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Black Sea SIERRA

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Authors	ARCES Team: Alessandro Pernice & Melinda Terranova
Contributors	All partners: Institute of Oceanology Bas (IO-BAS) Ordu Universitesi (ORDU) Ukrainian Scientific Center of Ecology of the Sea (UkrSCES) Mircea cel Batran Naval Academy (MBNAR) Gheorghe Asachi Technical University of Iasi (TUIASI)

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Introduction

The Black Sea is one of Europe's most environmentally fragile and geopolitical-ly sensitive marine regions. In recent decades, it has faced growing environmental degradation caused by industrial pollution, maritime transport, overexploitation of marine resources, climate change, marine litter and, more recently, the effects of armed conflicts [1]. These combined pressures have transformed the basin into a complex socio-ecological system requiring integrated solutions that combine environmental protection, technological innovation and regional cooperation.

In this context, the Black Sea SIERRA Project was created to strengthen the operational and institutional capacities of Black Sea countries in preventing, monitoring and responding to marine pollution [2]. The project promotes interdisciplinary cooperation among universities, scientific institutions, environmental authorities and maritime agencies from Romania, Bulgaria, Turkey, Ukraine and Italy. Through research, monitoring activities, digital innovation and educational initiatives, the project contributes to a shared regional framework for marine environmental resilience.

The present training curricula, developed under Task T5.5, represent the educational component of the project. They integrate the thematic priorities and scientific expertise of the partners while maintaining coherence with the overall objectives of the Black Sea SIERRA initiative. The document serves as both an academic and operational framework supporting professional training, institutional learning and cross-border knowledge transfer in marine environmental protection.

The curricula cover interconnected topics such as marine litter, heavy metal contamination, oil spills, underwater noise pollution, war-related contaminants, climate change, circular economy strategies, digital monitoring systems, environmental governance and innovative remediation technologies [3]. By combining these themes into a unified educational programme, the curricula aim to strengthen both technical skills and long-term strategic thinking for sustainable marine governance.

The programme is based on interdisciplinarity, practical applicability and regional integration. Because pollutants can rapidly spread across maritime borders due to the hydrodynamic characteristics of the Black Sea, isolated national responses are insufficient. Effective protection therefore requires coordinated monitoring systems, harmonised methodologies and shared operational procedures.

The curricula also address the growing importance of environmental security in geopolitical contexts. The Russo-Ukrainian conflict has introduced new risks linked to naval mines, underwater explosions, damaged petroleum infrastructure, military debris and underwater noise [4]. These developments highlight the need to include conflict-related environmental threats within marine pollution management strategies.

From an academic perspective, the programme supports the objectives of the European Green Deal, the Marine Strategy Framework Directive, the Water Framework Directive and the Sustainable Development Goals, especially SDG 14 on marine ecosystem protection and sustainable use of marine resources [5].

Overall, the document is designed not only as a technical training guide but also as a strategic educational tool supporting regional resilience, institutional cooperation and sustainable maritime governance across the Black Sea Basin.

1. Methodological Approach

The complementary training curricula were developed through an integrated and demand-driven methodology aligned with the operational realities of the Black Sea region. The approach adopted by the Black Sea SIERRA consortium is based on the idea that effective marine pollution management requires the integration of scientific knowledge, institutional coordination, operational preparedness and educational innovation.

The first methodological phase relied on the results of Task T5.1, which mapped stakeholders, governance structures and operational systems across participating countries. The analysis revealed major differences in institutional capacity, technical infrastructure and environmental monitoring systems. While some countries possess advanced technologies and specialised institutions, others still face fragmented responsibilities, limited access to environmental data and insufficient operational coordination.

Task T5.2 analysed existing training systems and educational practices related to marine environmental protection. The findings showed that, although strong expertise exists in the region, training activities remain mainly national and insufficiently harmonised at regional level. Cross-border educational cooperation is still limited, reducing the ability of stakeholders to respond effectively to transboundary pollution events. In addition, many programmes rely heavily on theory and include limited practical exercises, simulations and digital tools.

Task T5.3 further contributed by identifying pollution scenarios linked to industrial accidents, maritime incidents and conflict-related environmental threats. Special attention was given to new forms of pollution generated by military activities, including underwater explosions, naval mines, hydrocarbon spills, military debris and acoustic pollution caused by drones and sonar systems [6].

Based on these findings, the curricula adopt a scenario-based and competency-oriented educational model. The modules include case studies, risk scenarios, practical simulations and interdisciplinary exercises designed to reproduce realistic marine pollution situations in the Black Sea region.

The methodology also combines different educational formats to ensure accessibility and flexibility. Training activities include face-to-face sessions, on-line learning, blended approaches, digital presentations, educational videos and interactive tools such as Mentimeter, Google Forms and Educaplay. This hybrid model supports collaborative learning and allows participants from different countries and institutions to access the programme effectively.

Another important principle is the integration of partner expertise and national priorities. Each institution contributed thematic content reflecting its sci-

entific competencies and regional concerns. Romanian partners focused on war-related contaminants, environmental law and heavy metal pollution, while Bulgarian partners emphasised marine litter, biodiversity protection and ecosystem resilience [7]. Other partners contributed expertise in marine monitoring, sustainability, environmental engineering and operational response systems.

The methodology also includes continuous evaluation and adaptive improvement mechanisms. Participant feedback, assessments and practical exercises are used to evaluate the effectiveness of the programme and identify areas for further development. Digital evaluation tools support evidence-based improvements to both content and teaching methods.

Finally, the methodological approach reflects the broader goal of strengthening regional cooperation in the Black Sea Basin. The curricula are intended not only as educational materials but also as instruments for promoting long-term institutional collaboration, harmonised operational practices and a shared culture of environmental responsibility among Black Sea stakeholders [8].

2. Scientific and Environmental Context of the Black Sea

The Black Sea's semi-enclosed structure, limited water exchange through the Bosphorus Strait and extensive anoxic deep waters make it highly sensitive to pollution and human pressures [9]. Around ninety percent of the basin is characterised by anoxic conditions, which strongly influence biological productivity and the persistence of contaminants in marine sediments and waters.

The basin's hydrodynamic characteristics further increase its vulnerability. Counterclockwise surface circulation transports pollutants across large distances, turning local contamination events into transboundary environmental threats [10]. As a result, pollution generated in one coastal area can rapidly affect neighbouring countries, highlighting the need for coordinated regional monitoring and management systems.

The ecosystem is exposed to multiple pressures linked to industrial discharges, river pollution, maritime transport, fisheries exploitation, urbanisation and tourism. The Danube River introduces significant quantities of nutrients, heavy metals, pesticides and industrial contaminants into the sea, contributing to eutrophication, oxygen depletion and biodiversity loss [11].

Industrial facilities along the Romanian and Bulgarian coasts, including oil refineries, ports, shipyards and petrochemical plants, also represent major environmental risks due to potential oil spills and chemical discharges. Increased

maritime traffic further raises the probability of accidents with severe ecological consequences.

Climate change has added new forms of environmental instability through rising sea temperatures, salinity changes, coastal erosion and more frequent extreme weather events [12]. These processes interact with existing anthropogenic pressures, reducing ecosystem resilience and threatening marine biodiversity.

Since 2022, the Russo-Ukrainian conflict has introduced additional environmental and geopolitical risks, including drifting naval mines, damaged petroleum infrastructure, underwater explosions and military debris [13]. These threats may generate long-term ecological impacts on marine ecosystems.

Underwater acoustic pollution caused by sonar systems, naval exercises and autonomous underwater vehicles is another growing concern. Scientific research shows that chronic underwater noise can disrupt marine mammal communication, alter fish migration and affect ecosystem balance [14]. The increasing use of underwater drones and military technologies has therefore intensified interest in acoustic monitoring and mitigation strategies.

Marine litter and microplastics also represent major environmental challenges. Plastic waste from urban runoff, fisheries, tourism and rivers accumulates on beaches, seabeds and within marine organisms. Studies along the Romanian and Bulgarian coasts have identified increasing microplastic contamination in commercially important fish species and benthic organisms [15].

Within this complex context, the Black Sea SIERRA curricula aim to provide participants with a comprehensive understanding of ecological dynamics, pollution mechanisms and operational challenges in the region, supporting evidence-based environmental management and sustainable policymaking.

3. Justification for the four Training Courses

Over recent decades, pollution from agriculture, offshore activities, shipping and inadequate waste management has intensified in the Black Sea Basin. Rivers such as the Danube transport nutrients, plastics, pesticides, hydrocarbons and heavy metals into the sea, while coastal industrial infrastructure, ports and refineries contribute to chronic pollution pressures affecting biodiversity, fisheries and ecosystem health [16].

The Romanian coastline illustrates these vulnerabilities through the presence of refineries, shipyards, ports and military facilities that are economically important but also potential pollution sources. Similar pressures exist along the Bulgarian, Turkish and Ukrainian coasts. Together, these cumulative impacts

threaten the long-term sustainability of the Black Sea ecosystem and coastal communities [17].

The Russo-Ukrainian conflict has further intensified environmental risks by introducing new forms of pollution associated with warfare. Since 2022, military operations have caused infrastructure damage, oil spills, drifting naval mines, underwater explosions, military debris and contamination from explosives and heavy metals [18]. These events have increased the risk of long-term marine contamination and ecosystem disruption.

Military equipment and munitions contain hazardous substances such as lead, mercury, cadmium, arsenic, TNT and RDX, which can persist in sediments and enter aquatic food chains. Corrosion processes gradually release these compounds into marine ecosystems, creating chronic risks for marine life and potentially for human health through seafood consumption [19].

The growing use of underwater drones, sonar systems and advanced naval technologies has also intensified underwater acoustic pollution. Marine species are highly sensitive to acoustic disturbances, which may affect migration, reproduction and feeding behaviour. Despite the increasing relevance of this issue, monitoring methods and specialised training remain limited in many Black Sea countries [20].

These challenges have revealed important weaknesses in regional preparedness and response capacities. Although Black Sea countries possess valuable expertise, monitoring and training systems remain fragmented, with limited harmonisation of methodologies, operational protocols and cross-border co-operation [21]. This reduces the effectiveness of responses to transboundary pollution incidents.

The Black Sea SIERRA Project was created to address these limitations by strengthening regional cooperation, improving environmental monitoring and developing integrated training systems capable of responding to both conventional and conflict-related marine pollution risks [22].

The justification for the curriculum is therefore environmental, operational, institutional and strategic. Environmentally, the Black Sea faces unprecedented cumulative pressures requiring integrated management approaches. Operationally, pollution incidents are becoming more frequent and complex. Institutionally, there is a strong need to harmonise competencies and methodologies among Black Sea countries. Strategically, the programme supports broader European objectives related to blue economy development, environmental resilience and regional stability [23].

The curriculum also reflects the growing recognition that environmental protection and security are deeply interconnected. International initiatives such as the International Law Commission's Principles on the Protection of the Environment in Relation to Armed Conflicts (PERAC) highlight the importance of integrating environmental considerations into security governance frameworks [24].

In addition, the course directly supports European Union priorities related to marine protection, climate resilience and sustainable blue economy development. It aligns with key instruments such as the Marine Strategy Framework Directive, the Water Framework Directive and the European Green Deal, which aim to achieve Good Environmental Status in European marine waters [25].

For these reasons, the Black Sea SIERRA curriculum is not only an academic initiative but also a strategic capacity-building tool designed to strengthen regional resilience, interdisciplinary cooperation and the long-term sustainability of the Black Sea ecosystem.

4. Challenges in the Black Sea Basin

The Black Sea is one of the most environmentally vulnerable semi-enclosed marine basins in the world. Its limited water exchange with the Mediterranean through the Bosphorus Strait, strong anoxic deep waters, low salinity gradients and counterclockwise circulation make it highly sensitive to pollution and transboundary contamination [26]. These conditions reduce its natural self-purification capacity and promote long-term retention and redistribution of pollutants across coastal ecosystems.

The basin is affected by multiple pollution sources, including industrial discharges, maritime transport, agricultural runoff, oil spills, military activities, and riverine inputs from major rivers such as the Danube [27]. Once introduced, pollutants tend to persist for long periods, increasing ecological risks and affecting ecosystem stability.

A major concern is heavy metal contamination in sediments and marine organisms. Elements such as lead, cadmium, mercury, arsenic, copper, chromium and nickel have been detected in several coastal areas, particularly near industrial zones and regions influenced by military activity [28]. These substances can bioaccumulate and move through food chains, potentially impacting marine life and human health via seafood consumption.

Marine litter and microplastics represent another growing pressure. Urbanisation, tourism, fisheries, maritime transport and inadequate waste manage-

ment contribute to plastic accumulation in seawater, sediments and organisms. Studies from Romanian and Bulgarian coasts show increasing microplastic concentrations in sediments and commercial fish species [29], with impacts including ingestion by fauna, habitat degradation and chemical contamination.

Climate change further intensifies ecosystem vulnerability by altering temperature, salinity, coastal dynamics and extreme weather patterns. These changes influence pollutant behaviour, increase eutrophication risks and reduce ecosystem resilience.

The Black Sea SIERRA Project adopts an integrated ecosystem-based approach, combining environmental science, engineering, digital monitoring, legal frameworks and operational preparedness to improve regional responses to marine pollution.

5. Conflict-Related Marine Pollution in the Black Sea

The ongoing conflict in Ukraine has introduced unprecedented environmental risks to the Black Sea marine ecosystem, transforming military activities into a significant source of marine pollution. Since 2022, the intensification of naval operations, destruction of coastal infrastructure, deployment of naval mines, and attacks on energy facilities have generated multiple contamination pathways with potentially long-term ecological consequences [30].

One of the most visible threats concerns drifting naval mines and unexploded ordnance dispersed throughout the basin. These devices not only represent direct risks for maritime navigation and coastal communities but also contribute to the release of toxic compounds into marine sediments and seawater through corrosion and gradual degradation [31]. Explosive materials such as TNT (2,4,6-trinitrotoluene) and RDX (1,3,5-trinitro-1,3,5-triazine) may persist in the marine environment for extended periods, affecting benthic organisms and marine biodiversity.

Military-related pollution also includes hydrocarbon spills resulting from attacks on fuel depots, pipelines, oil terminals, and vessels. Such incidents release petroleum hydrocarbons and polycyclic aromatic hydrocarbons (PAHs) into marine waters, negatively affecting fish populations, plankton communities, seabirds, and coastal habitats [32]. The ecological consequences of these spills may extend far beyond national borders due to the transboundary circulation patterns of the Black Sea.

Another emerging concern relates to underwater acoustic pollution generated by naval warfare technologies. Sonar systems, underwater explosions, autonomous underwater vehicles (AUVs), unmanned underwater vehicles (UUVs), and military drones produce acoustic disturbances capable of affecting marine mammals, fish behavior, and ecosystem stability [33]. Scientific evidence suggests that chronic underwater noise exposure can interfere with cetacean communication, migration routes, feeding behavior, and reproductive patterns [34].

The destruction of coastal infrastructure has additionally increased the release of hazardous substances from industrial facilities and urban wastewater systems. Damaged ports, refineries, storage facilities, and industrial complexes can become secondary pollution sources during armed conflicts, contributing to the diffusion of heavy metals, chemical contaminants, and microplastics into the marine environment [35].

Within this context, the Black Sea SIERRA training curricula seek to strengthen the capacity of regional stakeholders to identify, assess, monitor, and mitigate conflict-related marine pollution scenarios. Particular emphasis is placed on interdisciplinary cooperation, operational preparedness, environmental monitoring, and the application of international legal frameworks governing environmental protection during armed conflicts.

6. Training Needs and Gap Analysis

The Black Sea region benefits from numerous environmental monitoring initiatives, research programmes and educational activities focused on marine protection. However, despite these efforts, important weaknesses still limit the effectiveness of regional marine pollution prevention and response capacities [36]. The analyses conducted under Tasks T5.1 and T5.2 of the Black Sea SIERRA Project showed that the main challenge is not the lack of information, but rather the fragmentation, unequal distribution and insufficient integration of existing knowledge systems.

Significant disparities exist among Black Sea countries in terms of technical infrastructure, institutional coordination, monitoring capacities, digitalisation and access to specialised training. Some institutions possess advanced laboratories, satellite monitoring systems and experienced scientific personnel, while others continue to face limitations related to equipment, financial resources, interoperability and technical expertise [37].

These asymmetries reduce regional coherence and complicate trans-boundary coordination during marine pollution incidents.

One of the main structural weaknesses identified is the predominance of nationally fragmented training systems. Existing programmes are often developed independently according to national priorities and rarely include harmonised methodologies or transboundary operational perspectives [38]. This becomes particularly problematic during cross-border pollution events, oil spills or environmental emergencies linked to maritime accidents and military conflicts.

Another important gap concerns the insufficient integration of digital technologies into training systems. Modern marine pollution management increasingly depends on satellite imagery, GIS platforms, remote sensing, acoustic sensors, predictive models and environmental databases [39]. Nevertheless, the practical use of these technologies remains uneven and is not systematically incorporated into existing curricula. As a result, many professionals still face difficulties in transforming environmental data into effective operational decisions.

The needs analysis also revealed that many training programmes do not adequately address emerging risks related to geopolitical instability and military activities in the Black Sea. Traditional marine pollution education has mainly focused on industrial pollution, accidental spills and ecosystem conservation, while recent armed conflicts have introduced entirely new environmental threats requiring specialised expertise [40].

These threats include contamination from explosive ordnance, drifting naval mines, military hydrocarbons, heavy metals from ammunition, damaged infrastructure, underwater acoustic disturbances and military debris entering marine ecosystems. Existing educational systems are generally not prepared to address such hybrid environmental-security risks [41]. The SIERRA curriculum therefore integrates conflict-related marine pollution into broader environmental governance and emergency-response frameworks.

Another weakness is the limited integration of climate change into pollution prevention strategies. Climate change acts as a risk multiplier by affecting sea temperatures, salinity, coastal erosion, storms and hydrological circulation [42]. These changes influence pollutant behaviour and increase the vulnerability of marine ecosystems and coastal communities. Despite growing scientific evidence, climate adaptation strategies remain insufficiently included in many training systems.

The project also identified deficiencies in the application of circular economy principles within marine sectors. Pollution management often remains reactive rather than preventive, focusing more on remediation than on reducing waste generation, improving recycling systems and promoting sustainable

production models [43]. The curriculum therefore includes circular economy approaches aimed at reducing pollution at its source.

Innovation-related gaps were another important finding. Technologies such as artificial intelligence, environmental modelling systems, autonomous underwater vehicles and geopolymer-based remediation materials have strong potential for improving marine protection, but awareness and operational knowledge remain limited among many stakeholders [44]. The curriculum addresses this issue by introducing innovative technologies and sustainable remediation solutions.

Interdisciplinary fragmentation also emerged as a major challenge. Marine pollution governance requires cooperation between environmental sciences, engineering, maritime law, security studies, ecology, economics and public administration [45]. However, many educational programmes remain confined within narrow disciplinary boundaries, limiting integrated learning and multi-disciplinary problem-solving capacities.

The project further highlighted shortcomings in public awareness and societal engagement. Marine pollution is often perceived mainly as a technical issue rather than a broader challenge affecting public health, food security, biodiversity and regional stability. Educational outreach activities targeting local communities and civil society therefore remain insufficiently developed. The curriculum aims to strengthen environmental literacy and encourage wider societal participation in marine protection.

Another important issue concerns the lack of standardised monitoring methodologies for conflict-related contaminants. While European legislation provides general frameworks for marine monitoring, few operational standards exist for assessing pollutants associated with military activities, underwater explosions or wartime debris [46]. The SIERRA programme contributes to developing more coherent regional methodologies for monitoring such pollutants.

Since 2022, the conflict in the Black Sea has also altered maritime traffic patterns and increased naval activities, creating new environmental pressures. The growing use of marine drones, autonomous underwater vehicles and surveillance systems has introduced additional concerns related to underwater noise pollution and risks to critical infrastructure [47].

Research on underwater acoustic pollution remains relatively underdeveloped despite increasing scientific evidence of its ecological impact. Marine mammals, fish and benthic species are highly sensitive to anthropogenic noise generated by shipping, sonar systems, drilling activities and underwater explosions [48]. Continuous monitoring of underwater noise is therefore be-

coming an essential component of marine ecosystem management and maritime security.

The SIERRA curriculum addresses these multiple gaps through a comprehensive, interdisciplinary and operational training framework. By integrating scientific knowledge, digital competencies, legal awareness, sustainability principles, technological innovation and crisis-management approaches, the programme seeks to strengthen regional preparedness and resilience in the Black Sea Basin [49].

7. General Objective

The general objective of the Black Sea SIERRA training curricula is to strengthen the institutional, scientific, operational, and societal capacity of Black Sea countries to prevent, monitor, manage, and mitigate marine pollution through integrated, interdisciplinary, and transboundary approaches. The programme seeks to enhance preparedness for both conventional and emerging pollution scenarios, including those associated with industrial activities, maritime transport, climate change, marine litter accumulation, and armed conflict.

The training framework has been conceived as a strategic capacity-building instrument capable of supporting the long-term sustainability and resilience of the Black Sea Basin. By combining environmental sciences, digital technologies, maritime governance, legal studies, engineering solutions, and operational crisis management methodologies, the curriculum aims to equip participants with the competencies necessary to address increasingly complex marine environmental challenges.

A central ambition of the programme is the consolidation of a regional culture of cooperation among public authorities, scientific institutions, maritime agencies, universities, emergency response bodies, and civil society organisations operating in the Black Sea area. The curriculum therefore contributes not only to technical knowledge transfer but also to the creation of common operational languages, shared monitoring methodologies, and harmonised response capacities across national borders [50].

Particular emphasis is placed on strengthening the ability of stakeholders to interpret environmental risks within the broader context of sustainable blue economy governance. The concept of the blue economy has become increasingly important within European and international environmental policy frameworks, promoting the sustainable use of marine resources for economic growth, social inclusion, and ecosystem preservation. However, the Black Sea region continues to face serious challenges related to overexploitation of re-

sources, biodiversity loss, pollution, geopolitical instability, and insufficient institutional coordination. The SIERRA curriculum addresses these concerns by promoting sustainable management approaches capable of reconciling economic development with environmental protection objectives [51].

The training programme also aims to support the implementation of European and international legal obligations related to marine environmental protection. Participants are expected to develop a stronger understanding of key legal instruments governing marine pollution prevention, maritime safety, environmental liability, biodiversity conservation, and environmental protection during armed conflicts. These include the United Nations Convention on the Law of the Sea (UNCLOS), the MARPOL Convention, the Water Framework Directive, the Marine Strategy Framework Directive, the Geneva Conventions and their Additional Protocols, and the International Law Commission's Principles on the Protection of the Environment in Relation to Armed Conflicts [52].

Another core objective concerns the promotion of science-based policy-making and evidence-driven operational decision-making. The programme seeks to improve participants' ability to use environmental data, digital monitoring systems, geographic information systems (GIS), satellite observations, underwater acoustic measurements, and laboratory analyses within environmental management and emergency response frameworks. Such competencies are increasingly necessary given the growing complexity of marine environmental threats and the accelerated digitalisation of environmental governance systems.

The SIERRA curriculum also contributes to strengthening resilience against the environmental consequences of geopolitical instability and military conflicts in the Black Sea region. Recent events have demonstrated that armed conflicts can generate severe and long-lasting environmental impacts through infrastructure destruction, contamination from munitions, oil spills, marine debris, underwater explosions, and disruption of environmental governance systems. The training programme therefore seeks to integrate environmental protection considerations into broader security and crisis-management frameworks, fostering preparedness for hybrid environmental-security risks.

An equally important dimension of the programme is the promotion of interdisciplinary education and innovation. Existing marine pollution training systems are often fragmented across disciplinary sectors, limiting the ability of professionals to understand the interconnected nature of environmental, technological, legal, and socio-economic processes. The SIERRA curriculum responds to this challenge by encouraging systems thinking, collaborative learning, and integrated problem-solving approaches capable of addressing multidimensional marine pollution scenarios.

Furthermore, the programme supports the dissemination of innovative environmental technologies and sustainable remediation solutions. Particular attention is devoted to advanced materials, circular economy approaches, bio innovation, artificial intelligence applications, and eco-technological solutions designed to prevent or mitigate marine pollution impacts. This emphasis on innovation reflects the increasing importance of sustainable technological development within European environmental policies and blue economy strategies.

Ultimately, the general objective of the curriculum is to contribute to the development of a more resilient, cooperative, and environmentally sustainable Black Sea region capable of responding effectively to both present and future marine pollution challenges.

8. Specific Objectives

The specific objectives of the Black Sea SIERRA training curricula derive directly from the environmental vulnerabilities, institutional needs, and operational gaps identified throughout the project's analytical activities. These objectives are intended to transform the broad strategic vision of the programme into concrete educational outcomes capable of producing measurable improvements in knowledge, competencies, coordination mechanisms, and operational preparedness across the Black Sea Basin.

One of the principal objectives is the development of "Blue Skills" in accordance with the European Union's BlueComp Competence Framework [53]. Blue skills refer to the set of competencies necessary to support sustainable ocean governance and resilient blue economy transitions. Within the SIERRA framework, these skills include systems thinking, environmental awareness, sustainability assessment, strategic foresight, interdisciplinary communication, and collaborative problem-solving. Participants are expected to acquire a deeper understanding of marine ecosystems as interconnected socio-ecological systems whose environmental, economic, and social dimensions cannot be addressed separately [54].

The programme also seeks to improve participants' knowledge regarding the main sources of marine pollution affecting the Black Sea ecosystem. Particular attention is devoted to heavy metals, hydrocarbons, marine litter, microplastics, oil spills, industrial discharges, military-related contaminants, and underwater acoustic pollution. By understanding the pathways through which pollutants circulate within marine ecosystems and food chains, participants will be better equipped to evaluate ecological risks, identify vulnerable areas, and

contribute to preventive environmental management strategies (**INCDPM & Ukr-SCES**).

Another major objective concerns the strengthening of digital and data-related competencies. Modern environmental governance increasingly relies on digital technologies capable of collecting, processing, visualising, and interpreting large volumes of environmental information. Nevertheless, significant gaps persist regarding the operational use of such technologies among regional stakeholders. The SIERRA curriculum therefore aims to improve participants' capacity to work with environmental databases, satellite monitoring systems, GIS applications, CTD sensors, acoustic monitoring equipment, remote sensing platforms, and digital reporting tools [55].

The development of these digital competencies is closely linked to the objective of improving evidence-based decision-making capacities. Environmental emergencies often require rapid interpretation of complex datasets under conditions of uncertainty. Participants are therefore encouraged to develop analytical thinking skills capable of integrating multiple sources of environmental information into coherent operational responses.

An additional specific objective focuses on strengthening sustainability and resilience capacities in the context of climate change and environmental instability. Climate change represents a significant multiplier of marine pollution risks in the Black Sea region by affecting sea temperatures, hydrological patterns, biodiversity distribution, coastal erosion, and ecosystem resilience. The curriculum consequently promotes adaptive management approaches capable of integrating climate considerations into marine pollution prevention and response strategies (**IO-BAS**).

The programme also seeks to enhance institutional and operational capacities for addressing pollution generated by armed conflicts and military activities. This objective reflects the growing recognition that environmental degradation associated with warfare constitutes not only an ecological problem but also a humanitarian, economic, and security challenge. Participants are expected to familiarise themselves with the environmental impacts of naval mines, explosives, hydrocarbons, military debris, underwater detonations, and acoustic disturbances associated with modern warfare technologies [56].

Closely related to this objective is the need to strengthen legal literacy concerning environmental protection during armed conflicts. The SIERRA curriculum introduces participants to relevant international legal frameworks, including UNCLOS, MARPOL, the Geneva Conventions, the Hague Convention, and the International Law Commission's PERAC principles. Participants are encouraged to understand how these legal instruments interact with environmental

governance systems and operational response mechanisms. The curriculum also aims to improve capacities related to environmental monitoring and ecological assessment methodologies. Particular emphasis is placed on the use of bioindicator species relevant to the Black Sea ecosystem, including *Mytilus galloprovincialis*, *Rapana venosa*, and *Pontogammarus maeoticus*. These organisms provide valuable information concerning contamination levels, ecosystem health, and long-term environmental changes [57]. Through practical exercises and scientific modules, participants are introduced to monitoring protocols, sampling techniques, laboratory analyses, and environmental assessment methodologies based on European and international standards **(TUIASI & MBNAR)**.

Another important objective concerns the promotion of circular economy principles and sustainable resource management approaches within maritime and coastal sectors. Marine pollution prevention cannot rely exclusively on post-incident remediation measures; it also requires systemic changes in production, consumption, waste management, and resource use patterns. The curriculum therefore encourages participants to explore strategies aimed at reducing pollution generation at source through recycling, waste valorisation, sustainable fisheries, eco-design practices, and innovative bioeconomy solutions.

Innovation and technological development constitute additional pillars of the programme's objectives. The curriculum promotes awareness regarding advanced remediation technologies, including intelligent geopolymer-based materials designed for pollution mitigation and ecosystem restoration. Such technologies represent promising tools for future environmental protection efforts, particularly in heavily contaminated marine environments.

Interdisciplinary cooperation and stakeholder coordination also represent central educational objectives. Marine pollution incidents typically involve multiple institutions operating across different administrative sectors and governance levels. Effective responses therefore depend on communication, coordination, and information-sharing capacities among authorities, scientific experts, emergency responders, and civil society actors. The SIERRA curriculum seeks to strengthen these collaborative capacities through group exercises, scenario simulations, and participatory learning methodologies **(ORDU)**.

All the programmes further aim to support the dissemination of environmental awareness among broader societal groups, including students, researchers, NGOs, local communities, and civil society organisations. Public awareness and environmental literacy are considered essential components of long-term marine ecosystem protection and sustainable development.

Finally, the SIERRA training curricula seek to contribute to the emergence of a shared regional environmental culture within the Black Sea Basin. By fostering cooperation among stakeholders from Romania, Bulgaria, Turkey, Ukraine, and Italy, the programme supports the gradual development of common perspectives, shared methodologies, and coordinated approaches to marine environmental governance. In this sense, the curriculum contributes not only to professional education but also to broader processes of regional integration, resilience-building, and environmental diplomacy.

9. Target Groups (TGs)

The Black Sea SIERRA training curricula are designed to address the needs of a highly diverse range of target groups reflecting the complexity of marine environmental governance in the Black Sea Basin. Marine pollution prevention and response require cooperation among numerous institutional actors operating across different governance levels, scientific disciplines, operational sectors, and geographical scales. Consequently, the programme adopts a broad and inclusive approach to participant selection, recognising that effective environmental protection can only be achieved through coordinated multi-stakeholder engagement.

The primary target groups include national and regional authorities responsible for environmental governance, maritime regulation, emergency response, and coastal management. These institutions play a central role in implementing environmental legislation, coordinating pollution response operations, monitoring ecosystem conditions, and ensuring compliance with European and international environmental standards.

The diversity of target groups reflects the interdisciplinary philosophy underlying the curriculum. Marine pollution constitutes not merely a scientific or technical problem but a multidimensional governance challenge involving environmental, economic, legal, social, technological, and geopolitical dimensions. Effective responses therefore require the active participation of stakeholders possessing different forms of expertise and operational experience.

9.1 Romania

In Romania, relevant institutions include the Ministry of Environment, Waters and Forests, the National Environmental Protection Agency, the National Environmental Guard, the National Administration “Romanian Waters,” and the Danube Delta Biosphere Reserve Administration. These authorities are directly in-

volved in environmental monitoring, pollution prevention, water management, biodiversity conservation, and implementation of environmental policies [58].

Operational actors responsible for maritime safety and emergency intervention also constitute essential target groups. Institutions such as the Romanian Naval Authority, the Romanian Naval Forces, the Coast Guard, port authorities, and the General Inspectorate for Emergency Situations possess direct responsibilities concerning maritime security, accident prevention, pollution containment, and crisis management operations in coastal and marine environments.

9.2 Bulgaria

Similar institutional structures are represented within the Bulgarian component of the programme. Bulgarian participants include representatives from the Ministry of Environment and Water, the Ministry of Transport and Communications, the Ministry of Agriculture and Food, the Executive Agency Maritime Administration, the Black Sea Basin Directorate–Varna, the General Directorate “Fire Safety and Civil Protection,” the Bulgarian Border Police/Coast Guard, and the Bulgarian Navy. These institutions contribute expertise related to maritime governance, environmental monitoring, emergency preparedness, and national security operations in marine areas.

Policymakers and public administrators represent another important category of participants. Effective marine environmental governance requires decision-makers capable of integrating scientific evidence, legal obligations, socio-economic considerations, and operational constraints into coherent policy frameworks. Participating institutions include the Bulgarian Academy of Sciences, the Institute of Oceanology, the Institute of Biodiversity and Ecosystem Research, technical universities, naval academies, and environmental research centres across the participating countries [59]. The curriculum therefore aims to support evidence-based policymaking processes and strengthen the capacity of public administrations to address complex environmental challenges.

9.3 Turkey

Stakeholders operating within blue economy sectors are also specifically targeted. These include representatives from fisheries, maritime transport, tourism, port management, offshore industries, coastal infrastructure operators, and waste management sectors. Since economic activities constitute both

drivers of marine pollution and essential components of regional development, their involvement in environmental protection initiatives is considered fundamental.

Research institutions, universities, and scientific organisations represent another central target group. The programme actively involves researchers, scientists, academic staff, doctoral candidates, and students from institutions specialising in marine sciences, environmental engineering, maritime law, ecology, oceanography, environmental chemistry, and sustainability studies.

9.4 Ukraine

The inclusion of students and early-career researchers reflects the programme's long-term educational vision. Building future expertise in marine environmental governance requires investment in the next generation of scientists, engineers, policymakers, and operational professionals capable of addressing future environmental challenges.

Civil society organisations, NGOs, technical experts, and environmental activists are likewise considered important target groups. Non-governmental actors often play significant roles in public awareness campaigns, environmental advocacy, citizen-science initiatives, community mobilisation, and independent environmental monitoring activities. Their participation contributes to strengthening societal engagement and promoting broader environmental responsibility within coastal communities.

The programme also recognises the growing importance of interdisciplinary collaboration between civilian and military sectors in addressing marine environmental risks associated with armed conflict. Consequently, representatives of naval forces, coast guards, defence institutions, and maritime security agencies are included among the target groups, particularly in modules related to underwater noise pollution, military contaminants, maritime risk assessment, and environmental security governance.

Particular attention is devoted to fostering cross-border interaction among participants from different Black Sea countries. One of the major weaknesses identified during the project's needs analysis concerned the fragmentation of national training systems and the limited integration of transboundary cooperation mechanisms. By bringing together participants from multiple institutional and national backgrounds, the SIERRA curriculum contributes to the development of shared knowledge networks and regional cooperation cultures capable of supporting future joint environmental initiatives.

10. Format

The Black Sea SIERRA training curricula are based on a flexible and multimodal educational structure designed to maximise accessibility, adaptability and operational effectiveness across different institutional and geographical contexts [60]. Considering the diversity of stakeholders involved in marine pollution governance and the different capacities of participating institutions, the programme adopts a blended-learning approach that combines traditional teaching methods with digital technologies and interactive training tools.

Training activities may therefore include face-to-face sessions, online learning modules, PowerPoint presentations, webinars, educational videos, practical exercises, field demonstrations, simulations and interactive digital platforms such as Mentimeter, Educaplay and Google Forms [61]. This flexible structure allows participants from different Black Sea countries to engage with the programme despite geographical or institutional constraints, while also encouraging transboundary cooperation and collaborative learning.

The use of blended-learning methods reflects broader changes within higher education and professional training systems. Digitalisation has expanded opportunities for remote participation, interdisciplinary collaboration and rapid dissemination of scientific and operational knowledge [62]. In the field of marine pollution governance, where stakeholders are spread across different coastal regions and sectors, digital learning environments are essential for maintaining continuous cooperation and capacity-building activities.

At the same time, face-to-face training remains a key component of the curriculum, especially for practical exercises, laboratory demonstrations, stakeholder discussions and operational simulations. In-person activities encourage direct interaction, interdisciplinary dialogue and the creation of professional networks that can strengthen long-term regional cooperation. Workshops may include environmental sampling, monitoring exercises, GIS mapping, acoustic measurements, data interpretation and crisis-management simulations related to marine pollution events [63].

Online modules complement these activities by offering flexible access to theoretical materials, scientific literature, recorded lectures, legal documents and digital resources. This structure allows participants to follow the programme according to their professional schedules while ensuring that educational content can be continuously updated in response to scientific developments and regional changes.

Interactive educational tools are another important feature of the SIERRA methodology. Traditional lecture-based teaching is often insufficient for ad-

addressing the complex and multidisciplinary nature of marine environmental governance [64]. The curriculum therefore promotes participatory learning approaches that encourage active engagement, collaborative problem-solving and critical thinking. Platforms such as Mentimeter and Educaplay support interactive quizzes, live discussions, scenario analysis and feedback collection, improving participant involvement and learning outcomes.

Scenario-based simulations represent a particularly important component of the training. Marine pollution incidents often occur under conditions of uncertainty, time pressure and institutional complexity. Effective responses therefore require not only theoretical knowledge but also practical decision-making, communication and coordination skills. Participants are exposed to simulated scenarios involving oil spills, hazardous materials, marine litter, underwater explosions, drifting naval mines and conflict-related environmental emergencies [65]. These exercises help trainees apply scientific, legal and operational knowledge in realistic crisis-management situations.

The multilingual dimension of the programme is also essential. Although English is the main language of instruction, training materials are translated into Romanian, Bulgarian, Ukrainian and Turkish to ensure accessibility for local stakeholders and facilitate broader participation across the region [66]. Multilingual education is particularly important in transboundary environmental governance, where effective communication among institutions can significantly improve coordinated responses.

The direct involvement of project partners as training providers further strengthens the practical relevance of the curriculum. Universities, research institutes, naval academies, environmental authorities and operational agencies contribute not only scientific expertise but also practical experience from monitoring activities, research projects and emergency-response operations [67]. This ensures that the programme remains closely connected to real regional challenges.

Evaluation mechanisms are integrated throughout the training process. Learning outcomes are assessed through questionnaires, tests, practical exercises, group discussions and digital feedback systems [68]. Tools such as Google Forms are used to measure knowledge acquisition, evaluate participant satisfaction and identify areas for improvement. This adaptive evaluation approach allows the curriculum to evolve continuously in response to participant needs and emerging environmental risks.

Finally, the SIERRA training structure supports long-term sustainability and scalability. By combining digital resources, multilingual materials and transferable methodologies, the curriculum can be continuously updated and poten-

tially replicated in other regional or European marine governance contexts. In this way, the programme contributes not only to immediate capacity-building objectives but also to the development of durable educational infrastructures supporting future environmental cooperation initiatives.

11. Monitoring Methodologies and Digital Environmental Assessment

Effective marine pollution management requires advanced monitoring systems capable of delivering reliable and interoperable data. The SIERRA Project promotes integrated methodologies combining traditional environmental sampling with digital technologies and data-driven tools.

Monitoring activities follow internationally recognized standards such as ISO 5667 for water sampling and environmental assessment, ensuring consistency across countries. Sampling campaigns target seawater, sediments and biological material in high-risk areas such as industrial zones, ports, military regions and river inflows like the Danube Delta.

Bioindicator species, including *Mytilus galloprovincialis*, *Rapana venosa* and *Pontogammarus maeoticus*, are used to assess contamination levels and bio-accumulation trends due to their sensitivity to pollutants.

Digital technologies play a central role in the monitoring framework. Satellite systems, remote sensing, GIS, CTD sensors, acoustic devices and environmental databases enable continuous observation and faster response to pollution events.

Artificial intelligence and predictive models further enhance environmental management by supporting spill forecasting, pattern detection and large-scale data analysis. Their integration strengthens decision-making and operational efficiency.

The project also promotes interoperable regional monitoring systems, shared databases and harmonised protocols to improve cross-border cooperation and response capacity across the Black Sea.

Conclusions

The Black Sea SIERRA Project represents a significant regional initiative aimed at strengthening the prevention, monitoring, and response capacity related to marine pollution in one of Europe's most environmentally and geopolitically sensitive marine basins. The training curricula developed within Task T5.5 provide an integrated educational framework capable of addressing both conventional and emerging pollution challenges affecting the Black Sea ecosystem.

The complexity of the Black Sea environment requires coordinated interdisciplinary responses involving scientific institutions, public authorities, operational agencies, civil society, and Blue Economy stakeholders. Industrial pressures, marine litter accumulation, heavy metal contamination, oil spills, climate change, and conflict-related pollution interact within a fragile semi-enclosed ecosystem characterized by limited resilience and strong transboundary interdependencies.

Particular importance is attributed to the growing environmental consequences of armed conflicts in the region. Military activities, underwater explosions, drifting mines, damaged infrastructure, hydrocarbon releases, and underwater acoustic disturbances have introduced new categories of environmental risks requiring specialized monitoring methodologies, legal frameworks, and operational preparedness capacities.

The project therefore promotes a comprehensive and forward-looking approach combining environmental science, digital innovation, marine governance, sustainability principles, and regional cooperation. Through the integration of digital monitoring systems, artificial intelligence applications, scenario-based learning, and cross-border coordination mechanisms, the training curricula contribute to strengthening institutional resilience and operational readiness across the Black Sea Basin.

At the same time, the project aligns with broader European environmental priorities, including the European Green Deal, the Zero Pollution Action Plan, the Marine Strategy Framework Directive, and Sustainable Development Goal 14 concerning the conservation and sustainable use of oceans and marine resources [69]. The emphasis placed on circular economy approaches, sustainability, environmental resilience, and technological innovation reflects the need for long-term adaptive governance strategies capable of addressing rapidly evolving environmental threats.

Ultimately, the Black Sea SIERRA training curricula aim not only to improve technical competencies but also to support the creation of a shared regional culture of environmental responsibility, scientific cooperation, and sustainable marine governance. The knowledge generated through this initiative may contribute to future European cooperation efforts and provide a valuable model for integrated marine pollution management in other vulnerable sea basins.

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