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Reducing Marine Oil Pollution through International Regulation: An Empirical Assessment of MARPOL Annex I Enforcement in Egypt

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المستخلص

لا يزال التلوث الزيتي الناجم عن أنشطة السفن يمثل تحديًا بيئيًا ملحًا في البيئة والممرات المائية المصرية. تبحث هذه الدراسة في مدى ارتباط فعالية إنفاذ الملحق الأول من الاتفاقية الدولية لمنع التلوث من السفن (ماربول) في مصر بتحسن نتائج الحد من التلوث الزيتي، كما تسعى إلى الكشف عن الآليات المؤسسية المؤثرة في فعالية التنفيذ. تعتمد الدراسة منهجًا تكامليًا قائمًا على أساليب كمية ونوعية (المنهج المختلط المتقارب)، يجمع بين تحليل سلاسل زمنية وطنية لبيانات حوادث التسرب المبلغ عنها خلال الفترة (١٩٩٠–٢٠٢٣)، وتحليل السلاسل الزمنية المقطعية (المتقطعة) المرتبطة بمحطات تنفيذ رئيسية، وتحليل متعدد المتغيرات لبحث العلاقة بين نتائج التسرب وعوامل مرتبطة بالإنفاذ (نشاط التفتيش، متابعة الإجراءات التنفيذية، وتوافر مرافق الاستقبال)، إضافة إلى التحليل المكاني باستخدام نظم المعلومات الجغرافية وتقدير كثافة النواة في ٣٣ منطقة ساحلية وميناىية، وتحليل موضوعي لعدد ٢٥ مقابلة شبه مُنظَّمة مع جهات معنية.

تشير النتائج عبر مختلف محاور الدراسة إلى تحسن ملحوظ في المخرجات خلال المراحل المتأخرة من التنفيذ مقارنة بالمراحل الأولى، مع تحقيق نتائج أفضل عند تكامل دورات الإنفاذ وتوافر البنية التحتية لمرافق الاستقبال بصورة عملية. كما يكشف التحليل المكاني عن استمرار وجود ممرات ومناطق اقتراب من الموانئ ذات مخاطر مرتفعة، بما يدعم تبني نهج قائم على تقييم المخاطر في توجيه أنشطة التفتيش والرصد.

وتبرز نتائج المقابلات أهمية وضوح الأدوار والتنسيق بين الجهات، وتعزيز القدرات الفنية والبشرية، وترسيخ مصداقية الإنفاذ، وتطوير نظم المعلومات للكشف والمتابعة. وتوصي الدراسة بتعزيز المسارات المتكاملة بين الإنفاذ والبنية التحتية ونظم المعلومات، وإضفاء الطابع المؤسسي على استهداف التفتيش بناءً على بؤر المخاطر، وتوحيد آليات الإبلاغ وتكامل البيانات بين الجهات، وإعطاء أولوية لبناء القدرات في المناطق عالية المخاطر والمحدودة الموارد، بما يسهم في خفض التلوث الزيتي الناجم عن السفن في مصر بصورة أكبر.

الكلمات البحثية: الملحق الأول من اتفاقية ما ربول - التلوث الزيتي الناجم عن السفن؛ الحد من التسربات النفطية - رقابة دولة الميناء - مرافق الاستقبال؛ قناة السويس - مصر؛ الحوكمة البيئية.

Abstract
Oil pollution from ship activities still constitutes a pressing concern for the Egyptian environment and waterways. This research examines whether the effectiveness of the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex I in Egypt is linked to improved oil pollution outcomes and seeks to uncover institutional mechanisms influencing the effectiveness of implementation. A convergent mixed-methods approach combines national time-series analysis of reported spill outcomes (1990-2023) with segmented (interrupted) time-series reasoning around critical implementation milestones, multivariate analysis associating spill outcomes with enforcement-related factors (inspection activity, enforcement follow-through, and reception capacity availability), geographic information system hotspot mapping with kernel density estimation in 33 port/coastal regions, and thematic analysis of 25 semi-structured interviews with relevant authorities. Across all strands, results support better outcomes in later stages of implementation compared to earlier stages, with greater success when enforcement cycles and reception infrastructure are practically accessible.

Spatial analysis indicates persistent higher-risk corridors and port-approach zones, supporting a risk-based interpretation of enforcement and monitoring needs. Interview evidence emphasizes the importance of role clarity and inter-agency coordination, technical and human capacity, enforcement credibility, and information systems for detection and follow-up. The study recommends strengthening integrated enforcement–infrastructure–information pathways, institutionalizing hotspot-informed inspection targeting, standardizing inter-agency incident reporting and data integration, and prioritizing capacity building in high-risk and resource-constrained locations to further reduce ship-source oil pollution in Egypt.

Keywords: MARPOL Annex I; ship-source oil pollution; oil spill reduction; port State control; reception facilities; Suez Canal; Egypt; environmental governance; maritime law; mixed-methods

1. Introduction

Oil pollution from ship operations remains a persistent environmental risk along Egypt’s maritime spaces, particularly near the Suez Canal corridor and adjacent port approaches(Kostianaia et al., 2020). While major spill events have declined in recent years, evidence indicates that chronic small-scale discharges (e.g., oily bilge/ballast residues and operational releases) continue to occur, especially in areas where enforcement capacity and port waste reception services are limited (Kostianaia et al., 2020; Abou El-Magd, 2021).

These spills create real-world ecological and economic costs for coastal ecosystems and regions that rely on tourism (Hoarau, 2022). The ratification of MARPOL 73/78 Annex I by Egypt created a legal system for the management of oil discharge emissions from vessels; nevertheless, legal transposition does not automatically ensure compliance (Carpenter & Kostianoy, 2018). The success of implementation depends on the credibility of inspections, the presence of reception facilities, coordination between agencies, and the ability to monitor and prosecute non-compliance (Ramahlo, 2022; Carpenter & Kostianoy, 2018). In Egypt, the enforcement of Annex I is the responsibility of several agencies, which has been identified as a possible source of confusion about the effectiveness of implementation (Kostianaiā et al., 2020). This research examines the link between the implementation and enforcement of Annex I in Egypt and the effects of oil spill emissions by combining (i) trend evidence from spill data and (ii) institutional evidence from enforcement mechanisms.

2. Literature Review

2.1 Effectiveness of MARPOL Annex I and the Role of Enforcement

There is a consensus in the literature that MARPOL Annex I has the potential to reduce ship-based oil pollution significantly, but its effectiveness relies largely on the enforcement capacity rather than mere ratification (Karim, 2016; Carpenter & Kostianoy, 2018). The literature also suggests that the port States that perform regular and credible Port State Control inspections, have sound verification of Oil Record Books, and have consistent sanctioning policies perform better in terms of environmental results. Conversely, the literature shows that there are often implementation deficits in developing port States that lack regular inspections, have weak evidence trails, or lack sufficient deterrent effects of sanctions (Kostianaia 2020; Cui 2024).

2.2 Determinants of Compliance: Reception Facilities, Detection, and Auditability

One of the most consistent results in the literature is that compliance with Annex I is highly dependent on operational feasibility. Receiving oily waters at shorelines is required, as lack of capacity could raise the attractiveness of illegal dumping (Carpenter & Kostianoy, 2018). On the other hand, the role of auditing and detection is also important, as a compliance mechanism based solely on paper documents without verification can be readily defeated (Jiang & Cao, 2011). The literature emphasizes the increasing role of satellite surveillance, ship tracking, and inter-agency reporting systems in raising the attractiveness of detection and the success of enforcement actions (Abou El-Magd, 2021).

3. Egypt: Institutional and Enforcement Context

The use of Annex I in Egypt is characterized by the existence of several actors with overlapping or contiguous mandates, including the Egyptian Environmental Affairs Agency (EEAA), the Egyptian Authority for Maritime Safety (EAMS), the Suez Canal Authority (SCA), and some naval or security bodies in specific regions (Hassan, E. A. 2020; MEEA, 2016). As per the current literature, the predictability of inspection and enforcement can be affected by overlapping mandates, which may lead to confusion among the leadership, duplication of efforts, and a lack of follow-through (Kostianiiaiaia et al., 2020). Some of the key operational challenges that have been identified include the inadequacies of reception facilities, particularly in the Red Sea ports identified, which contribute to the problem of illegal discharges by ships that do not wish to incur delays or costs (Kostianiiaiaia et al., 2020; Baghdady, 2024).

4. Empirical Oil-Spill Trends in Egypt (1990-2023)

Notwithstanding the available data on the number of incidents and the amount of oil spills, there has been a significant decrease in the number of major oil spill incidents, with the most significant improvements being recorded in the years that followed 2010 (Abdelkader, 2018).This is largely due to improvements in the inspection process and increased scrutiny of compliance documentation (Etkin, 2023; Abou El-Magd, 2021).

Spatial data also confirms that increased surveillance and tracking efforts can lead to a reduction in spill hotspots by increasing the probability of detection and facilitating faster enforcement response (Abou El-Magd, 2021). At the same time, there are a number of sources that confirm the difficulty in completely eliminating low-level operational spills, especially in areas where reception points are limited or enforcement is not coordinated (Kostianaia et al., 2020).

5. Regional Benchmarking

Regional benchmarking results show that Egypt's Annex I implementation indicators are more favorable than those of some regional countries, although regional performance is variable and depends on the capacity of countries (World Bank, 2021; UNEP, 2020). In this paper, regional comparison is used only as a point of reference to determine whether the observed Egyptian performance is in line with the expected performance related to improvements in enforcement capacity.

6. Synthesis and Research Gap

The existing literature provides three applicable findings. First, Annex I performance is not only dependent on the adoption of the treaty but also dependent on the credibility of inspections, probability of detection, and waste reception capacity (Karim, 2016; Carpenter & Kost͡ianoĭ, 2018).

Second, the presence of port states may have limitations in compliance because of institutional fragmentation and capacity, resulting in inconsistent performance (Mona et al., 2019). Third, Egypt-specific studies indicate a lack of coordination and facilities but do not normally link these to a spill outcome assessment (Kostianaia et al., 2020; Abou El-Magd, 2021).

The current Egypt-centric literature is basically descriptive, either based on pollutant data or treaty explanations, and does not normally combine spill trend data with institutional enforcement factors that may shed light on spill reduction and continued discharges (MEEA,2016). This study will address this problem by employing a mixed-methods design that combines spill trend data with enforcement factors such as inspection activity, reception facility adequacy, monitoring capacity, and interagency cooperation. (Bakr et al., 2024)

Oil pollution has impacts on the Egyptian coastal environment and also has economic costs in tourism and fishing, especially in the Red Sea resort areas. The presence of hydrocarbon resources in sediments and operational spills indicates the need for effective compliance mechanisms that go beyond the ratification of treaties (El-Sayed & Hassan, 2019; Zhao et al., 2025). Thus, the assessment of the effectiveness of Annex I treaty enforcement is not only a technical matter but also a governance matter with special implications.

7. Study Approach and Expected Practical Value

By analyzing the trends of temporal spills and comparing them with the conditions of enforcement and the statements of stakeholders, this paper reveals the factors that are most closely related to the reduction of oil spills in the implementation of Annex I in Egypt and the areas that still allow small-scale spills. The results of this paper can help improve specific areas.

8. Research Methodology

8.1 Research Design

This study adopts a convergent mixed-methods research design to assess whether the implementation and enforcement of MARPOL 73/78 Annex I in Egypt are associated with improved ship-source oil pollution outcomes along the Mediterranean coast, the Suez Canal corridor, and the Red Sea/Gulf of Suez. Quantitative and qualitative strands are conducted in parallel and integrated through systematic triangulation.

The quantitative component examines oil-spill outcomes over the period 1990–2023, focusing on (i) annual spill frequency, (ii) reported spill volumes were available, and (iii) spatial distribution of incidents across 33 port and coastal areas. The analysis combines national time-series assessment, panel data analysis of port areas, and hotspot mapping using Geographic Information Systems (GIS). Where possible, reported incidents are cross-validated with satellite remote-sensing data (MODIS and Sentinel-1 SAR) to enhance the precision of detection.

The qualitative component of the analysis involves a structured assessment of the national legal and policy frameworks in relation to the application of Annex I, as well as semi-structured interviews and observation visits to the ports. This component of the analysis seeks to offer insight into the reality of enforcement and to interpret the findings in the context of realities of enforcement.

The combination of the results is done through a joint display (triangulation matrix) that combines spill trends, spatial patterns, regulatory milestones, and perceptions of stakeholders.

8.2 Analytical Framework

The framework of the research is structured around three interrelated dimensions of analysis that link obligations, enforcement capacity, and environmental outcomes.

Regulatory Dimension

The regulatory dimension of analysis is concerned with the transposition of Annex I obligations into Egyptian law and policy, with a focus on the key steps of implementation, such as Law No. 4 of 1994 and Ministerial Decree No. 73 of 2013. The analysis will be focused on discharge controls, inspection rights, document checks, reporting obligations, and penalty provisions regarding the prevention of oil pollution.

Institutional Dimension

This category assesses the enforcement regime in which Annex I commitments are to be enforced, and the respective roles of the EEAA, EAMS, and the Suez Canal Authority. The key indicators are the allocation of responsibilities with respect to inspections, cooperation among agencies, the procedure for carrying out inspections, the procedure for enforcing follow-up actions, and the limitations of enforcement with respect to human resources, technical capacity, and exchange of information.

Environmental-Compliance Outcomes Dimension

This dimension evaluates the results of implementation based on the following indicators: (i) the number of oil spills per year, (ii) the volume of spills where possible, and (iii) the concentration of spills per region using GIS hotspot analysis. These indicators allow the assessment of the persistence of the risk of spills over time and space. Taken together, these dimensions operationalize the implementation of Annex I as a process whereby legal commitments are converted into environmental results.

8.3 Data Sources and Sampling

The main data is collected from three main sources:

(i) administrative records related to oil spill events, inspections, and enforcement, collected from EEAA, EAMS, and IMO (1990-2023);

(ii) twenty-five semi-structured interviews carried out in 2023 with purposively selected officials from EEAA, EAMS, and Suez Canal Authority.

(iii) observations at ports in Suez, Port Said, and Hurghada to determine the availability and functionality of oily-waste reception facilities.

The quantitative data are structured into 33 port and coastal areas, which include Egypt's Mediterranean coast ($n = 12$), the Suez Canal area ($n = 9$), and the Red Sea/Gulf of Suez ($n = 12$). These areas are determined by administrative port boundaries and surrounding operational areas where spill and enforcement data are available.

The secondary data include peer-reviewed literature related to Egypt, regional compliance rates, and satellite remote sensing images used for contextual validation.

8.4 Data Validation and Reliability

To enhance the accuracy of the data, a two-step verification process is adopted. First, the oil spill records are verified based on date-location matching criteria among the EEAA, EAMS, and IMO datasets. Later, for the post-2000 period, the recorded incidents are verified through MODIS and Sentinel-1 SAR satellite images within a temporal window of ± 3 days and a spatial window of ≤ 10km.

Instead of removing observations with extreme values by default, sensitivity analysis is conducted through re-estimation with and without extreme years to assess robustness.

8.5 Overview of Data Inputs and Analytical Purpose

Table.1 provides a concise summary of the relationship between data sources, time coverage, geographic focus, and analytical purpose, providing a comprehensive view of the empirical inputs that inform the mixed-methods design.

Table 1. Data

Data Type	Source	Temporal Coverage	Spatial Unit / Sample	Rationale
Oil spill frequency & volume (reported incidents)	EEAA, EAMS, IMO	1990–2023	33 port/coastal areas (Mediterranean n=12; Suez Canal corridor n=9; Red Sea/Gulf of Suez n=12)	Baseline for time-series trend analysis and outcome measurement (frequency and volume where available)
Satellite imagery (MODIS; Sentinel-1 SAR)	NASA; ESA	2000–2023	250 m–10 m pixels; matched to reported incidents (±3 days; ≤10 km)	Independent validation/corroboration of reported incidents and spatial extent (post-2000)
Legal and policy texts (Annex I transposition)	Official Gazette; Ministry of Environment	1994–2023	National instruments (e.g., Law No. 4/1994; Decree No. 73/2013)	Establish regulatory variables and implementation milestones used in the institutional/legal analysis
Institutional enforcement and coordination records	EEAA; EAMS; SCA	2005–2023	3 operational zones (Mediterranean; Suez Canal corridor; Red Sea/Gulf of Suez)	Assess enforcement architecture, inter-agency coordination, inspection workflows, and follow-up procedures by zone
Port observation visits (reception facilities and procedures)	Direct observation (author); port authorities	2023	3 ports (Suez; Port Said; Hurghada)	Assess availability and functionality of waste reception arrangements and operational constraints
Expert interviews (N=25)	EEAA (n=9); EAMS (n=8); SCA (n=8)	2023	Purposive; roles: inspectors (n=7), compliance/response (n=6), reception oversight (n=4), legal/policy (n=4), senior managers (n=4)	Capture experiential evidence on Annex I enforcement barriers, coordination gaps, and compliance behavior

Data Type	Source	Temporal Coverage	Spatial Unit / Sample	Rationale
Oil spill frequency & volume	EEAA, EAMS, IMO	1990–2023	33 port areas	Baseline for quantitative trend modelling
Satellite imagery (MODIS, Sentinel-1 SAR)	NASA & ESA	2000–2023	250 m–10 m pixels	Independent validation of reported incidents
Legal and policy texts	Official Gazette, Ministry of Environment	1994–2023	—	Establish regulatory variables
Institutional data	EEAA & SCA	2005–2023	3 main zones	Assess inter-agency efficiency
Expert interviews (N = 25)	EEAA, EAMS, SCA officials	2023	Purposive	Capture experiential knowledge and enforcement barriers

Sources, temporal coverage, and analytical purposes

The table above specifies the empirical inputs used in the research and the role of each input in the mixed-methods design. Administrative records and official documents offer the longitudinal framework for spill outcome description and enforcement actions during the time of the research, while satellite data

Table 1 illustrates the role of administrative records and official documents in offering the longitudinal framework for spill outcome description, satellite imagery in offering spatial validation, legal and policy texts in offering regulatory milestones, and interviews and port observations in offering institutional context for the interpretation of quantitative and spatial pattern.

8.6 Methodological Integration

The quantitative and qualitative analysis are carried out separately and then combined through triangulation. The quantitative findings identify when and where the changes in the outcomes of spills happen, and the qualitative findings explain how and why the changes are associated with enforcement practices, institutional coordination, and capacity. The combination of the two improves inferences by linking the observed environmental outcomes to the possible mechanisms of enforcement instead of relying on one source or technique.

9. Data Collection and Analysis

This section describes the quantitative and qualitative analysis methods used to evaluate the outcomes of MARPOL Annex I implementation in Egypt. The quantitative part of the analysis estimates the outcomes of oil spill changes at major implementation milestones, while the qualitative part of the analysis explains the institutional mechanisms and implementation challenges using document analysis and interviews.

Findings are integrated using a triangulation matrix, and robustness is assessed through standard diagnostic and sensitivity checks.

9.1 Quantitative analysis

The quantitative component evaluates whether (i) oil-spill outcomes declined following Egypt's MARPOL Annex I–aligned regulatory milestones and (ii) whether enforcement and port-capacity variables predict spill outcomes across ports and time. Analyses are conducted using (a) a national annual time series (1990–2023) and (b) a port-area-year panel (1990–2023) across 33 port/coastal areas (Mediterranean n=12; Suez Canal corridor n=9; Red Sea/Gulf of Suez n=12). Segmented (interrupted) time-series regression is used for milestone evaluation (Wagner et al., 2002; Lopez Bernal et al., 2017), count-data models are used for spill incidents (Cameron & Trivedi, 2013), and kernel density estimation is used for hotspot mapping (Silverman, 1986; Esri, n.d.). For contextual regional benchmarking, the study reports the MARPOL Annex I implementation index published by Badr (2023) as a secondary reference; this index is not constructed from the present study's administrative datasets.

9.1.1 Descriptive change (period comparison)

A simple descriptive effect size is computed as the percentage change between a baseline period and a comparison period (Stock & Watson, 2020):

$$\Delta\% \ = \left(\frac{\bar{Y}_{post} - \bar{Y}_{pre}}{\bar{Y}_{pre}}\right) \times 100$$

Where:

$\Delta\%$= percentage change between periods;

$\bar{Y}_{pre}$= mean annual outcome in the baseline period (e.g., pre-1994);

$\bar{Y}_{post}$= mean annual outcome in the comparison period (e.g., post-1994);

Y may be spill frequency (incidents/year) or spill volume (units as reported in official records).

9.1.2 Interrupted time-series segmented regression (policy milestone effects)

To estimate changes associated with key milestones (1994 and 2013), annual spill outcomes are modeled using segmented regression (Wagner et al., 2002; Lopez Bernal et al., 2017):

$$Y_t \ = \ \beta_0 + \beta_1\, time_t + \beta_2\, post1994_t + \beta_3\, time1994_t + \beta_4\, post2013_t + \beta_5\, time2013_t + \varepsilon_t$$

Where:

Y_t= national annual spill outcome in year t(spill incidents or spill volume);

$time_t$= time trend (e.g., $t = 1$for 1990, …, $t = 34$for 2023), or calendar year coded consistently;

$post1994_t$= 1 for years $t \geq 1994$, otherwise 0;

$time1994_t$= 0 for years before 1994; $(time_{1994})$for years $t \geq 1994$;

$post2013_t$= 1 for years $t \geq 2013$, otherwise 0;

$time2013_t$= 0 for years before 2013; $(time_{2013})$for years $t \geq 2013$;

β_0= baseline intercept;

β_1= baseline pre-1994 trend (slope);
β_2= immediate level change after 1994;
β_3= change in slope after 1994;
β_4= immediate level change after 2013;
β_5= change in slope after 2013;
ε_t= error term.

Autocorrelation and heteroskedasticity are addressed using HAC/robust inference as appropriate (Newey & West, 1987; White, 1980).

9.1.3 Panel model linking enforcement conditions to spill outcomes

When port-area-year observations are available, spill outcomes are related to enforcement proxies using a fixed-effects panel specification (Wooldridge, 2010; Cameron & Trivedi, 2013). For incident counts, a fixed-effects count model with log link is used:

$$E\,[X_{it}] \;=\; exp\,(\beta_3\,Reception_{it})$$

Where:

Y_{it}= spill outcome for port/coastal area $i$in year t(incident count, or volume where modeled);
α_i= port-area fixed effect (controls time-invariant differences across areas);
δ_t= year fixed effect (controls common annual shocks/trends);
$Inspect_{it}$= inspection frequency proxy in area i, year t;
$Enforce_{it}$= enforcement actions proxy in area i, year t;
$Reception_{it}$= reception capacity proxy in area i, year t;
$\beta_1, \beta_2, \beta_3$= estimated associations between enforcement proxies and spill outcomes.

Robust standard errors are used, and sensitivity checks may include alternative count specifications (e.g., Poisson FE; negative binomial sensitivity) as described in the robustness table.

9.1.4 Spatial hotspot mapping (kernel density estimation)

Spill clustering is mapped using kernel density estimation (Silverman, 1986) as implemented through ArcGIS Pro's kernel density tool (Esri, n.d.):

$$\hat{f}_h(s) \;=\; \frac{1}{n\,h^2}\sum_{i=1}^{n} k\left(\frac{d(s, s_i)}{h}\right)$$

Where:

$\hat{f}_h(s)$= estimated spill-event intensity (density) at location s;
s= spatial location (map coordinate) in the study region;
s_i= location of spill event i;
n= number of spill events included for the chosen period;
h= bandwidth (search radius) controlling smoothing;

$d(\cdot)$= distance metric used by the GIS setting;
$K(\cdot)$= kernel function weighting nearby points more than distant points.

Bandwidth/cell-size settings are reported and hotspot stability is tested using alternative defensible bandwidth values (Silverman, 1986; Esri, n.d.)

9.2 Qualitative analysis

Qualitative evidence is used to explain implementation mechanisms and interpret quantitative patterns. Two sources are analyzed: (i) document analysis of national legal/policy texts and institutional records, and (ii) semi-structured interviews with relevant officials and practitioners.

Document analysis follows established qualitative procedures for systematic extraction and triangulation of information from documents. Interview and document materials are coded using thematic analysis. The codebook combines (a) deductive codes aligned with Annex I enforcement functions (inspection routines, documentation verification, reception facility access, enforcement follow-up, monitoring/reporting, inter-agency coordination) and (b) inductive codes that emerge from interview narratives and observation notes.

9.3 Integration of quantitative and qualitative findings

A convergent mixed-methods approach is applied: quantitative and qualitative analyses are conducted separately and then merged using a joint display (triangulation matrix), which is a recommended method for transparent integration in mixed-method studies (Fetters et al., 2013). The matrix aligns quantitative results (e.g., post-milestone trend changes; hotspot persistence; predictor associations) with qualitative themes (e.g., coordination gaps, reception-facility barriers, inspection bottlenecks). Divergence across evidence streams is explicitly analyzed and reported as potential underreporting, definitional mismatch, or institutional/data limitations.

9.4 Validation, reliability, and robustness

Quantitative robustness. Robustness is assessed using alternative model forms for spill counts (Poisson vs. negative binomial), alternative intervention windows where justified, and re-estimation with and without extreme years (sensitivity checks) rather than automatic outlier deletion (Yaseen, 2018). Heteroskedasticity-robust inference is applied and where serial correlation is present, HAC estimators are used. Where relevant, serial correlation diagnostics can be reported (MacKinnon, 2012).

Data validation and triangulation.

Reported incidents are cross-checked across administrative sources (EEAA/EAMS/IMO) when overlap exists, and for the post-2000 period, remote sensing (MODIS/Sentinel-1 SAR) is used as an independent corroboration layer with a documented temporal/spatial matching window. Port observation visits are used to validate claims regarding reception-facility functionality and operational constraints.

Qualitative reliability.

Reliability is supported through codebook documentation, audit trails linking themes to underlying evidence, and re-coding checks. When multiple coders are used, agreement can be assessed using established content-analysis reliability procedures (Krippendorff, 2018). If the study includes any multi-item survey scales, internal consistency can be evaluated using Cronbach's alpha (Robinson,2018); otherwise, interview-based thematic analysis reliability is documented through codebook stability and audit procedures.

10. Discussion and Analysis

10.1 Overview of Analytical Approach

This section evaluates whether the implementation of MARPOL Annex I in Egypt is associated with improved oil-pollution outcomes during the period 1990–2023. The analysis combines four different strands of evidence: (i) national time-series trends, (ii) panel associations between enforcement conditions and spill outcomes for port areas, (iii) hotspot analysis employing GIS, and (iv) qualitative institutional evidence from interviews and document analysis.

The analysis is organized around three key questions: what have been the outcomes of spills over time, where have geographic changes occurred, and how have enforcement and institutional mechanisms affected these changes.

10.2 Temporal Trends in Oil-Spill Outcomes

The analysis combines four different types of evidence: (i) national time-series trends, (ii) panel associations between enforcement conditions and spill outcomes for port areas, (iii) hotspot analysis using GIS, and (iv) qualitative institutional evidence from interviews and document analysis. The analysis is organized around three key questions: What changes occurred in spill outcomes over time, where did geographic changes occur, and how did the mechanisms of enforcement and institutions bring these changes about.

Table 2. Descriptive period comparisons of oil-spill outcomes and enforcement activity

Period	Avg. annual spills	Avg. reported spill volume (tons)	Enforcement cases	Trend direction (descriptive)
1990–1993 (Pre-MARPOL)*	21	45,000	3	Escalating pollution
1994–2009 (Early enforcement phase)	9	18,000	14	Moderate decline
2010–2023 (Strengthened compliance phase)	4	7,000	26	Strong decline

The average results of spill and enforcement activity during the phases of implementation are shown in Table 2, providing a clear description of the type and timing of change. The interrupted time-series analysis also provides evidence of a structural shift in the results of spill around the important milestones of implementation, particularly those related to improved enforcement and documentation systems. While there is no possibility of establishing causality, the coincidence of changes in the strength of regulation and spill results is significant. The long-term trend in oil-spill incidents is illustrated in Figure 1, which shows a clear downward trajectory consistent with the descriptive and model-based findings.

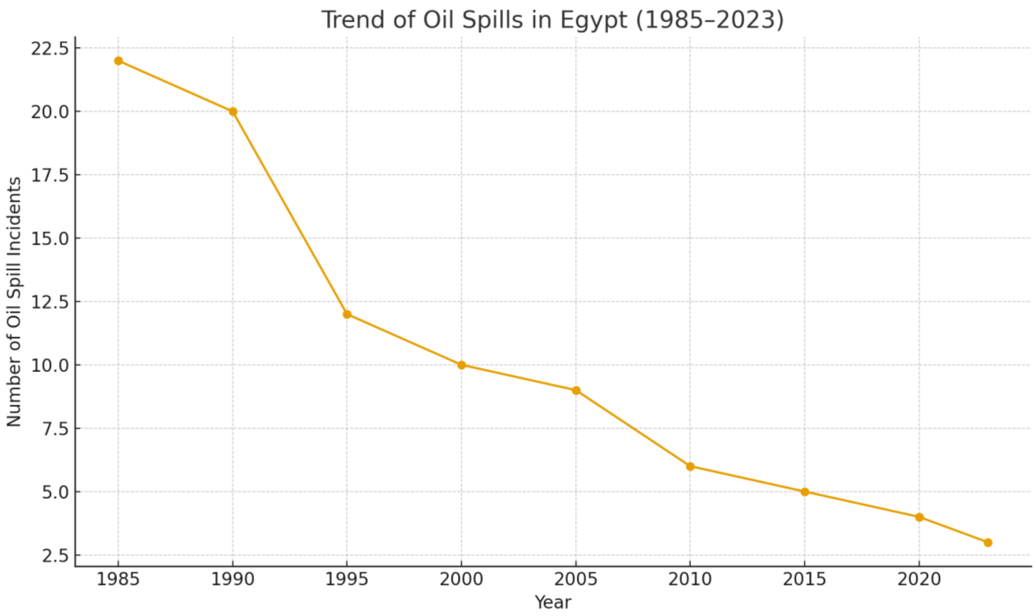


Figure 1. Trend of oil-spill incidents in Egypt (1990–2023)

10.3 Enforcement Conditions and Spill Outcomes

To complement the national trend analysis, this study examines whether variation in enforcement-related conditions is associated with differences in spill outcomes across ports and time. Multivariate analysis focuses on inspection frequency, enforcement actions, and reception-facility availability as key predictors consistent with Annex I compliance logic.

Table 3. Multivariate associations between enforcement-related predictors and spill outcomes

Predictor (standardized)	Standardized β	p-value	Interpretation (academic, non-causal)
Inspection frequency (X_1)	− 0.48	< 0.01	Higher inspection activity is related to worse spill outcomes, consistent with deterrence and improved compliance monitoring.

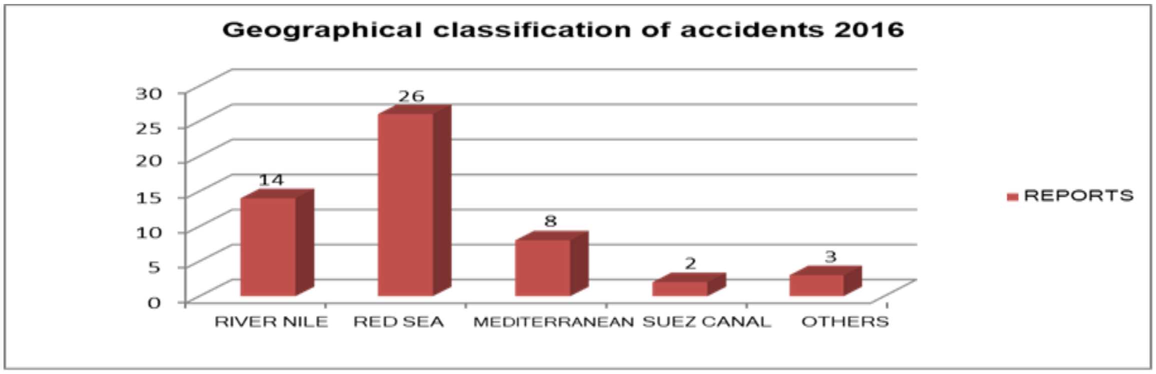
Predictor (standardized)	Standardized β	p-value	Interpretation (academic, non-causal)
Enforcement cases (X_2)	− 0.37	0.02	More enforcement activity is associated with lower spill outcomes, consistent with increased expected costs of non-compliance.
Reception capacity availability (X_3)	− 0.29	0.04	Greater reception-capacity availability is associated with lower spill outcomes, consistent with improved feasibility of compliant waste handling.

As shown in Table 3, higher inspection activity, stronger enforcement follow-through, and greater availability of reception facilities are each negatively associated with spill outcomes.
These findings are consistent with the interpretation that enforcement credibility and feasibility of enforcement are factors in the reduction of pollution incidents. The results are interpreted as being associational, rather than causal, in nature, recognizing the possibility of endogeneity and non-standard reporting practices. However, the consistency of the associations with temporal patterns and qualitative evidence improves their interpretive validity.

10.4 Spatial Distribution and Hotspot Dynamics

The kernel density analysis of spatial data reveals the existence of a fixed geographical pattern of oil spill incidents along the main operational routes, such as the Suez Canal and the approach areas to the ports. These areas are characterized by high ship density and complex operational patterns.
With time, the spill hotspot intensity becomes more fragmented and localized, suggesting a decrease in the number of major high-risk spill hotspots rather than the disappearance of spill risk. The geographical pattern of the spill hotspots at different times is shown in Figure 2.

Figure 2. Spatial distribution of oil-spill hotspots across Egyptian coastal/port areas (KDE surfaces, selected periods)



Source: Author based on data collected from Egyptian Environmental Affairs Agency.

Robustness checks confirm that these spatial patterns are stable across alternative GIS parameter settings, reinforcing their analytical reliability.

10.5 Institutional Mechanisms and Qualitative Evidence

Qualitative evidence from 25 semi-structured interviews provides insight into the institutional mechanisms underlying the quantitative and spatial findings as shown in table 4. Four recurring themes emerge: inter-agency coordination and role clarity, technical and human capacity constraints, legal consistency and enforcement credibility, and the role of information systems and monitoring technologies.

Table 4. Summary of thematic analysis of stakeholder interviews (N = 25)

Theme	Coding frequency (%)	Illustrative statement (anonymized)
Inter-agency coordination	32	"Overlapping inspection responsibilities can delay a unified response."
Technical & human capacity	26	"Regional units need more training and better real-time data tools."
Legal & enforcement consistency	23	"Stronger penalties improved deterrence, but consistency matters."
Technological modernisation	19	"Tracking and monitoring tools reduced undetected discharges."

Coding frequency (%) reflects the share of coded references across all interviews attributable to each theme (themes are not mutually exclusive; a single interview may contribute to multiple themes).

The respondents were consistent in pointing out that the initial implementation was hampered by overlapping responsibilities and fragmented workflows. The observed improvements after 2013 were attributed to better allocation of responsibilities, synchronization of inspection procedures, and improved access to vessel tracking and monitoring data.

The existing capacity and infrastructure deficits also help to explain the persistence of spill risk.

10.6 Integrated Interpretation and Triangulation

The convergent mixed-methods design allows for the combination of quantitative, spatial, and qualitative data through systematic triangulation. On all strands, the results point to a consistent pattern of change: spill outcomes are decreased in subsequent phases of implementation, enforcement-related conditions are associated with better outcomes, and the risk of spatial spill becomes less concentrated with time. Where there is divergence, this is due to the limitations of reporting, capacity differences, or localized operational constraints rather than a contradiction of the pattern. The evidence supports a mechanism-based interpretation in which MARPOL Annex I implementation is most effective when legal provisions, enforcement capacity, reception infrastructure, and information systems operate as an integrated chain.

11. Conclusion

This research examines the relationship between MARPOL Annex I compliant implementation in Egypt and recorded patterns of marine oil pollution outcomes from 1990 to 2023. Using a mixed-methods research design, this study combines national time-series evaluation, multivariate associations related to enforcement, geographic information system hotspot mapping in port and coastal regions, and qualitative evidence from semi-structured interviews with key implementing officials. By combining these approaches, this research seeks to enhance inference by connecting patterns of outcomes to likely mechanisms of enforcement and geographic operation, rather than focusing on a single body of data or research tradition.

Across the different bodies of evidence, the results suggest a pattern of improvement in oil spill outcomes in the latter stages of implementation compared to earlier stages. Descriptive time-series comparisons suggest a pattern of reduced spill outcomes in more contemporary stages of implementation, while the time-series reasoning supports an inference that changes in spill patterns are temporally associated with major implementation milestones.

The multivariate part of the analysis finds support for a mechanism-based interpretation, suggesting that enforcement-related factors, specifically the activity of inspections, the follow-through on enforcement, and the availability of reception facilities to facilitate compliant waste management, are each related to better spill outcomes. The geographic analysis provides a complement to the operational assessment by pointing to high-risk corridors and approaches to ports, suggesting that the effectiveness of implementation remains a concern in space despite improvements. The qualitative findings provide a holistic interpretation of the translation of legal and institutional provisions to operational success. The themes of the interviews suggest that progress is contingent upon mandates, technical capacity, human capacity, and information systems that can enable detection, verification of documentation, and subsequent action.

At the same time, there is recognition of the challenges that exist, such as the difficulties of coordination, disparities in capacity at different sites, and the requirements of high-traffic routes, which are typical in high-risk areas and suggest that the risk of spills may continue. the implications of the current study for policy and enforcement in Egypt are several. First, it is obvious that an integrated approach, which combines enforcement, infrastructure, and information, is necessary since the credibility of enforcement activities could be questioned if there is not a corresponding level of reception infrastructure and monitoring and reporting systems. Second, the hotspot method is a valuable tool for resource allocation since inspection and surveillance activities need to concentrate on high-risk roads and routes to ports, with periodic adjustment to reflect changes in traffic and infrastructure patterns.

Third, it is important to recognize that the importance of institutional coordination is an implementation consideration rather than a formality because the lack of coordinated mandates and different reporting systems could affect both deterrence and measurement.

Some limitations of the study are worth noting. Spill records could be prone to underreporting or changes in reporting patterns over time, and enforcement effort may react endogenously to perceived risk, making causal inference more complex. Nevertheless, the study chooses to view quantitative associations mainly as indicators of temporal coincidence and association, which are reinforced by spatial and qualitative mechanisms of triangulation. Future studies might improve causal inference by including measures of vessel traffic exposure, using quasi-experimental controls where appropriate (such as comparative corridors or ports with varying implementation intensity), and extending the spatial analysis with geocoding and exposure standardization.

In conclusion, there is evidence to support a mechanism-based inference that MARPOL Annex I-compliant implementation in Egypt is most likely to be related to better oil pollution outcomes when compliance is defined in terms of the integrated institutional roles, effective follow-up on inspection and enforcement, sufficient reception facilities, and information systems supporting targeted monitoring. Improving these interlocking elements, especially in areas of persistent high risk, provides a viable route to further mitigate marine oil pollution and to consolidate gains in regulation.

References

- Abdelkader, A., Elshorbagy, A., Tuninetti, M., Laio, F., Ridolfi, L., Fahmy, H., & Hoekstra, A. Y. (2018). National water, food, and trade modeling framework: The case of Egypt. *Science of The Total Environment*, *639*, 485–496. https://doi.org/10.1016/j.scitotenv.2018.05.197

- Baghdady, S. M., & Abdelsalam, A. A. (2024). Ten years of oil pollution detection in the Eastern Mediterranean shipping lanes opposite the Egyptian coast using remote sensing techniques. *Scientific Reports*, *14*(1), 18057. https://doi.org/10.1038/s41598-024-67983-x

- Bakr, K. A., Helal, H., & Abdelkader, S. (2024). Collision between supply vessels and offshore installations case cargo handling and personal transferring operation. *AIN Journal*, *48*(2). DOI NO. https://doi.org/10.59660/48701

- Carpenter, A., & Kostianoy, A. G. (2018). *Conclusions for Part I: The International Context* (pp. 325–344). https://doi.org/10.1007/698_2018_374

- Cui, B., Wang, C., Wu, Y., Zhu, C., Lin, J., & Yang, T. (2024). Intelligent monitoring of marine vessel dynamics based on data mining. *Ocean Engineering*, *313*, 119387. https://doi.org/10.1016/j.oceaneng.2024.119387

- Etkin, D. S. (2023). *Trends and Observations on 50 Years of Oil Spill Statistics*. https://doi.org/10.2139/ssrn.4674400

- El-Magd, I. A., Zakzouk, M., Ali, E. M., & Abdulaziz, A. M. (2021). An open source approach for near-real time mapping of oil spills along the mediterranean coast of Egypt. Remote Sensing, 13(14), 2733.

- El-Sayed, A., Hassan, N., & Farag, R. (2021). GIS mapping of oil pollution hotspots along Egypt's coasts. Environmental Monitoring Reports, 16(4), 44–60.

- Hoarau, J.-F. (2022). Is international tourism responsible for the outbreak of the COVID-19 pandemic? A cross-country analysis with a special focus on small islands. *Review of World Economics*, *158*(2), 493–528. https://doi.org/10.1007/s10290-021-00438-x

- Hassan, E. A. (2020). Maritime surveillance in Egypt: status of vessel traffic management system and opportunities for future improvements.

- Hegazy, I. R., & Tohlob, A. A. (2024). Strategic environmental assessment and SDG integration: enhancing sustainable development in Egypt. *Journal of Umm Al-Qura University for Engineering and Architecture*, *15*(3), 340–354. https://doi.org/10.1007/s43995-024-00062-4

- Khalil, M. (2020). Institutional overlaps in Egypt's maritime environmental governance. Cairo Journal of Public Administration, 6(2), 77–95.

- Karim, S. (2016, March). Marine pollution in the Bay of Bengal: In search of a legal response. In *Seminar*.

- Kanso, A. M., Nelson, R. A., & Kitchen, P. J. (2020). BP and the Deepwater Horizon oil spill: A case study of how company management employed public relations to restore a damaged brand. *Journal of Marketing Communications*, *26*(7), 703–731. https://doi.org/10.1080/13527266.2018.1559218

- Kostianaia, E. A., Kostianoy, A., Lavrova, O. Yu., & Soloviev, D. M. (2020). *Oil Pollution in the Northern Red Sea: A Threat to the Marine Environment and Tourism Development* (pp. 329–362). https://doi.org/10.1007/978-3-030-39593-3_12

- Krippendorff, K. (2018). *Content analysis: An introduction to its methodology*. Sage publications.

- Ministry of Environment, Egyptian Environmental Affairs Agency, Egypt State of the Environment Report (2016). http://www.eeaa.gov.eg/enus/mediacenter/reports/soereports.aspx

- MacKinnon, J. G. (2012). Thirty years of heteroskedasticity-robust inference. In *Recent advances and future directions in causality, prediction, and specification analysis: Essays in honor of Halbert L. White Jr* (pp. 437-461). New York, NY: Springer New York.

- Ramahlo, R. M., Pillay, A. M., & Madzimure, J. (2022). Assessing the effectiveness of compliance inspection in ensuring the quality of ICT products and services: a case of the compliance department at ICASA. *EUREKA: Social and Humanities*, (2), 15-25.

- Robinson, M. A. (2018). Using multi-item psychometric scales for research and practice in human resource management. *Human resource management*, *57*(3), 739-750.

- Radwan, M. E., Chen, J., Wan, Z., Zheng, T., Hua, C., & Huang, X. (2019). Critical barriers to the introduction of shore power supply for green port development: case of Djibouti container terminals. *Clean Technologies and Environmental Policy*, *21*(6), 1293–1306. https://doi.org/10.1007/s10098-019-01706-z

- Saputra, D., Gaol, F. L., Abdurachman, E., Sensuse, D. I., & Matsuo, T. (2023). A model of service-oriented architecture of e-certification system to support boat registration and site visit inspection to support maritime safety and crew health inspection. *Marine Systems & Ocean Technology*, *18*(1–2), 45–63. https://doi.org/10.1007/s40868-023-00128-3

- Ullah, S., Daud, H., Zainuddin, N., C Dass, S., Khalil, A., Fanaee-T, H., & Khan, I. (2021). Space-time Cluster Analysis of Accidental Oil Spills in Rivers State, Nigeria, 2011-2019. *Computers, Materials & Continua*, *66*(3), 3065–3074. https://doi.org/10.32604/cmc.2021.012624

- Yaseen, A. (2018). *Essays on Environmental and Labor Economics* (Doctoral dissertation, University of Kansas).

- Zafirakou, A., Palantzas, G., Samaras, A., & Koutitas, C. (2015). Oil Spill Modeling Aiming at the Protection of Ports and Coastal Areas. *Environmental Processes*, *2*(S1), 41–53. https://doi.org/10.1007/s40710-015-0100-8