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RESEARCH AND DEVELOPMENT OF ECOLOGICAL INTEGRITY ASSESSMENT TECHNIQUES FOR ESTUARINE ENVIRONMENTS

Pat T. Borja
University of Coimbra, Portugal.

Abstract: Estuaries are important transition areas connecting freshwater and marine environments and play an important role in maintaining biodiversity and ecosystem services. The ecological integrity of estuaries is critical to the sustainable management and conservation of ecosystems. This article conducts a bibliometric analysis on the ecological integrity evaluation of estuaries, focusing on the evaluation methods and index selection of estuary ecological integrity evaluation. It mainly includes physical and chemical indicators, biological indicators and socioeconomic indicators. The importance of selecting different indicators for the evaluation of estuary ecological integrity is systematically analyzed through case studies. Finally, it was pointed out that some problems still faced in the evaluation of estuary ecological integrity were pointed out, and several suggestions were put forward to address these problems.
Keywords: Ecology; Aquatic ecology; Estuarine ecology; Marine environment

1 BIBLIOMETRIC ANALYSIS OF ESTUARY ECOLOGICAL INTEGRITY

In a broad sense, an estuary refers to the junction area formed when a river merges into a receiving water body, and is the transition zone between a river and a receiving water body. According to the different water receiving bodies, estuaries can be divided into types such as estuaries entering the sea, estuaries entering the lake, estuaries entering the reservoir and tributary estuaries. The term's etymology comes from the Latin word "Aestus", meaning "tidal". The narrow concept of estuary only includes areas affected by tides and runoff, that is, estuaries that enter the sea [1]. The estuaries appearing in this article all refer to estuaries in a narrow sense. As the junction where fresh water and sea water meet, the estuary is an important area where land and marine ecosystems are interconnected. It not only carries the material exchange between the basin and the ocean, but also has the characteristics of river and marine ecosystems [2]. Due to its unique geographical and environmental conditions, the estuary area often becomes an economically developed and densely populated area [3]. In recent years, with the development of economy and society and population growth, estuary areas have been affected by a series of man-made stress factors, resulting in increased sediment, nutrient and pollutant loads, and habitat degradation [4-5]. They change the community composition and species diversity of the estuary area, destroy the ecological functions of the estuary, and also have a huge impact on the ecosystem services that the estuary can provide [6], seriously restricting the development of the estuary area. Therefore, it is of great significance to evaluate the integrity of the estuary ecosystem. In this regard, water environment quality is one of the important evaluation indicators. Various methods such as water quality index and pollution index can be used to evaluate the environmental quality of the estuary [7]. Aquatic ecological integrity evaluation is a quantitative and systematic evaluation method. It is a comprehensive and comprehensive evaluation of the structure, function and process of the ecosystem, which can provide scientific basis for ecological protection and management. Research on the integrity of aquatic ecosystems is an international hot spot, and maintaining the health and stability of aquatic ecosystems has become the goal and management strategy of countries around the world [8].

The concept of ecological integrity originates from ecology, and its development can be traced back to the mid-20th century. In 1949, Leopold first proposed the concept of "land ethics". He believed that "it is correct for human activities to develop in the direction of protecting the integrity, stability and beauty of biological communities. On the contrary, it is wrong [9]." However, he did not The integrity he mentioned was further explained; in 1981, Karr and Dudley gave the first clear definition of ecosystem integrity. Integrity is a health dimension that reflects the ability of an ecosystem to maintain its organization (structure and function). The degree to which an ecosystem maintains its natural state, stability and self-organization ability under external disturbance provides an effective tool [10]; in the early 1990s, the Organization for Economic Cooperation and Development (OECD) established The Pressure-State-Response Framework (PSR) was developed, which was used to establish ecological environment assessment index systems in various countries [11]; in 1989, Rapport proposed that an ecosystem with good integrity should have the ability to maintain its own organizational structure Integrity and the ability to self-recover after being stressed [12]; in 1992, Costanza summarized the definition of ecosystem integrity, that is, the ecosystem should be disease-free, stable or recoverable, while maintaining diversity or complexity, and has the potential for vitality or growth, while maintaining an automatic balance between the system and its elements [13]. At present, domestic and foreign scholars have carried out a large number of studies on the evaluation of water ecological integrity, and their research scope covers multiple ecosystems such as rivers [14-15], wetlands [16-17], lakes [18], and reservoirs [19] . However, most ecological integrity assessment studies are conducted in rivers and streams. Since the ecological characteristics of estuarine ecosystems are relatively complex and are greatly affected by human activities, there are relatively few studies on their integrity assessment [20]. This article will focus on the methods, index selection and weight allocation of estuary ecological integrity assessment, aiming to provide reference for the protection and management of estuary ecosystems.

In order to understand the current development process of research on estuary ecological integrity evaluation, as well as the emerging trends in the research frontier, methods such as cluster analysis, emergent analysis, and literature collection were used, and the knowledge graph tool CiteSpace was used to analyze the relevant aspects of estuary ecological integrity evaluation. A bibliometric analysis of the literature was conducted, which mainly summarized the annual changes in publications in the past 30 years, and determined the main subject categories; as well as identified emerging research hotspots, and finally predicted development trends.

1.1 Search Methods and Data Sources

This article selects the core collection database in the Web of Science (WOS) database as the source of research data. The document type is: article, the time span is set to 30 years, and the search time includes articles published from 1993 to January 1, 2023. , search using keyword combinations linked by Boolean operators "AND" and "OR", the search formula is: TS = ("Estuar *") AND ("ecological quality" OR"ecological integrity"OR"ecological health") . The obtained documents were identified and screened, and 590 records were finally identified, and their data sources were analyzed.

At the same time, CNKI data is selected as the Chinese literature database. Document type selection: papers, time span is not limited, and CNKI professional search tool is used. The search formula is: SU= ("estuary" * "ecology") and SU= ("health" + " "Completeness"), 52 records were obtained. After identifying and filtering the search results, only 29 relevant documents were obtained. Due to the low sample size, the imported software analysis could not obtain effective results, so this analysis only used the WOS database Literature was retrieved as data source.

1.2 Analysis of the Number of Articles Published Over the Years

Statistically analyze the number of articles published each year in the field of estuary ecological integrity assessment, and obtain the number of articles published over the years (Figure 1). The results show that the research interest in estuary ecological integrity evaluation has been increasing year by year in the past 30 years. In the first few years, from 1994 to 1999, only a small amount of literature was published. Starting from 2000, the number of articles published gradually increased, increased rapidly in 2005, and has remained at a high level since then. Especially after 2007, the number of published articles increased year by year, showing an exponential growth trend. The number of published articles reached a peak in 2012. According to Rocha et al. [21], the possible reason is the academic community’s evaluation of aquatic ecological integrity. The attention has become more and more intense, and some journals have even published special issues for it. For example, Biologia Acuatica published a special issue on ecological quality in 2012. In 2021 and 2022, the number of published articles reached 53 and 58 respectively, further demonstrating the rapid development momentum of this field. Judging from the general trend, research on estuary ecological integrity evaluation has continued to grow in the past 30 years, showing an increasing trend year by year, indicating that this field has received widespread attention and has important research value and practical application in the field of ecological environment significance.

1. 3 Keywords and Emergence Analysis

Figure 1 shows the occurrence time and duration of each keyword, reflecting the length of influence of the keyword in the research field. In addition, it should be noted that the blue line in the table represents the entire research period (2002-2023), and the red line represents the duration of the citation burst [22-23]. In addition, in order to more accurately explore the research topics in the field of estuary ecological integrity assessment and grasp its development rules, we divided the development from 2002 to 2023 into three periods. The current stage can be summarized as concept exploration of ecological integrity assessment (2002-2009), ecological indicator monitoring and ecological integrity assessment framework construction (2010-2016), ecological risk assessment and pollutant source tracing (2017 -2023). At this stage of exploring the concept of ecological integrity assessment, scholars are not very clear about the concept of ecological integrity, and they mainly focus on specific indicators such as water quality conditions for water bodies; at this stage of constructing the ecological indicator monitoring and ecological integrity assessment framework, researchers realize that water bodies It is inseparable from the ecosystem, and began to study the integrity of water ecology from a holistic perspective, pay attention to comprehensive assessment and management, and began to use various models to simulate the evolution of ecosystems; in the ecological risk assessment and pollutant source tracing stages, Scholars have conducted a series of studies on ecological risk assessment and the spatial and temporal distribution of trace metal elements, aiming to reveal the impact of pollutant distribution on ecosystem integrity.

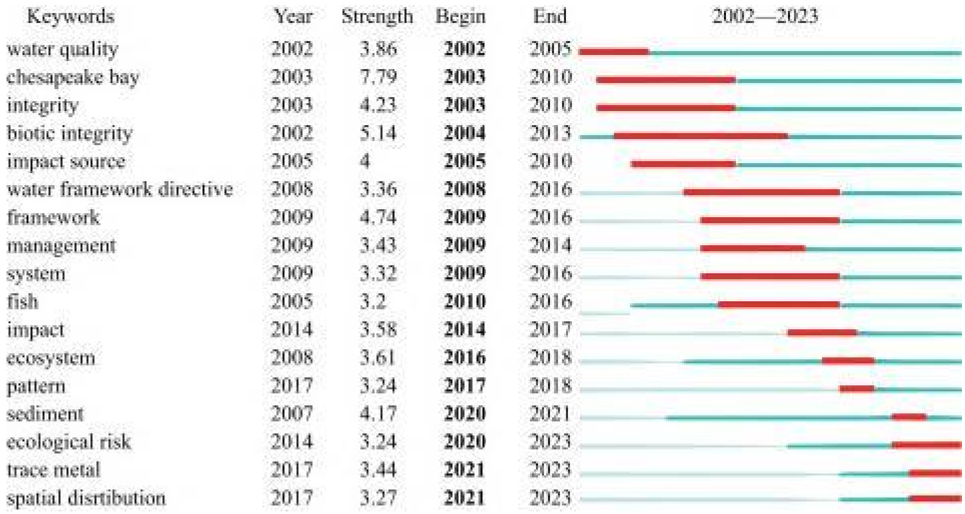

Figure 1 Time map of the top 17 keywords with emergent intensity in the field of estuary ecological integrity assessment

Note: The greater the value of emergence intensity, the faster the research interest of the keyword grows during this period; the start time and end time represent the time when the keyword emergence begins and the emergence ends respectively; the red segment in the timeline represents the explosive growth of keyword research. time period.

2 SELECTION OF ESTUARY ECOLOGICAL INTEGRITY EVALUATION INDICATORS

Estuaries show unique differences compared with other water bodies, mainly reflected in water mixing, tidal influence, sedimentation, ecosystem complexity, concentration of human activities, and salinity changes. According to the research of Elliott and Quintino [24], estuaries are places where fresh water and sea water meet each other, which leads to the complexity of hydrological and chemical characteristics. The effect of tides has a significant impact on the water level and flow in the estuary area, further increasing the complexity of hydrodynamics [25]. In addition, according to Stevenson and Kennish [26], the sedimentation phenomenon in the estuary area is caused by the slowdown of river water velocity, which has a profound impact on the evolution of topography and landforms. The ecosystem in the estuary shows extremely high complexity, supporting a rich variety of biological species due to the interaction of freshwater and saltwater [27]. Finally, the estuary area is a hotspot of human activities. Activities such as fishing, shipping, and urban development make this area a complex system in which natural and human factors interact. These differences make estuaries a key area of multidisciplinary research in ecology, geography, and hydrology, which are of far-reaching significance for understanding the functions and responses of complex aquatic ecosystems and promoting sustainable development.

The selection of estuary ecological integrity evaluation indicators is a key step in the research on estuary ecological integrity evaluation, and plays a decisive role in the scientific nature of subsequent evaluation results. In order to enable the estuarine ecosystem integrity assessment to solve practical problems and provide scientific basis for management decision-makers, it is necessary to select indicators based on the characteristics of the ecosystem [28]. Appropriate evaluation indicators should accurately reflect the key factors of ecosystem integrity [29]. The selection of estuary ecological integrity evaluation indicators should follow the following principles: indicators should be able to reflect the integrity status of the estuary ecosystem [30] and be able to accurately and reliably measure changes in the estuary ecosystem; indicators should be comparable [31] and be able to Comparisons should be made between different estuarine ecosystems; indicators should be operable [32] and can be measured through existing technical means. In addition, when selecting estuary ecological integrity evaluation indicators, a variety of indicators should be comprehensively considered, including water quality indicators, fish indicators, benthic biological indicators and heavy metal indicators in sediments, etc., to comprehensively and accurately assess the ecological integrity of the estuary. [33]. Combined with existing research, currently scholars mainly divide estuary ecological integrity evaluation indicators into three categories: physical and chemical indicators, biological indicators and socioeconomic indicators. Among them, biological indicators are the most commonly used indicators, because one component of evaluating ecological integrity is measuring biological integrity, which usually emphasizes the analysis of plankton, benthic organisms, macroalgae, and fish.

2.1 Physical and Chemical Indicators

When it comes to the assessment of estuarine ecosystems, physicochemical indicators are an essential part. Physical indicators are a direct measure of the physical environmental conditions of the estuary (such as water quality, sediment quality, and hydrology) [34] and help detect changes caused by human influence. Chemical indicators are used to evaluate the content and pollution of chemical substances in the estuary water. situation. Commonly used physical and chemical indicators in estuaries are shown in Table 1. The specific characteristics and functions of the estuary under study require careful consideration when selecting physicochemical indicators for estuarine ecological integrity assessment. For example, the hydrodynamics of an estuary, such as the magnitude and timing of tidal exchanges, can affect the suitability of certain indicators for assessing ecological integrity [35]. Tide is a crucial driving force in estuarine ecosystems, and its regularity has a profound impact on ecosystem structure and function. Scholars have emphasized the critical role of tides on estuarine hydrodynamics and hydrology. According to the research of Galois et al. [36], changes in water flow caused by tides have a significant impact on estuary sediment transport, dissolved oxygen distribution, and material circulation in the ecosystem. Under extreme meteorological events, tidal patterns may change, further affecting the stability and adaptability of estuarine ecosystems. In addition, research by Smith and Hollibaugh [37] showed that tides also have a significant impact on the spatial distribution and abundance of microorganisms and benthic organisms in estuarine ecosystems. Similarly, the specific characteristics of estuarine habitats, such as the type and distribution of vegetation, will also affect the selection of physical and chemical indicators to measure changes in habitat quality and quantity [38]. Furthermore, the selection of physicochemical indicators should be guided by the overall goals and objectives of the ecological integrity assessment, including the specific management issues that the assessment is intended to address. For example, if the main management goal is to reduce nutrients entering an estuary, then nutrient indicators such as nitrogen and phosphorus concentrations may be more meaningful than other indicators because nitrogen and phosphorus are the 2 major nutrients for biological growth and they are The concentration in the water body directly affects the growth and reproduction of algae and other organisms [39]. Excessive nitrogen and phosphorus can lead to eutrophication and trigger algal blooms. Estuary areas are often more prone to eutrophication due to the intersection of fresh water and seawater and intense human activities. It should be noted that any single indicator cannot reflect the full picture of the ecological integrity of the estuary, and a set of complementary indicators should be used to provide a more comprehensive assessment [25]. The selection of physicochemical indicators should also be regularly reviewed and updated to ensure that they continue to be relevant and effective in assessing ecological integrity. The selection of physical and chemical indicators in the ecological integrity evaluation of estuaries is not significantly different from that in other aquatic ecosystems.

Table 1 Commonly used physical and chemical indicators for estuary ecological integrity evaluation

Indicator type	Contains indicators	Indicator role
Hydrological indicators[14,16,40]	Salinity, substrate, depth, flow characteristics, flow deviation, tidal range and sediment transport rate, average rainfall, flood intensity index, proportion of annual runoff entering the sea, etc.	Provides information on estuarine circulation and sedimentation processes
Physical indicators Geomorphological indicators	Shoreline erosion, sedimentation rates and channel stability, etc.	Indicates the physical processes that shape estuarine environments and provide important habitat for aquatic species
Chemical indicators[14,43-45]	pH, dissolved oxygen, ammonia nitrogen, nitrate, phosphate, heavy metals, biochemical oxygen demand, etc.	Provide information on water pollution levels, nutrient content, accumulation of harmful substances, etc.

2.2 Biological Indicators

In addition to physicochemical indicators, biological indicators are also crucial for assessing the ecological integrity of estuaries, as they provide information on the impact of environmental stressors on biological communities and can help us understand biodiversity, ecological processes and ecosystem stability Sex[46]. These indicators typically involve measurements of species richness, species composition, and biodiversity in ecosystems. For example, species diversity index can be used to evaluate the number and relative abundance of different species in estuarine ecosystems, which helps to understand the interactions between various organisms and the allocation of ecological niches in estuarine ecosystems. Indicators such as species composition can more specifically describe the biological composition of the estuarine ecosystem, including fish, zooplankton, phytoplankton, benthic organisms, etc., and evaluate their ecological functions. Benthic invertebrates, phytoplankton, and fish are often used as biological indicators for estuarine ecological integrity assessment because they are sensitive to changes in water quality and habitat conditions [47] .

In specific applications, Ma Tingting et al. [48] selected multiple indicators, including the phytoplankton Shannon-Wiener index, to comprehensively assess the integrity of the main estuaries in the Taihu Lake Basin in my country; Hallett et al. [49] used the fish community index to quantify Ecological status of estuaries in southwestern Australia; Kido[50] used the stream biological integrity index to evaluate the integrity status of 18 streams in Hawaii, USA, and confirmed this by sampling and analyzing 39 locations (including 6 estuary sections). effectiveness of this method. However, it is worth noting that due to the existence of the estuary quality paradox [24, 51], that is, due to the high variability of the physical and chemical properties of estuaries, compared with other freshwater or marine ecosystems, estuarine biological communities are less resistant to environmental pressures. More acceptable. Under the same stress conditions, freshwater or marine ecosystem species may regard it as an environmental stress, while estuarine organisms have negligible impact on them due to their high tolerance. Le et al. [33] pointed out that some common endemic species in estuaries include special fish, crustaceans, and plant species with high salt tolerance that can survive in the transition zone between fresh water and sea water. In terms of adaptive strategies, some studies have shown that estuarine biota often exhibit a high degree of adaptability to changing salinity, water temperature, and hydrodynamic conditions. This may include changes at multiple levels such as behavioral adaptation, physiological adaptation, and genetic adaptation [52]. For example, fish species in some estuarine areas may exhibit migratory behavior under different salinity conditions to adapt to seasonal changes in the waters. Therefore, when selecting biological indicators (species composition, biodiversity, etc.) based on the structural characteristics of the estuary to evaluate the ecological integrity of the estuary, the error caused by this situation on the evaluation results should be taken into consideration. In order to solve the impact of the estuary quality paradox on the evaluation results, many scholars have proposed some corresponding solutions. For example, Elliott and Quintino [24] pointed out that we cannot rely too much on the structural characteristics of the ecosystem to identify the degree of stress that human activities have on estuarine ecology. Instead, it is necessary to combine structural characteristic indicators with functional characteristic indicators, and Hess et al. [53] found that using foraminiferal monitoring methods to detect environmental disturbances in estuaries can effectively solve the problem of estuary quality paradox.

2.3 Socioeconomic Indicators

Socioeconomic indicators can reflect the interrelationship between the estuary ecosystem and human activities. It includes the consideration of social and economic activities around the estuary, which have a direct or indirect impact on the integrity of the estuary ecosystem. According to Rapport et al. [54], the selection of socioeconomic indicators should be based on their impact on and dependence on ecosystem services, as well as their interaction with ecological indicators. Through literature search, the most commonly used socioeconomic indicators include population density, land use, agricultural and industrial activities, and water resource utilization [55]. Population density is an important socioeconomic indicator, which represents the ratio of population to area in the area surrounding the estuary. Increased population density often means increased demand for land and water resources, which may lead to increased land development and water use, thereby impacting estuarine ecosystems. Research shows that estuaries in areas with high population density often face greater pollution pressure and resource pressure, which may lead to reduced water quality, habitat degradation, and loss of biodiversity [56]. At the same time, the land use patterns in the surrounding areas of the estuary have a profound impact on the integrity of the estuary ecosystem. Different land use types may have different impacts on estuarine ecosystems. For example, urbanization and agricultural expansion may lead to the reduction of habitats such as wetlands and mangroves, thereby affecting biodiversity and ecological functions [57]. Proper planning and management of land use is one of the important measures to maintain the ecological integrity of estuaries. Agricultural activities can pollute estuarine waters through the use of pesticides and fertilizers, especially when farmland runoff enters estuaries. Industrial activities may discharge harmful substances and wastewater, causing direct negative impacts on estuarine ecosystems. Water resource utilization is also a key indicator for evaluating socioeconomic impacts. Water is a key element of estuarine ecosystems and a basic need for agriculture, industry and urban life. Excessive utilization of water resources may lead to excess nutrients in the water body, triggering algae blooms and deteriorating water quality, including reduced salinity, changes in nutrient dynamics, increased sedimentation, and disruption of physical processes such as tidal mixing and scouring. Negatively affecting estuarine ecosystems [58], these changes may adversely affect biodiversity, impair ecosystem services such as fisheries and coastal protection, and undermine the overall function of estuaries. Salinity is an important indicator for assessing the impact of reduced seawater flow, because when it deviates from the natural balance it signals an increase in ecological stress. Monitoring salinity levels provides us with valuable information to help us understand the extent and severity of this flow reduction and is a key parameter in understanding the ecological consequences for estuarine biodiversity, ecosystem services and overall functioning of balanced water resources use and Protecting estuarine ecosystems is an important issue in socioeconomic planning and management. Balancing water resource utilization and protecting estuarine ecosystems are important issues in socioeconomic planning and management. Since estuaries are closely related to human activities and economic development, compared with other aquatic ecosystem integrity assessments, socioeconomic indicators have a greater impact on the evaluation results when evaluating estuary ecological integrity. The selection is an integral part of the evaluation process.

3 ESTUARY ECOLOGICAL INTEGRITY EVALUATION METHOD

Ecosystem integrity assessment methods can be divided into two categories: indicator species method and indicator system method. The indicator system method can be further subdivided into methods such as comprehensive indicator evaluation method, analytic hierarchy process, principal component analysis method and entropy weight method [42]. When evaluating ecosystem integrity, multiple ecological indicators are often used, and their weighted scores are integrated through mathematical methods to form a comprehensive indicator system to describe the structure and function of the ecosystem [44]. In recent years, a large number of specific quantitative methods have been used in the practical application of the indicator system method, and multiple methods are used in combination and cross-wise, not limited to a single fixed method system. Since the indicator species method is usually applicable to a single ecosystem and requires a large amount of species measurement data, while the indicator system method is not limited by the number or type of ecosystems or data sources, the latter is currently used for ecological integrity assessment methods. It is more extensive than the former [59].

3.1 Indicator Species Method

The indicator species method is one of the two main assessment methods for evaluating ecosystem integrity. This method is mainly based on the number of dominant species, key species and sensitive species in the community to analyze environmental changes and assess the integrity of natural ecosystems. It includes three categories: biological index method, diversity index method and biological integrity index method. In 1981, Karr and Dudley proposed an evaluation method based on the Fish Integrity Index (F-IBI) [10], and later developed the Benthic Integrity Index (B-IBI) and Algae Integrity Index. Index (D-IBI)[60]. At present, IBI evaluation methods have included a variety of biological groups, such as phytoplankton [61-62], macrobenthos, fish and algae [63]. The IBI is mainly used to assess the integrity of aquatic ecosystems based on fish and zooplankton [64-66], while the Shannon-Weaver Biodiversity Index is generally used to assess the integrity of aquatic ecosystems based on phytoplankton and zooplankton [67] . Benthic macroinvertebrate communities are the most consistently emphasized biotic component of aquatic ecosystems when developing methods to assess biotic integrity. There are currently a large number of methods, including a variety of indices, indicators and evaluation tools [68]. Due to the specificity of the estuary itself, not all indicators can be applied to the ecological integrity evaluation of the estuary. For example, AZTI's marine biotic index (AMBI) and benthic biotic index (BENTIX), and other indices designed to determine stress are related to the abundance of tolerant species, and estuarine waters due to their Unique ecological characteristics, such as high natural organic matter content, are typical of tolerant species. These characteristics may cause the application of indices such as AMBI and BENTIX in estuarine waters to produce inaccurate results, that is, it is mistakenly believed that the ecological status of the estuary has been downgraded. Furthermore, due to the low species diversity in estuarine waters, some indices (such as AMBI and biomass quality index (BQI)) may not be used or calculated because their thresholds for use or calculation are reached.

Although the indicator species method was developed in the early days and widely used in ecosystem integrity assessment, in the estuary ecosystem integrity assessment, there are also cases where fish community index and zooplankton integrity index are used to assess ecological conditions [48-49] . However, the indicator species method also has certain limitations, as follows: depending on the identifiability of the species, this method requires accurate identification and classification of benthic organisms, but some species may be difficult to identify or classify, resulting in poor assessment Inaccuracy; relies on the consistency of environmental conditions. This method assumes that certain species only occur under specific environmental conditions. If environmental conditions change, the reliability of these species will also be affected; affected by human interference, Human activities have had extensive and complex impacts on ecosystems, which may interfere with the survival and distribution of benthic organisms, thus affecting the accuracy and effectiveness of the indicator species method. Therefore, compared with composite ecosystems, the indicator species method is more suitable for evaluating natural ecosystems that are rarely disturbed by human activities.

3.2 Indicator System Method

The indicator system method is based on ecosystem characteristics and service functions, and uses mathematical methods to determine the integrity of the ecosystem. This method combines multiple indicators, including ecosystem structure, functional succession process, ecological services, etc., and reflects the integrity status and change trend of the ecosystem. For example, Jiang et al. [69] used multi-source remote sensing data and field measurements, and adopted a comprehensive evaluation method to study the ecological integrity and changes of the Jiulong River Estuary from 2004 to 2009. Compared with the indicator species method, the indicator system method can reflect the transformation of ecosystem integrity assessment at different scales. It is a more comprehensive and comprehensive ecosystem integrity assessment method. It is also the most widely used ecosystem integrity assessment method at home and abroad. Evaluation method[70]. The main steps of the indicator system method are shown in Figure 3. Indicator selection and indicator weight allocation are two very important key steps. The relevant content of indicator selection has been discussed in Section 2 of this article. This section mainly introduces the methods related to indicator weight allocation.

In the evaluation of estuary ecological integrity, different evaluation indicators may have different effects on the evaluation results. Therefore, it is necessary to more accurately consider the contribution of each indicator through reasonable weight distribution, so as to comprehensively reflect the integrity status of the estuary ecosystem. . At present, in the ecological integrity evaluation, the methods commonly used by scholars include the analytic hierarchy process, the entropy weight method, the fuzzy comprehensive evaluation method, and the gray correlation analysis method. Among them, the analytic hierarchy process calculates the weight of each indicator through the hierarchical structure model and judgment matrix; the entropy weight rule uses the information entropy principle and the entropy weight criterion to determine the weight of indicators; the fuzzy comprehensive evaluation rule uses the concepts and algorithms of fuzzy mathematics to The indicators are converted into fuzzy numbers and comprehensively evaluated; the basic idea of the gray correlation analysis method is to find out the correlation between different indicators by calculating the correlation between indicators, thereby identifying indicators of relative importance. The principles and applicability of the above methods.

3.3 Differences in Ecological Integrity Assessment Methods Between Estuaries and Other Water Body Types

A major difference between estuaries and other freshwater ecosystems is that the estuary environment is highly variable, including physical and chemical changes in salinity, substrate, depth, fine particles, and maximum turbidity zones rich in organic matter [41]. In addition, estuaries are also subject to human impacts, including water pollution, changes in estuary surface size, and channel management [74]. Due to frequent human activities, the estuary area has been disturbed by river management, construction, industry, agriculture, and urbanization. These disturbances are more serious than inland ecosystems. Based on the characteristics of the estuary ecosystem, there are differences between the ecological integrity evaluation of estuaries and the ecological integrity evaluation of other water body types. The evaluation object of estuary ecological integrity assessment is the estuary and its surrounding sea areas and coastal zones, while the evaluation object of inland ecological integrity assessment is the ecosystem in inland areas. The evaluation of estuary ecological integrity needs to consider the special environment and species composition of the estuary ecosystem. The evaluation indicators include factors such as hydrodynamic conditions, seawater and river water quality, species diversity, land use and human activities. The evaluation of inland ecological integrity evaluation Indicators mainly include factors such as land use, vegetation cover, soil quality, biodiversity and hydrological conditions. In addition, because the estuarine ecosystem is at the junction of land and sea, data acquisition is relatively difficult and requires data from multiple departments and fields. The evaluation process is more complex than that of inland ecosystems.

To sum up, the ecological integrity evaluation of estuaries is mainly reflected in three aspects compared with the ecological integrity evaluation of other water bodies: (1) differences in evaluation objects and their own characteristics; (2) differences in selection of evaluation indicators; (3) data acquisition Differences in difficulty.

4 RESEARCH CASES OF ESTUARY ECOLOGICAL INTEGRITY ASSESSMENT

At present, scholars at home and abroad have done a lot of research on the ecological integrity evaluation of estuaries. In these studies, most indices are calculated based on species community composition and ecosystem structural and functional attributes, combined with multiple independent indicators. For example, Ferreira [75] considered the physical characteristics and biochemical characteristics of the estuary, combined with independent indicators such as water quality characteristics, dynamics, sediment characteristics, and anti-interference ability, to construct a comprehensive evaluation system for ecological integrity. Borja and Dauer [76] pointed out that when different indicators covering various responsive ecological and community characteristics are combined together, more accurate and comprehensive assessment results will be obtained. Among the indicator groups, species richness-composition indicators are the most widely used in current indices. Among them, indicator species or taxa related to estuary quality characteristics usually dominate the index.

Generally speaking, foreign research on the evaluation of estuary ecological integrity is relatively in-depth, involving many aspects, including the application of physical, chemical, and biological indicators, model simulation methods, and research on comprehensive evaluation methods. For example, research in European and American countries focuses on using comprehensive evaluation methods to combine multiple ecological indicators to comprehensively assess the integrity and functions of estuarine ecosystems. For example, Chiu and Wu [77] developed a statistical modeling method for the latent health factor index (LHFI), which combines multiple ecological indicators, including water quality, habitat, and biodiversity, to conduct a comprehensive assessment of estuarine ecosystems. In addition, foreign scholars have also applied remote sensing technology to the evaluation of estuary ecological integrity, using high-resolution satellite data and geographic information systems to conduct refined research on the spatial distribution and changes of estuary ecosystems [78]. In China, the research trend of estuary ecological integrity evaluation has gradually expanded from single biological indicators to multi-disciplinary comprehensive evaluation. Many studies focus on establishing an evaluation system and index system suitable for China's unique estuaries, such as studies on the Yangtze River Estuary, Yellow River Estuary, etc., emphasizing the comprehensive consideration of the impact of specific environmental conditions such as tides and salinity on the evaluation results [43,45]. At the same time, domestic scholars have also begun to pay attention to the impact of socioeconomic factors on estuarine ecosystems, and gradually introduced socioeconomic indicators to comprehensively evaluate the ecological integrity of estuaries [28].

At present, domestic scholars have established an appropriate evaluation index system based on the characteristics of my country's estuaries. Sun Tao and Yang Zhifeng [79] pointed out that the integrity of the estuary ecosystem should comprehensively consider three aspects: environmental quality, biological quality, and the impact on the watershed and humans; Peng Tao and Chen Xiaohong [14] considered the environmental, ecological, and socioeconomic aspects A total of 17 indicators were selected from 3 aspects to evaluate the ecosystem integrity status of typical estuaries in the Haihe River Basin; Liu Chuntao et al. [40] improved the PSR model and established the DPSRC model, from "driving force-pressure-state-system response"Control" five aspects to evaluate the ecological integrity level of Liaohe Estuary; Hui Xiujuan et al. [80] used principal component analysis to comprehensively reflect the physical and chemical characteristics of water bodies, aquatic life characteristics, water body hygiene characteristics, and habitat environmental characteristics; Dong Junjie et al. [15] By comprehensively integrating indicators such as bank slope stability, riverbank vegetation coverage, and the degree of artificial interference in the riparian zone, the integrity of the riparian zone in the river section from Yuehe Mouth to Shihe Mouth was evaluated; Niu Mingxiang et al. [43] based on the PSR model, from the Yellow River Based on the biological ecology, environmental quality, social economy, management measures and human health of the estuary area, 50 evaluation indicators were selected to construct an evaluation index system for the ecosystem integrity of the Yellow River estuary area; Zhang Rui et al. [81] based on the fish in the Yellow River estuary waters Based on the characteristics of the regional composition, 12 evaluation indicators were proposed from the aspects of fish species composition, breeding symbionts, fish tolerance and nutritional structure, etc., and an evaluation index system for the fish biological integrity index in the Yellow River estuary waters was constructed and formulated. evaluation criteria.

In summary, foreign research has made great progress in the evaluation of estuary ecological integrity, but there are still some differences in the understanding of the connotation of ecological integrity [82]. Domestic research, based on learning from foreign research, has formed an evaluation index system and methods suitable for China's estuarine wetlands, but it is still necessary to strengthen the comprehensive evaluation of river ecosystems and habitat research. Table 2 lists some relevant research cases on ecological integrity evaluation by domestic and foreign scholars. Future research can learn from foreign experience, strengthen cooperation and exchanges in domestic and foreign research, and jointly promote the development of the field of estuary ecological integrity assessment.

5 PROBLEMS AND PROSPECTS

Evaluating the ecological integrity of an estuary is a complex task involving multiple ecological factors, evaluation indicators and evaluation methods. Although many studies have made progress in this field and established various evaluation systems and methods, there are still some problems that need to be solved.

(1) Complex structure and ecological integrity challenges

Estuarine ecosystems have attracted much attention due to their complex structures. Biodiversity and structural complexity complicate the evaluation of ecological integrity, which requires comprehensive consideration of various biotic and abiotic factors. The estuarine system is composed of three main parts: land, rivers and oceans, including a wide range of biotic and abiotic components. There are complex interactions and feedback mechanisms between these components. The biodiversity and structural complexity of the estuarine system increase the ecological Challenges of integrity assessment.

(2) The impact and complexity of human activities are increasing

The impact of human activities on estuarine systems cannot be ignored. Activities such as water pollution, coastline development, and fishing have serious impacts on the ecosystem, and may even lead to irreversible changes in the ecosystem. How to identify the response relationship of human activities to the ecological integrity of the estuary puts forward higher requirements for evaluation work.

(3) Inconsistency in evaluation methods limits comparison and comprehensive evaluation

The lack of consistent and standardized evaluation methods globally or even nationwide makes the evaluation of estuarine ecosystems face greater limitations in cross-national and cross-regional comparisons and overall comprehensive evaluation. The lack of universally accepted evaluation standards and methods leads to insufficient comparability of evaluation results between different regions and countries, thus hindering a consistent and comprehensive understanding of global estuarine ecosystems.

Based on this, in the future ecological integrity evaluation of estuaries, we should focus on the following aspects: 1) Comprehensively consider various factors and select appropriate evaluation indicators and methods to comprehensively and accurately assess the integrity of the estuary ecosystem. Including multiple indicators, such as species diversity, ecosystem functions and ecosystem services; 2) Establish a comprehensive ecological monitoring network. The network should cover multiple key areas, including water quality, soil, vegetation, animal communities, etc., to ensure comprehensive coverage of all aspects of the ecosystem. The long-term accumulation of monitoring data will help to gain a deeper understanding of the actual effects of human activities and help identify key factors related to changes in biological integrity; 3) Develop estuary-related standards. Data sharing and exchange should be promoted, unified evaluation standards and methods should be researched and developed, comparative and comprehensive evaluation of estuary ecological integrity evaluation should be achieved, and the protection and sustainable development of estuary ecosystem should be promoted.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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