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Recalibrating Coastal and Marine Environmental Governance Through Integrated Data Infrastructures: The EMMERA Platform

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Abstract

Maritime transportation, a traditionally polluting sector, is engaged in sustainable innovation; advanced detection of marine pollution incidents can help control improvements in this sector. However, coastal and marine environmental governance is increasingly constrained by fragmented monitoring architectures in which environmental, operational, and regulatory datasets remain distributed across institutions and jurisdictions. Comprehensive governance mechanisms that cross the sea–land continuum are limited. Public authorities, port administrations, research institutes, and private operators independently monitor marine pollution, vessel movements, coastal pressures, and urban and ecological risks; however, these data streams remain siloed across organizational, sectoral, and jurisdictional boundaries. The absence of interoperability, real-time exchange, and coordinated analytics generates a gap between monitoring capacity and regulatory effectiveness, resulting in delayed detection of multi-risks, such as pollution incidents. Weak governance and assignment of responsibility and largely reactive enforcement practices further reinforce the problem. Anticipatory interventions are needed to improve coastal and marine sustainability. This paper examines the EMMERA (East Med Cross-border Marine Environmental Risk Assessment through E-Platform Integrated Data Management) platform established by three port authorities as a data-centric intervention designed to address some of these structural limitations. Implemented in port and coastal environments in Cyprus, Greece, and Israel, EMMERA integrates heterogeneous static and dynamic data sources—including satellite observations, administrative records, vessel information, and drone-based monitoring—into a unified operational framework accessible to competent authorities. Through data fusion, cross-validation, and automated anomaly detection combined with targeted drone verification, the platform aims to transform fragmented monitoring streams into coherent, actionable environmental intelligence, strengthening the evidentiary basis for regulatory intervention. The paper presents the platform design and provides a baseline assessment. It argues that EMMERA's primary contribution lies not in the introduction of additional monitoring tools, but in enabling more effective coastal and marine environmental governance through integrated data infrastructures. EMMERA is proposed as a governance-oriented integrated data infrastructure whose anticipated contribution lies in improving institutional interoperability, risk visibility, and evidence generation for environmental oversight, even as operational effectiveness will require future evaluation

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following sustained deployment. More broadly, the paper proposes that integrated data architectures can recalibrate environmental governance, shifting emphasis from post hoc documentation toward anticipatory, coordinated, and performance-oriented regulatory practices.

Keywords: environmental-management; prevention; detection

1. Introduction

The Eastern Mediterranean is a key hub of maritime transportation; it is also a tourism hub that thrives through the availability of pristine beaches and touristic waterfronts. Sustainable maritime transportation is a key requirement for this area. However, the governance of coastal and marine environments in the Eastern Mediterranean is constrained by a structural deficiency: although environmental and spatial data are widely collected, they remain institutionally fragmented. Public authorities, port administrations, and research institutes independently monitor vessel movements, bathing water quality, and land-based pollution, yet these datasets remain siloed across organizational and jurisdictional boundaries and focus on maritime spaces. The absence of interoperability and real-time exchange creates a gap between monitoring capacity and regulatory effectiveness. As a result, enforcement is largely reactive, with delayed incident detection and limited capacity to attribute responsibility to specific maritime actors. The lack of comprehensive data collection is further compounded by the absence of relevant governance mechanisms that across land and sea and link relevant institutions across the Eastern Mediterranean.

This paper presents the formal technical design and provides a comprehensive baseline assessment of the EMMERA platform. Developed under the European Commission's Union Civil Protection Mechanism [1] and completed on 30 May 2026, the system represents a mission-ready data-centric architecture delivered to the Cyprus Shipping Deputy Ministry. It has not yet entered full operational live service following deployment. Consequently, this study establishes the pre-operational baseline metrics derived from multi-year historical port logs (2019–2023) across the port of Limassol, framing the platform as an anticipatory governance framework rather than an evaluation of live operational effectiveness.

Several European policy instruments acknowledge that marine environmental governance depends upon interoperable monitoring systems. The Marine Strategy Framework Directive [2], the INSPIRE Directive [3], and EMSA-operated services including CleanSeaNet and SafeSeaNet collectively illustrate efforts toward harmonized environmental intelligence. Nevertheless, fragmented governance and monitoring also produces a systemic governance blind spot by preventing integrated coastal risk profiling. This constraint is increasingly significant as coastal zones undergo rapid multi-sector development, including ports, energy, tourism, logistics, and urban uses.

Regulatory assessments are typically sector-specific and often conclude that individual impacts remain within acceptable limits. However, spatial and temporal accumulation of pressures may generate substantially higher environmental degradation than sectoral evaluations indicate. When pollution indicators, vessel activity, ecological stress signals, and operational risk variables are assessed separately, cumulative and interaction effects tend to be underestimated. Such compartmentalized visibility weakens sustainability management, which requires system-level assessment. Consequently, sectoral compliance may coexist with rising aggregate environmental pressure, creating a

multi-risk scenario. The absence of integrated risk visibility thus constitutes a structural barrier to long-term coastal sustainability.

EMMERA provides a unified operational framework for competent authorities. Unlike stand-alone monitoring tools, it applies data fusion and automated anomaly detection to convert fragmented streams into actionable environmental intelligence. The platform applies a dynamic multi-risk assessment framework in which risk is defined as the product of Likelihood and Consequence. A linear factor aggregation model enables continuous hazard recalculation as new data are ingested through drone operations and authority-connected or third-party API feeds. This supports prioritized monitoring of high-risk hotspots and more efficient allocation of enforcement resources. The system also enables continuous KPI computation to track pollution trends, operational efficiency, and environmental performance. This advances both coastal environmental risk assessment methodology and applied governance capacity for anticipatory, sustainability-oriented maritime oversight.

The primary contribution of EMMERA is therefore not solely technical but governance-oriented. By reducing informational asymmetries and strengthening situational awareness, the platform supports a transition from post hoc documentation toward anticipatory, coordinated, and performance-based regulatory practice. Accordingly, this paper aims: (i) to explore the transition of fragmented marine and coastal environmental monitoring into an integrated data-governance framework; (ii) to introduce the design logic of the EMMERA platform as a cross-border decision-support system for marine pollution detection and risk assessment; (iii) to demonstrate how dynamic risk assessment and KPI-based reporting can support anticipatory and performance-oriented environmental governance; and (iv) to identify the governance implications of integrated data architectures for port authorities and competent public bodies in the Eastern Mediterranean.

Literature Review

The literature on maritime environmental governance consistently identifies institutional fragmentation and data silo effects as persistent structural constraints [4–6]. Public authorities and private operators independently monitor diverse data streams—from vessel movements to ecological risks—yet these datasets often remain separated across sectoral and jurisdictional boundaries. This fragmentation creates a significant gap between technical monitoring capacity and regulatory effectiveness. In the Eastern Mediterranean context, limited interoperability contributes to informational asymmetries, delayed pollution detection, and predominantly reactive enforcement practices. Prior research indicates that more effective governance requires integrated data architectures capable of enhancing situational awareness and coordinated oversight [4,5].

Recent literature on port and coastal governance as well as on sustainability has suggested that environmental monitoring systems should be seen as integrated decision-support infrastructures embedded in larger governance frameworks rather than as discrete technical tools. This perspective is particularly important in port and coastal areas, where the interaction between maritime transport, logistics [7], port activity, tourism, urban growth and ecological sensitivity create environmental pressures. New research on coastal marine governance highlights the importance of institutional coordination, adaptive governance and integrated approaches to coastal zone management that can respond to complex socio-ecological pressures across land–sea interfaces [8]. Likewise, research on ocean governance emphasizes that sustainability-focused marine management needs legal, institutional and operational structures that can support coordinated decision-making at national and regional scales [9]. In this context,

fragmented monitoring systems constrain authorities' ability to identify cumulative risks, attribute responsibility, and apply timely environmental interventions.

The smart and green port literature further shows that digital transformation has become a core element of port sustainability. The concept of smart green ports is increasingly seen as an integrated system that combines environmental sustainability principles with the latest digital technologies, such as the Internet of Things, artificial intelligence, big data, blockchain, real-time monitoring, predictive maintenance and data-driven logistics management [10,11]. These technologies facilitate more efficient and environmentally responsible port operations through enhanced situational awareness, reduced operational uncertainty, and more proactive environmental management. Similarly, Othman et al. (2022) [12] argue that integrated assessment frameworks linking smart port practices and sustainability performance are needed for sustainable smart ports. Their Sustainable Smart Sea Port Index underlines the importance of assessing port sustainability through multiple domains rather than through purely operational indicators. This is especially relevant for platforms like EMMERA, where environmental monitoring, vessel data, incident reporting, drone verification and KPI based assessment are brought together into a unified decision support architecture oriented towards governance.

Ioras and Bandara (2025) [13] examine the role of artificial intelligence in promoting sustainable practices in coastal marina management, using Monaco and Ibiza as comparative case studies. Their work demonstrates that AI can assist in informing environment-related decisions by analyzing complex data, predicting outcomes, improving day-to-day operational management and reducing ecological impacts in high-pressure coastal tourism and boating environments. This paper is also particularly relevant to EMMERA, as it reinforces the argument that AI-enabled and data-driven systems can improve coastal environmental governance when they are integrated into broader sustainability-oriented management frameworks.

Recent studies also demonstrate the potential of remote sensing, UAVs, artificial intelligence, and indicator-based monitoring to enhance environmental surveillance and support evidence-based marine and coastal management. Drone remote sensing has been used for high-frequency monitoring of marine litter and coastal pollution, with benefits in spatial coverage, responsiveness and observational accuracy in comparison with conventional field surveys [14]. Simultaneously, AI-aided research for ocean sustainability shows potential for enhancing the identification of pollutants and other environmental anomalies in extensive water bodies through satellite- and drone-based remote sensing, supported by machine-learning algorithms [14]. From a governance perspective, such technologies are most valuable when they are embedded in integrated reporting and decision-making systems, rather than being used as stand-alone monitoring instruments. Therefore, integrated data architectures could improve coastal and marine environmental governance through mitigation of information asymmetries, enhancement of real-time situational awareness, support to dynamic risk assessment [15] and more coordinated and performance-oriented regulatory oversight.

Qu, Hou and Xu (2026) [16] analyse the operational efficiency of smart seaports from a sustainable development perspective, using DEA and fsQCA to examine eight representative smart seaports in China between 2019 and 2024. Their findings indicate that smart seaport efficiency is not determined by one single factor, but by the combined interaction of technological, organizational, and environmental conditions. This study is useful for EMMERA because it reinforces the importance of integrated digital infrastructures, data-sharing platforms, and multi-dimensional assessment frameworks in improving port efficiency and supporting sustainable [17] port governance.

Effective port risk management begins with a standardized understanding of core terminology as established by the International Maritime Organization and academic consensus [18–20]. Risk is defined as the combination of the frequency of an adverse event and the severity of its consequences. Systematic risk analysis uses structured information to identify hazards and estimate risks to people, property, and the marine environment. This process feeds into risk assessment, where analyzed data are evaluated against defined criteria to determine tolerability and inform management decisions. International environmental initiatives such as the Eco Ports Initiative and the Green Marine Programme have provided frameworks for maritime organizations to assess and reduce their environmental footprint through standardized reporting and self-diagnosis [21,22]. Port risk is further compounded by risk conditions in nearby cities and territories. Comprehensive assessment is essential for multi-risk perspectives, such as promoted by the MIRACLE project (https://www.iuav.it/sites/default/files/2025-09/MIRACLE-ENG.pdf) (accessed on 7 July 2026).

The chronological evolution of risk assessment methodologies over the last two decades reflects a shift from qualitative expert judgment toward quantitative and hybrid analytical models. Early studies focused on hazard identification and safety performance metrics [23]. Frameworks such as bow-tie risk analysis combined Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) to evaluate both accidental and operational risks [11]. Subsequent research classified hazards across categories including human error, technical failure, environmental factors, and security threats [16]. This creates a foundation for advanced qualitative analysis.

From 2013 onward, methodological development expanded toward multi-criteria decision models and fuzzy logic approaches to address uncertainty in maritime operations. Techniques such as the Analytic Hierarchy Process (AHP) and fuzzy risk models were applied to specialized port and terminal activities [24–26]. At the same time, spatio-temporal and environmental risk models began incorporating meteorological and oceanographic variability in port areas [27–29], laying the foundation for dynamic, data-driven monitoring platforms. More generally, the Port City Atlas (2023) [30] has started to provide more comprehensive insights into port city territories.

The contemporary Smart Port paradigm positions digitalization as a central instrument for sustainability and risk reduction [4,5]. Current research emphasizes the integration of ICT and IoT infrastructures to enable near real-time monitoring of operational and environmental impacts. This transformation requires the fusion of heterogeneous data sources, including satellite observations, vessel information systems, drone verification outputs, and external dynamic monitoring data services. Integrated architectures enable port authorities to move from post hoc documentation of environmental degradation toward anticipatory and performance-oriented regulatory practices.

The role of specialized technologies—particularly unmanned aerial vehicles (UAVs) and IoT-based sensor networks—is increasingly recognized as central to real-time anomaly validation and environmental surveillance [31]. Drone systems provide high-resolution observational inputs that can be cross-validated with additional dynamic monitoring data from external services [27]. The literature supports the integration of such sensing technologies into unified cloud-based platforms to strengthen the evidentiary basis for regulatory intervention, especially in cases of illegal discharge and pollution events.

Within the European Union and adjacent maritime borders, marine pollution monitoring is legally bound by environmental statutes, most notably the EU Marine Strategy Framework Directive (MSFD, ref. [1] which mandates the achievement of Good Environmental Status (GES) across descriptor matrices including marine litter and

contaminants. Operational surveillance mechanisms managed by the European Maritime Safety Agency (EMSA), such as the CleanSeaNet satellite-based oil spill monitoring service and the SafeSeaNet vessel traffic monitoring system, provide high-level regional overviews. However, a significant operational gap remains at the localized port-sea interface where localized anthropogenic activities aggregate under discrete municipal and national jurisdictions, causing critical compliance blind spots.

The remainder of paper unfolds as follows: (i) we define the architectural design of a multi-layered, cloud-based data fusion infrastructure capable of integrating heterogeneous data streams across international port authorities; (ii) we formalize a quantitative, dynamic linear factor risk-modeling framework that translates multi-year historical port incident data into localized hazard vulnerabilities; and (iii) we formulate and simulate a risk-proportional drone scheduling algorithm designed to optimize airborne surveillance frequency over high-impact operational hotspots, providing a standardized baseline for cross-border environmental governance in the Eastern Mediterranean. We showcase the incipient implementation of the system with baseline results from the Limassol port. The paper concludes with discussion and conclusions.

2. Materials and Methods: The EMMERA System Design

2.1. Cross-Border Cooperation and Benchmarking

The EMMERA project is built upon a strategic transnational consortium designed to address the unique environmental challenges of the Eastern Mediterranean. The partnership integrates academic expertise from Frederick University (Cyprus), the University of Haifa (Israel), and the University of Piraeus Research Center (Greece) with the operational insights of the Cyprus Port Authority and the Elefsis Port Authority. By focusing on key maritime hubs—the Port of Limassol, Haifa Port, and Elefsis Port—the project establishes a collaborative network for data integration and shared environmental surveillance. This collective approach is funded with a total of 1.2 million Euros over a 24-month duration to ensure the development of interoperable detection and warning systems. The geographical scope and cross-border operational coverage of the EMMERA platform across the three case-study ports are presented in Figure 1 The next part of the article presents the design of the EMMERA platform and the selection of data and layers.

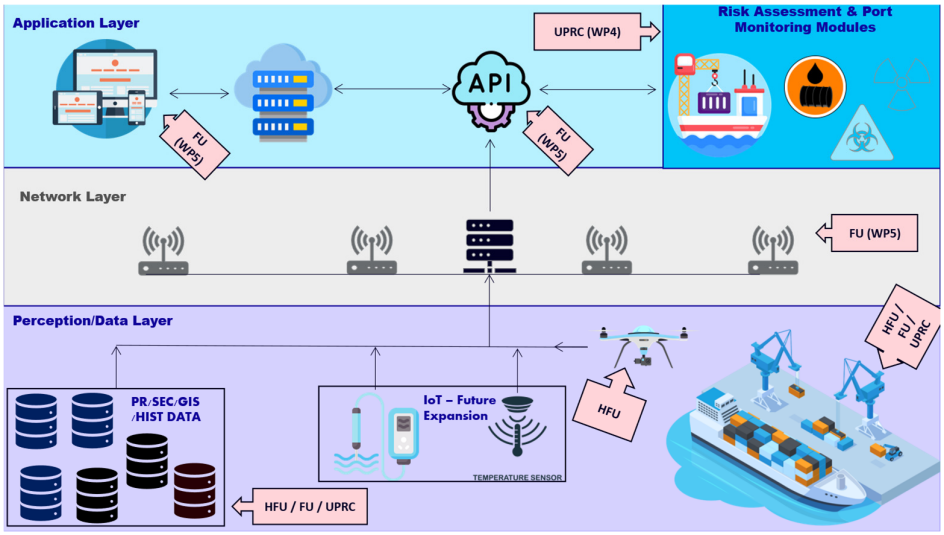


Figure 1. EMMERA Design.

2.2. Architectural Layers

The EMMERA platform utilizes a multi-layered, cloud-based architecture designed for scalability, security, and real-time responsiveness. The system is categorized into three primary functional layers: (a) Perception/Data Layer, (b) Network and Back-end Layer, and (c) Application and Front-end Layer.

The Perception/Data Layer serves as the sensory foundation of the platform. It integrates primary input from the specialized drone systems operated within the EMMERA project, including imagery and real-time analytical outputs used for anomaly detection and environmental verification. In addition, the layer incorporates dynamic monitoring data provided by external authorities and third-party services, such as meteorological and oceanographic factors and other operational monitoring feeds. Data exchange with monitoring authorities is supported through dedicated APIs developed within the platform to enable structured ingestion of externally collected datasets. The architecture allows future integration of additional compatible monitoring technologies—such as environmental sensor networks—following the same connection model. The platform also supports controlled manual data insertion by authorized users, including incident reports submitted by authorities or citizens, which are geolocated and incorporated into the analytical workflow.

Complementing these dynamic inputs, the platform maintains a structured set of static reference data consisting of relatively stable geospatial and operational datasets that change infrequently and provide contextual baselines for analysis. These include coastal and geographical characteristics, anchorage and bunkering zones, protected archaeological and environmentally sensitive coastal areas, fixed infrastructure elements, river discharge points and land-based outflow pipes, and other regulated coastal operational zones. These reference layers support spatial interpretation and risk aggregation but are not treated as real-time streams.

The Network and Back-end Layer, powered by ASP.NET and MS SQL, manages data storage, processing, and system interoperability. It supports the RESTful APIs required for structured data exchange with monitoring authorities and for future integration with additional monitoring and IoT-based systems. It also includes a Web Content Management System responsible for ingestion and management of GIS datasets, satellite imagery, and historical incident logs, ensuring consistent data governance and traceability.

The **Application and Front-end Layer** provides a responsive web interface with multi-access control customized by country and user role. It enables competent authorities to visualize and manage integrated datasets through dedicated modules for geospatial monitoring, dynamic risk assessment, KPI calculation, and early warning alerts. Through data fusion and automated processing, this layer combines drone-derived observations, authority-provided dynamic data, manually reported incidents, and static reference layers into a unified operational picture supporting decision-making and regulatory action.

The overall architectural structure of the EMMERA platform, including the interaction between the perception, back-end, and application layers, is illustrated in Figure 1.

This layered architecture follows a modular and technology-agnostic design, allowing additional monitoring sources and analytical modules to be integrated without structural redesign of the core platform.

2.3. Risk Assessment

The EMMERA platform adopts a dynamic multi-risk assessment [32] framework designed to support anticipatory environmental governance in coastal and port

environments. Risk is conceptualized as a function of the probability of occurrence of an adverse event and the severity of its expected consequences, consistent with formal maritime safety assessment methodologies [19,20].

Likelihood is drawn directly from the conditional probability of historical and real-time port activity incident logs. The variable is dynamic and continuously updated as new data is ingested through drone operations, authority-connected feeds, or external APIs.

The consequence coefficients used in the model are derived through structured expert assessment rather than statistical estimation. During platform configuration, specialists from maritime operations, port management, environmental protection, and regulatory authorities jointly evaluate each operational activity according to a common set of criteria including expected environmental persistence, spatial extent of potential impact, ecological sensitivity of the affected area, anticipated remediation effort, and potential regulatory implications. The resulting coefficients represent relative severity weights on an interval scale and remain fixed during routine platform operation, whereas likelihood values are continuously updated from incoming operational data. This separation between empirical likelihood estimation and expert-derived consequence weighting follows established practice in maritime risk assessment, where event frequencies can be estimated objectively from historical observations but consequence severity frequently requires expert judgement. To preserve consistency over time, the coefficients are reviewed every four years, or earlier if major infrastructural developments, regulatory changes, or new environmental evidence materially alter the expected consequences associated with a specific activity.

The total aggregated risk score for port i is given by

$$TR_i = \sum_{j=1}^{n} \sum_{k=1}^{m} b_{j,k} A_k$$

where

$\boldsymbol{k}$ represents distinct port operational activities including anchorage operations, berthing, cargo handling, bunkering, vessel maneuvering, dry docking [33], waste collection activities, and vessel transit.

$\boldsymbol{j}$ defines nature of environmental or operational hazard (i.e., oil spill, leakage, ballast disposal, sewage discharge).

$\boldsymbol{A_k}$ captures the activity hazard intensity factor is calculated as the conditional probability of a realized accident assigned to activity k.

$\boldsymbol{b_{j,k}}$ is the risk loading coefficient that weights, or "loads", the activity based on its severity of consequences.

The final outcome of the model is normalized to a scaled percentile index ranging from 0 to 100 where 100 represents certainty of the worst–case scenario.

The global equation is designed to handle a large, multi-dimensional matrix where a single activity (like *Berthing*) could simultaneously cause an oil spill (Hazard 1), a chemical spill (Hazard 2), and a solid waste infraction (Hazard 3). However, it can also be simplified by localizing the matrix and reducing dimensionality without significant loss of information (at least with regard to risk calculation). For local port i = port of Limassol, the intensity factor $A_{k,i}$ can map directly into Risk Factor k (RF_k) based on its conditional probability, while $\sum_j^n b_{j,k}$ collapses into Risk Loading (RL_k) based on its severity level. This yields

$$TR = \sum_{k}^{m} (RF_k \times RL_k)$$

A demonstrative example, for purposes of reproducibility, is provided from the base results of the port of Limassol. Consider activity k = *Berthing*.

1. Total Sample Population: N = 12,336 total vessel calls over 5 years.
2. Total n. of incidents during the same period = 156
3. Incident Attribution: recorded incidents for berthing I_{berth} = 25 incidents.
4. Risk Factor RF_{berth}: Conditional Probability = 25/12,336 = 0.002056
5. Risk Loading RL_{berth}: Consequence Score = 86
6. Resulting Activity Risk contribution: $Risk_{berth} = RF_{berth} \times RL_{berth} = 0.174$
7. Repeating over all other activities and summing up yields a port risk of 0.6636 or a normalized score of 52.47/100.

The model allows for automatic updates as data is fed into the system via APIs from drones and/or third-party sensors. At a minimum, the system is updated through API feeds from related institutions. While the likelihood of incidents is updated dynamically at arbitrarily small-time intervals, the review of anticipated consequences is required every four years or upon significant infrastructural developments. This ensures the assessment remains sensitive to anthropogenic stressors that may act synergistically. An indicative application of the risk calculation methodology for the Port of Limassol is presented in Section 3 of the paper, demonstrating how individual activity risks are aggregated into total risk scores.

Future operational deployment will permit sensitivity analyses and empirical recalibration of the consequence coefficients as larger incident datasets become available, allowing the governance model to evolve from expert-informed parameterization toward progressively data-driven calibration.

2.4. Drone Scheduling and Integration

A core innovation of EMMERA is the integration of a dedicated drone system that acts as both a data collector and a real-time verification tool. The platform calculates and visualizes optimized flight routes based on the dynamic risk assessment output. The logic follows a risk-proportional frequency model: locations with the highest probability of "anomaly" detection (i.e., higher risk scores) are visited by the drone system more frequently. These drones are equipped with advanced image processing capabilities to detect potential spoilage or pollutants, which can be triggered either by a pre-set schedule or in real-time by port authorities. Once an anomaly is detected, the spatio-temporal and imagery data are immediately transmitted back to the platform for visualization and institutional reporting. The scheduling algorithm is given as follows:

Step 1: Target Selection

Priority risk areas are marked by a centroid and a polygon, and flight distances are established. Priority Target Areas are then ranked based on risk priority of Area and time elapsed since last flight over the area. This yields a priority score of

$$P = (R \times T_{last})/100$$

R is the risk factor and Tlast is time elapsed since last flight over the area. The formula pushes risk areas first, until the factor T_{last} increases so much that it forces the schedule to consider less risky areas.

Step 2: Flight Execution

The flight execution is cleared through pre-flight validation of the following parameters: weather, operator availability, drone charge and security clearance. When the preflight validation is completed the drone selects Area based on P score, executes its primary flight to the first target, and then proceeds to the second highest P score area, and

beyond, until battery charge is less than 20%. The drone returns home, logs and resets Tlast to zero for areas visited.

Algorithmic extensions are available for maximum coverage, via penalizing the priority score by distance to area (i.e., $P = (R \times T_{last}/D)$ and/or seasonality coverage, by increasing the priority score by seasonality factor (i.e., $P = (R \times T_{last} \times S)/D$).

Validation of Flight Algorithm Against Alternative Scheduling

We evaluate the proposed drone scheduling algorithm through a Monte Carlo simulation designed to identify an optimal daily surveillance path across the seven monitored activity locations reported in the Limassol baseline case: Anchorage, Berthing, Waste Handling, Innocent Passage, Maintenance/Dry-Dock, Manoeuvring, and Other/Unknown Port Activities. We clarify that Innocent Passage, which is defined as the "The navigation of a foreign vessel through the territorial sea of a coastal State for the purpose of traversing that sea without entering internal waters, or proceeding to or from internal waters, provided that such passage is continuous, expeditious, and not prejudicial to the peace, good order, or security of the coastal State (Articles 17–19 United Nations Convention on the Law of the Sea)" does not constitute an operational activity per se, however it is associated with polluting activities such as illegal disposal of ballast water, sewage and oily leaks. From historical data, we observe an atypical large number of instances of Innocent Passage across the Limassol bay, to the extent that this warrants a separate category for purposes of regulatory and governance policy. The atypical number of vessels "passing through" can be traced to the geopolitical position of the island and the sustained conflict in around the Eastern Mediterranean.

Each simulated flying day requires the algorithm to choose one three-stop surveillance path from the feasible set of alternative paths. The selected path maximizes the priority score $P = R \times T_{last}$, where R is the normalized risk score of each location and T_{last} is the number of days elapsed since the location was last inspected. We benchmark our algorithm against three plausible alternatives: (a) a random patrol, (b) a uniform rotation, and (c) a fixed schedule focusing only on risky areas.

The simulation uses historical Limassol incident frequencies from 2019 to 2023 to generate daily anomaly arrivals under a Poisson process. Consequence scores are used to compute consequence-weighted detection outcomes. Each simulated year consists of 365 days, with a 15% probability of no-flight days reflecting weather, operator, battery, or authorization constraints. On each flying day, the drone can inspect three of the seven locations. Anomalies are assumed to remain detectable for one additional day after occurrence, reflecting the practical possibility that pollution traces or visual evidence may persist beyond the exact day of discharge. The simulation is repeated over 1000 iterations (artificial years) to obtain stable average detection rates. The basic parameters of the simulation are provided in the Table 1 below.

Table 1. Simulation Details.

Parameter	Symbol	Value	Description/Justification
Simulation horizon	T	365 days	One operational year
Number of replications	N	1000 years	Sufficient to ensure convergence of mean detection rates
Random seed	–	123	Ensures reproducibility
Spatial Domain	K	7	Anchorage, Berthing, Waste Handling, Innocent Passage, Maintenance/Dry Dock, Manoeuvring, Other/Unknown
Number of feasible daily paths	Ω	35	Ensures finite number of discrete paths

Maximum inspections per flight	m	3 locations/day	Assumed drone endurance
No-fly probability	p_{nf}	0.15	Represents weather, operator availability, airspace restrictions and maintenance
Battery reserve threshold	B_{min}	20%	Based on conservative UAV operational guidelines
Annual arrival rate	λ_k	Incident frequency/5 years	Estimated from Limassol baseline data
Daily arrival rate	$\lambda_k/365$	Varies by location	Input to Poisson generator
Consequence scale	C_k	{25,50,66,86}	Low, Moderate, Significant, High
Risk score normalization	R_k	0–100	Linear transformation
Priority function	P_k	$R_k \times T_{last}$	Scheduling objective function
Random patrol	–	Benchmark	Three locations selected randomly
Uniform rotation	–	Benchmark	Longest unvisited locations selected
Fixed high-risk	–	Benchmark	Always inspect highest-risk locations
Optimized risk-time path	–	Proposed method	Maximizes Σ(R_k × T_last,k)
Detection rate	DR	(%)	Detected anomalies/Total anomalies
Consequence-weighted detection rate	$CWDR$	(%)	Severity-adjusted detection effectiveness
Path frequency	F_p	Count	Number of times a given path is selected

Overall, the exercise aims to compare alternative scheduling strategies under identical stochastic environmental conditions rather than to predict actual incident occurrence. In the same spirit, the simulation is intended to provide preliminary evidence regarding the relative efficiency of the proposed scheduling rule and should not be interpreted as post-deployment validation of the EMMERA platform. The results are provided in Table 2 below:

Table 2. Simulation Benchmarking for Flight Schedule Algorithm.

Scheduling Strategy	Detection Rate	Risk-Adjusted Detection Rate	Note
Random patrol	59.64%	59.64%	Lowest benchmark
Uniform rotation	72.79%	73.02%	Maximum coverage, weaker overall risk targeting
Fixed high-risk patrol	75.65%	86.76%	Strong on severe hotspots, ignores low-risk areas
Optimized risk-time path	**88.36%**	**91.96%**	**Best overall performance**

The optimized path generated by the algorithm prioritizes Other/Unknown Port Activities, Berthing, and Manoeuvring most frequently, but periodically inserts Innocent Passage, Anchorage, Maintenance/Dry-Dock, and Waste Handling as their elapsed time since last inspection increases. A representative recurring path pattern is: Other/Unknown → Berthing → Manoeuvring, followed by Other/Unknown → Berthing → Innocent Passage, then returning to Other/Unknown → Manoeuvring → Berthing. This provides a risk-sensitive but not risk-blind inspection cycle. Compared with uniform, random, and fixed high-risk strategies, the optimized path produces the highest overall and consequence-weighted detection rates.

We note that the spatial distribution of environmental hotspots, and its aerial detection, is also influenced by underlying physical and operational processes. Hydrodynamic circulation affects the transport, dilution, accumulation, and persistence of pollutants as the prevailing winds, wave conditions, and coastal currents affect their dispersion. From an operational perspective, these processes are particularly relevant for aerial surveillance because they determine the visibility and persistence of pollution signatures that can be detected by drone-based imaging systems. While the platform itself does not perform computational hydrodynamic simulations (increasing the lag between reporting and detection) it is designed to account for dynamic meteorological and oceanographic information through external APIs. Operational pressures also exhibit comparable temporal variability. For example, vessel traffic density, one of the principal drivers of environmental risk, displays seasonal fluctuations, where commercial shipping, cruise operations, recreational boating, and tourism-related maritime activities increase substantially during the summer months. These seasonal patterns influence both the probability of pollution incidents and the expected allocation of surveillance resources. Within EMMERA, such temporal variability is reflected through the continuously updated likelihood component of the risk model and a modified schedule of drone surveillance.

2.5. Ongoing Monitoring and Reporting: Dynamic KPI Calculation

The EMMERA platform facilitates a shift from static reporting to an active, performance-oriented regulatory practice through the continuous monitoring of Key Performance Indicators (KPIs). This ongoing monitoring is operationalized via the dynamic updating of the platform's analytical modules, which integrate real-time data from drone operations, third-party APIs, and future IoT sensor networks. Unlike traditional environmental oversight, which relies on periodic manual inspections, EMMERA's reporting mechanism is inherently tied to the risk assessment output, allowing for the automatic recalculation of performance metrics at arbitrarily small-time intervals. This ensures that port authorities maintain constant situational awareness regarding the effectiveness of their risk mitigation strategies.

The KPIs in the EMMERA platform are not just metrics for reporting but governance tools for continuous monitoring, risk-based prioritization and performance-oriented environmental oversight. This choice is motivated by the broader literature on port sustainability performance and smart port assessment which stresses the need to assess port systems along a number of domains such as operations, environment, energy, safety, security and human resources, rather than focusing only on traditional operational indicators. EMMERA's KPI framework connects pollution incidents, detection rates, vessel activity, response capacity and environmental performance indicators to a dynamic monitoring architecture. This allows the platform to differentiate between environmental KPIs, operational-efficiency KPIs and wider socio-economic contextual indicators, thereby helping to reinforce the evidential basis for sustainability-oriented governance and decision-making.

The KPI framework is also aligned with existing approaches for marine environmental governance and monitoring. The Marine Strategy Framework Directive (MSFD) at European level highlights the importance of systematic monitoring of the state of the marine environment, of pollution pressures and human-induced impacts, while EMSA-supported surveillance systems, such as CleanSeaNet and SafeSeaNet, demonstrate the importance of integrated vessel, pollution and incident-related data in the context of maritime environmental oversight. At the same time, IMO Conventions and port environmental management frameworks emphasize the need for measurable indicators to support pollution prevention, compliance monitoring and institutional

accountability. Therefore, the KPIs of EMMERA are devised not only for operational performance measurement, but also for environmental monitoring, risk-based inspection, evidence-based enforcement, and sustainability-oriented decision-making.

The calculation of KPIs within the platform is categorized across three critical domains: Operations, Environment, and Safety & Security. Environmental KPIs are designed to monitor externalities such as the number of spills per vessel stop, greenhouse gas (GHG) emissions, and water quality indices. These metrics are quantified using a composite indexing approach, where raw spatio-temporal and imagery data collected by drones are processed through advanced image analysis to detect "anomalies" or potential spoilage. This real-time data is then cross-referenced with historical datasets on water incidents to validate the current performance against established environmental benchmarks.

A distinctive feature of the EMMERA reporting system is the feedback loop between KPI performance and operational command. When a specific KPI—such as the frequency of undetected anomalies—falls outside of tolerable standards, the system automatically adjusts the drone surveillance schedule. The highest-risk locations, identified by poor KPI performance or high likelihood of incident, are prioritized with increased visit frequencies. This risk-based reporting structure ensures that institutional reporting is not merely a documentation exercise but a tool for optimizing enforcement resources across the ports of Limassol, Haifa, and Elefsis.

3. Baseline Results

3.1. The Case of Limassol

We operationalize the EMMERA platform on the Port of Limassol, providing a baseline case for the efficacy of the system. The platform delivers: (a) a dynamic risk assessment mapping port activities to specific and aggregated risks and (b) a monitoring facility that dynamically estimates a number of Key Performance Indicators. A snapshot of these outputs is provided in Table 3 below.

Table 3. Example of Risk Calculation: Port of Limassol.

Year	**2019**	**2020**	**2021**	**2022**	**2023**	**Total**
N. of Vessel Calls	2701	2325	2299	2596	2416	12,337
Activity	**Incidents**	**Raw Probability**	**Conditional Probability**		**Concequence**	**Risk**
Anchorage	3	0.00024	0.01923		25	0.00608
Berthing at port (bunkering, cargo handling, de-ballast)	25	0.00203	0.16026		86	0.174287
Collection and handling of waste	1	0.00008	0.00641		25	0.002027
Innocent Passage (including passage and anchoring)	30	0.00243	0.19231		25	0.060798
Maintenance operations at Port facilities (dry-docks)	1	0.00008	0.00641		66	0.00535
Manoeuvring in or out of the Port and/or anchorage	20	0.00162	0.12821		66	0.107004

Other activities impacting the Port or Unknown	76	0.00616	0.48718	50	0.308042
Total	**156**	**0.01265**	**1**		**0.663586**
Total Number of Vessel Calls	12,336				
Max Risk		1.26			
Normalized (Total Risk)		**52.47 ***			

* The interpretation of the final total risk (52.47) is that current risk level slightly exceeds the midpoint, with 0 representing zero risk and 100 representing highest possible risk (certainy of adverse event.

The table demonstrates the results of the platform's dynamic, 2-dimensional vector approach to marine risk management, which defines risk as a product of likelihood (probability) and consequence. Grounded in historical data from 12,336 total vessel calls spanning 2019 to 2023, the table outlines the localized baseline risk assessment for the Port of Limassol. By analyzing 156 total recorded incidents against specific maritime activities—such as anchorage, berthing, waste handling, and maneuvering—the model converts historical data into actionable raw and conditional probabilities. These structural metrics establish the fundamental baseline weights necessary to compute specific hazard vulnerabilities within the platform's linear factor aggregation model.

Evaluating the specific activities reveals that cumulative risk is heavily driven by distinct operational hotspots rather than uniform pressures. "Other activities impacting the Port or Unknown" and "Berthing at port (bunkering, cargo handling, de-ballast)" yield the highest calculated risk indices at approximately 0.308 and 0.174, respectively. This correlates with the literature's emphasis on tracking anthropogenic stressors synergistically, as berthing operations [34] involve high-impact events like bunkering and cargo handling that carry severe environmental consequences (scored at 86). Conversely, while "Innocent Passage" accounts for the highest individual incident count (30 incidents), its lower consequence score (25) results in a mitigated risk value of 0.061. This variation demonstrates why evaluating indicators separately causes interaction effects to be severely underestimated, proving the necessity of EMMERA's multi-risk integrated visibility.

Ultimately, the table aggregates these figures into a total historical risk score of 0.663586, which is then converted into a Normalized Total Risk of 52.47 *. As detailed in the table's note, this score slightly exceeds the governance midpoint on a scale of 0 to 100 (where 100 represents a certainty of an adverse event). In the context of the EMMERA platform, this baseline score triggers the dynamic drone scheduling algorithm. Because the platform utilizes a risk-proportional frequency model, areas linked to high-risk scores—such as bunkering or maneuvering zones—are prioritized for more frequent drone flights. Dynamic application of the model allows the Port of Limassol to shift away from rigid, post hoc documentation and establish an anticipatory, risk-based optimization of limited surveillance resources.

Table 4 operationalizes the platform's ongoing monitoring and reporting layer by showcasing the chronological trend of Key Performance Indicators (KPIs) for the Port of Limassol from 2019 to 2023.

Table 4. Example of KPI's Estimation: Port of Limassol.

	2019	2020	2021	2022	2023
Incident Rate	1.00%	1.68%	1.74%	0.65%	0.99%
Detection Rate	37.04%	30.77%	27.50%	17.65%	37.50%
Incident Rate × Detection Rate	0.37%	0.52%	0.48%	0.12%	0.37%
Response to Reported	22.22%	48.72%	30.00%	23.53%	33.33%
Punishable Over Reported	14.81%	28.21%	15.00%	11.76%	4.17%
Oil Spills/Vessels	0.15%	0.26%	0.35%	0.19%	0.17%
N. of Spillage/Tonnage × 100	2.36%	3.12%	2.30%	1.96%	2.08%
Sewage/Vessels	0.33%	0.60%	0.57%	0.12%	0.21%
Unemployment/V calls × 100	26.29%	32.69%	32.62%	26.19%	24.01%
Unemployment/Cargo Throughput × 1000	41.85%	39.46%	21.57%	26.62%	30.22%
GDP/V Calls	0.967%	1.059%	1.211%	1.205%	1.354%
GDP/Cargo Throughput	15.39%	12.79%	8.01%	12.24%	17.05%

This dynamic framework transitions environmental oversight from static, post hoc documentation into an active, performance-oriented regulatory practice. By categorizing metrics across operational, environmental, and socio-economic domains, the platform continuously tracks port externalities against historical baselines. The data points reflect the historical baseline context before the integration of EMMERA's real-time data infrastructures—such as automated drone surveillance and authority API feeds—which are explicitly designed to stabilize and improve these volatile percentages.

A close examination of the enforcement and environmental metrics reveals critical vulnerabilities in the port's historical oversight capabilities. The "Detection Rate" exhibits a fluctuating and concerning downward trajectory, dropping from 37.04% in 2019 to a low of 17.65% in 2022, before rebounding to 37.50% in 2023. This historical gap aligns with the paper's assertion that traditional monitoring suffers from localized institutional fragmentation, leading to a weak assignment of responsibility and a significant gap between technical capacity and regulatory effectiveness. Similarly, the environmental stressors highlight persistent pressures; for instance, the "Oil Spills/Vessels" ratio peaked at 0.35% in 2021, and the "N. of Spillage/Tonnage × 100" remained consistently above 1.95% throughout the five-year period. Within the EMMERA architecture, whenever these environmental KPIs fall outside tolerable standards, a vital feedback loop is triggered to automatically alter drone schedules and prioritize high-risk locations. Finally, the table incorporates broader socio-economic and structural indicators, such as vessel interaction with regional unemployment and GDP fractions, to provide a comprehensive coastal risk profile. The "GDP/V Calls" ratio demonstrates a steady upward trend, rising from 0.967% in 2019 to 1.354% in 2023, signaling the growing economic intensity and development of the maritime hub. However, this expanding multi-sector development underscores why a compartmentalized, sector-specific view tends to underestimate cumulative environmental degradation.

By binding these multi-dimensional KPIs into a single, cloud-based web interface, the platform provides monitoring authorities with transparent, measurable metrics. This ensures that performance measurement functions as a continuous learning loop to systematically optimize enforcement resources and bolster regional marine resilience.

3.2. Policy Implications: Re-Calibrating Governance

The transition from traditional maritime surveillance to the integrated framework proposed by the EMMERA platform represents a fundamental shift in coastal and marine

environmental governance. Historically, maritime oversight has been characterized by a reactive posture, where intervention occurs only after a pollution incident has been documented or reported. By leveraging integrated data architectures, EMMERA re-calibrates this governance model toward an anticipatory, coordinated, and performance-oriented regulatory practice. This section explores how the platform's technical capabilities translate into policy-level innovations that address the structural deficiencies of current maritime monitoring.

3.3. Shifting from Reactive to Anticipatory Governance

The primary policy contribution of EMMERA is the reduction in informational asymmetries that lead to delayed detection and weak attribution of responsibility. In the current fragmented landscape, public authorities often lack the interoperability required to cross-validate data across organizational boundaries. The EMMERA platform addresses this by enabling more effective oversight through integrated data infrastructures. By integrating heterogeneous static and dynamic data from multiple national, municipal, and private institutions, as well as drone-based monitoring—the platform provides a coherent operational framework.

From a policy ideation perspective, this allows regulators to move beyond "post hoc documentation". Instead of investigating a spill after it has dispersed, authorities can utilize the platform's dynamic risk assessment to identify high-risk maritime activities, such as oil and gas operations, and monitor them synergistically with other anthropogenic stressors. This anticipatory approach improves situational awareness, allowing for targeted drone verification before an anomaly escalates into a significant environmental crisis.

3.4. Risk-Based Optimization of Surveillance Resources

A critical challenge for port authorities in Cyprus, Greece, and Israel is the efficient allocation of limited monitoring resources. EMMERA introduces a methodology where the frequency of surveillance is directly proportional to the calculated risk level of a specific location or activity. This policy innovation shifts the focus from rigid, scheduled patrols to a dynamic "anomaly" detection model.

By quantifying risk, the platform identifies "hotspots" where the probability of detection is highest. Policy-wise, this allows for the establishment of early warning systems and Key Performance Indicators (KPIs) that trigger automated drone inspections. For port administrations, this means that drone surveillance methods can be customized per port based on technical needs and obtained governmental approvals, ensuring that the highest risk areas receive the most frequent inspections.

3.5. Strengthening the Evidentiary Basis for Enforcement

One of the most persistent hurdles in marine environmental governance is the "evidentiary gap"—the difficulty of collecting robust data that can hold polluters accountable in a court of law. EMMERA addresses this by transforming fragmented monitoring streams into "actionable environmental intelligence". The platform provides a unified framework where data fusion and cross-validation serve as a strengthened evidentiary basis for regulatory intervention.

Specifically, the use of advanced image processing on the drone system allows for the real-time tracking of anomalies and the collection of spatio-temporal imagery data. This data is integrated with historical records of water incidents and vessel location data to create a comprehensive audit trail. For policymakers, this infrastructure reduces the ambiguity of pollution events, enabling more effective enforcement mechanisms and better-informed decision-making.

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3.6. Cross-Border Collaboration and Action Plans

Marine pollution does not respect national borders, yet governance is often restricted by jurisdictional limits. The cross-border nature of the EMMERA consortium—incorporating ports in Limassol, Haifa, and Elefsis—sets a precedent for regional environmental cooperation. The platform supports the development of both local and cross-border action plans to mitigate significant risks.

By utilizing a cloud-based web platform with multi-access control, authorities in different countries can access shared visualizations of imagery data for environmental monitoring. This interoperability allows for the exchange of data on maritime pollution across sea borders, fostering a coordinated response to regional threats. From a policy standpoint, this collaborative model enhances institutional capacity for response, ensuring that the East Mediterranean is managed as a single ecological unit rather than a series of disconnected national zones.

3.7. Continuous Improvement Through Performance Measurement

Finally, the EMMERA platform incorporates performance measurement as a core component of its governance cycle. The system is designed for iterative refinement; for example, while the likelihood of incidents is updated in arbitrarily small-time intervals via drone and IoT inputs, a review of anticipated consequences is mandated every four years.

This policy of "dynamic updating" allows the regulatory framework to remain relevant in the face of significant developments or new maritime technologies. By establishing KPIs and utilizing the platform for statistical analysis and visualization, authorities can measure the effectiveness of their mitigation strategies over time. This KPI-driven monitoring framework also strengthens accountability among monitoring authorities by making oversight performance and response effectiveness measurable and transparent. This feedback loop transforms governance into a learning process, where data-driven insights are continuously used to recalibrate risk assessment and improve the resilience of the marine environment.

4. Conclusions and Discussion

The results of this study should be discussed in the context of the wider literature on data-driven environment management, smart ports and coastal monitoring. Recent research indicates that data-driven and AI-enabled systems can assist in environmental decision-making through the processing of complex data sets, improving operational management, and reducing environmental impacts in coastal and port environments. This is directly relevant for EMMERA, as the platform integrates heterogeneous data sources, drone-based observations, anomaly detection and KPI-based reporting into an integrated decision-support framework for sustainability-oriented port governance [13].

Furthermore, recent studies on drone remote sensing have demonstrated that UAV imagery can assist in coastal and marine environmental surveillance by providing high-resolution spatial evidence for pollution and marine litter monitoring. EMMERA takes this logic further by integrating drone-based verification into a wider governance framework that connects data fusion, risk assessment and regulatory reporting. Therefore, the platform's value lies not only in the application of advanced monitoring technologies, but also in the integration of these technologies into a coordinated and evidence-based system of marine environmental governance [14,16].

The implementation results and case applications presented in this study indicate that the EMMERA platform enables operational integration of heterogeneous monitoring data, dynamic risk-based surveillance scheduling, and KPI-linked regulatory reporting

within a unified governance framework. The integration of multi-source data with dynamic KPIs also strengthens accountability among monitoring authorities through measurable and transparent oversight performance.

The EMMERA project represents a pivotal shift in the governance of the Eastern Mediterranean, moving the region from a structural condition of fragmented, institutionally siloed monitoring toward a unified data framework. By addressing the core deficiencies in data management and surveillance identified in the literature, the platform successfully bridges the gap between monitoring capacity and regulatory effectiveness. Through the strategic integration of specialized drone technology, satellite observations, and administrative datasets, EMMERA transforms raw environmental streams into a coherent evidentiary basis for institutional intervention.

The technical architecture—characterized by its multi-layered design and dynamic risk assessment methodology—enables a transition from reactive enforcement to an anticipatory governance model. By quantifying risk through a dynamic linear factor model, the system allows real-time updating of maritime hazards and optimized allocation of surveillance resources based on high-probability anomaly detection. This performance-oriented approach ensures that activity hotspots receive prioritized oversight, reducing informational asymmetries and enhancing situational awareness for port authorities in Cyprus, Greece, and Israel.

The quantitative evidence presented in this study should be interpreted as establishing a pre-operational benchmark rather than demonstrating post-deployment effectiveness. Specifically, the historical risk model provides reproducible baseline estimates of activity-specific environmental risk, while the Monte Carlo simulation shows that the proposed risk-proportional drone scheduling algorithm consistently outperforms alternative scheduling strategies under identical stochastic conditions. Accordingly, improvements in detection rates, response times, inspection efficiency, and environmental outcomes remain testable hypotheses that will be assessed through longitudinal monitoring once the platform enters routine operational use.

Ultimately, EMMERA can help assure that the future of coastal and marine environmental governance lies not merely in the proliferation of new monitoring tools, but in the creation of integrated data infrastructures that support cross-border cooperation. The platform's ability to facilitate collaborative action plans across the ports of Limassol (Cyprus), Haifa (Israel), and Elefsis (Greece) highlights the potential for a coordinated regional response to shared environmental threats. As maritime activities and anthropogenic stressors continue to evolve, the EMMERA framework provides the necessary scalability and robustness to protect the marine environment through data-driven, coordinated regulatory practice. This approach provides a unique foundation for advanced integration of quantitative data on sea and land and for further qualitative analysis.

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