructure, toxic vapours, unstable sites or military hazards.
- Precaution: when the risk of serious environmental harm is plausible but incomplete information is available, early protective action is justified.
- Prevention and source control: stopping an active release is usually more effective than treating diluted contamination after dispersion.
- Polluter pays and accountability: where legally possible, those responsible for damage should contribute to monitoring, remediation and restoration.
- Integrated coastal zone management: land-based sources, rivers, ports, lagoons and coastal waters must be considered together.
- Ecosystem-based management: the goal is not only contaminant reduction, but recovery of ecological functions and services.
- Adaptive management: actions must be revised as monitoring data, risk maps and site conditions evolve.

Figure 3 translates these principles into an integrated response sequence.

Integrated response framework

A practical sequence from safety screening to verified ecosystem recovery



Core message

No single measure is enough. Effective response combines safety, monitoring, containment, treatment and verification.

Figure 4. Integrated framework for conflict-related marine decontamination. Source: author-created diagram based on the Black Sea SIERRA remedial measures guide.

These principles are especially relevant for public communication. People often expect immediate cleanup after a pollution incident. In practice, the first step may be restriction of access, mapping, sampling or containment. The public should understand that delays are sometimes necessary because unsafe or poorly planned intervention can spread pollutants, disturb sediments, expose workers or create additional waste.

Plain-language version: do not rush into the polluted area; identify the hazard, stop the source, choose the right method, document the result and monitor whether the site is really recovering.

5. Available remedial measures by contaminant class

The specific remedial measures guide provides a stronger structure for presenting remedial measures by pollutant class. For awareness purposes, the following classification is useful because it links each contaminant with realistic first-line and complementary options. The list should not be read as a universal recipe. Each polluted site requires site characterization, risk assessment and professional selection of technologies.

5.1 Oil spills and petroleum hydrocarbons

Oil and fuel releases are among the most urgent marine pollution events because they can spread rapidly, affect shorelines and damage sensitive habitats. The preferred first response usually combines source control, containment and mechanical recovery. Booms can limit horizontal dispersion, while skimmers and vacuum systems recover floating hydrocarbons when sea state and weather allow it. Sorbents can be useful locally, but spent sorbents become contaminated waste and must be collected and managed safely.

Chemical dispersants may reduce shoreline contamination but can also move oil into the water column, where organisms may be exposed. Their use must therefore be based on a formal environmental risk assessment and regulatory approval. Bioremediation can support long-term degradation of petroleum compounds, especially when oxygen, nutrients and temperature are favourable, but it is not an instant emergency solution.

5.2 Plastics, debris and military waste

Large debris and macroplastics should be intercepted and removed before they fragment. Floating barriers, passive interception systems, shoreline cleanup, autonomous collection vessels and port waste reception systems can reduce accumulation. However, collection is only the first step. Sorting, safe storage, recycling where feasible, and disposal of contaminated or hazardous fractions are equally important.

Conflict-related debris may contain sharp materials, chemicals, fuels, asbestos, electrical components or explosive hazards. Awareness campaigns must therefore avoid encouraging untrained volunteers to handle suspicious materials. Public reporting, photographic documentation from a safe distance and professional cleanup are preferred in high-risk areas.

5.3 Eutrophication and nutrient pollution

Damage to wastewater infrastructure can increase nitrogen, phosphorus, organic matter and pathogens in rivers and coastal waters. Aeration and oxygenation can help in hypoxic water bodies, while sediment removal may be considered where nutrient-rich sediments act as an internal source. Chemical precipitation and coagulation can reduce phosphorus quickly, but they require careful management of added chemicals and resulting sludge.

Nature-based systems such as constructed wetlands, vegetated buffer zones, algae cultivation and seagrass restoration can provide long-term benefits. They are not emergency tools for acute hazardous contamination, but they can support recovery, nutrient retention, biodiversity and coastal resilience.

5.4 Heavy metals and contaminated sediments

Heavy metals such as Pb, Cd, Cu, Zn, Ni, Cr and Hg persist because they do not biodegrade. They may remain dissolved, bind to particles, accumulate in sediments or enter organisms. Remedial options include dredging, capping, stabilization,

immobilization, permeable reactive barriers, adsorption media, phytoremediation and, in selected cases, nanotechnology-based materials.

Dredging can remove highly contaminated sediments quickly, but it can also resuspend contaminants and requires safe disposal or treatment of dredged material. Reactive capping and stabilization can reduce mobility in situ. Adsorbents such as zeolites, activated carbon, biochar and geopolymer-based media can retain or immobilize contaminants if properly designed and monitored.

5.5 Explosive residues, emerging contaminants and radiological hazards

Modern conflicts may introduce TNT, RDX, HMX, propellants, combustion products, pharmaceuticals, pesticides, PFAS-like industrial chemicals and other emerging contaminants. These compounds require specialized analytical methods and often cannot be managed through standard cleanup alone. Remedial options may include removal of the source, controlled excavation or dredging, advanced oxidation, adsorption, bioremediation, immobilization or long-term monitored natural recovery, depending on the compound and site conditions.

Radiological hazards are exceptional but require a very different response logic. If radioactive contamination is suspected, ordinary environmental teams should not collect samples without specialized authorization and protective protocols. Radiological assessment, containment, dosimetry, institutional notification and long-term surveillance become mandatory.

Table 3. Available remedial measures by contaminant class.

Problem	First-line response	Complementary remedial options	Main caution
Oil / fuel slick	Stop source, deploy booms, recover mechanically.	Sorbents, shoreline protection, bioremediation, selected dispersant use.	Weather dependent; dispersants require regulatory and ecological assessment.
Plastic and debris	Map, remove macrodebris, segregate waste.	Recycling, controlled disposal, interception systems, public reporting.	Military debris may be dangerous; avoid volunteer handling of suspicious objects.
Nutrients / eutrophication	Control wastewater source, monitor oxygen and nutrients.	Aeration, sediment management, wetlands, algae systems, restoration.	Chemical treatment creates sludge and must be monitored.
Heavy metals	Characterize water, sediment and biota; restrict exposure.	Dredging, capping, stabilization, zeolite/geopolymer media, phytoremediation.	Dredging can resuspend contaminants; immobilized metals need leaching verification.
Explosive residues	Safety perimeter, EOD input, specialized sampling.	Source removal, adsorption, advanced oxidation, bioremediation, monitored recovery.	Do not sample or disturb UXO without specialist clearance.
Radiological risk	Notify competent authorities; restrict access.	Specialized containment, radiological monitoring, removal by authorized teams.	Requires radiation protection expertise and long-term surveillance.

6. Advanced material solutions: geopolymer-zeolite filters and carbon polishing

Advanced material solutions are relevant because many conflict-related contaminants are dissolved, fine, persistent or mixed. Conventional mechanical removal is not enough for metal ions, ammonium, phosphates, some organic compounds or fine suspended particles. Adsorbent and reactive materials can complement mechanical containment by retaining, immobilizing or transforming pollutants.

Black Sea SIERRA-related research materials highlight porous geopolymers and geopolymer-zeolite composites as promising options for saline water decontamination. Geopolymers are inorganic aluminosilicate materials obtained through alkaline activation of precursors such as metakaolin, fly ash, slag, red mud or mineral wastes. Their three-dimensional Si-O-Al structure can provide chemical stability, while their porosity allows contact between contaminated water and active sites.

The project-related patent material describes a porous geopolymeric composite with zeolitic aggregates for the decontamination and remediation of saline solutions. The material is designed as granules or filters and combines the mechanical and chemical stability of the geopolymer matrix with the ion-exchange properties of zeolite aggregates. The use of zeolite in aggregate form is important because it preserves permeability, reduces pressure drop and limits clogging compared with powder-based media. The main geopolymer-zeolite mechanisms are summarized in Figure 4.

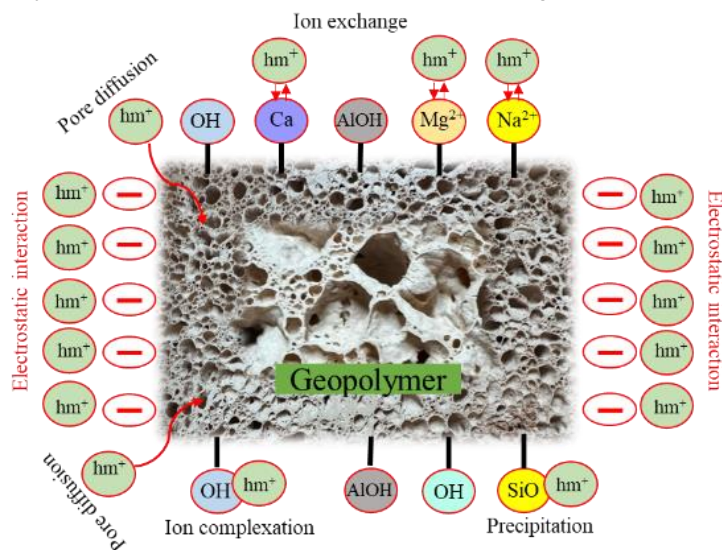


Figure 5. Geopolymer-zeolite filtration concept and main mechanisms. Source: author-created diagram based on Black Sea SIERRA project materials.

The main components of the hybrid filtration system and their awareness interpretation are summarized in Table 4.

The main mechanisms are adsorption, ion exchange, surface complexation, precipitation, pore diffusion and encapsulation. In simple terms, pollutants may attach to surfaces, replace exchangeable ions, form less soluble compounds or become trapped in a stable mineral matrix. This is why geopolymer-based materials are interesting not

only as filters, but also as immobilization systems that can reduce the risk of secondary release.

The Black Sea field and presentation materials also show the importance of combining the geopolymer stage with a carbon finishing stage. Activated carbon or biochar can reduce residual organic contaminants, colour, odour, fine particles and turbidity after primary filtration. In an awareness context, this should be presented as a hybrid solution: no single material does everything, but a layered system can address several pollutant classes more effectively. The resulting hybrid filtration concept is shown in Figure 5.

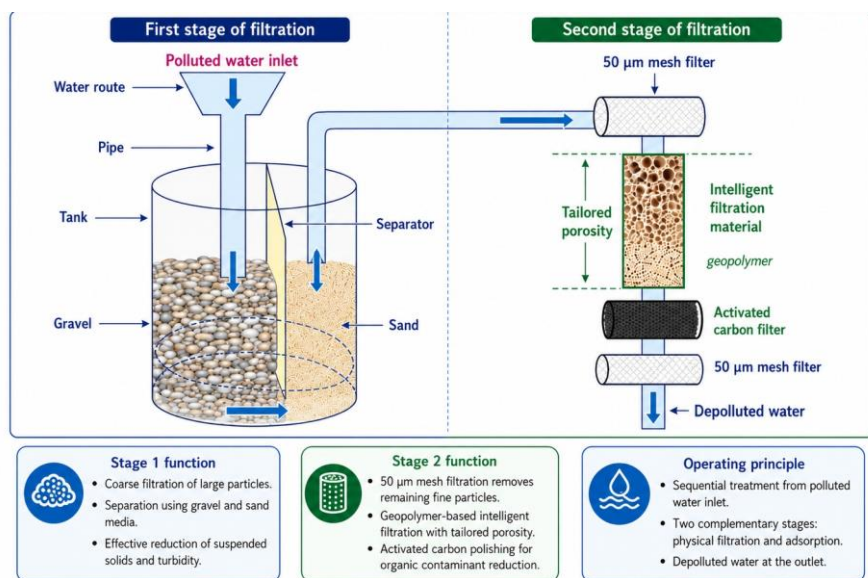


Figure 6. Two-stage filtration concept with geopolymer-based material and activated carbon polishing stage. Source: Black Sea SIERRA project materials / TUIASI field campaign materials.

Table 4. Technical role and awareness interpretation of geopolymer-zeolite and carbon filtration features.

Feature	Technical role	Awareness interpretation
Tailored porosity	Provides water pathways and contact area for contaminants.	The material must let water pass while keeping pollutants in contact with active sites.
Zeolite aggregates	Support ion exchange and preserve permeability.	Aggregates can help capture ammonium and some metal ions without blocking the filter.

Geopolymer matrix	Provides mineral stability and contaminant immobilization.	Captured pollutants should remain fixed, not return to the water.
Carbon polishing	Improves removal of organics and fine particles after primary filtration.	A finishing stage can reduce turbidity and improve final water quality.
Spent filter management	Controls end-of-life risk.	A saturated filter is contaminated material and needs regeneration, reuse, stabilization or safe disposal.

Balanced communication: geopolymer-zeolite filters are innovative and promising, but field deployment requires washing, conditioning, leaching tests, hydraulic design, breakthrough monitoring and safe end-of-life planning.

7. Emergency monitoring, remote response and digital tools

The remedial measures guide strongly reinforces the role of remote and digital systems in conflict-affected environments. Direct access may be dangerous because of military activity, mines, unexploded ordnance, damaged infrastructure or chemical hazards. Digital tools can help identify hotspots, guide sampling and reduce personnel exposure. Figure 6 illustrates field water sampling as the link between remote detection and laboratory confirmation.

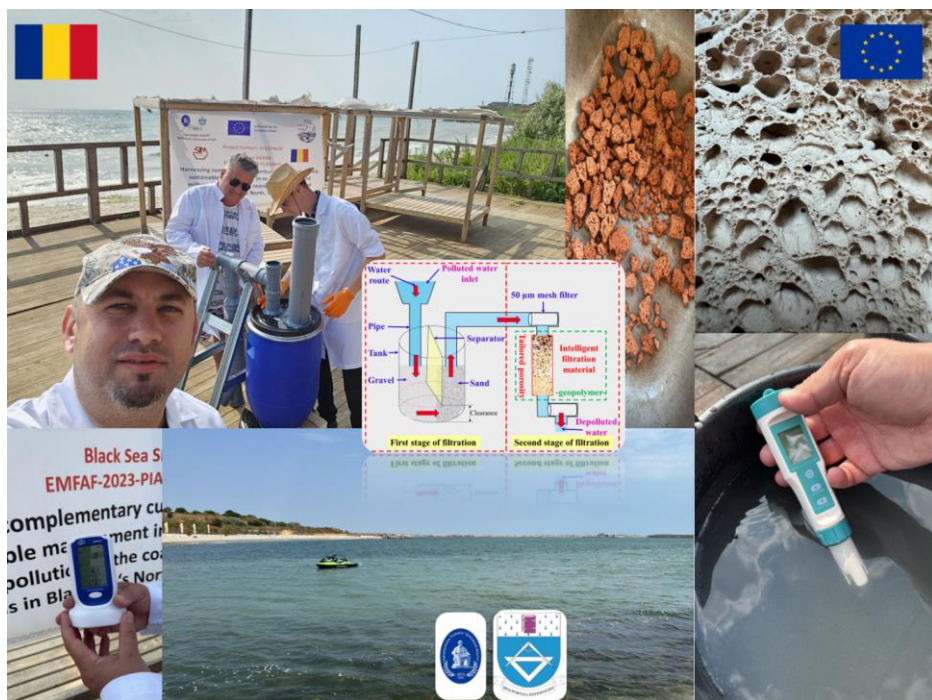


Figure 7. Field monitoring and water sampling. Source: Environment Protection Authority Victoria / Wikimedia Commons, CC BY 4.0.

Satellite monitoring can detect oil slicks, suspended sediment plumes, chlorophyll anomalies, turbidity, flooding, damaged infrastructure and large debris patterns. Synthetic Aperture Radar is especially useful for oil spill detection because it can operate under cloud cover and at night. Multispectral optical data can support interpretation of turbidity, algal blooms and land-to-sea runoff. The strengths and limitations of the main monitoring elements are summarized in Table 7.

Drones, unmanned surface vehicles and remotely operated underwater vehicles can support shoreline inspection, sampling, bathymetric mapping, debris identification and underwater infrastructure assessment. They are particularly useful where field teams cannot safely enter. However, remote tools must be interpreted carefully and should not replace laboratory confirmation when chemical identity or toxicity is at stake.

In situ sensors can measure pH, salinity, temperature, conductivity, dissolved oxygen, turbidity and, in some cases, selected nutrients or contaminants. These parameters help interpret water quality, pollutant mobility and remediation performance. For example, pH and salinity influence metal speciation and adsorption; turbidity can indicate particle

release or sediment resuspension; oxygen affects eutrophication and ecosystem stress. The digital monitoring and smart response sequence is summarized in Figure 7.



Figure 8. Digital monitoring and smart response chain. Source: author-created diagram based on Black Sea SIERRA monitoring and remedial guidance.

Table 5. Monitoring elements, possible outputs and main limitations.

Monitoring element	What it can show	Main limitation
Satellite / SAR	Oil slicks, surface anomalies, flooding, large-scale changes.	Cannot identify all chemicals; needs validation.
Drones / USV / ROV	Restricted shorelines, debris, infrastructure, sampling locations.	Weather, battery, access permissions and security restrictions.
Field sensors	Rapid water quality parameters and trends.	Screening only; many pollutants need laboratory analysis.
Laboratory methods	Metals, hydrocarbons, nutrients, explosive residues, QA/QC results.	Slower and dependent on sampling quality.
GIS and models	Hotspot maps, dispersion, exposure pathways, priority ranking.	Uncertainty must be communicated clearly.

8. Risk prioritization and decision support

Because resources are limited during and after conflict, not every site can be treated immediately. The guide proposes a risk-based decision logic that begins with site characterization and baseline assessment, then classifies priority based on contaminant hazard, exposure probability, ecological sensitivity, human use and transboundary consequences. The sequential decision-support logic is illustrated in Figure 8.

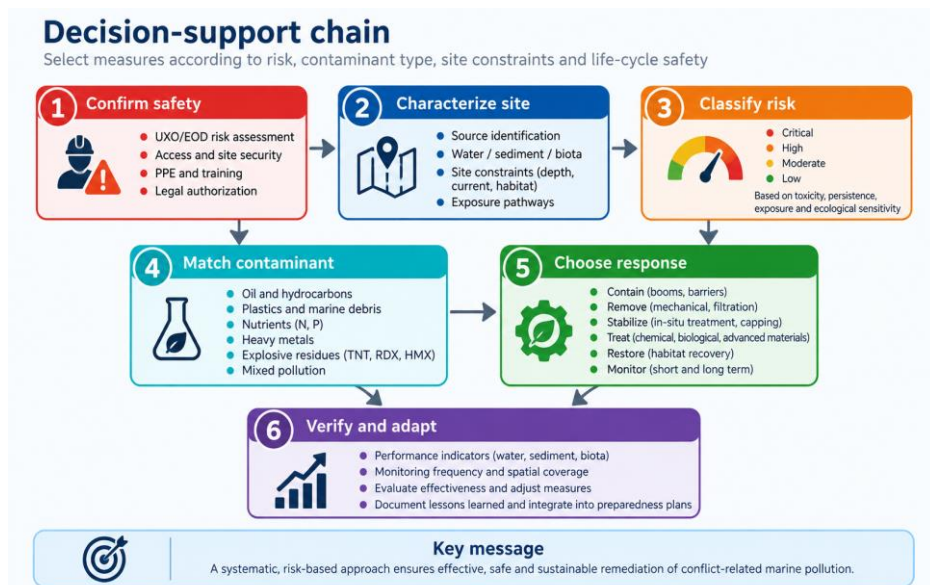


Figure 9. Decision support for selecting remedial measures. Source: author-created diagram based on the *Black Sea SIERRA remedial measures guide*.

The risk-level classification used for awareness and planning is summarized in Table 8.

Site characterization should identify contamination sources, pollutant types, affected compartments, sensitive receptors and potential exposure routes. Key questions include: Is the source still active? Are people exposed? Are fisheries, shellfish harvesting areas, beaches, wetlands, lagoons, ports or protected habitats affected? Can field teams access the site safely? Are contaminants likely to spread across borders?

Risk classification helps communicate urgency. Critical-risk sites may require immediate containment, public restrictions and emergency sampling. High-risk sites need planned intervention and frequent monitoring. Moderate-risk sites may be managed through scheduled remediation and verification. Low-risk sites may be monitored for natural recovery if evidence supports that approach. Table 7 compares the main remediation technology families with their typical advantages and limitations.

Table 6. Risk levels and response priorities for conflict-related marine pollution.

Risk level	Typical situation	Response priority
Critical	Active release; severe human exposure; sensitive habitat threatened; high toxicity; spreading plume.	Immediate containment, restrictions, emergency monitoring and decision-maker notification.
High	Confirmed contamination above relevant thresholds; significant habitat or fisheries risk.	Detailed assessment, technology selection and rapid implementation of remedial measures.
Moderate	Measurable degradation but limited immediate exposure or slower spread.	Planned remediation, source control and periodic monitoring.
Low	Residual or uncertain contamination with low exposure and evidence of natural recovery.	Monitoring, communication and reassessment if conditions change.

Technology selection should not be based only on removal efficiency. It should also consider cost, maturity, timeframe, operating conditions, waste generation, ecological side effects, monitoring needs and social acceptability. In many cases, hybrid systems are more realistic than single technologies. For example, oil spill response may combine booms, skimmers, sorbents, shoreline protection and bioremediation. Metal-contaminated sediments may require mapping, restrictions, capping, stabilization and long-term bioaccumulation monitoring.

Table 7. Main remediation technology families and key limitations.

Technology family	Best suited for	Key advantage	Key limitation
Mechanical containment and recovery	Oil slicks, floating debris, immediate releases.	Fast first response; no added chemicals.	Weather/sea-state dependent; misses dissolved contaminants.
Chemical treatment / stabilization	Phosphorus, metals, selected hazardous substances.	Can reduce mobility or bioavailability quickly.	May create sludge or require strict control.

Technology family	Best suited for	Key advantage	Key limitation
Bioremediation	Hydrocarbons and selected organic compounds.	Lower secondary impact; supports natural degradation.	Slow and dependent on oxygen, temperature and nutrients.
Dredging / excavation	Highly contaminated sediments and debris.	Removes contaminant inventory.	Costly; resuspension and disposal risks.
Reactive capping / barriers	Sediments, seepage, groundwater-to-sea pathways.	In situ control; passive operation possible.	Contaminants remain in place and require monitoring.
Adsorbents and advanced materials	Metals, ammonium, organics, mixed waters.	Modular; can be tailored and combined.	Breakthrough, leaching and spent media management must be verified.
Nature-based solutions	Nutrients, suspended particles, long-term recovery.	Habitat and resilience co-benefits.	Need space, time and protection from new pollution.

9. Life-cycle safety, circular economy and responsible end-of-life management

One of the most important messages for future remediation work is that a successful technology must not simply move pollution from water to land. If contaminants are captured in a filter, sorbent, sediment cap or biomass, the resulting material must be managed safely. Otherwise, decontamination can become a transfer of risk rather than a reduction of risk. The life-cycle safety logic for decontamination materials is summarized in Figure 9.

Life-cycle safety of decontamination materials

Do not transfer pollution from water to a new land-based waste problem



Figure 10. Life-cycle safety of decontamination materials. Source: author-created diagram based on circular remediation and life-cycle safety principles.

Life-cycle thinking starts before the material is produced. Raw materials must be checked for contaminants, variability and leaching potential. In the case of waste-derived precursors, circular economy benefits are real only if the material does not introduce new hazards. During production, alkaline activators, powders and additives must be handled safely. During deployment, hydraulic design must ensure sufficient contact time and avoid uncontrolled particle release. The minimum life-cycle questions that should be asked at each stage are summarized in Table 8.

During operation, monitoring should include not only target pollutant removal, but also pH, conductivity, turbidity, salinity, flow rate, pressure drop, visual integrity and possible release of matrix-derived elements. Breakthrough monitoring is essential for adsorbents and filters: once a material is saturated, it may stop removing pollutants and can even release retained substances under changing conditions.

End-of-life management should be planned at the design stage. Options may include regeneration, controlled reuse, incorporation into construction materials, stabilization, hazardous waste disposal or long-term storage, depending on contaminant type and legal requirements. For geopolymer-based filters, their mineral nature and immobilization

potential may support safe stabilization or secondary use, but only after leaching and ecotoxicity testing.

Table 8. Life-cycle stages, key questions and minimum awareness messages.

Life-cycle stage	Questions to ask	Minimum awareness message
Material selection	Does the raw material contain contaminants? Is it locally available and consistent?	Waste-derived does not automatically mean safe.
Production	Are powders, alkaline activators and additives handled safely?	Green materials still require safe production protocols.
Deployment	Can the material operate in saline, turbid and variable conditions?	Laboratory success must be validated in real water.
Operation	Is there breakthrough, pH drift, turbidity release or clogging?	Monitor the system, not only the first water sample.
End-of-life	Can the spent material be regenerated, reused, stabilized or disposed of safely?	A saturated filter is contaminated material.

Circular economy rule: reuse is acceptable only when environmental safety is demonstrated. The hierarchy should be: prevent secondary release, verify stability, then choose regeneration, reuse, stabilization or disposal.

10. Multilingual communication package

Awareness material becomes more effective when all language versions use the same visual structure, terminology and order of messages. This is especially important in a regional sea basin where incidents, pollutants and response measures may involve several countries. The purpose of multilingual communication is not only translation, but also harmonization of understanding. Figure 10 presents the recommended structure of a multilingual awareness package.

Multilingual awareness package

Same visual structure, same core message, local language

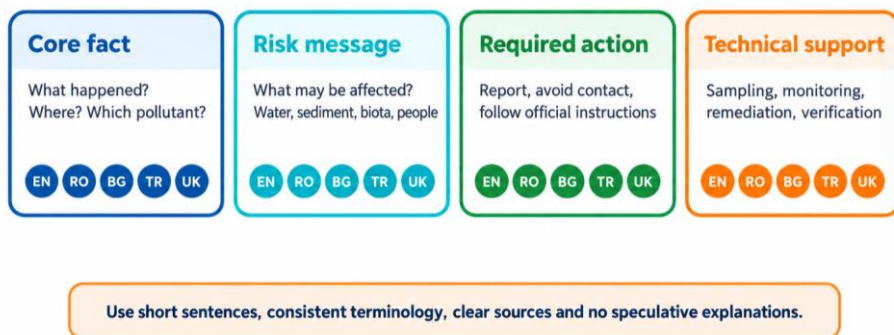


Figure 11. Multilingual awareness package structure. Source: author-created diagram for the Black Sea SIERRA awareness manual.

Recommended communication products and indicative lengths are summarized in Table 9.

Each translated version should preserve four elements: the core fact, the risk message, the recommended action and the technical contact or institutional pathway. Technical terms should be translated consistently and accompanied by short explanations. For example, “bioaccumulation” should be explained as pollutants building up in organisms over time. “Leaching” should be explained as pollutants being released again from a contaminated solid or filter.

For posters and leaflets, the text should be shorter than in this manual. Each poster should contain one main idea, one strong image or diagram and three to five action points. For workshops, a two-page fact sheet can add background, examples and references. For public communication, speculative explanations should be avoided until laboratory or official confirmation is available.

Table 9. Communication products recommended for multilingual awareness work.

Communication product	Recommended content	Length
Poster	One risk, one action message, one visual and an official contact point.	1 page
Leaflet	Short explanation of source, pathway, risk and safe behavior.	2 pages
Training handout	Contaminants, response options, checklists and glossary.	4-8 pages
Stakeholder brief	Risk prioritization, technologies, governance and roadmap.	4-6 pages
Social media card	Verified fact, safe action and where to report.	Very short

- Use the same title and project identity in all language versions.
- Avoid overloaded text and long technical sentences.
- Separate confirmed facts from assumptions and from ongoing investigations.
- Do not encourage unsafe cleanup by untrained volunteers.
- Always include source, date and responsible institution where relevant.
- Keep a short glossary for translators and reviewers. Practical checklists and glossary terms are provided in Annex A and Annex B.

The six operational stages are summarized in Table 10.

11. Operational roadmap for post-conflict marine recovery

The specific remedial measures guide culminates in a six-stage operational roadmap for post-conflict marine recovery. For awareness use, this roadmap is valuable because it shows that remediation is not a single action. It is a process that begins with screening and continues through assessment, containment, active remediation, ecosystem recovery and monitoring.

Table 10. 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 assessment and risk classification	Generate technical information for evidence-based decisions: site characterization, contaminant data and risk ranking.
3	Emergency containment	Stabilize contamination and prevent further dispersion using booms, barriers, wastewater diversion or emergency recovery.
4	Active remediation technologies	Implement physical, chemical, biological, material-based or hybrid technologies selected according to site conditions.
5	Habitat restoration and ecosystem recovery	Recover habitat structure and function, integrating nature-based solutions and long-term sustainability.
6	Continuous monitoring and institutional strengthening	Verify durability of recovery through monitoring, adaptive management, training and governance capacity-building.

For stakeholder workshops, this roadmap can be converted into a simple exercise: participants select a hypothetical incident, identify the pollutant classes, assign a risk category, choose first-response actions, select complementary remediation tools and define performance indicators. This approach helps participants understand that technology selection depends on evidence, not on preference for a single method.

The roadmap also supports institutional communication. It clarifies that emergency responders, environmental authorities, laboratories, maritime institutions, local administrations and scientific partners have different but connected roles. The more clearly these roles are defined before an incident, the faster response can be implemented when pollution occurs.

Workshop message: the best remedial solution is not the most advanced technology, but the combination of tools that safely reduces risk, fits the site and can be monitored until recovery is confirmed.

Conclusions

Marine pollution related to armed conflicts is complex, mixed and often long-lasting. It may involve oil, metals, plastics, nutrients, persistent organic pollutants, explosive residues, contaminated sediments and damaged infrastructure at the same time. In the Black Sea, the semi-enclosed basin, river connections and transboundary circulation make coordinated monitoring and response especially important.

This awareness material highlights that effective decontamination requires integrated action. Safety screening, remote detection, field verification, containment, technology selection, active remediation, habitat restoration and long-term monitoring must be connected in a single process. No single remedial technology is sufficient for all conflict-related contamination scenarios.

Available solutions include mechanical containment and recovery, plastic and debris removal, chemical stabilization, bioremediation, nutrient control, dredging, reactive capping, permeable reactive barriers, nature-based systems, nanotechnology-based approaches, adsorbent materials, digital monitoring and advanced geopolymer-zeolite filtration systems. These tools should be selected according to pollutant type, environmental compartment, ecological sensitivity, operational constraints and life-cycle safety.

The main innovation-oriented message is that advanced materials, including porous geopolymer and geopolymer-zeolite systems, can contribute to marine decontamination by combining filtration, adsorption, ion exchange and immobilization. However, their use must remain scientifically controlled, with attention to salinity, competing ions, pH, turbidity, stability, leaching behavior and spent material management.

The final message for future researchers, authorities and practitioners is clear: remediation must be safe, circular, traceable and transboundary. The objective is not only to remove pollutants from water, but to prevent secondary contamination and support long-term recovery of marine ecosystems.

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Annex A. Ready-to-use awareness messages and checklists

A1. Public observation checklist

- Observe from a safe distance. Do not touch oil, chemical containers, dead animals, munitions, military debris or suspicious objects.
- Record the location, time and visible characteristics: colour, smell, sheen, foam, dead organisms, debris, smoke or unusual water colour.
- Take photographs only if it is safe and without entering the affected area.
- Report the observation to local authorities or the designated environmental contact point.
- Follow official instructions on bathing, fishing, seafood consumption and beach access.
- Do not spread unverified explanations on social media.

A2. Field team checklist

- Confirm safety and access status before deployment.
- Check whether UXO, damaged infrastructure, fuel, chemical hazards or military debris may be present.
- Prepare bottles, preservatives, blanks, replicates, labels, GPS and chain-of-custody forms.
- Record coordinates, depth, weather, sea state, matrix, sample type and visible observations.
- Preserve and transport samples according to method requirements.
- Document uncertainty and distinguish observations from confirmed analytical results.

A3. Institutional response checklist

- Activate the national or local coordination chain and identify the lead authority.
- Classify the event: oil spill, chemical release, sediment disturbance, munitions-related risk, wastewater discharge or mixed event.
- Request remote sensing, modelling and scientific support where relevant.
- Decide whether public warnings, bathing restrictions, fishing restrictions or shoreline access controls are required.
- Ensure recovered waste, spent sorbents and used filters are stored and disposed of safely.
- Prepare a post-incident report and update training materials with lessons learned.

A4. Short awareness statements

The ready-to-use statements are organized in Table 11 for direct adaptation in posters, briefings or social media cards.

Table 11. Ready-to-use awareness statements.

Message title	Ready-to-use wording
Safety first	If pollution is linked to conflict, do not touch debris or suspicious objects. Report and wait for authorized response.
Invisible risk	Clear water does not always mean safe water. Metals, hydrocarbons and explosive residues may be hidden in sediments or organisms.
Integrated response	Containment, monitoring, treatment and recovery must work together. One technology is not enough.
Circular remediation	A saturated filter or sorbent is contaminated material. It must be regenerated, stabilized, reused only when safe, or disposed of properly.
Regional cooperation	In a shared sea basin, pollution and data cross borders. Monitoring and communication must also cross borders.

Annex B. Compact glossary for multilingual translation

Table 12. Compact glossary for multilingual translation.

Term	Plain-language definition
Adsorption	Retention of pollutants on the surface of a material.
Bioaccumulation	Build-up of pollutants in organisms over time.
Bioremediation	Use of microorganisms or biological processes to degrade or transform pollutants.
Capping	Placement of a clean or reactive layer over contaminated sediment to reduce exposure and release.
Encapsulation	Trapping pollutants inside a stable solid matrix.
Eutrophication	Excess nutrient enrichment that can cause algal blooms and oxygen depletion.
Geopolymer	Inorganic aluminosilicate material produced by alkaline activation of precursors such as metakaolin, fly ash or slag.
Ion exchange	Replacement of ions in a material by pollutant ions from water.
Leaching	Release of substances from a solid material into water.
Permeable reactive barrier	A subsurface or in-situ reactive zone that treats contaminated water as it passes through.
Remediation	Action taken to reduce pollutant concentration, mobility, exposure or ecological risk.
UXO	Unexploded ordnance; military explosive material that did not detonate and may remain dangerous.