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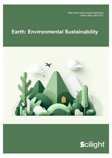

Review

Global Standards and Protocols for Port Aquatic Environment Assessment and Management: An Integrative Review

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Abstract: Port operations have been widely recognised as posing significant risks to adjacent aquatic environments through diverse pollution pathways. In response, contemporary port environmental management has been anchored in two foundational pillars: water quality assessment and ecological-integrity evaluation. In this review, prevailing international standards and state-of-the-art methodologies for assessing port waters and aquatic ecosystems were systematically synthesised. The application contexts for each approach were delineated, and the coherence of respective frameworks was appraised through comparative analysis of strengths and limitations. It was found that, although mature systems have been established for water-quality and ecosystem-integrity assessment when applied independently, these systems remain poorly integrated in practice, leading to partial environmental diagnoses. Accordingly, future progress is considered to hinge on the development of an integrated framework that explicitly couples water-quality metrics with ecological-integrity indicators. This review provides a theoretical basis and practical recommendations for comprehensive port aquatic environmental management and pollution control.

Keywords: port; water quality; aquatic ecological integrity; evaluation frameworks; integrated assessment

1. Introduction

Driven by the continuous expansion of the global shipping industry, ports are growing in both number and scale. According to the 2022 China Shipping Development Report [1], China's port cargo throughput and container throughput in 2022 increased by 33% and 56%, respectively, compared with a decade earlier. By the end of 2022, China's shipping fleet capacity had reached 370 million deadweight tons (DWT), ranking second globally. For instance, the Shanghai port recorded a container volume exceeding 47 million twenty-foot equivalent units (TEUs) in 2021. Monthly container throughput at major US ports peaked at approximately 4.6 million TEUs, while Busan Port in South Korea and Singapore handled record-breaking transshipment volumes in recent years [2].

Port construction and operation pose significant challenges to adjacent aquatic environments and aquatic ecosystems. Changes in shoreline morphology, water quality, and hydrodynamic conditions negatively affect aquatic biodiversity [3]. The discharge of oily wastewater and chemicals from port activities can lead to eutrophication and harm aquatic life [4]. Furthermore, Ballast water discharge is a particularly well-documented pathway for alien species introduction, threatening native habitats and biodiversity [5,6]. The ecological impacts of invasive species include altered community structure, local species extinction, disruption of food chains, and direct impacts on human habitats and local economies [7]. Although the International Maritime Organization (IMO) Ballast Water Management Convention established binding international standards in 2017, compliance and enforcement remain inconsistent across flag states [8].

Due to their semi-enclosed nature, port environments are particularly vulnerable to the cumulative effects of human activities [9]. Currently, the environmental impact assessment of port operations typically focuses on two key domains: water quality and aquatic ecological integrity. Water quality assessment involves evaluating physical and chemical parameters against specific regulatory criteria [10]. Conversely, ecological integrity assessment involves dynamically monitoring biological elements to derive indices that reflect overall ecosystem health [11]. These two assessment domains are distinct yet mutually reinforcing: water quality focuses on resource utilization and pollution prevention, while aquatic ecology emphasizes biodiversity and ecosystem resilience. The condition of the aquatic environment directly influences aquatic habitats, just as the composition of aquatic communities reflects long-term water quality conditions. Therefore, a comprehensive evaluation of port water bodies should integrate both dimensions to support effective environmental management and sustainable port development [12,13].

Despite research on these impacts, the evaluation of water quality and ecological integrity is often conducted separately. This separation results in incomplete diagnoses that do not meet the needs of modern port management. Existing research often lists evaluation methods without providing a synthesis of their strengths and weaknesses. This article aims to address this gap by reviewing existing methods and standards, analyzing the limitations of each approach, identifying opportunities for integration, and proposing recommendations aligned with dual-carbon policies and governance needs.

2. Methodology

2.1. Search Strategy

A systematic literature review was conducted following the PRISMA 2020 guidelines to identify and synthesise prevailing standards, methodologies, and empirical findings relevant to port aquatic environment assessment and management [14]. Three major academic databases were searched: Web of Science (WoS) Core Collection, Scopus, and China National Knowledge Infrastructure (CNKI). The search strategy employed a combination of Boolean operators with the following query structure, adapted for each database's syntax: ("port" OR "harbour" OR "harbor" OR "seaport" OR "marina") AND ("water quality" OR "water pollution" OR "aquatic environment" OR "ecological integrity" OR "ecological assessment" OR "biological integrity" OR "environmental impact assessment") AND ("assessment" OR "evaluation" OR "monitoring" OR "standard" OR "framework" OR "index"). Equivalent Chinese search terms were utilized for the CNKI database.

2.2. Selection Criteria

Studies were included if they met the following criteria: (1) focused on water quality assessment, ecological integrity evaluation, or integrated environmental assessment in port, harbour, or adjacent coastal environments; (2) described, evaluated, or proposed specific assessment methodologies, indices, or regulatory frameworks applicable to port water management; (3) were peer-reviewed journal articles, official regulatory documents, government reports, or international conventions; and (4) were published in English or Chinese. Exclusion criteria comprised: (a) studies dealing exclusively with open-ocean or inland water bodies irrelevant to port environments; (b) purely monitoring studies reporting raw data without methodological discussion; (c) conference abstracts, editorials, and non-peer-reviewed grey literature; and (d) duplicate publications.

2.3. Screening Process and Results

The initial database searches yielded a total of 4276 records. After automated and manual removal of duplicates across databases, 1914 unique records remained. Two independent reviewers screened all titles and abstracts against the inclusion and exclusion criteria, with disagreements resolved through discussion. This screening phase excluded 1701 records that were clearly outside the scope of this review. The remaining 213 records were retrieved for full-text assessment. Of these, 148 were excluded after full-text reading. An additional 12 relevant studies were identified through manual screening of reference lists of included articles and recent reviews. The final review included 77 documents, 50 were published between 2020 and 2026, reflecting an emphasis on the most recent literature.

3. Impacts of Port Construction on Adjacent Aquatic Systems

The environmental impacts of ports on water quality and aquatic ecology are well documented, operating through two principal pathways: degradation of water quality and disruption of ecological integrity. Port operations generate substantial domestic sewage, industrial wastewater, and oily discharges, contributing to measurable declines in water quality [15]. For example, high levels of Cd, Cr, Cu, and Pb were measured in the surface water and sediment of Shanghai Port, exceeding marine water quality standards [16]. During port operations, emissions of suspended solids, chemical oxygen demand (COD), total phosphorus, ammonia nitrogen, and petroleum increase substantially relative to the construction phase [17]. Additionally, emerging contaminants such as microplastics, pharmaceutical residues, and antifouling biocides have been found in port sediments at levels that exceed ecological safety limits [18,19].

Regional data support these findings. According to the 2022 Shanghai Ecological Environment Status Bulletin, the average COD concentration in seawater outside the Yangtze River estuary increased by 13.0% compared to 2021 [20]. Similarly, single-factor evaluations at Tianjin Port found that levels of COD, oil, active phosphate, and inorganic nitrogen were above recommended limits [21]. The discharge of ballast water also changes the bacterial communities in port waters. Ballast water discharge has been found to lead to a dominance of Bacteroidetes and Gamma-Proteobacteria [22]. Recent findings further suggest that specific microbial groups act as key mediators of environmental change, reflecting the complex pollution dynamics within river basins and coastal interfaces [23].

Port construction and operational activities also alter hydrodynamic conditions and shoreline resources, disrupting aquatic habitats [24]. Large benthic communities are especially affected, with land reclamation and ferry terminal operations diminishing invertebrate diversity, simplifying community structures, and reducing secondary productivity [25,26]. Sediment disturbance caused by reclamation significantly changes the composition of meiofaunal communities in subtidal habitats [27]. The combined effects of ballast water and human activities put pressure on microbial communities, leading to eutrophication, heavy metal accumulation, and the spread of pathogens [28]. Invasive species introduced from biofouling and ballast water make up 60–90% of invasive aquatic organisms in receiving waters [7]. Therefore, an integrated assessment framework is needed to manage these impacts (Figure 1).

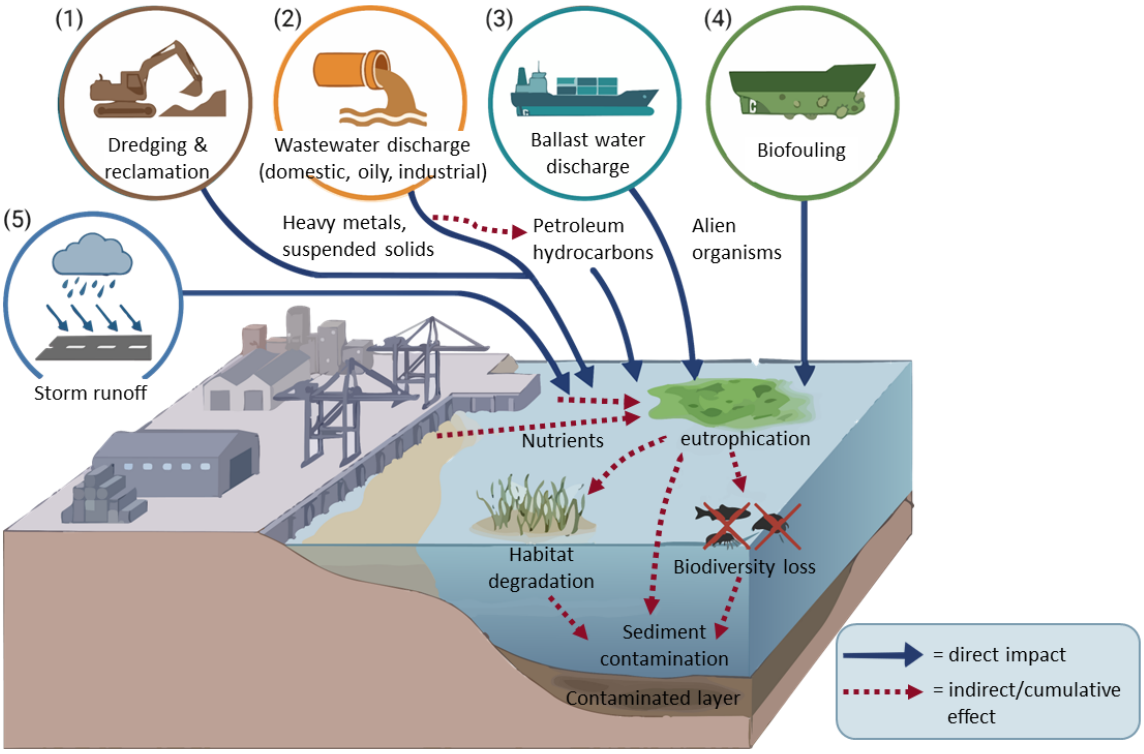

Figure 1. Schematic diagram of pollution pathways from port operations to aquatic systems.

4. Water Quality Assessment

4.1. Regulatory Frameworks

Many countries employ legislative frameworks to assess port water quality through functional zone classification. In China, the Environmental Quality Standards for Surface Water (GB 3838-2002), the Sea Water Quality Standard (GB 3097-1997), and the Technical Specification for Surface Water Environmental Quality Monitoring (HJ 91.2-2022) provide the primary national basis for single-factor evaluation [10,29,30]. Other specific guidelines include the Environmental Impact Assessment Specification for Port Construction Projects (JTS 105-1-2011) and its updated version (JTS/T 105-2021), which cover hydrodynamic conditions, sediment, and groundwater [31,32]. The Technical Points for EIA of Port Master Plans also provides rules for managing oily sewage and calculating total pollutant discharges [33].

Internationally, the US Clean Water Act(CWA) regulates the discharge of pollutants and sets surface water standards for conventional and toxic substances [34]. Japan uses the Environmental Basic Law and the Water Pollution Prevention and Control Law to monitor health and environmental indicators in nearshore waters [35,36]. The EU Water Framework Directive (WFD) is a comprehensive system that evaluates the ecological status of water based on chemical, biological, and hydromorphological factors [37]. A comparison shows that while Chinese standards focus on physicochemical parameters and COD thresholds, the EU WFD integrates biological elements, and the US CWA focuses on technology-based effluent limits [37,38]. These differences can make it difficult to compare port environments across different regions. The relevant standards and evaluation indicators for port water environment management are shown in Table 1.

Table 1. Relevant standards and evaluation indicators for port water environment management.

Relevant Standards	Evaluation Indicators
Environmental quality standards for surface water (GB 3838-2002)	Water temperature, pH, DO, permanganate index, COD, five-day biochemical oxygen demand, ammonia nitrogen, total nitrogen Total phosphorus, petroleum, volatile phenols, cyanides, heavy metals, etc
Technical Points for Environmental Impact Assessment of Port Overall Planning (2012)	The generation and discharge of port domestic and production wastewater, ship wastewater, estimation of oily wastewater, tank washing water, tank washing water and other wastewater, and calculation of the total discharge of characteristic pollutants such as COD and petroleum
Specifications for Environmental Impact Assessment of Port and Waterway Engineering (JTS/T 105-2021)	Hydrodynamic environment, erosion and deposition environment, water quality environment, sediment environment, groundwater environment
Technical Guidelines for the Preparation of Regional Assessment (Environmental Impact) Report (Trial Implementation)	Sewage collection and management rate, sewage standard treatment rate, proportion of sea discharge outlet treatment, water quality standard rate of surface water and groundwater environmental functional zones
US Clean Water Act	Biochemical oxygen demand, total suspended solids, Escherichia coli, total phosphorus, total nitrogen, pathogenic microorganisms and other conventional and toxic pollutants
EU Water Framework Directive	Priority pollutants mainly composed of chemical pesticides, heavy metals, and environmental hormones, as well as priority hazardous substances mainly composed of POPs
Japan Environmental Basic Law / Water Pollution Prevention and Control Law	27 health items including cadmium and total cyanide; 13 living environment projects including BOD and COD; Necessary monitoring items such as trichloromethane and phenol

Various methods are employed to evaluate port water quality. Single-factor evaluation involves monitoring individual physicochemical parameters against specific criteria to identify water quality classes [39,40]. The pollution index method calculates sub-indices by comparing results with standard values and statistically combines them into an overall water pollution index [39]. Fuzzy comprehensive evaluation applies membership function theory to assess each parameter's probability of meeting a given quality standard, accommodating inherent uncertainty in water quality classification [41].

Moreover, constructing evaluation models has become prevalent in assessing port water quality. For instance, an EW-GRA-TOPSIS model integrating conventional physicochemical factors has been developed to evaluate seawater quality in port waters [42]. Another proposed evaluation method is based on improved grey relational analysis and a particle swarm optimisation multi-class support vector machine [43]. The DPSIR model has also been applied to evaluate port water quality, proposing indicators that include sensitive water area characteristics, pollution source trends, and sewage treatment rates [44,45]. Furthermore, the Delphi method and Analytic Hierarchy Process have been utilized to identify factors influencing waterway water quality across natural, socio-cultural, physical, and management dimensions [46]. More recently, machine-learning approaches—including random forests, support vector machines, and neural networks—are increasingly applied to water quality classification and prediction, showing promise for real-time port water monitoring [47,48].

Overall, current assessments of port aquatic environments have integrated hydrological morphology and pollutant evaluation indicators alongside conventional physical and chemical measures. There has been increased focus on understanding pollution from human activities, particularly sewage discharge from port ships. Evaluation methods have evolved from single-factor assessments to combining multiple methodologies, reflecting a more comprehensive approach to safeguarding water quality.

4.2. Limitations of Current Port Water Environment Assessment

Various methods are used to evaluate port water quality, each with certain strengths and weaknesses. The widely used single-factor evaluation method, while straightforward in calculation, tends to reflect only the most severely polluted parameters, failing to capture overall pollution trends and changing water quality characteristics [49]. The pollution index evaluation method offers quantitative descriptions and qualitative comparisons over time or between water bodies, but it lacks standardization across different indices and between index grades and environmental quality standards, impairing cross-study comparability [50]. The fuzzy comprehensive evaluation method integrates various factors but is computationally complex and may obscure primary pollution drivers, hindering the comparison of evaluation results across different water samples [41]. The grey relational evaluation model handles small-sample data and explores interrelationships between indicators, but it introduces subjectivity and uncertainty in setting indicator weights and membership degrees [43].

Among model-based approaches, the DPSIR framework categorizes and grades indicators logically and systematically. However, its linear causal approach oversimplifies complex realities and reflects a traditional responsive environmental protection concept [44,45]. The EW-GRA-TOPSIS model uses entropy weighting to calculate objective weights, but it ignores the subjective preferences of decision-makers, which can lead to discrepancies between weighted values and real-world priorities [42]. The Delphi-AHP method involves structured expert input, but the independence of expert opinions can introduce subjective biases [43].

A critical shared deficiency among these methodologies is their almost exclusive focus on physicochemical parameters, which leads to incomplete environmental assessments. This methodological narrowness is problematic for three reasons: (i) chemical concentrations reflect only instantaneous pollution loads, whereas biological communities integrate exposure over time, providing a more ecologically meaningful signal of cumulative stress; (ii) aquatic ecosystems possess inherent self-regulatory capacity—relatively minor or transient chemical perturbations may produce detectable biological responses before exceeding physicochemical thresholds; and (iii) port-specific pollutants such as petroleum hydrocarbons, heavy metals, and antifouling biocides exert sublethal biological effects that are invisible to conventional chemical monitoring but detectable through bioassays and ecological integrity indices [12]. Relying solely on these chemical-based evaluation systems creates significant economic risks. Because these methodologies fail to detect long-term ecological degradation or sublethal toxicity, the resulting environmental diagnosis is often incomplete. Such an incomplete diagnosis can lead to delayed or ineffective management responses, which in turn result in fishery closures, high remediation expenditures, and damage to port reputation [51,52]. Therefore, adopting an integrated evaluation methodology that includes biological elements is a more cost-effective long-term strategy. Analyzing changes in the species composition, abundance, and physiological behaviors of aquatic organisms provides insights into ecological risks that chemical methods miss, offering a more comprehensive evaluation grounded in ecosystem properties (Table 2).

Table 2. Common methods for evaluating the water environment of ports.

Evaluation Method	Usage Scenario	Evaluating Indicator	Advantage	Disadvantage	The Benefits of Integrating with Aquatic Ecology
Single factor evaluation method	River water quality evaluation	Conventional physical and chemical indicators such as water temperature, pH, dissolved oxygen, fecal coliforms, harmful substances, etc.	identify water quality categories	Unable to reflect the overall pollution situation and changing characteristics of water quality	Incorporating ecosystem factors into evaluations allows for a comprehensive assessment of various influences and the broader ecological impacts of pollution through material flow analysis. For instance, focusing on algae can mitigate limitations associated with momentary conditions and provide insights into long-term changes in water quality and biological conditions.
Pollution Index Evaluation Method	River water quality evaluation	Based on the evaluation indicators in the Surface Water Environmental Quality Standards	It can quantitatively describe and qualitatively evaluate overall water quality, providing an easy-to-calculate method for comparing pollution statuses across water bodies over time.	Lack of comparability between different indices, index grading, and environmental quality standards	Analyzing the pollution index from an ecosystem perspective enables not only the assessment of environmental pollution but also a deeper analysis of inherent ecosystem properties, thereby enhancing the accuracy of evaluation results.
Fuzzy evaluation method	Suitable for evaluating and making decisions on environmental water quality, groundwater resources, urban water resources, and water environment	Based on the evaluation indicators in the Surface Water Environmental Quality Standards	Integrating various evaluation factors to assess water quality enables the determination of each factor's likelihood of meeting quality standards.	The evaluation process is relatively complex, lacks operability, and struggles to pinpoint the primary pollution factors. This limitation may obscure the impact of pollutants that pose significant threats to human health and the ecological environment, and hinders the comparison of evaluation results across different water samples.	Ecosystems can stabilize water environments through their regulatory effects, maintaining a relatively stable state. Aquatic ecosystems exhibit corresponding ecological responses under varying hydrological conditions, which can be reflected in water quality assessments using biological monitoring indicators in ecological assessments
Grey correlation evaluation model	Water quality assessment of rivers and lakes	Based on the evaluation indicators in the Surface Water Environmental Quality Standards	The calculation method is simple, does not require a large amount of sample data, makes it easier to explore the interrelationships between indicators, and can handle incomplete information	There is subjectivity and uncertainty in the setting of indicator weights and interval membership degrees	
DPSIR	Mainly used for decision-making and implementation in water, marine resources, coastal organisms, soil, and environmental management science	Sewage discharge per 10000 tons throughput, annual discharge of water pollutants, per capita domestic sewage discharge, water quality compliance rate of water environment functional zones, sewage treatment and compliance discharge rate, urban sewage pipe acceptance rate	This method classifies and grades the indicator system, with strong logic and systematicity	The linear causal relationship in this model simplifies the actual situation	The selection of indicators is more logical, which saves time and costs to some extent, allows for obtaining a wider range of information, and facilitates mutual support through comparisons.
EW-GRA-TOPSIS	Evaluate the ecological quality status of port waters	Evaluation indicators for salinity, suspended solids, dissolved oxygen, chemical oxygen demand, inorganic nitrogen, active phosphate, petroleum, etc.	This evaluation model employs the entropy weight method to calculate weights, effectively utilizing actual data to determine precise weight values.	Decision makers have subjective preferences when assigning importance to evaluation indicators, which can lead to deviations in indicator weights from actual circumstances.	
Delphi -AHP	Widely used in fields such as prediction, risk assessment, decision support, technical evaluation, and expert opinion solicitation	Four primary indicators: natural environment, socio-cultural, physical environment, and management factors	Each expert's opinion is independent and not influenced by each other	When determining the weight of evaluation indicators, it will be influenced by subjective factors	

5. Aquatic Ecological Integrity Assessment

5.1. Assessment Standards and Tools

The evaluation of aquatic ecological integrity in port waters currently relies on methodologies developed for general aquatic environments, as few specific indicators have been tailored for the unique conditions of port systems. The Index of Biological Integrity (IBI) remains the most widely endorsed approach, integrating metrics such as taxonomic composition, species richness, and individual health to measure ecosystem condition relative to undisturbed reference sites [53]. This method is widely applied across various watersheds, such as in the EPA Rapid Biological Assessment Program in the United States [54]. In China, the Guidelines for Environmental Impact Assessment of Water Transport Engineering Construction Projects (JTS/T 105-2021) categorise aquatic ecology evaluations into rivers, lakes, and marine environments [32]. These guidelines are supported by the Chinese Technical Guidelines for Evaluating Water Ecological Carrying Capacity, which utilize sub-indicators such as the aquatic habitat index and the aquatic organism index to assess shoreline vegetation, connectivity, and the integrity of fish, algae, and benthic communities.

The EU Water Framework Directive (WFD) evaluates ecological status through a combination of biological, hydromorphological, and physicochemical elements [55]. This framework is complemented by the Marine Strategy Framework Directive (MSFD; 2008/56/EC), which addresses biodiversity, non-indigenous species, and seafloor integrity in marine systems [56]. In recent years, several countries have introduced standards and regulations specifically for assessing port aquatic ecology. China’s Environmental Impact Assessment Specification for Port Construction Projects (JTS 105-1-2011) highlights the importance of evaluating ecological status based on port type, with indicators encompassing biomass, population, productivity, diversity of aquatic plants, plankton, swimming animals, fish, protected species, and intertidal and benthic organisms [31]. The European Sea Ports Organisation (ESPO) initiated the Eco-Ports Programme, concentrating on indicators spanning port environment, biology, management, and economic benefit dimensions [57].

Researchers have also developed innovative port-specific approaches. A holistic port environmental condition index was established to characterize benthic habitat conditions in Canadian port communities, utilizing remote sensing to evaluate coastal vegetation distribution [51]. Comprehensive approaches combining non-biological and biological data have been adopted to assess the ecological status of ports in the southern Iberian Peninsula [58]. Furthermore, a semi-quantitative global harbour environmental risk mapping method has been proposed [52]. The ecological status of Mediterranean ports has been compared using the benthic macrofauna index from the WFD [59]. More recently, a multi-metric ecological quality index specifically calibrated for Mediterranean port environments was developed, representing an important advance in port-specific assessment tools [60].

A range of methodological approaches has been applied to assess ecological integrity. Beyond the IBI, the River Invertebrate Prediction and Classification System (RIVPACS) compares observed to expected macroinvertebrate communities as a measure of ecological departure from reference conditions [61]. The AZTI Marine Biotic Index (AMBI) assesses soft-bottom benthic community composition across ecological groups ranging from sensitive to opportunistic taxa, and it has been widely applied in European port assessments [62]. Composite frameworks such as the Pressure-State-Response (PSR) model, the DPSIR model, and the more recent SPIR hybrid provide structured approaches for integrating multiple indicator types [63,64]. Additionally, the EW-GRA-TOPSIS model applies objective entropy-based weighting to marine biological indicators—including phytoplankton diversity and abundance, zooplankton diversity and abundance, and benthic biodiversity and abundance—for port sea area ecological quality assessment [42].

Currently, countries evaluate port water ecological quality by adapting assessments from broader water body evaluations, focusing on indicators such as port environment, biology, and habitat. Evaluation methods have evolved from single indicator assessments to comprehensive evaluations considering both biological and habitat conditions. The selection of evaluation indicators remains flexible, tailored to the specific environmental characteristics of each port (Table 3).

Table 3. Relevant standards and evaluation indicators for port water ecological management.

Relevant Standards	Evaluation Indicators
Specifications for Environmental Impact Assessment of Port Engineering (JTS105-1-2011).	The biomass, population, productivity, diversity of aquatic plants, plankton, swimming animals and fish, as well as protected species, and intertidal and benthic organisms
Technical guidelines for hydro-ecological carrying capacity evaluation	Coastal vegetation coverage, water area index, river connectivity, ecological rapids protection rate, fish integrity index, algae integrity index, and large benthic animal integrity index
EIA of Port and Waterway Engineering (JTS/T 105-2021)	Assess the scope and degree of impact of each operational stage of the port on protected species and fishery resources, as well as the scope and degree of impact of land occupation on animals, protected species, and habitats

Table 3. *Cont.*

Relevant Standards	Evaluation Indicators
EU MSFD (2008/56/EC)	11 descriptors: biodiversity, non-indigenous species, food webs, eutrophication, seafloor integrity, etc.
US Clean Water Act/EPA Rapid Biological Assessment	Biological habitats, species diversity, and ecosystem services

5.2. Limitations of Current Methods for Assessing Ecological Integrity in Port Waters

Evaluating aquatic ecological integrity presents several ongoing challenges related to methodological sensitivity, data collection, and analytical subjectivity. The Index of Biological Integrity (IBI) provides valuable insights into the diversity of biological groups, but its sensitivity to environmental changes varies considerably. Natural variations across watersheds can lead to inconsistencies in evaluations, necessitating the careful selection of indicator species, parameters, and standards appropriate for local environmental conditions [11]. This reference condition problem is particularly acute for ports located in estuarine transition zones. In these areas, heavily urbanized settings make truly undisturbed reference sites unavailable, and natural abiotic variability confounds biological signal detection [65]. Consequently, IBI metrics developed for pristine riverine conditions may produce systematically biased results when applied to port environments without recalibration [66].

Establishing critical indicator values based on local conditions is crucial but requires high technical expertise. While this process ensures accurate assessments of aquatic ecology, the absence of standardized protocols for determining local thresholds creates inconsistency across studies and regions [12]. For example, the European intercalibration exercise under the Water Framework Directive has attempted to harmonize ecological status boundaries across member states, but substantial methodological diversity persists [55,66]. Furthermore, assessing aquatic ecological integrity demands strict adherence to monitoring schedules and robust data collection, relying heavily on comprehensive baseline data and consistent reference conditions, which can pose logistical challenges [67]. The temporal resolution of most ecological assessments is also frequently inadequate. Port ecological conditions vary seasonally and in response to episodic events like storm runoff and vessel accidents, yet most assessments are conducted at annual or biennial intervals. This sampling frequency is insufficient to detect transient perturbations or early-warning signals of ecosystem regime shifts [51,68].

The selection of monitoring taxa introduces inherent trade-offs among ecological sensitivity, taxonomic expertise requirements, and practical costs [66]. While benthic invertebrates are effective for assessing specific environmental types, their utility may be limited if changes in other species are not adequately reflected, potentially leading to incomplete assessments of port aquatic environments [61]. Benthic macroinvertebrates are widely used owing to their sedentary lifestyle and well-characterized pollution tolerance spectra, but they may miss impacts primarily expressed through pelagic or epibenthic communities [65]. Fish-based metrics are more visible to stakeholders but require greater survey effort and are subject to migratory variability [53]. Similarly, the AZTI Marine Biotic Index (AMBI), while efficient for soft-bottom marine environments, requires regional calibration and has limited applicability outside European contexts [62,69].

When developing evaluation models for aquatic ecological integrity, the selection of indicators and the determination of their weights are often influenced by subjective factors. Various comprehensive models have been developed to evaluate ecological security and adaptability, including the Pressure-State-Response (PSR) model integrated with the Analytic Hierarchy Process (AHP), the Entropy Weight-Grey Relational Analysis-TOPSIS (EW-GRA-TOPSIS) model, and the System-Pressure-Impact-Response (SPIR) model for waterway engineering [42,63,70]. While these models encompass indicators related to humanities, society, and nature, they often lack consideration of the response relationships between environmental factors and ecosystems [13]. The assignment of weights through AHP or expert elicitation introduces bias that can lead to divergence between modeled assessments and observed ecological conditions. Quantitative approaches such as EW-GRA-TOPSIS mitigate this subjectivity to some extent but introduce their own assumptions about the linearity and independence of indicator contributions [42].

From an economic standpoint, aquatic ecological integrity assessments are generally more resource-intensive than water quality monitoring, as they involve multi-taxon sampling, laboratory processing, and expert identification [51,52]. This cost differential can discourage port operators from voluntarily adopting integrated biological monitoring. Policy mechanisms, such as the EU WFD's binding ecological status classification requirements or the ESPO Eco-Ports voluntary certification scheme, are important drivers for adoption and should be considered in national regulatory design [55,71]. Future approaches to assessing aquatic ecosystem integrity should integrate water quality assessment methods, analyze interactions between environmental factors and selected monitoring targets, evaluate the impacts of diverse environments on aquatic biological communities and shoreline ecosystems, and assess organismal performance in varied environments to enhance monitoring indicators and standard systems [12] (Table 4).

Table 4. Common methods for evaluating the integrity of port water ecosystems.

Method	Scenario	Evaluating Indicator	Advantages	Limitations	Integration Benefits with Water Quality
IBI	Evaluate the health status of river, lake and wetland water ecosystem	Number of fish species, resource abundance, dominant families, nutritional structure, proportion of adult fish, composition of invasive alien species, fish status index; Key protected species and regional representative species composition important species index; Water connectivity, shoreline hardening, and habitat condition index of fishery water quality composition	By comprehensively reflecting the biological status of water bodies through multiple biological parameters, it better illustrates the advantages and disadvantages of water environmental conditions. This approach intuitively reflects the diversity and integrity of different functional groups or communities within the water bodies.	The response relationship between this method and environmental factors is weak, and the impact of certain natural or human activities on aquatic biological groups is difficult to quantify; Need to determine reasonable indicator species, evaluation parameters, and evaluation criteria	Environmental Context and Organism Selection: The environmental background significantly influences species selection. Ignoring water environment background values when selecting organisms may unfairly bias assessments towards species thriving in highly polluted environments. Water Environment Quality Evaluation: Conduct qualitative and quantitative analyses of water pollution to assess its quality. By examining the interrelationships between water environment disturbances and the reproduction and development of aquatic organisms, one can gain deeper insights into ecosystem health and resilience.
Diagnostic indicators for watershed health	Analyze the overall quality or functional level of the watershed	River hydrology, morphological characteristics, riparian conditions, water quality, and aquatic organisms	Can analyze the overall quality of the watershed and the trend of environmental quality changes	It is necessary to determine the critical values of indicators in a timely manner based on local environmental conditions	Taking into account the environmental background helps accurately portray the pollution status within the watershed. Coupled with detailed analysis of water pollution, this approach allows for the identification of patterns in pollutant migration and transformation over time.
WFD	Evaluate the ecological environment quality of water bodies	Physical and chemical quality elements of water bodies; Biological quality factors, including: composition and quantity of phytoplankton, composition and quantity of large benthic invertebrates, composition, quantity, and age structure of fish; Quality elements of hydrological morphology	This evaluation method requires a rigorous integration of physical and chemical evaluation outcomes with biological findings. It is a comprehensive approach that considers multiple factors to provide a holistic assessment of the environment.	There is a strong subjectivity and a lack of quantitative judgment basis; The accuracy of its evaluation is influenced by the amount of basic data and reference conditions	Combining environmental factors for analysis can reflect the long-term cumulative effect of human interference on habitat destruction and predict the harmful biological effects under multiple pollution stresses
RIVPACS	Evaluate the health status of rivers	Biodiversity and functional monitoring of large invertebrates	Can accurately evaluate specific types of environments; Can be used for long-term monitoring and evaluation	Using benthic invertebrates as monitoring objects simplifies the selection of indicators. However, if the health of the river is damaged and reflected only in changes to other species, it may not accurately reflect the true condition of the river.	Water environment quality assessment evaluates pollution levels caused by environmental factors affecting water quality. It examines how these factors relate to selected monitoring objects, such as aquatic biological communities, and analyzes relationships and differences among ecological indicators, such as species, across various environmental gradients. This analysis aids in understanding the performance of environmental organisms under varying conditions.

Table 4. *Cont.*

Method	Scenario	Evaluating Indicator	Advantages	Limitations	Integration Benefits with Water Quality
PSR	Evaluate ecological environment protection, natural resource utilization, and sustainable development	Annual wastewater discharge, annual total industrial wastewater discharge, total COD discharge in industrial wastewater, annual ammonia nitrogen discharge in industrial wastewater, agricultural fertilizer and pesticide use, annual total water consumption, surface water and groundwater resources, water use qualification rate in water functional areas, and soil erosion control in the region	Beginning with the mutual influence and correlation between social development and the natural environment, accurately reflecting the interrelationships among water ecological security factors involves integrating the Analytic Hierarchy Process (AHP) and Entropy Weight Method (EWM). This approach mitigates subjective preferences and addresses the limitations of EWM caused by data bias in dependent variables, ensuring alignment with actual situations.	Limited scope of use; When using the AHP method, there is less quantitative data and more qualitative components, making it difficult to convince people	Evaluating the integrity of aquatic ecosystems based on the construction of evaluation models can save time and cost to a certain extent, obtain a broader amount of information, and support each other through comparison
EW-GRA-TOPSIS	Evaluate the ecological quality status of port waters	The primary indicator is marine organisms, and the secondary indicators include phytoplankton diversity index, phytoplankton abundance, zooplankton diversity index, zooplankton abundance, benthic biodiversity index, and benthic animal abundance	Avoiding the subjectivity of data, being able to draw the comprehensive impact of multiple influencing indicators, determining indicator weights through objective weighting methods, and avoiding bias caused by human factors	Simplified methods for determining evaluation level intervals can influence the evaluation results to some extent. Additionally, decision makers' subjective preferences in assigning importance to evaluation indicators may lead to deviations in indicator weights from actual situations.	
SPIR	Ecological and environmental impact assessment of the Yangtze River downstream navigation channel project	Selecting water flow and river connectivity as hydrological evaluation indicators; comprehensive water quality index, suspended solids concentration, and sediment quality as environmental indicators; species diversity as a biological indicator; and bank slope form, riparian zone status, beach surface status, and river status as habitat indicators.	Ability to systematically analyze and quantitatively evaluate the ecological effects generated after taking measures in engineering design, construction, and operation processes	There is still a certain subjectivity in the selection of indicators and the formulation of standards, which can bring uncertainty to the evaluation results	

6. Towards an Integrated Assessment Framework

6.1. The Case for Integration

Individual assessments of water quality and aquatic ecological integrity, applied in isolation, are insufficient to characterize the complex environmental impacts of port operations. The two assessment domains are mutually dependent. Water quality conditions fundamentally constrain ecological outcomes, while biological community composition provides information on cumulative and chronic stressor effects that chemistry alone cannot capture [12,13]. The benefits of integration operate bidirectionally. Incorporating biological indicators into water quality assessment enables the evaluation of long-term pollutant trends and chronic exposure effects, which mitigates instantaneous-condition bias. Conversely, incorporating water quality data into aquatic ecological integrity assessment provides an environmental baseline context, supports dose-response characterization, and enables a more accurate interpretation of biotic index scores under high natural variability.

A key advantage of technical integration relates to algae-based monitoring. Evaluating algal community composition can mitigate instantaneous condition biases and provide insights into long-term water and biological conditions [19]. Invertebrates and plankton used in ecological assessments possess high diversity and sensitivity to environmental factors, playing vital roles in material cycling and energy flow. Changes in their population numbers indicate water quality conditions and the pace of species community disruption and recovery. These processes are inherently gradual and invisible to chemical snapshot monitoring.

6.2. Invasive Species as a Cross-Cutting Challenge

Ports serve as primary gateways for non-native species through biofouling and ballast water discharge. Species introduced via these pathways account for 60–90% of invasive aquatic organisms globally [7]. The ecological impacts range from individual-level stress to population declines, local extinctions, and the restructuring of community composition [72]. The economic costs are substantial. Biological invasions facilitated by shipping impose measurable ecological, economic, and health damages, including fishery losses, elevated maintenance costs, and public health risks from pathogens such as Vibrio cholerae [73,74].

Current assessment frameworks are poorly equipped to detect early-stage invasions. Conventional physicochemical monitoring provides no information on biological community composition, while ecological assessments conducted at annual intervals may lag invasion events by years. Therefore, future port assessment systems should incorporate environmental DNA (eDNA) metabarcoding as a complementary early-warning tool for invasive species detection [75,76].

6.3. Role in Global Climate Mitigation and Carbon Neutrality

The integration of water quality and aquatic ecological integrity assessments aligns with international climate agreements and global targets for achieving carbon neutrality. Aquatic ecosystems function as vital carbon reservoirs, and changes in their structure driven by port pollution and infrastructure development can significantly alter net carbon fluxes [77]. Evaluating aquatic ecological integrity is therefore essential for quantifying and preserving the carbon sequestration and cycling capacity of port waters [78]. Such integration supports international maritime initiatives, including the International Maritime Organization (IMO) 2023 Strategy on the Reduction of GHG Emissions from Ships, which seeks a pathway toward net-zero emissions [79]. Monitoring the relationship between pollutant concentrations and biological health helps clarify how environmental management influences carbon emission patterns, providing a scientific basis for integrated strategies that simultaneously reduce pollution and mitigate carbon emissions [80]. A comprehensive evaluation system encompassing both dimensions is necessary to optimize the carbon balance and enhance the overall sustainability of port-influenced systems.

6.4. Future Recommendations

Based on the critical analysis presented in this review, several priority actions are recommended to improve port environmental management. First, port-specific integrated assessment standards should be developed because existing frameworks were not designed for the semi-enclosed, multi-stressor environments of commercial ports. Dedicated standards should couple physicochemical thresholds with biological integrity indices and address port-specific reference condition challenges. Second, a tiered, risk-based monitoring approach should be adopted. This approach involves routine physicochemical monitoring for regulatory compliance, periodic biological status assessments using multi-taxon biological indices at least biannually, and intensive assessments triggered by major pollution events or invasive species alerts. Third, emerging molecular and remote sensing tools should be integrated. Environmental DNA metabarcoding enables rapid, cost-effective biodiversity assessment without physical specimen collection [75]. Additionally, satellite remote sensing can monitor large-scale changes in water color, turbidity, and coastal vegetation at intervals impractical for field monitoring [81]. Fourth, the economic valuation of port environmental impacts should be standardized. Adopting ecosystem service valuation methodologies would enable cost-benefit analyses of monitoring investments and support evidence-based policy decisions. Fifth, international coordination should be strengthened. Divergent national frameworks limit cross-border comparability, so an international port ecological assessment standard coordinated by the International Maritime Organization, building on the EU Water Framework Directive model, would advance global port environmental governance. Finally, data fragmentation must be addressed. The development of open, interoperable port environmental data platforms aligned with FAIR (Findable, Accessible, Interoperable, Reusable) principles would accelerate research and enable meta-analyses of global port environmental trends.

7. Conclusions

This review has systematically examined global standards and methodologies for port water quality assessment and aquatic ecological integrity evaluation. Both domains have evolved from single-indicator to comprehensive multi-criteria systems, but they remain poorly integrated in practice, producing partial environmental diagnoses inadequate for holistic port management. A critical analysis reveals that physicochemical water quality monitoring is limited by its inability to capture cumulative biological effects, while aquatic ecological integrity assessments suffer from reference condition challenges, temporal resolution constraints, and indicator weighting subjectivity. Each domain's weaknesses are substantially addressable through integration with the other. Furthermore, invasive species represent a cross-cutting challenge inadequately addressed by existing assessment domains. Future frameworks must incorporate biological surveillance tools such as eDNA metabarcoding. Alignment with dual-carbon policy goals provides additional rationale for an integrated assessment approach. The recommendations proposed in this review—port-specific standards, tiered monitoring, molecular and remote sensing tools, economic valuation, international coordination, and data infrastructure—provide a roadmap for advancing port environmental assessment into a more comprehensive and effective era.

Author Contributions

J.F.: conceptualization, methodology, writing—original draft preparation; X.Y.: data curation, investigation, writing—original draft preparation; Y.K.: visualization, formal analysis; E.M.M.: writing—reviewing and editing; L.W.: investigation, data curation; S.S.: validation; X.C.: formal analysis; G.W.: writing—reviewing and editing; C.G.: conceptualization, project administration, supervision; J.X.: project administration, funding acquisition, writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used large language models to assist with English language polishing, grammar correction, and improving the overall readability of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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