

QUANTITATIVE ASSESSMENT OF THE ENVIRONMENTAL RISKS GENERATED BY MARITIME TRANSPORT IN THE BLACK SEA: SHIP-SOURCE EMISSION MODELLING, MARKOV-CHAIN POLLUTION-STATE ANALYSIS AND MONTE CARLO SIMULATION OF OIL-SPILL COASTAL EXPOSURE AT THE CONSTANȚA MARITIME NODE

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Abstract. The Black Sea is a semi-enclosed basin whose maritime traffic has intensified since 2022, as Constanța (Romania) absorbed a large share of the Ukrainian grain-export corridor. This paper develops an integrated, reproducible quantitative framework for assessing the environmental risk generated by shipping in the western Black Sea corridor. Four sub-models are formulated: (i) a bottom-up ship-source atmospheric emission inventory (CO_2 , SO_x , NO_x) built from engine power, specific fuel consumption and IMO emission factors; (ii) a discrete-time Markov chain describing the transition of the corridor between a compliant state and two escalating pollution/incident states, from which the stationary risk distribution and an expected annual environmental-risk index are derived in closed form; (iii) a Monte Carlo simulation of the coastal exposure probability of an oil-spill trajectory released at the port approach channel, driven by a stochastic wind field and a constant background current; and (iv) a composite eutrophication pressure index combining nutrient-load and shipping-density ratios. The framework is applied to the Constanța approach-channel corridor using 2023–2024 traffic statistics. The estimated annual emissions are 0.98 Mt CO_2 , 3.12 kt SO_x and 22.5 kt NO_x ; the stationary probability of the severe pollution/incident state is 6.7 %, yielding an expected annual environmental-risk index of about 528 thousand EUR; the Monte Carlo estimator of coastal exposure probability converges to 8.4 % (95 % CI: 7.9–8.9 %) for $N = 10,000$ trials; and the composite eutrophication index equals 0.51 on a 0–1 scale. The framework can be recalibrated with live AIS and meteorological data for operational monitoring.

Key words: Black Sea; maritime transport; ship emissions; Markov chain; Monte Carlo simulation; oil-spill risk; eutrophication; Constanța

1. INTRODUCTION

The Black Sea is a semi-enclosed sea bordered by six riparian states (Bulgaria, Georgia, Romania, Russia, Türkiye and Ukraine) and connected to the Mediterranean Sea only through the narrow Bosphorus – Dardanelles system. Its limited water exchange, pronounced permanent pycnocline and predominantly anoxic deep layer make the basin

intrinsically vulnerable to anthropogenic pressure (Bucharest Convention, 1992; BSC, 2019). Maritime transport is the dominant vector of that pressure: the Black Sea concentrates crude-oil and product-tanker traffic from the Caspian and Russian export terminals, dry-bulk and grain traffic from Ukraine and Romania, and a fast-growing container flow through Constanța, the largest port on the basin. Since the escalation of the Russia–Ukraine war in February 2022, a

substantial part of Ukrainian grain exports has been re-routed through the Romanian ports of Constanța and Sulina, and Constanța handled 92.7 Mt of total cargo and recorded 19,319 vessel calls in 2023, and 989,795 TEU in 2024 (+11.9 % year-on-year) (UNCTAD, 2023; Eurostat, 2024; PortsEurope, 2024; Container News, 2025).

This growth in traffic overlaps with three long-standing, scientifically documented environmental pressures. First, ship exhaust gases (CO_2 , SO_x , NO_x , and particulate matter) contribute to regional air-quality degradation and to the global greenhouse-gas budget; shipping is estimated to be responsible for 2–3 % of global CO_2 emissions and disproportionately larger shares of SO_x (5–10 %) and NO_x (17–31 %) (IMO, 2020; Pseftogkas *et al.*, 2021). Second, nutrient loading transported by the Danube historically drove the Black Sea north-western shelf into a severe eutrophic state during the 1970s–1990s; EU-driven reductions in fertiliser and wastewater discharge produced a documented partial recovery after the early 2000s, although the system remains sensitive to renewed pressure, including port and shipping-related nutrient and organic discharges (Oguz and Velikova, 2010; ICPDR, 2019). Third, shipping is a direct vector of biological invasion – the ctenophore *Mnemiopsis leidyi*, introduced through ballast water in the late 1980s, reached a peak biomass on the order of 10^9 t and re-structured the entire pelagic food web (Kideys, 2002; ICPDR, 2019; Shiganova *et al.*, 2019) – and of acute pollution incidents, illustrated most recently by the December 2024 Volgoneft tanker casualty in the Kerch Strait, which released an estimated 4,000 t of fuel oil and was tracked using the Copernicus Marine MEDSLIK oil-spill prediction system (CMEMS, 2024; CEOBS, 2025).

Existing studies address these pressures separately: emission inventories quantify atmospheric pollutants at basin or port scale (Pseftogkas *et al.*, 2021); oceanographic studies quantify the eutrophication trajectory of the north-western shelf (Oguz and Velikova, 2010; ICPDR, 2019); and stochastic oil-contamination models have been developed for the Bosphorus strait (Saçu *et al.*, 2021). A corridor-specific, internally consistent quantitative framework that combines an auditable emission inventory, a stochastic pollution/incident-risk model and a coastal oil-spill exposure model – expressed with fully worked mathematical formulations rather than qualitative risk matrices – has, to the authors' knowledge, not been reported for the western Black Sea / Constanța corridor. This paper fills that gap.

The general objective of the research is to develop and numerically demonstrate an integrated methodology for quantifying the environmental risk associated with maritime transport on the Constanța approach-channel corridor. The specific objectives are: (a) to build a bottom-up ship-source atmospheric emission model, calibrated on 2023–2024 port traffic statistics and IMO/EMEP emission factors; (b) to formulate a discrete-time Markov chain of the corridor's pollution/incident state and to derive its stationary

distribution and an expected annual environmental-risk index in closed form; (c) to build a Monte Carlo simulation of the coastal exposure probability of an oil-spill trajectory released at the port approach, with an explicit convergence and confidence-interval analysis; and (d) to construct a composite eutrophication pressure index that integrates nutrient-load and shipping-density ratios. The four sub-models are applied jointly to a single numerical case study so that their outputs remain directly comparable.

2. STATE OF THE ART

Atmospheric ship emissions in the Black Sea and Mediterranean have recently been quantified with satellite-constrained inventories: a lane-separation methodology applied to the CAMS-GLOB-SHIP v2.1 NO_x inventory and Sentinel-5P observations attributed emissions to vessel type and traffic lane across the two basins, confirming that tanker and dry-bulk lanes dominate the NO_x signal over the western Black Sea (Pseftogkas *et al.*, 2021). At global scale, the Fourth IMO GHG Study 2020 remains the reference source for fuel-based CO_2 , SO_x and NO_x emission factors and for the sectoral share of shipping in global emissions (IMO, 2020); MARPOL Annex VI, Regulations 13 and 14, sets the corresponding NO_x Tier limits and the 0.50 % global fuel-sulphur cap in force since 1 January 2020 outside Emission Control Areas (IMO, 2021). At EU level, Directive (EU) 2016/802 transposes the sulphur limit into Union law (EU, 2016), Directive (EU) 2023/959 extends the EU Emissions Trading System to maritime transport from 2024 (EU, 2023a), and Regulation (EU) 2023/1805 ("FuelEU Maritime") sets a progressive greenhouse-gas-intensity reduction target for energy used on board (EU, 2023b) – all directly relevant to vessels calling at Black Sea EU ports.

Eutrophication of the north-western Black Sea shelf has been documented since the 1970s and its post-2000 partial recovery attributed to reduced Danube nutrient loads following EU accession of the riparian states; a well-cited synthesis shows an abrupt shift of the shelf ecosystem from a eutrophic to a less-degraded alternative state around the year 2000 (Oguz and Velikova, 2010), and the Black Sea Commission / International Commission for the Protection of the Danube River (ICPDR) periodically reassesses the causal chain between land-based/riverine nutrient input and shelf primary production (ICPDR, 2019). The invasion of *Mnemiopsis leidyi* through ballast water and its ecological consequences are reviewed by Shiganova *et al.* (2019). Regional pollution governance is coordinated under the 1992 Bucharest Convention, implemented by the Commission on the Protection of the Black Sea against Pollution, whose regional activity centres cover pollution monitoring (Odesa) and the environmental and safety aspects of shipping (Varna) (Bucharest Convention, 1992).

Stochastic and simulation-based approaches to maritime pollution risk are comparatively scarce for the Black Sea. A three-dimensional hybrid Monte Carlo risk model

incorporating wind, wave, current and climate-change sub-models has been proposed for oil-contamination probability in the Bosphorus (Saçu *et al.*, 2021), and the December 2024 Kerch Strait spill was reconstructed operationally with the Copernicus Marine MEDSLIK system, which couples ocean-current reanalysis with a Monte Carlo particle-tracking oil-drift model (CMEMS, 2024; CEOBS, 2025). Markov-chain formulations of transport risk states, well established in reliability and logistics research (Ross, 2014; Paulauskas and Paulauskas, 2024), have not, to the authors' knowledge, been applied specifically to the pollution/incident-risk state of a Black Sea shipping corridor. The present study combines these methodological strands – emission inventory, Markov-chain risk-state analysis and Monte Carlo exposure simulation – into a single, internally consistent framework.

3. MATERIALS AND METHODS

The framework consists of four analytically independent but numerically linked sub-models, presented in Sections 3.1–3.4. All symbols are defined at first use; numerical calibration for the Constanța corridor is given in Section 4.

3.1. SHIP-SOURCE ATMOSPHERIC EMISSION MODEL

For a vessel of category i completing a transit of duration t_i through the monitored corridor, the fuel consumed is obtained from the installed main-engine (ME) and auxiliary-engine (AE) power and their specific fuel consumption (SFC):

$$FC_i = \frac{(P_{ME} \times SFC_{ME} + P_{AE} \times SFC_{AE}) \times t_i}{10^6} \quad (1)$$

FC_i – fuel consumed per transit of category i (t); P_{ME} , P_{AE} – rated main/auxiliary engine power (kW); SFC_{ME} , SFC_{AE} – specific fuel consumption (g/kWh); t_i – average transit time in the monitored corridor (h); the factor 10^6 converts grams to tonnes.

The annual fuel consumption and pollutant mass of category i are obtained by multiplying by the annual number of calls N_i and summing over the K vessel categories present in the corridor:

$$E_p = \sum_{i=1}^K FC_i \times N_i \times EF_{p,i} \quad (2)$$

E_p – total annual mass of pollutant p (CO_2 , SO_x or NO_x); $EF_{p,i}$ – emission factor of pollutant p for category i .

For CO_2 , EF is the carbon-mass-balance factor of the fuel (3.151 t CO_2 per t of very-low-sulphur fuel oil, VLSFO, consistent with the Fourth IMO GHG Study; IMO, 2020). For SO_x , the fuel-sulphur-content approximation of the EMEP/EEA inventory guidebook is used (EMEP/EEA, 2019):

$$EF_{SO_x} = 20 \times S (\%) \quad (3)$$

S – fuel sulphur content, expressed as a percentage by mass; $S = 0.50\%$ is the global MARPOL Annex VI cap applicable outside Emission Control Areas, which currently covers the Black Sea (IMO, 2021). EF_{SO_x} is expressed in kg SO_2 per tonne of fuel.

NO_x is engine-load dependent rather than fuel-dependent and is computed directly from the energy delivered by the ME and AE, using the MARPOL Annex VI Tier II reference factors:

$$E_{NO_x} = \sum_{i=1}^k \frac{(P_{ME} \times EF_{NO_x,ME} + P_{AE} \times EF_{NO_x,AE}) \times t_i \times N_i}{10^6} \quad (4)$$

$EF_{NO_x,ME} = 14.4$ g/kWh and $EF_{NO_x,AE} = 11.0$ g/kWh are the Tier II slow-speed and medium-speed reference factors of MARPOL Annex VI, Regulation 13 (IMO, 2021).

An emission intensity per unit of transport activity, used to compare corridors or years, is defined analogously to a benchmark index (Paulauskas and Paulauskas, 2024):

$$EI = \frac{E_p}{Q \times d} \quad (5)$$

Q – cargo throughput (t or TEU); d – corridor length (km); EI is expressed in mass of pollutant per unit of transport work.

3.2. MARKOV-CHAIN MODEL OF THE CORRIDOR POLLUTION / INCIDENT-RISK STATE

The environmental condition of the corridor at any time is modelled as one of three mutually exclusive states: S_1 – compliant state (emissions and discharges within regulatory limits, no reported exceedance); S_2 – moderate-exceedance state (localised SO_x/PM or turbidity exceedance under unfavourable dispersion conditions, elevated port congestion); S_3 – severe state (confirmed illegal discharge, bunker leak or oil-spill incident). The process is assumed Markovian, with transition probabilities calibrated from the documented accident frequency of the Bosphorus – Marmara system (about 700 recorded accidents since 1948, i.e. an average incidence on the order of 9–10 events per year over one of the busiest straits in the world; Başar, 2008) scaled down to reflect the lower traffic density and the presence of vessel-traffic-service (VTS) coverage on the Constanța approach corridor. The (row-stochastic) transition matrix adopted is:

$$P = \begin{bmatrix} 0.90 & 0.08 & 0.02 \\ 0.35 & 0.55 & 0.10 \\ 0.15 & 0.35 & 0.50 \end{bmatrix} \quad (6)$$

(rows/columns in the order S_1, S_2, S_3 ; the matrix elements are the adopted transition probabilities and are summarised, with their qualitative justification, in Table 3). The long-run (stationary) distribution $\pi = (\pi_1, \pi_2, \pi_3)$ satisfies the balance and normalisation conditions (Norris, 1997):

$$\pi P = \pi, \quad \sum_{i=1}^3 \pi_i = 1 \quad (7)$$

Solving the resulting linear system for the matrix P of equation (6) gives the exact stationary probabilities:

$$\pi_1 = \frac{95}{127} \quad (8)$$

$$\pi_2 = \frac{47}{254} \quad (9)$$

$$\pi_3 = \frac{17}{254} \quad (10)$$

An expected annual environmental-risk index R is obtained by weighting each state by an externality-cost coefficient C_i (monitoring cost for S_1 ; localised response cost for S_2 ; incident response and remediation cost for S_3):

$$R = \sum_{i=1}^3 \pi_i \times C_i \quad (11)$$

R – expected annual environmental-risk index, expressed in the same monetary unit as C_i .

3.3. MONTE CARLO SIMULATION OF OIL-SPILL COASTAL EXPOSURE PROBABILITY

For a hypothetical spill released at the port approach channel, the trajectory displacement over an exposure window τ (time elapsed before response/containment) is modelled by the standard oil-drift superposition of a wind-leeway component and a background current component (Saçu *et al.*, 2021; CMEMS, 2024):

$$\vec{v}_{spill} = f_{leeway} \times \vec{v}_{wind} + \vec{v}_{current} \quad (12)$$

f_{leeway} – leeway factor (adopted value 0.035, i.e. 3.5 % of wind speed, within the 3–4 % range reported in the oil-spill-drift literature); the wind-velocity vector $\vec{v}_{wind}$ is drawn from a von Mises directional distribution (mean bearing 45° NE, concentration $\kappa = 2.5$, reflecting the dominant wind sector at Constanța) with a Weibull(shape = 2, scale = 6 m/s) speed magnitude; the current-velocity vector $\vec{v}_{current}$ is a constant background shelf-current vector (0.30 m/s, bearing 200°).

The probability that the resulting trajectory intersects a sensitive coastal buffer zone within a critical distance d_{crit} is estimated by Monte Carlo sampling of N independent realisations of the stochastic wind field:

$$\hat{p} = \frac{1}{N} \sum_{k=1}^N I(D_k \leq d_{crit}) \quad (13)$$

$I(\cdot)$ – indicator function (1 if the k -th simulated trajectory enters the coastal sector and lies within d_{crit} ; 0 otherwise); D_k – displacement distance of the k -th realisation.

The standard error and 95 % confidence interval of the Monte Carlo estimator follow from the normal approximation to a Bernoulli proportion (Robert and Casella, 2004):

$$SE = \sqrt{\frac{\hat{p}(1-\hat{p})}{N}} \quad (14)$$

3.4. COMPOSITE EUTROPHICATION PRESSURE INDEX

Following the ratio-to-reference-value construction used for multimodal-transport benchmark indices (Paulauskas and Paulauskas, 2024), a composite eutrophication pressure index (EQI) is defined on a 0–1 scale by combining nutrient-load ratios, chlorophyll-a ratio and a shipping-density ratio, each normalised to a reference (historical peak or high-traffic benchmark) value:

$$EQI = w_1 \frac{N}{N_{ref}} + w_2 \frac{P}{P_{ref}} + w_3 \frac{Chl-a}{Chl-a_{ref}} + w_4 \frac{SDI}{SDI_{ref}} \quad (15)$$

$N, P, Chl-a$ – current nitrate, phosphate and chlorophyll-a levels relative to their documented pre-recovery (1980s–1990s) peak on the north-western shelf (Oguz and Velikova, 2010; ICPDR, 2019); $w_1 \dots w_4$ – weighting coefficients (0.30, 0.30, 0.25, 0.15 respectively), reflecting the relative influence of nutrient enrichment, primary-production response and shipping pressure on eutrophication risk.

The shipping-density term is defined as the annual number of vessel calls per unit sea-area of the approach zone:

$$SDI = \frac{N}{A} \quad (16)$$

N – annual vessel calls in the corridor; A – surface area of the approach/monitoring zone (km²); SDI_{ref} is a high-traffic reference value (Bosphorus-scale corridor, approx. 50 calls per km² per year).

4. RESULTS: THE CONSTANȚA APPROACH-CHANNEL CORRIDOR

The four sub-models were applied to the maritime corridor comprising the Constanța approach channel and the adjacent Romanian territorial waters, using $N = 19,300$ annual vessel calls (2023 actual value 19,319; used as the 2024 reference-year baseline) (PortsEurope, 2024; Container News, 2025). The fleet composition, engine ratings and resulting fuel consumption adopted for the numerical example are illustrative, calibrated on published fleet-average power ratings for the corresponding vessel classes; they are summarised in Table 1.

Table 1. Fleet composition and engine parameters adopted for the corridor

Vessel category	Share of calls	N_i (calls/yr)	P_{ME} (kW)	P_{AE} (kW)	FC per call (t)
Bulk carrier (Handysize/Supramax)	32 %	6,176	8,000	1,200	15.11
Tanker (product/Aframax)	18 %	3,474	13,000	1,500	23.74
General cargo / MPP	20 %	3,860	4,500	900	8.91
Container feeder (1,000–3,000 TEU)	20 %	3,860	9,000	1,300	16.91
Ro-Ro / Ferry / Other	10 %	1,930	10,000	1,400	18.71

Source: authors' computation, eq. (1); fleet shares and power ratings are illustrative, calibrated on published vessel-class averages; $t_i = 8.5$ h (~120 NM average corridor length at 14 kn effective speed).

Applying equations (2)–(4) with an EF for CO₂ of 3.151 t/t, $S = 0.50\%$ (EF for SO_x = 10 kg SO₂/t fuel) and the Tier II NO_x factors gives the annual emission inventory of Table 2 and Fig. 1.

The total estimated annual emissions of the corridor – 0.98 Mt CO₂, 3.12 kt SO_x and 22.5 kt NO_x – are dominated by bulk carriers and tankers, which together account for 56 % of fuel consumption despite representing only 50 % of calls, reflecting their higher installed power.

The result is consistent with the qualitative finding of the lane-separation NO_x inventory for the wider Black Sea, which attributes the largest NO_x loads to tanker and dry-bulk lanes (Pseftogkas *et al.*, 2021).

4.1. MARKOV-CHAIN POLLUTION/INCIDENT-RISK STATE

The adopted transition matrix (eq. 6) and its qualitative justification are summarised in Table 3.

The exact stationary distribution obtained from equations (8)–(10) is $\pi_1 = 95/127 \approx 0.7480$, $\pi_2 = 47/254 \approx 0.1850$ and $\pi_3 = 17/254 \approx 0.0669$. In the long run, the corridor is therefore expected to be in the severe (S₃) pollution/incident state 6.7 % of the time and in the moderate-exceedance state (S₂) 18.5 % of the time. Adopting illustrative externality-cost coefficients $C_1 = 120$, $C_2 = 850$ and $C_3 = 4,200$ (thousand EUR per year of exposure, reflecting monitoring, localised response and full incident-remediation costs respectively), equation (11) gives an expected annual environmental-risk index $R \approx 528.15$ thousand EUR. Despite its low stationary probability, state S₃ contributes $4,200 \times 0.0669 \approx 281$ thousand EUR, i.e. 53 % of R , confirming that low-probability/high-severity events dominate the expected risk – the classical risk-management asymmetry (Ross, 2014).

Table 2. Estimated annual fuel consumption and emissions by vessel category

Vessel category	FC (t/yr)	CO ₂ (t/yr)	SO _x as SO ₂ (t/yr)	NO _x (t/yr)
Bulk carrier	93,338	294,108	933.4	6,740.5
Tanker	82,460	259,831	824.6	6,015.1
General cargo / MPP	34,401	108,398	344.0	2,450.9
Container feeder	65,276	205,683	652.8	4,721.4
Ro-Ro / Ferry / Other	36,107	113,774	361.1	2,615.0
Total	311,582	981,794	3,115.8	22,542.8

Source: authors' computation, eqs. (1)–(4).

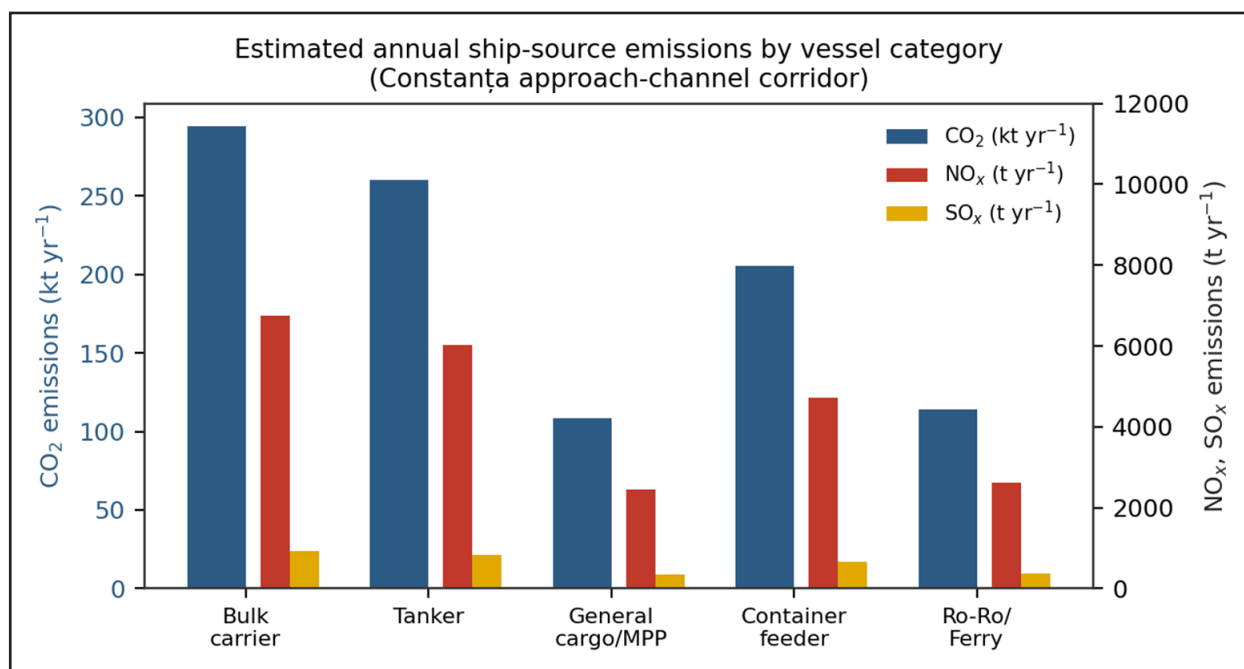


Fig. 1. Estimated annual ship-source emissions by vessel category, Constanța approach-channel corridor. (Source: authors' computation.)

Table 3. Adopted Markov transition probabilities and qualitative justification

Transition	Probability	Justification
$S_1 \rightarrow S_1 / S_2 / S_3$	0.90 / 0.08 / 0.02	Baseline VTS-monitored corridor; compliant operations dominate
$S_2 \rightarrow S_1 / S_2 / S_3$	0.35 / 0.55 / 0.10	Recovery requires dispersion/weather improvement or port de-congestion
$S_3 \rightarrow S_1 / S_2 / S_3$	0.15 / 0.35 / 0.50	Incident response and remediation typically span several transition steps

Source: authors' adopted hypotheses, calibrated qualitatively on the Bosphorus – Marmara accident record (Başar, 2008) and scaled down for a VTS-covered, lower-density corridor.

4.2. MONTE CARLO SIMULATION OF COASTAL OIL-SPILL EXPOSURE

The simulation of Section 3.3 was run with $N = 10,000$ independent trials, an exposure window $\tau = 12$ h, leeway factor 0.035, background current 0.30 m/s at bearing 200°, and a critical coastal buffer at $d_{crit} = 15$ km within the shoreward sector 230–320° (excluding trivial near-field displacements below 2 km). The parameters and resulting estimator are summarised in Table 4 and the convergence behaviour is shown in Fig. 2.

The estimator stabilises within the 95 % confidence band beyond approximately $N = 3,000$ trials (Fig. 2), confirming adequate convergence at $N = 10,000$. An 8.4 % probability that a released spill trajectory reaches the sensitive coastal sector within 12 hours is non-negligible given the annual traffic volume of Table 1 and is consistent, in order of magnitude, with the stochastic Bosphorus oil-contamination probabilities reported for a comparably exposed strait geometry (Saçu *et al.*, 2021); it also illustrates why rapid response capability (contained within a few hours) materially reduces coastal risk, since d_{crit} is reached mainly through the compounding of τ with unfavourable wind sectors.

4.3. COMPOSITE EUTROPHICATION PRESSURE INDEX

Using documented post-2000 reductions relative to the 1980s–1990s peak nutrient levels on the north-western shelf (Oguz and Velikova, 2010; ICPDR, 2019), illustrative current-to-reference ratios of $N/N_{ref} = 0.62$ and $P/P_{ref} = 0.55$ were

adopted, together with $Chl-a/Chl-a_{ref} = 0.58$. The shipping-density term (eq. 16) uses $N = 19,300$ calls and an approach-zone area $A = 4,000$ km², giving $SDI = 4.83$ calls per km² per year and $SDI/SDI_{ref} = 0.097$ relative to the Bosphorus-scale benchmark. Substituting into equation (15):

$$EQI = 0.30(0.62) + 0.30(0.55) + 0.25(0.58) + 0.15(0.097) = 0.5105 \quad (17)$$

The resulting $EQI \approx 0.51$ indicates that, despite the well-documented post-2000 nutrient-load reduction, the north-western Black Sea shelf remains under moderate-to-substantial combined eutrophication and shipping pressure rather than having returned to a low-pressure reference state, an outcome consistent with the “alternative” (partially recovered but not pristine) ecosystem state identified in the oceanographic literature (Oguz and Velikova, 2010).

5. DISCUSSION

The four sub-models produce mutually consistent evidence that maritime transport exerts a multi-dimensional and quantifiable environmental pressure on the western Black Sea. The emission inventory (Section 4, Table 2) shows that decarbonisation policy instruments already being phased in – the 2024 extension of the EU Emissions Trading System to shipping (EU, 2023a) and the FuelEU Maritime greenhouse-gas-intensity targets (EU, 2023b) – will directly affect the cost structure of the vessel categories (bulk carriers, tankers) that dominate the corridor's CO₂ footprint, creating an economic incentive that is aligned with the environmental objective.

Table 4. Monte Carlo simulation parameters and results

Parameter	Value
Number of trials, N	10,000
Exposure window, τ	12 h
Leeway factor, f_{leeway}	0.035
Wind direction distribution	von Mises, $\mu = 45^\circ$, $\kappa = 2.5$
Wind speed distribution	Weibull ($k = 2$, $\lambda = 6$ m/s)
Background current	0.30 m/s @ 200°
Estimated exposure probability, $\hat{p}$	0.084 (8.4 %)
Standard error, SE	0.00277
95 % confidence interval	[0.0786, 0.0894]
Mean/median displacement distance	9.47 km / 9.33 km

Source: authors' Monte Carlo simulation, eqs. (12)–(14), Python/NumPy implementation, random seed fixed for reproducibility.

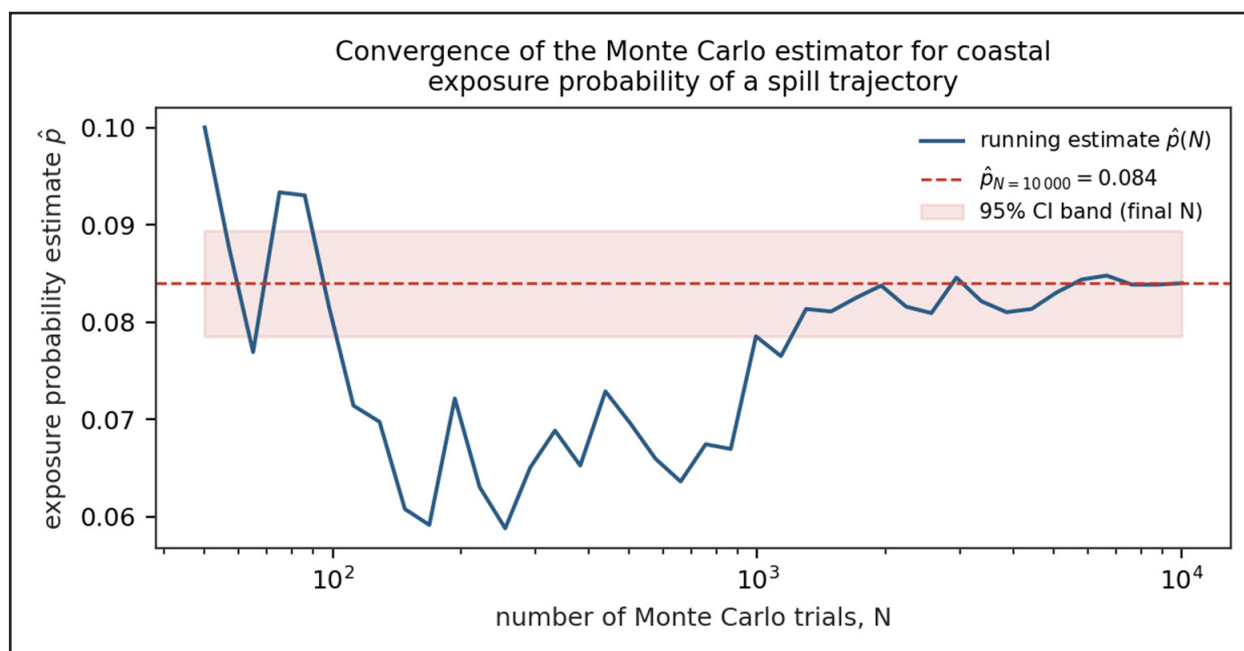


Fig. 2. Convergence of the Monte Carlo estimator for coastal exposure probability. (Source: authors' computation.)

The Markov-chain analysis (Section 4.1) shows that the expected annual environmental-risk index is driven primarily by the low-probability, high-severity state S_3 , which implies that risk-reduction investment is more cost-effective when targeted at reducing the severity/duration of incidents (lower C_3 or faster $S_3 \rightarrow S_1$ recovery, i.e. a higher transition probability out of S_3) than at further reducing the already-low $S_1 \rightarrow S_3$ probability.

The Monte Carlo exposure model (Section 4.2) quantifies this severity dimension directly: an 8.4 % probability of coastal exposure within a 12-hour response window is an operationally actionable figure that can be compared against alternative response-time targets, and the model structure (eqs. 12–14) allows the exposure probability to be re-estimated in near-real time once live wind/current forecasts replace the stationary von Mises/Weibull parameterisation used here. The composite eutrophication index (Section 4.3) situates the shipping-density pressure explicitly alongside nutrient loading, showing that, at the current traffic level, nutrient-related terms (nitrate and phosphate, weights 0.30 and 0.30, contributing 0.351 to EQI) still dominate over the shipping-density term (0.15 weight, contributing 0.015), i.e. further reductions in riverine nutrient input remain the primary lever for eutrophication risk, even as shipping traffic continues to grow.

The framework has three main limitations. First, the fleet composition, engine ratings and Markov transition probabilities are adopted working hypotheses, calibrated qualitatively on published fleet averages and on the documented Bosphorus – Marmara accident record rather than on corridor-specific AIS and incident-log data; the framework is designed so that these parameters can be re-

estimated once such data are available, without changing the model structure, and their influence on the outputs can be quantified through global sensitivity analysis (Saltelli *et al.*, 2008). Second, the oil-spill exposure model uses a simplified leeway-plus-current superposition rather than a full hydrodynamic drift model (e.g. MEDSLIK-class particle tracking; CMEMS, 2024); it is intended as a first-order, rapidly re-computable screening tool rather than a substitute for operational spill-response modelling. Third, the transition matrix and the wind/current parameterisation are treated as time-invariant, whereas both traffic density and meteorological conditions exhibit pronounced seasonality; a seasonally indexed (non-homogeneous) Markov chain and a season-conditioned Monte Carlo sampler are natural extensions.

6. CONCLUSIONS

This paper formulated and numerically demonstrated an integrated, four-part quantitative framework for the environmental risk generated by maritime transport in the Black Sea, applied to the Constanța approach-channel corridor. The bottom-up emission model estimates annual ship-source emissions of 0.98 Mt CO_2 , 3.12 kt SO_x and 22.5 kt NO_x for the corridor, dominated by bulk-carrier and tanker traffic. The Markov-chain pollution/incident-risk model yields a stationary probability of 6.7 % for the severe state and an expected annual environmental-risk index of about 528 thousand EUR, of which the severe state accounts for slightly more than half despite its low probability. The Monte Carlo simulation of coastal oil-spill exposure converges, at $N = 10,000$ trials, to an exposure probability of 8.4 % (95 % CI 7.9–8.9 %) within a 12-hour response window.

The composite eutrophication index of 0.51 confirms that the north-western shelf remains under moderate combined nutrient and shipping pressure notwithstanding its documented post-2000 partial recovery. Because every sub-model is expressed as a closed-form or explicitly reproducible stochastic procedure, the framework can be

recalibrated with live AIS traffic feeds, meteo-oceanographic forecasts and updated nutrient-monitoring data to support an operational, continuously updated environmental early-warning system for the Black Sea shipping corridors, which the authors identify as the natural direction for further research.

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