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A critical analysis of the marina environmental risk assessment method applied to Portugal

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ABSTRACT

The MERA (Marina Environmental Risk Assessment) procedure was applied for the first time along the coast of Portugal to classify the risk of 26 marinas on water quality. A risk ranking Atlas was produced to provide managers or decision-makers with spatial information that can help achieve sustainable development goals. The results indicate that the eight marinas in the south coast of the country (Algarve) face the highest risk, primarily due to pressures from navigation activities. However, the ranking generated along the Algarve using indicators of trophic status (TRIX and Eff. Coeff.) based on chemical analysis of in-situ water samples do not align with MERA. The MERA methodology, as it stands, presents significant limitations. Specifically, it does not account for water chemical parameters, sediment contamination, or temporal variability, all of which are crucial for accurate assessments. To enhance the robustness of MERA, this study suggests incorporating additional parameters and metrics that encompass broader environmental indicators.

1. Introduction

Marinas are key infrastructures within the expanding coastal and maritime tourist sectors. They are an important driver of economic wealth, generating 24.38 billion US Dollars in revenue with an estimated growth rate of 5.8 % in 2025 (The Buiseness Research Company, 2025). In Portugal, the tourism and leisure sector connected to the sea is the largest contributor to the maritime economy (65 % of the gross added value), employing 77,000 people and generating around 4.8 billion euros in annual business volume (DGPM, 2024). Marinas are no longer just facilities for recreational sailing but offer a wide range of activities and services that enrich the attractiveness of the locations where they are established, hence contributing to their social and economic development. The management of these infrastructures involves a complex array of technical and operational tasks related to environmental issues, service offerings, marketing, and infrastructure maintenance (European Comission, 2017). In all these aspects, poor or inadequate environmental protection practices can result in local water quality degradation and human health problems. Despite their significance, marinas in many parts of the world, including Portugal, lack the application of simple methodologies designed to provide a quick and cost-effective environmental risk assessment based on existing data, that can apply uniformly to all the marinas at the national and/or regional level.

A national-scale environmental risk assessment of marinas is particularly critical for Portugal due to several factors. Firstly, Portugal's long, diverse coastline, combined with its economic reliance on coastal tourism and maritime economy, amplifies the relevance of marina-related impacts. Secondly, a national assessment is necessary for Portugal to establish a comprehensive baseline, enabling standardized data collection and comparison. This is crucial for meeting national regulatory requirements and enables the development of targeted mitigation strategies and Portugal-specific best practices. The assessment of susceptibility to pollution is particularly relevant in the south coast of the country (Algarve) due to the high ecological value the Ria Formosa and the Guadiana River estuary, which are among the most important wetlands in mainland Portugal. Ria Formosa hosts a remarkable diversity of habitats and biodiversity and is of fundamental importance for several species of migratory birds, providing unique nesting conditions and supporting some declining species (Moura et al., 2019). Furthermore, the Ria Formosa also supports a fishery and aquaculture industry of national significance (Galvão et al., 2019). The Guadiana estuary is one of the most intact coastal ecosystems in southern Iberia, where at least 460 plant species are recorded, including several rare and endemic species (Connor, 2017). The saltmarsh area in

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this estuary is well known for its ecological, botanical, ornithological, ichthyological, archeological and economic aspects, such as fishing, salt production and tourism (Gomes and Camacho, 2017).

The existence of marinas generates conditions for reduced water circulation leading to increased pollutant concentrations in the water column and sediments (Birch, 2018; Briant et al., 2022; Chouba et al., 2024; Gómez et al., 2017; Morsy et al., 2022; Valdor et al., 2019). The most common pollution problems found in marina's water column are decreased levels of dissolved oxygen due to organic matter discharges, waste or stormwater runoff, increased levels of metals mainly due antifoulants used in boat paints, and petroleum hydrocarbons from fuels and oil spills (Briant et al., 2022; Guerra-García et al., 2021; Rivero et al., 2013). Contaminants that accumulate in sediments are mainly petroleum hydrocarbons, metals such as copper, zinc and lead, pathogens and litter, especially plastic objects (EPA, 2024). Marinas can, thus, be considered sinks for physical, chemical, and biological pollutants and for this reason their environmental assessment is becoming vital to protect waters, sediments and aquatic systems in general from vessel-related activities.

Literature reviews on marina sustainability and management highlight that marine pollution and water quality are among the primary research concerns (Martín and Yepes, 2021; Martínez-Vázquez et al., 2021). Most studies focus on the threat to ecosystems posed by leaks of petroleum derivatives, heavy metals and the introduction of invasive species, on eutrophication due to excess nutrients, and on the detection of chemical pollutants originating from sewage discharge, agricultural leaching, industrial activity, and urban runoff (Abreu et al., 2020; Dragović et al., 2016; Jupp et al., 2017; Martínez-Laiz et al., 2019; Petrosillo et al., 2010). The recognition of these threats has promoted the development of studies and new environmental assessment methodologies specific to marinas, for example, dedicated to the risk of noise pollution (Mensa et al., 2011), ecosystem health (Bebianno et al., 2015; Morsy et al., 2022), air pollution (Chen et al., 2019) and the assessment of carbon and water footprints (Cruz-Pérez et al., 2021). Recently, an index called Marinas Environmental Pollution Index, has been proposed based on measured concentrations of 15 different types of contaminants in sediments (Guerra-García et al., 2021). Another category of methodologies less dependent on physico-chemical datasets and more designed for planning strategies falls within the context of Environmental Risk Assessment (ERA) methods . The ERA methods have been widely applied to commercial ports, but the number of studies dedicated to marinas is much smaller (Parra et al., 2018; Petrosillo et al., 2009).

Among specific applications of ERA methods to marinas, the production of a global Atlas of susceptibility to water pollution in ports and marinas has been advocated as a very useful management tool, and its application and dissemination worldwide have been encouraged as an important step towards a sustainable global market (Gómez et al., 2019, 2017; Valdor et al., 2020, 2019, 2016). The MERA (Marina Environmental Risk Assessment) procedure is based on the Pressure-State-Response (PSR) framework, which is intended to develop indicators of sustainability and describe human activities that exert pressures on the environment and change the quality or quantity state of natural resources (Jago-on et al., 2009; OECD, 1993). The PSR framework provides a rational and logical approach in which indicators can be identified and classified for every purpose. It is claimed to be a bridging tool among scientists, policy-makers and stakeholders, and is used globally on multi-field assessments that link environmental aspects with economic, societal, and political dimensions (Kelly, 1998; Meyar-Naimi and Vaez-Zadeh, 2012; Neves et al., 2021). Moreover, the MERA procedure integrates the Driving Force-Pressure-State-Impact-Response (DPSIR) model, adjusted by the European Environment Agency (EEA, 2005), to define specific indices of Pressure, State and Response. These indices group and classify a limited set of indicators to evaluate environmental risk at the marina level.

This study applies the MERA risk mapping procedure, previously used for 320 marinas along the Spanish coast (Gómez et al., 2019) and adapted for 15 harbors worldwide (Valdor et al., 2020), addressing a knowledge gap by evaluating risk factors affecting water quality in the major marinas along the Portuguese coast. The method presents several advantages, namely, the simplicity of the application as it only requires data that can be easily obtained and processed using geographic information systems (GIS), versatility as it can be applied to different types of marinas, and adaptability as it is possible to include indicators tailored to specific ecoregions. The resulting maps reveal the spatial distribution of the relative risk of each marina classification and inform decision-makers, such as government agencies and harbor managers, with scientifically based information that helps to prioritize environmental protection actions in marinas and neighboring waterfronts. To the best of our knowledge, this study is original, as its primary goal is to apply the MERA methodology along the Portuguese coast, enabling a comparative analysis of different marinas at the national level, something that has not been done before. This study adds value by complementing the work of Gómez et al. (2019), providing previously unavailable MERA data for the remainder of the Iberian region, specifically extending the analysis to the Portuguese coast.

In Portugal, the organizations responsible for managing marinas conduct regular water monitoring. However, the data are mostly not publicly available, and some studies were focused on assessing the ecosystem health of specific commercial ports such as Bebianno et al. (2015) along Arade Estuary, in South Portugal. In this study, a field campaign was conducted to analyze water quality in a small number of marinas, aiming to verify whether the mapped environmental risk by MERA was consistent with the results of an index of water quality analyses. The index chosen to classify the water quality was TRIX (Vollenweider et al., 1998), which is an ecological indicator of the trophic status of the marine coastal waters related to eutrophication. Eutrophication occurs commonly in ports and marinas due to accumulation of organic matter (Morsy et al., 2022). This process is driven when the environment receives an excessive nutrient load and leads to an overwhelming growth of primary producers that, after a certain point, leads to an accumulation of organic matter on the sediments that ultimately lead to oxygen depletion. In this context, TRIX uses nitrogen and phosphorus nutrients, chlorophyll a (as a proxy of phytoplankton biomass) and dissolved oxygen as key state water quality variables. The environmental legislation and regulations of the Water Framework Directive (2000/60/E.C.) emphasize the importance of the ecological and chemical status of coastal waters and identify eutrophication as a priority issue for water protection (European Commission, 2009).

2. Methodology

2.1. MERA methodology

This study follows the MERA methodology (Gómez et al., 2019; Valdor et al., 2020) which integrates indices of Pressures Pr_i, State St_i, and Response Rs_i into one equation to compute the index of the environmental risk in water quality R_i at each marina (i) as,

$$R_i = \mathrm{Pr}_i \times St_i + Rs_i \tag{1}$$

MERA is an adaptation of the PSR model which is based on the concept of causality: human activities exert pressures on the environment (State), and society responds to these changes (Response). The use of the PSR model as a conceptual framework inherently gives equal importance to these three pillars in understanding environmental risk (OECD, 1993). Although Eq. (1) combines the factors additively and multiplicatively, the components undergo normalization and categorization using equidistant percentiles as explained below.

The first step of the methodology consists of estimating the environmental pressures related to human activities with negative impacts in water quality, namely, navigation (NV_i), port (PT_i), dredging (DG_i), and external (EX_i) activities related to the hazardousness used of land. The indicators and parameters for these activities include the density of boats (berth/m^2), the presence of gas stations and dry docks, the frequency of dredging operations and the types of land use (industrial, mining, urban or agriculture) developed in a 1 km buffer surrounding the marina. These indicators are organized into four categories that contribute equally to the pressures:

$$\mathrm{Pr}_i = \quad NV_i + PT_i + DG_i + EX_i \tag{2}$$

The second step includes the assessment of environmental conditions at each marina described by a functional relationship between the environment's susceptibility to disturbance or pollution (SU_i), the ecological value (EV_i), and the naturalness of the environment (NA_i):

$$St_i = \quad SU_i + EV_i + NA_i \tag{3}$$

The indicators for the environmental state are a combination of the flushing capacity of the water volume where port activity takes place (proxy for SU), the number of ecological singular elements such as the protected areas in the marina's vicinity (proxy for EV) and a parameter for the marina's typology (anchorage, harbor or dock) used as a proxy for naturalness (NA). The flushing capacity of semi-enclosed aquatic environments is inversely proportional to the retention of contaminants and consequently is a direct measure of the susceptibility to pollution. Among several empirical methods of estimating the flushing capacity, this study uses the Marinas Complexity Tidal Range Index (CTRI) which is the best in terms of statistical analysis and comparisons with numerical model results in a study along the Spanish coast (Gómez et al., 2017). The third step in the MERA methodology considers the management actions, or responses (Rs_i), applied at the marina level to mitigate and prevent the effects of human pressures. The indicators for responses are the number of adopted measures (AM_i), such as waste management practices, and instruments (AI_i) to reduce the pressures and improve environmental performance, such as the ISO 14001 (Environment) and ISO 9001 (Quality) certifications (ISO, 2024), the Blue Flag (FEE, 2024) or the Blue Star Marina given by International Marine Certification Institute (ICMI, 2024).

$$Rs_i = \quad AM_i + AI_i \tag{4}$$

The multi-parametric index of the environmental risk for water quality was computed for the main 26 marinas (names and numbers listed in Table 1) along the Portuguese coast registered in the inventory of the national Directorate-General for Natural Resources, Safety and Maritime Services (DGRM, 2024). A database with the characteristics of each marina was compiled based on information from Marinas de Portugal (APPR, 2024), DocaPesca (DocaPesca, 2024), and the Hydrographic institute of Portugal (IH, 2024). For all marinas, the digitalization needed to compute the indicators, parameters, and metrics was performed using Geographic Information Systems (QGIS), Google Earth Satellite Image Data and CORINE Land Cover Data. Fig. 1 shows an example of the data classification and buffers considered to estimate the indicators and metrics of environmental risk. According to the MERA method all the indicators were normalized by the maximum value so that they vary between 0 and 1 at the parameter level. Categories for Pressures, States and Conditions are defined according to percentiles: 4 classes for pressures and state (separated by percentile 25th, 50th and 75th and classified as very low, low, moderate and high) and 2 classes for responses (separated by the 50th percentile and classified as optimal and insufficient). The criteria and thresholds obtained for the Portuguese marinas are depicted in Table 2. Finally, a multi-linear regression model was applied using Python (Statsmodel Package) to estimate the relationship between risk (R_i) and all the factors considered in the model.

While the proponents of the MERA methodology (Valdor et al., 2020; Gómez et al., 2019) do provide justifications for the selection criteria under each category (Pressures, State, Response), the explicit prioritization of some criteria over others, such as urban runoff, is not always clear. The prioritization seems to lean towards activities directly occurring within or immediately associated with the marina for which the impact might be more directly related with the available data. Gómez et al. (2019) acknowledge that ideally, more detailed information on the type, flow, and contaminant concentration of external discharges would be preferred, suggesting that if such data were available and consistently measurable across study sites, they could potentially be considered more explicitly. The normalization using maximum values for scaling and percentiles for categorization to allow for comparative analysis across marinas is also presented without citing previous literature or discussing alternative methods to justify the specific normalization approach or the use of the specific percentiles.

Table 1
Water quality risk assessment of recreational harbors in Portugal.

Region	Nr.	Marina	Pressure	State	Response	Risk
West coast	1	Marina de Viana do Castelo	2	2	0	1
	2	Marina da Póvoa De Varzim	1	3	4	2
	3	Marina Porto Atlântico	2	2	4	2
	4	Porto de Recreio do Carregal	2	2	0	1
	5	Marina da Torreira	1	3	0	1
	6	Porto de Recreio da Figueira da Foz	1	3	0	1
	7	Núcleo de Recreio do Porto da Nazaré	1	3	0	1
	8	Marina do Parque das Nações	4	1	0	1
	9	Marina de Cascais	3	4	0	3
	10	Doca de Alcântara	1	1	4	1
	11	Doca de Recreio de Santo Amaro	2	1	4	2
	12	Doca de Belém	3	1	4	2
	13	Porto de Recreio de Oeiras	1	1	4	1
	14	Doca de Recreio do Bom Sucesso	2	1	4	2
	15	Doca de Recreio das Fontaínhas	3	2	4	2
	16	Marina de Tróia	2	2	4	2
	17	Porto de Recreio de Sesimbra	2	4	0	2
	18	Porto de Recreio de Sines	3	3	0	2
Algarve	19	Marina de Lagos	3	4	4	4
	20	Marina de Portimão	4	3	4	4
	21	Marina de Albufeira	2	1	4	2
	22	Marina de Vilamoura	1	2	4	2
	23	Doca de Recreio de Faro	4	4	0	4
	24	Marina de Olhão	4	4	0	4
	25	Porto de Recreio de Tavira	1	4	0	1
	26	Porto de Recreio V.R. S.A.	3	4	0	3

2.2. Field survey and TRIX calculation

Complimentary to the application of the MERA methodology we selected the 8 marinas of the Algarve for a simple assessment of the water quality based on field data, and on two indicators of the trophic status: TRIX index and Efficiency Coefficient (Table S2 in supplementary material). The TRIX trophic index (Giovanardi and Vollenweider, 2004; Vollenweider et al., 1998) initially used for Mediterranean waters is widely used to classify the trophic status of coastal marine areas and consists of a linear combination of the logarithms of four state variables: chlorophyll-a (ChA, in μg/L), Oxygen as absolute percent deviation from 100 saturation (aD%O), dissolved inorganic nitrogen (DIN, sum of ammonium+nitrate+nitrite, in μg/L) and dissolved inorganic phosphorus (DIP, in μg/L) as indicated in the following equation:

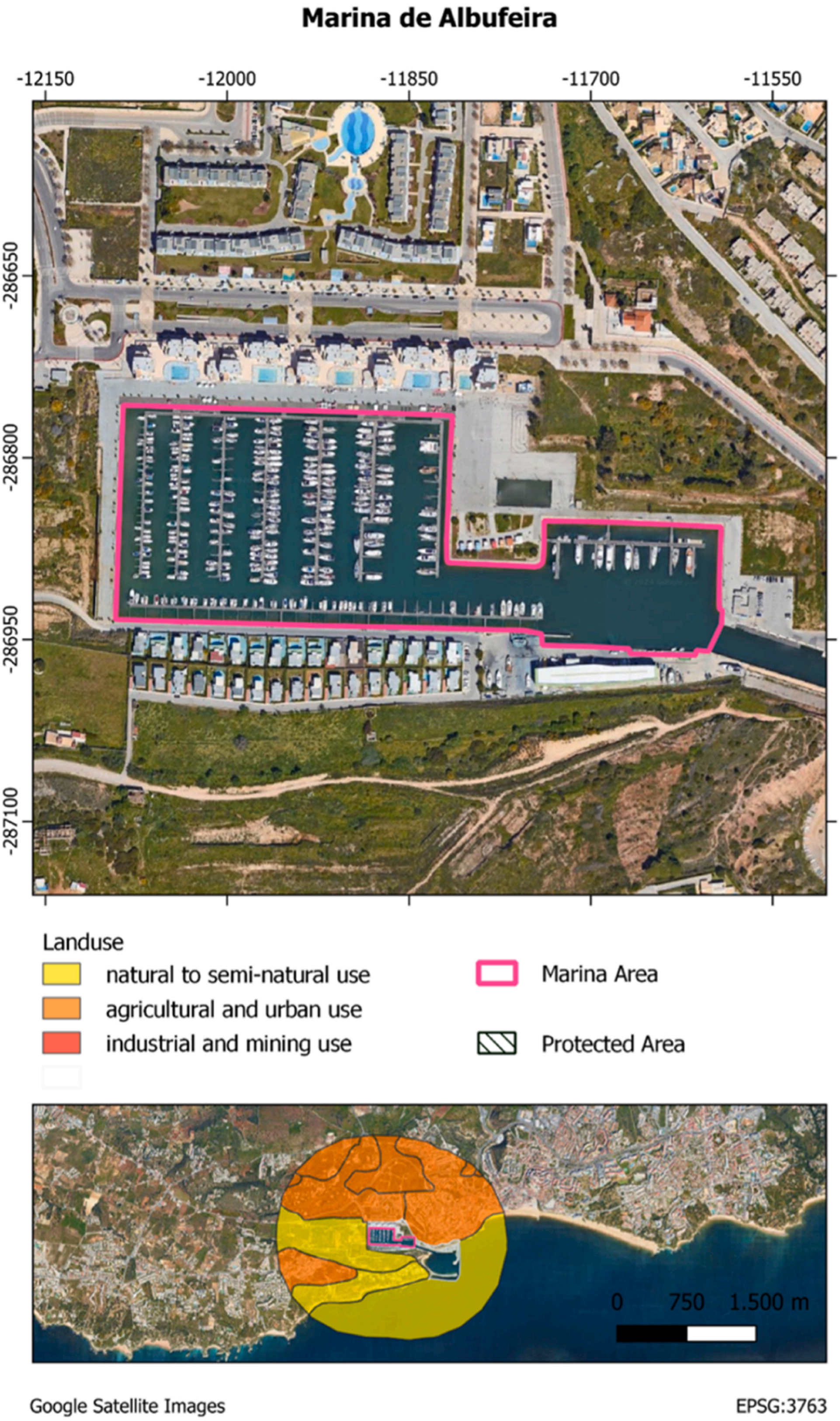

Fig. 1. Example of marina delimitation to evaluate Pressures-State-Response.

$$TRIX = (\mathrm{Log}_{10}\,[\mathrm{ChA} \times \mathrm{aD\%O} \times \mathrm{DIN} \times \mathrm{DIP}] + 1.5)\ /\ 1.2 \tag{5}$$

However, as the measured biotic (ChA × aD%O) and abiotic variables (DIN × DIP) may have different relative contributions to TRIX, we use a supplementary indicator of trophic status designated as Efficiency Coefficient, defined as (Giovanardi and Vollenweider, 2004),

$$Eff.Coeff. = \log\left(\frac{ChA \times aD\%O}{DIN \times DIP}\right) \tag{6}$$

Table 2
Criteria and thresholds used to assess the Pressures, State and Response in Portugal.

Factor	Category	Criteria	Portuguese thresholds
Pressures (Pr)	VL (8/16)	$Pr_i \leq P25$	$Pr_i \leq 1.48$
	L (8)	$P25 < Pr_i \leq P50$	$1.48 < Pr_i \leq 1.81$
	M (6)	$P50 < Pr_i \leq P75$	$1.81 < Pr_i \leq 2.31$
	H (4)	$Pr_i > P75$	$Pr_i > 2.31$
State (St)	VL (7)	$St_i \leq P25$	$St_i \leq 0.60$
	L (6)	$P25 < St_i \leq P50$	$0.60 < St_i \leq 0.74$
	M (6)	$P50 < St_i \leq P75$	$0.74 < St_i \leq 1.44$
	H (7)	$St_i > P75$	$St_i > 1.44$
Response (Rs)	Optimal (13)	$Rsi \geq P50$	$Rsi \geq 0.15$
	Insufficient (13)	$Rsi < P50$	$Rsi < 0.15$

VL: Very low; L: low; M: moderate; H: high; P25: 25th Percentile; P50: 50th percentile

The Eff. Coeff. measures the degree to which nutrients are utilized. Systems with lower efficiency (e.g., Eff. Coeff. < -2) exhibit lower nutrient conversion to primary producer biomass, indicating greater "potential" productivity, while systems with higher efficiency (e.g., Eff. Coeff. > -2) exhibit higher nutrient conversion to primary producer biomass, indicating greater "actual" productivity. The Efficiency Coefficient can help to differentiate between systems with similar TRIX values but different nutrient utilization patterns (Fiori et al., 2016; Giovanardi and Vollenweider, 2004).

In-situ measurements and water samples were collected in May 2024, on 06/05/2024 in the West, and on 15/05/2024 in the East regions of the Algarve. Measurements and water samples were taken at three different points in each marina, one at the entrance, one in the middle and one at the inner end. Three samples were collected at each sampling location. The value considered for each marina is the average of the mean values from the three locations. A set of 3 measurements were also taken at sea, on Faro beach, and their average value was used as a reference. A TRIX (or Eff. Coeff.) value calculated from one or two days of sampling provides a snapshot of the trophic conditions at a specific time and does not capture the natural temporal variability driven by seasonal changes in factors like temperature, sunlight, rainfall, river runoff, and biological activity, or tidal conditions (Andricevic et al., 2021; EEA, 2001; Primpas and Karydis, 2011; Rosa et al., 2022). The decision to not conduct a seasonal analysis of the trophic conditions at this stage can be justified by the initial goal of comparison with MERA, the potential limitations of the available data for a robust seasonal study, and the recognition that such a detailed temporal investigation is a significant undertaking suitable for future research with dedicated long-term data and resources.

In-situ measurements of temperature, salinity, pH and dissolved oxygen were obtained using a multiparameter probe (Yellow Spring, model EXO2, previously precalibrated for salinity, pH and dissolved oxygen; for specifications, please see Cravo et al.,2020). The water samples collected at each of the marinas were kept in an ice box and transported to a laboratory at the University of Algarve. The collected water samples were subsequently filtered at the laboratory with specific filters both for suspended solids (Gelman, cellulose acetate membranes 0.45 μm) and chlorophyll a (Whatmann GF/F 0.7 μm) determination. The water filtered through the Gelman filters was kept and frozen for subsequent nutrients determination. Suspended solids, chlorophyll a and dissolved inorganic macro-nutrients (nitrate, nitrite, ammonium, phosphate, and silicate) were quantified using gravimetric and spectrophotometric methods, respectively (see APHA (American Public Health Association), 2017; Cravo et al., 2022 for details).

Several studies have highlighted the site-specific nature of eutrophication indicators and the limitations of applying a fixed scale or equation across diverse marine systems (Fiori et al., 2016; Giovanardi and Vollenweider, 2004; Primpas and Karydis, 2011; Tugrul et al., 2019; Vollenweider et al., 1998), emphasizing also the necessity of incorporating hydro-morphological conditions and type-specific reference sites to improve assessment accuracy. The relative importance of the biotic (chlorophyll-a, oxygen) and abiotic (nutrients) variables in the TRIX index and Eff. Coeff. can vary significantly between different coastal systems due to differences in nutrient limitation, productivity, and other factors.

Using a modified TRIX equation with coefficients tailored to the specific characteristics of the Algarve will allow a more robust analysis. However, a rigorous assessment of the trophic state of Algarve marinas, incorporating the modified TRIX coefficients alongside tidal effects, loading inputs, and river discharges, is beyond the scope of the present work. We use the same combination of variables as Rosa et al. (2022), who both applied the same TRIX formulation and coefficients within the Ria Formosa coastal lagoon in the Algarve.

3. MERA results for Portugal

Typical Portuguese marinas have high port activity with the presence of gas stations and dry docks, have industrial land use in their vicinity and most are of interior type, having high dredging probability (or activity). Overall, the characteristics of Portuguese marinas are similar to those of Spanish marinas located on the Atlantic coast (Gómez et al., 2019) having a mean tidal range of approximately 2 m and a mean number of berths of 331. Navigation activity, estimated as the density of boats (number of berths per square meter), is very low or low in most marinas being high in only three of them (#20, #22, #23) (Fig. 2). Concerning state, the susceptibility given by the flushing capacity varies widely with the highest values of the CTRI index (> percentile 75th) being found in 7 marinas, 4 of each located in the Algarve. Marinas with high ecologic value (6 out of 26) are also concentrated in the Algarve, particularly in the East, namely Faro, Olhão and Tavira located in the Ria Formosa natural park and Vila Real de Santo António (V.R.S.A.) located in the Guadiana estuary. The marina's typology controls the

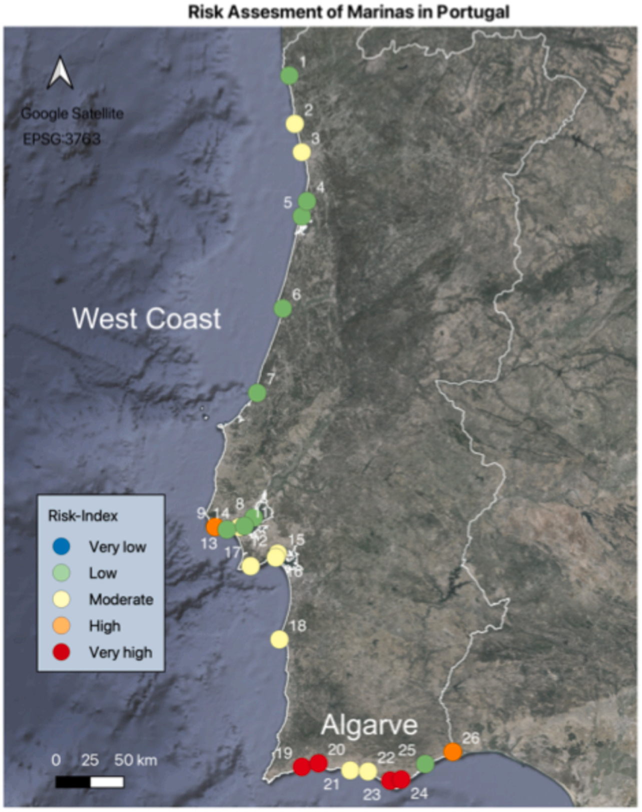

Fig. 2. Map of environmental risk of water quality for Portuguese Marinas according to MERA.

naturalness which is classified as moderate (interior marina type) in 76 % of marinas. The responses estimated according to the adopted measures and instruments are insufficient in most marinas, being optimal in only 38 % and 23 % of the marinas, respectively. The graphical representations of the most relevant characteristics of marinas in Portugal can be seen in Fig. S1 of supplementary material.

The environmental risk (Eq. 1) has been classified in five categories: Very Low-risk ($R_i = 1$), low-risk ($1 < R_i < 5$), moderate-risk ($5 \leq R_i < 10$), high-risk ($10 \leq R_i < 15$), and very high-risk ($R_i \geq 15$). A spatially explicit representation of these categories of risk is provided in Fig. 2. The regions with the largest number of marinas, the Greater Lisbon area (with 9 marinas) and Algarve coast (with 8 marinas), are also the ones where the environmental risk is more heterogeneous. It is hard to disentangle the factors that most contribute to this heterogeneity since the same category of risk is obtained with different levels of pressures, state environmental conditions and societal responses (Table 1). However, it was possible to identify the most relevant factors at the national scale. According to the results of the multi-linear regression model, the most significant statistical predictors of risk in Portugal are the navigation activity (NV$_i$), the ecological value (EV$_i$), the flushing capacity (SU$_i$), the response measures, and instruments adopted to reduce pressures (AM$_i$ and AI$_i$) (Table S1 of supplementary material). This kind of analysis allows managers to adopt an adaptative management approach by focusing their environmental strategies on these factors. For example, they may promote local interventions to ensure optimal flushing capacity at the marina level or decide to reduce the navigation activity by reducing the number of berths or by establishing partnerships with neighboring marinas.

The quick comparison of the relative risk and the identification of high-priority marinas in terms of necessary corrective or preventive measures to reduce water pollution is the main advantage of this method. In Portugal, most marinas in the north display low to moderate risk, and, except for Cascais (#9), all the marinas with high to very high risk are concentrated in South Portugal. The ones with the highest risk are Lagos (#19) and Portimão (#20) in the western sector of the Algarve, and Faro (#22) and Olhão (#23) in central Algarve. The factors that most contribute to the risk in Portimão, Faro and Olhão are the pressures as these are the marinas in Portugal with the highest indicator of navigation activity. In Lagos, the factor that dominates the risk is the susceptibility which is related to the flushing capacity of the water volume combining hydrodynamic and morphological characteristics of the Marina through the Complexity Tidal Range Index. In fact, Lagos is the Marina in Portugal presenting the highest CTRI (normalized value 1) followed by Portimão (normalized value 0.68). These high values are mainly due to marina's shape with a large elongation when compared with the entrance dimension.

The quality of water may be disturbed by the input of freshwater from rivers, particularly in Portimão (#20), Tavira (#25) and V.R.S.A. (#26), although their environmental risk is classified as low. In these conditions, the Complexity Tidal Range Index (CTRI) used to evaluate the susceptibility to pollution may not be the most appropriate empirical method to calculate the flushing capacity. This method was found optimal in Spanish marinas where the flushing capacity is basically due to tidal action and river discharges can be neglected (Gómez et al., 2017). However, river inflow into the marina's water domain in some of the Algarve marinas may alter the hydrodynamics as well as the nutrients, dissolved oxygen and chlorophyll-a concentration in the marinas (Fig. S2 supplementary material). In future studies, a detailed analysis of the flushing capacity should be conducted to evaluate the suitability of the CTRI method in marinas affected by river discharges. An alternative method may consider the estuarine flow ratio (R/P), defined as the ratio of river discharge during a tidal cycle (R) to the transport, P, due to the tide or tidal prism (estuary water volume between the surface levels of high and low tide = volume of water entering the estuary during the flood) (Dyer, 1997). This ratio may be suitable for evaluating flushing capacity when significant river discharge occurs, which varies seasonally between wet and dry periods. However, validating the applicability of this method to the Algarve is beyond the scope of the present study.

4. Water quality based on field data

Most sampled marinas in the Algarve exhibit mesotrophic or oligotrophic conditions, with TRIX values predominantly in the High (0−4) or Good (4−5) quality ranges (see details in Table S2 in supplementary material). Only Lagos and Doca de Faro showed moderate TRIX values (5−6) corresponding to poorer quality parameters, for instance due to an increased input of nutrients, where DIN and phosphate were maxima. In all the Algarve marinas, the percentage contributions of chlorophyll-a and dissolved oxygen is on average only 20 % of the total (Log(ChA+aD %O) range: 5.9 % – 29.6 %) implying that the abiotic factors are exerting a stronger influence on the overall trophic status (Log (DIN*-DIP) range: 70.4 % – 94.1 %). High percentages from dissolved inorganic nitrogen and phosphate, combined with a low percentage from chlorophyll-a, could indicate that there are increased levels of available nutrients that are not being efficiently converted into phytoplankton biomass. However, the two indicators of trophic conditions used in this study are poorly correlated (Fig. 3), which suggests that the factors driving the overall trophic state (TRIX) might be different from those influencing nutrient utilization efficiency (Eff. Coeff.). For example, high nutrient loading from external sources (like river runoff) could lead to a high TRIX value regardless of the efficiency of uptake and conversion into biomass. In fact, the productivity of the studied systems could be limited by factors other than nutrients, implying that nutrients are not utilized to their maximum potential, as referred by Giovanardi and Vollenweider (2004) in Mediterranean coastal systems. Nonetheless, the distribution of the data on Fig. 3 indicates two distinct classes of waters: the less efficient (low nutrients utilization) and least productive waters have been found in the Lagos, Portimão, Albufeira, Doca de Faro and VRSA marinas (Eff. Coeff. < -2) while the most efficient (high nutrients utilization) and most productive were found in Olhão, Tavira and Vilamoura. It is important to note that the reference station (Praia de Faro) can be considered productive (Eff. Coeff. $= -1.67$) despite having the lowest nutrient and chlorophyll-a concentrations (Table S2), typical of oligotrophic waters (minimum TRIX $= 3.06$). Albufeira stands out as the marina having the best trophic conditions in terms of TRIX (lowest TRIX value $= 3.85$) but having a low Efficient Coefficient (Eff. Coeff. $= -2.75$).

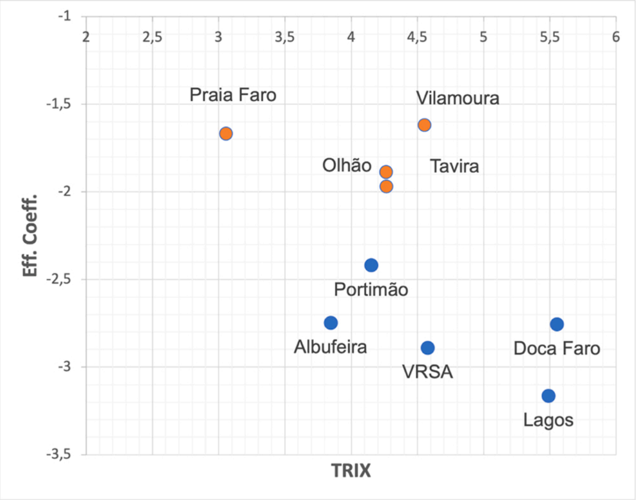

Fig. 3. Efficiency Coefficient versus TRIX values for water samples collected in the Algarve Marinas.

5. Discussion and conclusions

The comparison of TRIX, Eff. Coeff., and MERA results in the Algarve reveals heterogeneous and inconsistent spatial distributions (maps of the spatial distribution of TRIX and Eff. Coeff. are provided in supplementary material, Figs S2 and S3), revealing the complexity of coastal ecosystems, where different factors can independently influence overall productivity, the efficiency of nutrient cycling, and other different aspects of water quality. While TRIX and Eff. Coeff. provide a basis for comparison based on field data, their inconsistency prevents a definitive assessment of MERA's reliability. Moreover, MERA fails to align with either TRIX or Eff. Coeff, highlighting MERA's primary limitation: its inability to incorporate physico-chemical parameters and ecosystem health indicators. It can be argued that the TRIX and Eff. Coeff. values calculated for the Algarve marinas in two days of water sampling are only representative of the snapshot conditions. Repeated measurements over longer periods to cover the expected natural temporal variability, either in terms of different tidal conditions or different seasons, will allow a more comprehensive understanding of their overall trophic status. It is known that in mesotidal systems, semi-enclosed aquatic environments, like Ria Formosa, such factors significantly influence water quality variability (Rosa et al., 2022). Nevertheless, the trophic status results provide a picture of water quality, like the static assessment offered by MERA, which cannot account for time-dependent factors. Indeed, the MERA method is constrained by the inherent limitations of the PSR (Pressure-State-Response) model, namely its difficulty in addressing complex interactions between model components and its neglect of dynamic information (Meyar-Naimi and Vaez-Zadeh, 2012). Marine systems are indeed characterized by intricate interactions and feedback loops that are poorly represented by linear models. For instance, the PSR model often overlooks synergistic or antagonistic effects between pressures and the cascading consequences of responses (Kelly, 1998). Another key weakness of MERA lies in its limited representation of environment-economy-social interactions. These limitations suggest a need for more advanced frameworks capable of handling non-linear dynamics, feedback mechanisms, and the intricate connections between environmental, social, and economic factors. Alternative approaches, such as ecological risk assessment with Bayesian networks (Chen et al., 2022; Kaikkonen et al., 2021) or Analytic Network Process frameworks capable of linking socio-economic and ecological factors (Gonzalez-Urango et al., 2024; Parra et al., 2018; Wolfslehner and Vacik, 2008), may offer more robust methodologies.

Case studies using advanced analytical methods and examining the impact of anthropogenic sources on water quality highlight the limitations of traditional linear models used in the present study (Karadeniz et al., 2024; Neves et al., 2016; Tokatlı et al., 2024; Yazman et al., 2024; Yüksel et al., 2021). By analysing multiple parameters and contaminants simultaneously and integrating them into pollution and health risk assessment indices, these studies offer a more comprehensive assessment of environmental pressures. The methodologies they employ, particularly advanced statistical analyses such as Principal Component Analysis, Hierarchical Cluster Analysis, and Correlation Matrices, alongside sensitive analytical techniques like Inductively Coupled Plasma-Mass Spectrometry for quantifying metal levels in water samples, provide valuable insights. These approaches can inform and enhance the MERA framework by incorporating multivariate analyses and improving the understanding of complex environmental interactions.

More specifically, MERA does not incorporate sediment contamination (Birch et al., 2020) or key water column parameters such as trace metal elements (TMEs) and organotin compounds (OTCs) and hydrocarbons/polycyclic aromatic hydrocarbons (PAHs), which are crucial for understanding pollution dynamics in marinas (Chouba et al., 2024). A study of marinas in the Southern Iberian Peninsula, which included the Faro marina, found that water quality was primarily influenced by turbidity and Irgarol, an antimicrobial pesticide used in antifouling paints for boat hulls. At the same time, sediments were mainly contaminated by hydrocarbons and fecal coliforms (Guerra-García et al., 2021). That study proposed a new index specifically designed for marinas, the Marinas Environmental Pollution Index (MEPI), focused on quantifying pollution levels in sediments based on pre-defined thresholds and guidelines (e.g. Environmental Quality Standards and Sediment Quality Guidelines). Other studies emphasize the need to assess ecosystem health in harbors through combined analysis of sediment chemistry, bioaccumulation of contaminants/pollutants, biomarker responses, and bioassays (Bebianno et al., 2015). From the available literature it is clear that additional parameters and measurements need to be considered to improve the accuracy of MERA methodology as suggested in Table 3, namely:

1. **Incorporate Sediment and Water Quality Parameters** using indices for sediment contamination (e.g. hydrocarbons, Total Metal Elements (TMEs), fecal coliforms) and water column monitoring (e.g. organotin compounds (OTCs) and dissolved TMEs) as outlined by Guerra-García et al. (2021) and Chouba et al. (2024).
2. **Enhance Spatio-Temporal Monitoring** by incorporating dynamic parameters into the State Factor of the PSR model. This will require systematic monitoring at strategic locations within the marina and at various times throughout the year, considering different tidal conditions and seasonal influences. In particular, it is recommended to measure parameters related to the Complexity Tidal Range Index and to external pollutant influxes at regular intervals to capture temporal fluctuations (Chouba et al., 2024; Gómez et al., 2015).
3. **Integrate Ecological Indicators** such as bioaccumulation of contaminants/pollutants in organisms, and sediment toxicity tests to assess the ecological impacts of contaminants. Monitoring these indicators will provide insight into the cumulative effects on the marina's ecosystem as suggested by Bebianno et al. (2015).
4. **Establish Regional Thresholds for contaminants** based on local conditions to improve accuracy. This adaptation will address variability in environmental conditions across different marinas (Birch, 2018; Guerra-García et al., 2021).

In conclusion, the integration of sediment analysis, water quality monitoring, and ecological indicators into the more holistic evaluation of the MERA framework, can provide a more comprehensive and dynamic tool for assessing the risk of water pollution in Marinas. This can significantly increase both the complexity and cost of assessments, since these tests require systematic sampling, specialized laboratory analyses, and long-term monitoring to capture trends accurately. Additionally, incorporating such evaluations would necessitate defining clear thresholds, establishing standardized methodologies, and ensuring consistency across different study areas. While these enhancements would strengthen MERA's capacity to evaluate environmental and ecological risks, it is essential to balance analytical rigor with practical applicability. Despite the challenges posed by data requirements and threshold adaptability the approach will enable marina managers to develop more effective, data-driven strategies for environmental protection, leveraging the strengths of both MERA and other complementary methodologies.

CRediT authorship contribution statement

Neves Maria: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Jacob José:** Writing – review & editing, Resources, Data curation. **Cravo Alexandra:** Writing – review & editing, Validation, Methodology. **Correia Catia:** Data curation.

Table 3
Additional parameters, metrics and criteria to improve the MERA method of assessment of environmental risk in marinas. TMEs (Trace Metal Elements), OTCs (Organotin Compounds), EQS (Environmental Quality Standards), SQGs (Sediment Quality Guidelines).

Parameter	Metric	Sampling location	Frequency of measurement	Seasonal considerations	Exceedance of thresholds (EQS/SQGs)
Water Column Contamination	Dissolved concentrations of TMEs (e.g., Cu, Zn) and OTCs (e.g., tributyltin)	- Technical zones - Berthing areas - Reference sites outside marina	Monthly or quarterly, depending on the specific contaminant	Yes, especially for TMEs	Indicate whether concentrations exceed EQS for each sampling location and time point
Sediment Contamination	Concentrations of TMEs, OTCs, hydrocarbons, and other relevant contaminants	- Technical zones - Berthing areas - Reference sites outside marina	Annually or bi-annually, depending on the contaminant and marina characteristics	Consider potential seasonal variations due to changes in sedimentation patterns	Indicate whether concentrations exceed SQGs for each sampling location
Spatio-temporal changes in Susceptibility	Flushing capacity	Multiple points within the marina, chosen strategically to represent different zones	Monthly or quarterly, alongside measurements of tidal range, current patterns, and weather conditions	Yes, flushing capacity can vary significantly with tidal cycles and weather patterns	N/A
Spatio-temporal changes in External Activities	- Land use patterns (e.g., industrial, agricultural, urban) - Activities in surrounding areas (e.g., wastewater discharges, stormwater runoff)	- Upstream locations of rivers and streams discharging into the marina - Points along the marina's perimeter to capture potential runoff sources	Frequency will depend on the nature of the external activity and its potential to influence contaminant inputs	Yes, many external activities can exhibit seasonal variations	Compare contaminant loads to established limits or guidelines for discharges and runoff

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author Agreement Statement

I the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere. I confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. I further confirm that the order of authors listed in the manuscript has been approved by all authors. I understand that the Corresponding Author is the sole contact for the Editorial process. He/she is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rsma.2025.104210.

Data availability

Data will be made available on request.

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