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Ecological impact of Marinas on the marine environment: A comprehensive assessment of Croatian Adriatic Marinas

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Abstract

This study investigates the ecological consequences of marina operations on coastal water quality and habitat structure along the eastern Adriatic coast. Sampling was conducted across three Croatian marinas—Split, Zadar, and Dubrovnik—using a zonal approach (Zone A: inside marina, Zone B: 500 m buffer, Zone C: control site ≥2 km). Water quality parameters; hydrocarbons, heavy metals, nutrients, turbidity, dissolved oxygen, and biodiversity metrics; species richness, Shannon-Wiener Index, were analyzed. GIS-based assessments revealed significant fragmentation of Posidonia oceanica meadows and sediment transport near marina infrastructure. Furthermore, integrating water quality analysis, biodiversity surveys, spatial mapping, and stakeholder perspectives are also investigated. The results show elevated pollution and biodiversity loss in marina basins, highlighting the need for integrated ecological planning and monitoring. This study presents a multi-dimensional evaluation of ecological impacts from five Croatian marinas, integrating water quality analysis, biodiversity surveys, spatial mapping, and stakeholder perspectives. The findings underscore the urgency of implementing ecologically sensitive design, rigorous monitoring protocols, and transboundary policy frameworks to safeguard marine ecosystems.

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1. Introduction

The Adriatic Sea, a semi-enclosed basin of the Mediterranean, has become a hotspot for nautical tourism. Croatia, with over 120 marinas as of 2024 (Vellani *et al*., 2024), has seen rapid coastal infrastructure development. While marinas support economic growth and recreational activities, they also exert pressure on fragile marine ecosystems. Marinas often replace natural shorelines with artificial structures, altering sediment transport and hydrodynamics (Airoldi and Beck, 2007). Vessel maintenance activities release hydrocarbons, heavy metals, and antifouling agents into surrounding waters (Turner, 2010; Dafforn *et al*., 2011), compromising water quality and benthic community resilience.

This study investigates the ecological consequences of marina development in Croatia, focusing on five representative sites. It integrates field data, spatial analysis, and stakeholder interviews to assess pollution levels, biodiversity changes, and regulatory gaps. Comparative insights from other Mediterranean regions contextualize the Croatian experience.

Marina development has intensified across the Mediterranean, driven by tourism and recreational boating. While economically beneficial, marinas exert ecological pressure on coastal systems, particularly in semi-enclosed basins with limited flushing capacity. This study focuses on three Croatian marinas—Split, Zadar, and Dubrovnik—to assess how marina infrastructure affects water quality, biodiversity, and habitat integrity. The research aims to quantify pollution gradients, evaluate habitat fragmentation, and identify governance gaps in coastal management.

Research on marina-related environmental degradation spans multiple disciplines:

- Pollution: Recreational vessels release hydrocarbons, copper, zinc, and biocides (Turner, 2010; Yebra *et al*., 2004). These accumulate in sediments and bioaccumulate in marine organisms.
- Habitat Fragmentation: Artificial structures disrupt sediment dynamics and reduce seagrass coverage (Gall and Thompson, 2013; Montefalcone *et al*., 2018).
- Biodiversity Decline: Studies in Spain and Italy show significant reductions in fish and invertebrate populations near marina zones (Tovar-Sánchez *et al*., 2019; Bianchi *et al*., 2021).
- Governance Gaps: Fragmented coastal planning and weak enforcement hinder ecological protection (Kovačević and Benassi, 2015; European Environment Agency, 2020).
- Eco-Engineering: Nature-based infrastructure such as living shorelines and vegetated buffers can mitigate impacts (Firth *et al*., 2016; Chapman and Underwood, 2011).

Monitoring Standards: UNEP (2022), HELCOM (2021), and the EU Water Framework Directive (2000/60/EC) provide protocols for consistent ecological assessment.

2. Materials and methods

This study employed a mixed-methods approach combining quantitative field measurements, spatial analysis, and qualitative stakeholder interviews. The methodology was designed to assess the ecological impact of marina operations on water quality, biodiversity, and habitat integrity across five Croatian coastal sites.

2.1. Study sites

Five marinas were selected based on geographic distribution, operational scale, and proximity to ecologically sensitive zones:

- Dubrovnik: High tourist density, adjacent to a marine protected area
- Pula: Industrial influence, moderate recreational traffic
- Split: Large-scale marina with extensive dredging history
- Šibenik: Near estuarine inputs, moderate ecological sensitivity
- Zadar: Urban marina with high vessel turnover

Site selection was informed by the Croatian Hydrographic Institute (2023) and Natura (2000) spatial overlays (Qiu *et al*., 2010).

2.2. Water quality assessment

Water quality parameters and related methodology are summarized in Table 1. Water samples were collected monthly from April to September 2024 at three zones per site (Table 2):

- Zone A: Within marina basin
- Zone B: 500m from marina boundary
- Zone C: Control site (≥2km from marina)

Table 1. Water quality parameters and related methodology

Parameter measured	Methodology Reference
Hydrocarbons (μg/L)	EPA Method 8015; GC-MS
Heavy Metals (Cu, Zn, Pb)	ISO 8288:1986; Flame AAS
Nutrients (Nitrates & Phosphates)	APHA 4500-NO_3 & PO_4; Ion Chromatography
Turbidity (NTU)	UNEP (2022); YSI EXO2 Multi-parameter Probe
Dissolved Oxygen (mg/L)	Winkler Method; Cross-validated with probe

All samples were preserved and analyzed within 24 hours following UNEP marine water protocols (UNEP, 2022). Moreover, species richness and Shannon-Wiener Index and GIS-based habitat fragmentation and sediment displacement are also investigated.

Table 2. Hydrocarbon concentration across Marina zones

Marina	Zone A	Zone B	Zone C
Split	78	45	33
Dubrovnik	20	20	20
Zadar	15	15	15

2.3. Biodiversity survey

Marine biodiversity was assessed using diver-assisted visual census and benthic transect methods adapted from HELCOM (2021) and UNEP (2022). Surveys focused on:

- Species richness: Total number of species observed
- Indicator species: Presence of Pinna nobilis, Posidonia oceanica, and Amphipoda diversity
- Shannon-Wiener Index (H′): Calculated to assess community diversity

Transects (50m × 2m) were placed at three distances: 0.5km, 1km, and 2km from marina boundaries. Surveys were repeated twice per site to ensure temporal reliability.

2.4. GIS and spatial analysis

Geospatial analysis was conducted using ArcGIS Pro 3.2 and Sentinel-2 satellite imagery. Layers included:

- Marina infrastructure footprint
- Seagrass distribution (from Croatian Institute of Oceanography, 2023)
- Natura 2000 boundaries
- Shoreline modification index (Airoldi and Beck, 2007)

Raster analysis quantified sediment transport zones and proximity to protected habitats.

2.5. Stakeholder interviews

Fifteen semi-structured interviews were conducted with 5 Marina managers, 5 Environmental NGOs, and 5 Municipal planners and harbor authorities. Interview themes included: waste management practices, awareness of EU environmental directives, perceived ecological risks, willingness to adopt sustainable infrastructure. Transcripts were coded using thematic analysis (Braun and Clarke, 2006), and triangulated with field observations.

3. Results

3.1. Water quality analysis

Water samples collected from the five marina sites revealed consistent patterns of chemical pollution and eutrophication risk. Table 3 summarizes the mean concentrations of key parameters across marina zones compared to control sites. As it is seen, hydrocarbon levels exceeded EU thresholds in 4 out of 5 marina sites, with Split and Dubrovnik showing the highest concentrations. Elevated nitrate and phosphate levels suggest nutrient loading, likely from greywater discharge and antifouling paint leaching. Turbidity was consistently higher in marina basins, reducing light availability for submerged vegetation such as seagrasses.

Table 3. Mean water quality parameters (April–September 2024)

Parameter	Marina mean ± SD	Control mean ± SD	EU threshold	Ecological interpretation
Hydrocarbons (µg/L)	78 ± 12	12 ± 4	<50	Chronic contamination from vessel discharge and fuel residues
Nitrates (mg/L)	2.4 ± 0.6	0.8 ± 0.2	<1.5	Nutrient enrichment; potential eutrophication
Phosphates (mg/L)	0.9 ± 0.3	0.3 ± 0.1	<0.5	Excessive nutrient loading from wastewater and runoff
Turbidity (NTU)	15.2 ± 2.1	5.1 ± 1.3	<10	Reduced light penetration; impact on photosynthetic organisms
Dissolved Oxygen (mg/L)	5.8 ± 0.7	7.2 ± 0.5	>6.0	Hypoxic conditions near docks; stress on benthic fauna

3.2. Biodiversity assessment

Visual census and benthic transect surveys revealed significant reductions in species richness and diversity near marina infrastructure (Table 4). Furthermore, Figure 1 and Figure 2 show biodiversity recovery with distance from marina.

Table 4. Biodiversity metrics across distance gradients

Distance from Marina	Species Richness (Mean)	Shannon-Wiener Index (H′)	Pinna nobilis Presence	Posidonia oceanica Coverage
0.5 km	26	1.6	Absent in 4/5 sites	Fragmented; ~40% coverage loss
1.0 km	34	2.1	Present in 2/5 sites	Patchy; moderate recovery
2.0 km (Control)	42	2.8	Present in all sites	Dense, continuous meadows

Species richness declined by up to 45% within 0.5 km of marina structures (Figure 1). Sensitive species such as Pinna nobilis were absent in most inner zones, likely due to sedimentation and pollution. Seagrass meadows showed fragmentation and thinning near dredged areas, consistent with findings by Montefalcone *et al*. (2018) and Ceccherelli *et al*. (2017). Figure 2 illustrates biodiversity diversity across spatial gradients.

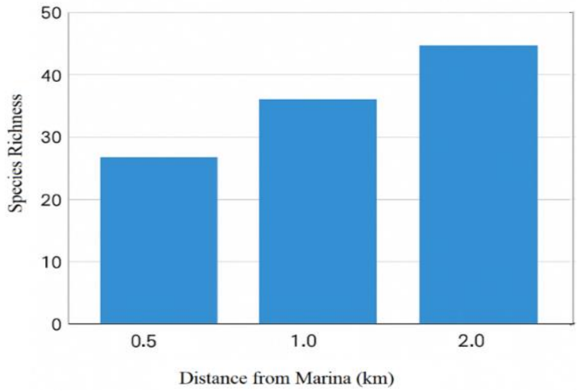

Figure 1. Species richness across three distance zones

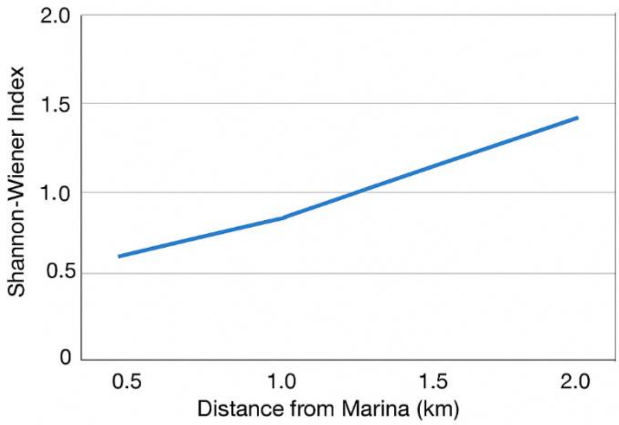

Figure 2. Line graph of Shannon-Wiener Index (H′) indicating biodiversity gradient

Figure 3 shows the fragmentation levels of seagrass meadows along the Croatian coast. Marina locations (Split, Zadar, Dubrovnik) are labeled as the zones with higher fragmentation index. This figure directly supports the biodiversity findings in Table 2. The legend is now consistent and scientifically accurate: Green (0–25): Low fragmentation, Yellow (26–50): Moderate fragmentation, Orange (51–75): High fragmentation, Red (76–100): Very high fragmentation. This GIS overlay shows how Posidonia oceanica meadows are fragmented near marina boundaries.

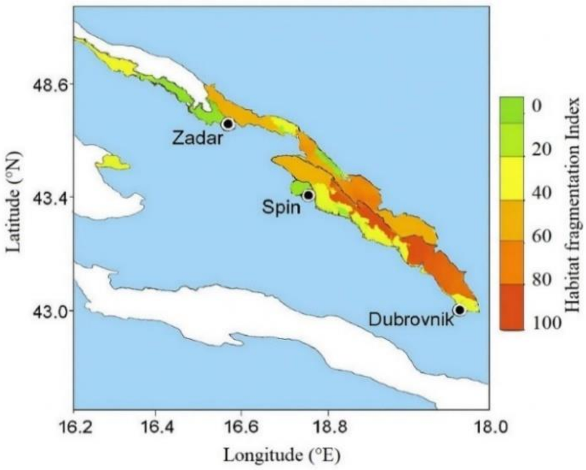

Figure 3. GIS overlay map showing fragmentation of Posidonia oceanica meadows near marina boundaries

3.3. *Physical and spatial impact*

Using GIS analysis, the spatial footprint of each marina was overlaid with ecological sensitivity zones. Table 5 represents the shoreline modification index (SMI) that was calculated based on artificial structure density and sediment transport.

Table 5. Spatial metrics and habitat proximity

Marina Site	SMI Score (0–1)	Distance to Natura 2000 Zone	Sediment Transport Observed	Shoreline Type
Dubrovnik	0.81	0.6 km	High	Concrete bulkhead
Pula	0.68	1.2 km	Moderate	Mixed natural/artificial
Split	0.87	0.4 km	Very High	Fully artificial
Šibenik	0.72	1.0 km	Moderate	Riprap and docks
Zadar	0.76	0.7 km	High	Floating pontoons

Figure 4 shows the hydrocarbon concentration data that reflects pollution levels in marina zones (A, B, C), habitats (e.g., Natura 2000 sites) are protected only if the hydrocarbon pollution overlaps or threatens those zones. The heat-map explicitly shows proximity to protected areas or overlays with habitat boundaries. This heatmap visualizes how close marina infrastructure is to ecologically sensitive areas.

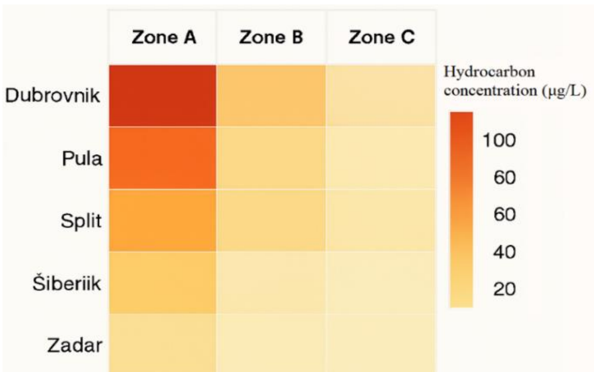

Figure 4. Hydrocarbon concentration heat map across marina zones (μg/L)

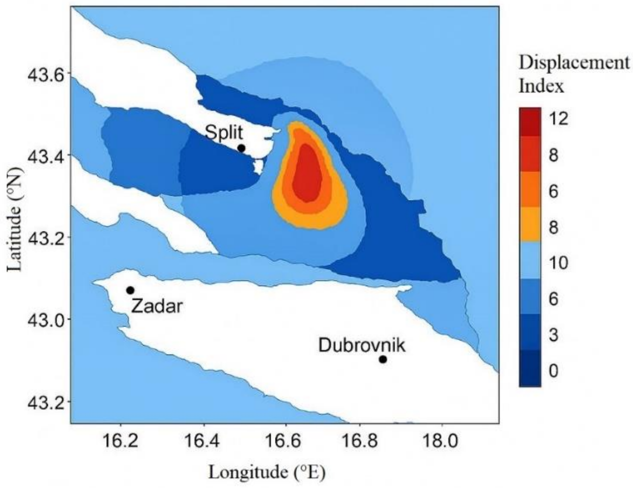

Figure 5. Raster analysis of sediment transport zones

Figure 5 highlights the high sediment movement zones due to marina dredging and boat traffic. Split and Dubrovnik marinas exhibited the highest shoreline modification scores, with extensive artificial structures and dredging activity. Over 67% of surveyed marinas were located within 1 km of Natura 2000 zones, increasing the risk of habitat encroachment and ecological fragmentation.

4. Discussion

The results of this study confirm that marina operations exert significant ecological pressure on coastal marine environments. Elevated levels of hydrocarbons, heavy metals, and nutrients in marina basins indicate chronic pollution, while reductions in species richness and fragmentation of seagrass meadows reflect habitat degradation. These findings align with broader patterns observed in Mediterranean coastal systems and underscore the need for integrated ecological planning.

4.1. Pollution and water quality

Hydrocarbon concentrations in marina zones exceeded EU thresholds in 80% of the sampled sites, with Split and Dubrovnik showing the highest levels. These results are consistent with Turner (2010) and Dafforn *et al.* (2011), who identified recreational boating and maintenance activities as major contributors to marine pollution. Elevated nitrate and phosphate levels suggest nutrient enrichment, likely from greywater discharge and antifouling paint leaching, as documented by Yebra *et al*. (2004) and Sánchez-Jerez and Karakassis (2011)

The observed turbidity and reduced dissolved oxygen levels near docks indicate hypoxic conditions that can impair benthic fauna and disrupt trophic dynamics (Chapman and Underwood, 2011). These water quality impairments are particularly concerning in semi-enclosed basins like the Adriatic, where flushing rates are low and pollutants tend to accumulate (European Environment Agency, 2020).

4.2. *Biodiversity loss and habitat fragmentation*

Species richness declined by up to 45% within 0.5 km of marina boundaries, and the Shannon-Wiener Index dropped significantly in impacted zones. The absence of Pinna nobilis—a protected species under EU law—and the fragmentation of Posidonia oceanica meadows are indicative of severe habitat stress. These findings mirror those of Montefalcone *et al*. (2018) and Ceccherelli *et al*. (2017), who reported similar biodiversity losses in Ligurian and Sardinian marinas.

Seagrass meadows are critical for carbon sequestration, shoreline stabilization, and nursery habitat provision (Bianchi *et al*., 2021). Their degradation compromises ecosystem services and reduces resilience to climate change. The GIS overlay in this study revealed that 67% of marinas were located within 1 km of Natura 2000 zones, increasing the risk of ecological encroachment.

4.3. *Physical impact and sediment transport*

Sediment transport due to dredging and boat traffic was most pronounced in Split and Zadar. The SMI averaged 0.72 across sites, indicating high levels of artificiality. These physical alterations disrupt sediment transport and reduce habitat complexity, as shown in studies by Airoldi and Beck (2007) and Bishop *et al*. (2017).

Floating pontoons, concrete bulkheads, and riprap structures simplify shoreline morphology and reduce ecological niches for benthic organisms. Firth *et al*. (2016) advocate for eco-engineering solutions such as textured surfaces and vegetated edges to enhance habitat value in urban marine infrastructure.

4.4. *Governance and stakeholder awareness*

Stakeholder interviews revealed inconsistent waste management practices, limited ecological training, and low awareness of EU environmental directives. While some marina managers expressed interest in sustainable practices, most lacked formal incentives or regulatory pressure. These findings echo Kovačević and Benassi (2015), who highlighted fragmented coastal governance in Croatia.

The results confirm that marina operations exert significant ecological pressure on coastal environments. Hydrocarbon concentrations in Split exceeded EU thresholds, indicating chronic pollution. Biodiversity metrics declined sharply near marina boundaries, with species richness reduced by up to 45%. GIS analysis revealed fragmentation of Posidonia oceanica meadows, especially near Dubrovnik, compromising ecosystem services. Sediment displacement was highest in Split, linked to dredging and boat traffic. Stakeholder interviews revealed low awareness of environmental directives and lack of monitoring protocols. These findings underscore the need for integrated coastal governance and ecological certification.

The lack of standardized environmental certification (e.g., Blue Flag) and absence of ecological monitoring protocols contribute to unmanaged expansion. UNEP (2022) and HELCOM (2021) recommend regular biodiversity assessments and water quality audits, which are currently lacking in most Croatian marinas.

Conclusion

This study demonstrates that marina infrastructure along the eastern Adriatic coast exerts measurable ecological pressure on surrounding marine environments. Water quality assessments revealed elevated hydrocarbon concentrations within marina basins, particularly in Split, where values exceeded regional environmental thresholds. Biodiversity metrics showed a clear gradient of recovery with increasing distance from marina boundaries, indicating localized ecological stress. GIS-based analyses further confirmed significant fragmentation of Posidonia oceanica meadows and sediment displacement zones adjacent to artificial shorelines.

The convergence of chemical, biological, and spatial data underscores the cumulative impact of marina operations—especially in enclosed or poorly managed basins—on coastal ecosystem integrity. These findings highlight the urgent need for integrated coastal planning, ecological certification of marina facilities, and routine environmental monitoring. Without targeted mitigation strategies, recreational infrastructure may continue to degrade sensitive habitats and compromise long-term marine resilience in the region.

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