

Review

Assessing the Landscape Ecological Health (LEH) of Wetlands: Research Content and Evaluation Methods (2000–2022)

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Abstract: Wetlands are often referred to as the Earth's kidneys. However, wetlands worldwide are still negatively affected due to a lack of comprehensive understanding of wetland landscape ecological health (WLEH). Based on this background, we analyzed and compared the conceptual definitions, research progress, contents (in terms of structural, functional, and process health), and methods (indicator species approach, ecological integrity assessment, conceptual model evaluation including the vigor–organization–resilience (VOR), pressure–state–response (PSR), and ecological feature–function–socioeconomic (EFFS) models, and water–gas CO₂ calculation) over the past 20 years (2000–2022). Moreover, the concept definition and research progress of ecosystem health (EH) and landscape ecological health (LEH) and WLEH research outlook were analyzed. In this study, it was shown that WLEH could be considered a LEH subset, while the LEH is a specific EH perspective. These three concepts share a common focus on ecosystem conditions, functions, and services while considering ecological processes and habitat characteristics. However, they differ in the scope and specific types of ecosystems considered. This review may provide references for ecological conservation and restoration of artificial and restored wetland landscapes.

Keywords: wetlands; landscape ecological health; research content; assessment methods; ecological health



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1. Introduction

Wetlands, along with forests and oceans, are considered one of the world's three major ecosystems, serving vital roles in providing material production, regulating climate and hydrology, maintaining the global ecological balance, and protecting species genetics and the Earth's ecological environment [1].

In recent years, with rapid economic growth and an increasing population, ecological problems have become increasingly severe, resulting in varying degrees of damage to ecosystems, including wetlands, and seriously impacting regional ecosystem health (EH) [2]. With the deepening of the concept of sustainable development, research on wetland ecosystems has increased, and especially since 2000 EH has received much attention from scholars [3–5]. Furthermore, the concept of landscape ecological health (LEH) has been proposed [6,7]. In recent years, wetland landscape ecological health (WLEH) has been seriously degraded due to pollution and has even gradually disappeared under the interference of extensive human activities [8–11].

Based on the aforementioned issues, the main objectives of this paper were (i) to identify the research content and logical relationships among EH, LEH, and WLEH; (ii) to explore the various concept definitions, research contents, and evaluation methods for artificial or restored wetlands over the past 20 years (2000–2020); and (iii) to further outline prospective research directions and identify technical tools to obtain the LEH of wetlands.

Overall, our findings may provide a reference for future investigations on the ecological health and construction management of wetland landscapes.

2. Ecosystem Health (EH)

Currently, there is no general consensus among academics on the definition of EH. The EH concept is evolving as scientific research and understanding continue to advance [6,12,13]. However, different organizations and scholars have explored and defined the EH concept from different perspectives and contexts.

2.1. Definition by Scholars

The term “health” was originally used in the medical field to refer to a dynamic equilibrium state in which an organism is free from disease and able to maintain normal function [14–16]. Since the Stockholm Conference on the Human Environment in 1972, ecologists have given close attention to the study of the response of natural ecosystems to anthropogenic stress. In 1788, Scottish physician and the father of modern geology James Hutton first connected ecosystems with health in *Theory of the Earth*, likening the Earth to an organic organism capable of maintaining its own healthy functioning [17]. In 1979, Rapport et al. [18] studied common symptoms and stages of adaptation to stress in the mammalian community through subjective identification to measure the ecosystem responses to stress, but they did not study the symptoms of ecosystem dysfunction. This constituted the prototype of the EH concept, where the physiological approach was innovatively introduced into ecological studies [19]. Furthermore, Canadian scholar Brenda J. Lee also introduced the EH concept, linking it to ecosystem resilience and persistence [14]. Karr et al. [15] emphasized EH as focusing on ecological integrity, suggesting that the ecosystem can maintain its integrity with minimal external support even when disturbed and has the ability for self-repair. Aldo Leopold, a renowned ecologist in the United States, was the first to identify symptoms of land sickness, such as soil erosion, decreased productivity, and declining quality of agricultural and forestry products. He viewed the land as a living organism with the same health characteristics as living organisms, including humans [20].

In the 1970s, D.J. Rapport, a well-known ecologist at the University of Guelph in Canada, proposed the concept of ecosystem medicine based on the health diagnosis of individual organisms, providing a clear and comprehensive definition of the EH concept. He believed that an ecosystem with the ability to maintain its organizational structure, self-regulation, and resilience over time is a healthy ecosystem, with an emphasis on stability and sustainability overall [21,22]. Therefore, evaluating the health of an ecosystem requires considering three aspects: whether the stability and integrity of the internal structure, function, and process of the system can be maintained; whether the system provides a certain self-recovery ability when facing external stress; and whether the system’s service functions can adequately meet the reasonable needs of social development.

In 1992, ecological economist Robert Costanza described the importance of EH and its assessment (*Ecological Economics: The Science and Management of Sustainability*), which has profoundly impacted the adoption and application of the EH concept. Furthermore, he proposed that EH can be measured by assessing the capacity of ecosystems to provide services and support human well-being, which he referred to as the ecosystem service capacity [23]. In 1995, Maguau et al. [16] defined EH from the perspective of ecosystem services, suggesting that a healthy ecosystem should meet human ecological needs and provide necessary ecological services. In 1998, ecologist Daniel Simberloff defined EH as the ability of an ecosystem to persist in the face of disturbance and to retain the components, structures, and processes necessary for continued existence [24].

In contrast, in the 1990s, extensive critical discussions occurred among scholars regarding the EH concept. Early criticisms focused primarily on the argument that ecosystems do not possess the attributes of organisms in terms of their structure and function; therefore, they lack the properties of health possessed by organisms [25,26]. Meanwhile, scholars have contended that the EH concept is not objectively scientific. Specifically, using the

term “health” to describe an ecosystem suggests the existence of a state that is either good or bad for the system, and yet the evaluation of such states of ecosystems can only be based on the type of ecosystem expected by society [27]. Further, EH is a term that involves value judgments, and these judgments can change as our understanding of nature evolves. Therefore, it is inappropriate to use the EH concept as a scientific basis for environmental management [28].

In general, most ecologists currently consider EH the normal state of ecosystem processes and functions, aimed at diagnosing the health level of ecosystems similar to human health diagnosis [23,29,30]. However, as argued by Costanza [31], EH is a normative concept, suggesting specific social goals rather than constituting an objective scientific concept. Ecological balance may not be a shared attribute of organisms and ecosystems, which is not a reason to discard the useful EH concept.

2.2. Definition by Institutions

Furthermore, the normative term of EH has been institutionalized in national and international policies and laws [32]. For instance, the EH concept was used in the Rio Declaration on Environment and Development, setting a global agenda for ecosystem management by the United Nations General Assembly in 1992. Additionally, ecosystem services have been incorporated into environmental management in various organizations and countries. For example, in 1992, the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro, Brazil, proposed that countries should strengthen cooperation to protect and restore the health and integrity of the Earth’s ecosystems, indicating that there was a preliminary global EH consensus. Unfortunately, the UNCED has not provided a specific or formal definition of EH because of its primary focus on broader environmental issues, sustainable development, and the need for global cooperation to address these challenges.

In addition, the Society for Ecological Restoration (SER) has defined EH as the capacity of an ecosystem to sustain ecological processes, functions, biodiversity, and productivity over time. The Millennium Ecosystem Assessment (MA) considers EH to be the ability of an ecosystem to maintain its structure and function over time in the face of stresses, disturbances, and other external influences. The United States Environmental Protection Agency (EPA) defines EH as the condition of an ecosystem based on the extent to which it can support resilience, stability, and sustainability over time. The Resilience Alliance (RA) has described EH as the capacity of an ecosystem to maintain its desired functions, processes, and structures and to adapt to change and disturbance.

Furthermore, in the United Kingdom, the National Ecosystem Assessment (2011) has provided a foundation for advocating the transition toward a more sustainable state. In China, national programs such as the Natural Forest Conservation Program (NFCP) and the Grain to Green Program (GTGP), which involve payments for ecosystem services, have improved ecosystem conditions and generated positive socioeconomic effects [33].

Based on the aforementioned aspects, we believe that EH is widely regarded as a broad concept primarily used to assess the condition and functioning of the entire ecosystem. The EH concept emphasizes species diversity and the ecological processes, biogeochemical cycles, and services and resources provided by the ecosystem. EH evaluation typically involves examining biodiversity, ecological functions, and resilience and stability of the ecosystem [12,34].

3. Landscape Ecological Health (LEH)

3.1. Concept Definition of the LEH

Distinguished from the discipline of ecosystems, the International Association for Landscape Ecology (IALE) Executive Committee considers landscape ecology as an interdisciplinary field that connects natural sciences and related human sciences, focusing on landscape spatial changes across different scales, including biotic, geographic, and social factors that contribute to landscape heterogeneity [35]. As we have known, the difference

between LEH and EH lies in the research scale. EH mainly captures the self-sustaining and renewing ability of an ecosystem, whereas LEH primarily entails the spatial differences in the self-sustaining ability among ecosystems. As the object of study in landscape ecology, the landscape is considered a spatially heterogeneous (or patchy) attribute of ecosystems within an ecosystem region through the interconnection of its structural, functional, and process components [36] and a suitable scale for studying the impact of human activities on the environment [37]. Therefore, LEH can reflect the dynamic balance of ecosystems. In other words, if the system can maintain near equilibrium during frequent or minor disturbances or can quickly recover from a larger disturbance, the ecological landscape can be considered very healthy.

The LEH concept is based on EH and draws on ideas from natural health [22], land health [29], and ecological medicine [14,18], describing the health issues of landscapes. Currently, due to the lack of a consensus among scholars regarding the appropriate definition of EH [31], the LEH concept still lacks an authoritative meaning. Currently, many scholars have defined LEH from different research perspectives [38]. For example, Ferguson [39] first extended the concept of health to the landscape level, considering LEH to be a dynamic equilibrium where regulating and feedback mechanisms maintain the self-regulating function of the entire landscape. Rapport et al. [18,21,30] suggested that a healthy landscape needs to provide a satisfactory range of ecological services. Cao et al. [40] argued that, on the one hand, active human intervention should not cause damage to the maintenance of the stable landscape structure and normal functions, while on the other hand, over time, landscape evolution and development should not affect or disrupt the orderly, healthy, and sustainable development of adjacent landscapes and human socioeconomic systems. Fu et al. [41], however, considered LEH to be the stability and sustainability of different types of ecosystems in providing a diverse range of ecosystem services within a certain temporal and spatial range while maintaining their own health.

Numerous studies have shown that healthy landscapes possess the ability for self-regulation and renewal, thereby maintaining spatial structure, ecological processes, and stress recovery and ensuring the sustainable and optimal provision of ecosystem services [1,7]. Therefore, we argue that LEH focuses on patterns, ecological processes, and ecosystem functions within a given geographic area, emphasizing the consideration of the effects of different habitat types and land uses on ecosystems on a larger scale, such that LEH assessment typically involves the analysis of landscape diversity, connectivity, fragmentation, habitat quality, and landscape service functions [6,18,38].

3.2. Research Progress of the LEH

In the 1960s, Leopold further refined the concept of land health into EH and landscape health components, proposing land self-renewal capacity as a criterion for landscape health evaluation. Initially, Leopold and others believed that the evaluation criteria for health should be based on the performance or basic data provided by healthy land because the self-renewal capacity of fallow land is unaffected or damaged by human activities [29]. With the deepening of related research, Leopold and others acknowledged the important role played by humans as part of the landscape in maintaining the ecological system's landscape processes and structures, but the impact of landscape changes caused by humans on its fundamental ecological functions was not considered. Therefore, the degree to which the landscape meets human needs should be a component of landscape health evaluation [20]. Costanza [23] studied EH from an ecological perspective and believed that it refers to the ability of all organizational structures of the ecosystem to function normally and achieve self-recovery. To evaluate whether an ecosystem is healthy, it should meet six criteria: stability, disease-free state, diversity, vitality, recoverability, and balance. Therefore, the internal health status of the landscape refers to the absence of ecological diseases or stress factors caused by human activities, also referred to as ecosystem distress syndrome (EDS). A healthy ecological landscape should provide ecological services that include benefits for both humans and other organisms [30].

With the deepening of research on human health, the meaning and extension of health have continuously evolved. The concept of landscape health has been extended from a simple medical environment to various levels of social landscapes, derived from the basis of the comprehensive EH, as a deep form of expression of sustainable landscapes. For example, Cao et al. [40], from a human-interest perspective, proposed that a healthy ecosystem should provide ecological services such as healthy food, clean drinking water, and clean air needed by human society. Xie [42] argued that the health state that merely satisfies the needs for providing ecological or landscape services may be a static and external pseudo-health phenomenon that does not reflect the essence of EH. They also studied the content of the LEH concept from a landscape ecology perspective and proposed that LEH includes the healthy structure and pattern of landscapes, healthy ecological processes, and healthy ecological functions. Further, Li et al. [43] conducted research based on D.J. Rapport's work and noted that EH should include an appropriate landscape structure and pattern, efficient ecological processes, and necessary ecological service functions.

In recent years, scholars have also assessed the EH status at different landscape scales. For example, Wu et al. [19] demonstrated a conceptual model for the impact of a large open-pit coal mine site on the LEH of a semiarid grassland and established a landscape index-pattern evolution-driver-spatial statistics (IEDS) research system based on the Shengli coal mine in the Xilinguole grassland, Inner Mongolia, China. Their results showed that coal mining led to a gradual increase in landscape patches, landscape fragmentation, a gradual decrease in landscape connectivity, complex and irregular landscape shapes, increased landscape heterogeneity and complexity, a gradual decrease in landscape stability, a gradual decrease in grassland landscapes, and a yearly increase in unhealthy grassland landscapes. In conclusion, the grassland LEH basically indicated a state of slight deterioration. Currently, assessments of urban forest health at the landscape scale are still lacking. Zhao et al. [44] used the Southern Peach Orchard in China as an LEH case study to show that there exists a close relationship between LEH and the internal structure of the forest landscape when both the patch area and the number ratio of forest/nonforest remain relatively stable and constant, indicating that the urban forest landscape is healthy; the healthiest forest landscapes were distributed mainly in the forest and nonforest transition zone, and unhealthy forest landscapes were distributed mainly in single natural forests.

In summary, it is generally accepted that the LEH concept is interdisciplinary in nature and that research must combine the fields of landscape ecology, health medicine, habitat environment, and socioeconomics [10,45]. With the continuous health concern in the whole society, the current intense discussion of the LEH concept, especially in specific scopes such as wetlands, cities, and grasslands, has continuously deepened its connotation, despite the varying degrees of LEH research by scholars worldwide [1,7,42,46,47].

4. Wetland Landscape Ecological Health (WLEH)

Studies have shown that wetland landscapes are highly governed landscapes that are directly influenced by human activities [48]. Bertollo [48,49] defined highly governed landscapes as those where human management measures can maintain a relatively stable landscape structure, adapt to traditional land use practices, balance biophysical integrity and human cultural elements, and maintain the ability of the landscape system to provide basic biophysical resources and processes for humans and other organisms [37,48,50]. Based on this definition, introducing the concept of landscape health into wetland landscape research has important theoretical and practical significance in coordinating the relationship between wetland protection and utilization under active human management conditions.

In regard to wetland or WLEH research, numerous research institutions and scholars worldwide have conducted extensive studies. For example, as early as the 1970s, the Commonwealth Scientific and Industrial Research Organization of Australia (CSIRO) established a diagnostic indicators of catchment health (DICH) system to evaluate the quality of the basin ecological environment. This system can be employed to analyze changes in the quality or health of aquatic ecosystems [51]. In 2000, the EU Water Framework Directive

(WFD) was officially implemented by the European Parliament and the Council of the European Union. It established an indicator system based on biological, hydrological, and physicochemical factors, providing a guiding framework for the evaluation, management, and protection of wetland aquatic ecosystems [52]. In 1992, the University of Lund in Sweden developed the Riparian, Channel, and Environmental (RCE) Inventory with the hypothesis that natural river and shore structure disturbances constitute the main cause of river biological structure and function degradation. An effective method was provided for the evaluation of the physical and biological health statuses of small rivers in agricultural landscapes [52]. In 1997, the UK Environment Agency developed the River Habitat Survey (RHS), focusing on river morphology, topographic features, and cross-sectional morphology, emphasizing the irreversibility of river ecosystems. The RHS is suitable for large-scale human-modified rivers [53]. Additionally, Victoria, Australia, developed the Index of Stream Conditions (ISC), which assesses health through comparisons between the current and original states, emphasizing long-term evaluation of the major environmental characteristics that affect river health. ISC-based evaluation studies mainly include hydrology, river physical morphology, riparian zones, water quality, and aquatic organisms. The river health status is divided into five grades based on the total score, revealing the degree of river disturbance.

Significant studies have been conducted in the United States to determine the health of wetland ecosystems within watersheds. For example, the National Sanitation Foundation (NSF) developed the NSF Water Quality Index (WQI) to reflect the water quality characteristics of a region or area by considering the weight of the impact of each parameter on the water quality [54]. In 1995, the US Army Corps of Engineers developed the hydrogeomorphic (HGM) method, which focuses on evaluating the functional value of river ecosystems. In this method, riverine wetlands are divided into four categories and fifteen functions, including animal habitats (four functions), hydrology and water quality (five functions), biogeochemistry (four functions), and plant habitats (two functions), and ratios are calculated to measure the degree of functionality on a scale from 0 (indicating complete loss of function) to 1 (indicating ideal conditions). In 2001, the Oregon Water Quality Index (GWQI) integrated eight water quality parameters, including temperature, dissolved oxygen, pH, ammonia–nitrogen, nitrate–nitrogen, total phosphorus, total suspended solids, biochemical oxygen demand, and fecal coliform, and converted these parameters into a dimensionless secondary index with a rating ranging from 10 to 100 to reveal the extent of their impact on the water quality [55]. Furthermore, the US EPA comprehensively evaluated the wetland EH throughout the country based on hydrological, soil, and biological scales, which resulted in the development of three levels of wetland EH assessment systems [56–58]:

Level I: Landscape development intensity (LDI) and synoptic method;

Level II: Rapid evaluation method;

Level III: HGM method and index of biological integrity (IBI).

After years of research, a theoretical system for the sustainable development, restoration, and evaluation of wetlands has been established overseas. However, the current research on wetlands focuses more on evaluation indices, ecological protection, public education, and ecotourism and less on landscape ecological system health, particularly the research on wetland landscape ecological processes and functions based on ecological theory.

In China, a search for “wetland” or “wetland park” in the China National Knowledge Infrastructure (CNKI) yielded over 4000 research articles, but there were only 15 studies on wetland landscape health. Most wetland landscape studies focus on structure and function, such as health concepts, diagnostic indicators, health recovery, wetland system spatial scale, and ecological design [17,59–62], with a clear bias toward wetland landscape health assessment research. There are few case studies that focus on specific wetland landscape ecological processes. Liu et al. [46] believed that the WLEH concept encompasses the spatial heterogeneity of the wetland ecosystem landscape structure, landscape process, and landscape function at the landscape scale. Wetland landscape processes include

material flow processes, information flow processes, and species movement processes. Information flow processes mainly involve the flow of water in the landscape and habitat use by birds in the landscape. In addition, Chinese scholars have shifted their research on wetland landscape health from macrolevel holistic to microlevel specific studies (or particular cases). For example, Wu et al. [63] used remote sensing (RS) technology to study the spectral characteristics of wetland plants in an estuary delta and summarized the WLEH research progress. To compensate for the inability of wetland evaluation to reveal the spatial heterogeneity within wetlands, Wu and Chen [60] constructed a wetland health index system consisting of five level 1 indicators (including water, soil, vegetation, landscape, and society) and 12 level 2 indicators based on RS technology and the landscape index and applied the analytic hierarchy process (AHP) to calculate corresponding weights. Their study showed that the health index of the edge of Hongze Lake was relatively low, whereas the interior was relatively healthy (a whole health index value of 5.63). Other scholars have also studied the LEH of riverine wetlands [64] and coastal wetlands in depth [65,66], among which the Xixi National Wetland in Hangzhou, Zhejiang Province, as the first national wetland established by the State Forestry and Grassland Administration of China in 2005, has been studied several times [67,68]. During different development periods, the conceptual definition, research content, and research methods for the WLEH have differed among academics (refer to Table 1). Therefore, introducing the concept of landscape health into wetland landscape research to explore the LEH issues of wetlands under active management is highly important for the protection and utilization of wetlands and for achieving sustainable wetland development.

Table 1. Comparison of the concept definition, research content, and research methods for WLEH among different periods.

Time Period	Concept Definition	Research Content	Research Method
Early research	Limited definition.	Wetland biodiversity and ecological processes, etc.	Field surveys, species inventories, ecological assessments, etc.
Early 1990s	Recognition of spatial aspects.	Spatial structure and functionality of wetland landscapes, etc.	Landscape metrics, spatial analysis, remote sensing, GIS, etc.
Mid-1990s	Linkage with ecosystem services.	Economic and environmental contributions of wetland landscapes	Ecosystem service assessment, valuation techniques, etc.
Early 2000s	Focus on vulnerability and threats.	Pressures and threats faced by wetland landscapes, etc.	Vulnerability assessment, threat identification, risk analysis, etc.
Late 2000s	Integration with sustainable development.	Sustainable utilization and management of wetland landscapes, etc.	Sustainable development frameworks, policy analysis, stakeholder engagement, etc.
Recent developments	Emphasis on restoration and rehabilitation.	Recovery of ecosystem functionality and services, wetland landscape restoration and rehabilitation approaches, etc.	Ecological restoration techniques, hydrological modeling, landscape planning and design, participatory approaches, etc.

From a landscape ecology perspective, the study of wetland landscape health includes three aspects: landscape ecological structural health, landscape ecological functional health, and landscape ecological process health [42]. Therefore, the study of WLEH should evaluate the LEH of the structures and processes based on the classification of functions. Due to different types of wetlands, the indicators, standards, and content used to measure their health status also vary. Therefore, WLEH can be considered a subset of LEH, and LEH is a specific EH perspective. They share a common focus on the condition, functioning, and services of ecosystems while considering ecological processes and habitat characteristics. However, their differences lie in the scope and specific types of ecosystems considered (refer

to Table 2). From the perspective of wetland types, the WLEH research content includes two aspects: natural wetland ecosystems (including watershed-scale natural wetlands, lake and swamp area natural wetlands, and estuarine and river mouth natural wetlands) and artificial or restored wetlands (including urban wetlands, reservoir surrounding areas, and artificial terraced wetlands) [69]. In this review, we therefore focused primarily on the LEH of artificial and restored wetlands.

Table 2. Comparison of the ecosystem health, landscape ecological health, and wetland landscape ecological health.

Indicators	Ecosystem Health/EH	Landscape Ecological Health/LEH	Wetland Landscape Ecological Health/WLEH
Concept definition	Emphasis on species diversity and ecological processes, biogeochemical cycles, and the services and resources provided by ecosystems.	Focus on the ability of ecosystems at the landscape scale to maintain the integrity of their structure, function, processes, and services in the face of external disturbances.	Focus on patterns, ecological processes, and functionality of wetland landscapes.
Influencing factors	Species diversity, ecological processes, biogeochemical cycles, ecosystem services, and resource-provisioning capacity.	Landscape diversity, connectivity, fragmentation, habitat quality, and landscape service functionality.	Wetland diversity, wetland area, wetland connectivity, water quality, and wetland community health.
Assessment methods	Comprehensive consideration of various ecosystem aspects, such as indicator sets, models, and indices.	Analysis of landscape indicators, pattern dynamics, driving forces, spatial statistics, etc.	Analysis of wetland ecological indicators, wetland health assessment models, ecological drivers, wetland monitoring indicators, etc.
Research content	- Assessment of the overall ecosystem structure and functioning. - Study of the biodiversity and species interactions within an ecosystem. - Examination of ecological processes, such as material flow, energy flow, and information flow. - Evaluation of the ecosystem services provided, such as water purification, and carbon sequestration. - Analysis of the resilience and stability of ecosystems in the face of disturbances. - Other topics.	- Evaluating the organization, vitality, and resilience of landscape ecosystems. - Analysis of landscape patterns and their impact on ecological processes. - Assessment of diversity, heterogeneity, and connectivity and fragmentation of landscape ecosystems. - Examination of landscape functionality in terms of ecosystem service provision. - Evaluating the integrative effects of disturbances on landscape ecosystems and their ability to self-regulate - Other topics.	- Assessment of the wetland ecosystem condition and functioning. - Study of wetland biodiversity, including plant and animal species adapted to wetland environments. - Analysis of hydrological processes, water quality, and nutrient cycling within wetlands. - Evaluation of wetland connectivity and the potential for wildlife movement. - Examination of wetland ecosystem services, such as water filtration, flood control, and habitat provision for aquatic species. - Other topics.
Application areas	National and international policies, environmental management, and sustainable development.	Land planning, landscape design, ecological restoration, and conservation.	Wetland conservation, wetland management, wetland restoration, and ecosystem service assessments.
Application cases	Research on the impact of ecosystem health on human well-being and sustainable development.	Analysis of landscape changes, ecological processes, and the influences of human activities in specific regions.	Assessment of the wetland health status, effectiveness of wetland restoration projects, and wetland conservation management.

5. WLEH Research Content

5.1. Structural Health

Wetland landscape structural health is an important indicator for assessing the overall condition and function of wetland ecosystems, and its research is very important for wetland conservation, management, and sustainable use. In the study of wetland landscape structural health, early research focused on species diversity in wetlands. As research progressed, the focus of research on the structural health of wetland landscapes gradually shifted to spatial structure and function aspects in the mid-1990s. Researchers began to assess the spatial characteristics of wetland landscapes, such as patch distribution,

connectivity, and shape complexity. For example, Miller et al. [70] used aerial photographs and geographic information system (GIS) technology to examine changes in the Rawhide Wildlife Management Area in southeastern Wyoming following changes in the flood frequency and intensity of the North Platte River between 1937 and 1990, showing that as the wetted area of the river decreased, the area occupied by cottonwood (*Populus* spp.) with less than a 30% canopy closure accounted for an increased proportion of the area, while certain traditional landscape structural metrics (i.e., abundance, diversity, dominance, mean patch perimeter, and mean patch shape) were insensitive to change.

From 2000 to 2010, research on wetland landscape structural health became increasingly connected to ecosystem services. Attention was directed toward the contributions of wetland landscapes to the economy and environment, particularly the ecosystem services provided by wetlands. Researchers have employed ecosystem service assessments and valuation techniques to quantify the contributions of wetland landscapes to aspects such as water regulation, flood control, water purification, and carbon storage. These studies have highlighted the close linkages between wetland landscape structural health and human well-being and sustainable development. As determined by Saunders et al. [71] based on the assumed depth-of-edge influence (DEI), road construction in the northern Great Lakes area (US) increased the number of patches and patch density, reduced the mean patch size and maximum patch index, and significantly altered the landscape structure across multiple forest cover types and different ecological scales. Moreover, most scholars have attempted to investigate the temporal and spatial evolution characteristics of wetland landscape structures to identify the driving factors of changes. For instance, Liu et al. [72] systematically studied the temporal and spatial changes in the wetland landscape structure of the Nenjiang River Basin, China, over 50 years (1949–2000) using RS and historical data. They found that large-scale land development activities and hydraulic engineering construction were the main driving forces behind the changes in the wetland landscape structure in the basin.

Over the last decade, research on wetland landscape structural health has placed greater emphasis on vulnerability and threats (refer to Table 3). Human activities and climate change greatly threaten the health of wetland landscape structures, such as land use changes, water pollution, species invasions, and sea-level rise. Researchers have begun to explore the vulnerability and response capacities of wetland landscapes to these threats. They have used methods such as model simulations, field investigations, and long-term monitoring to study the dynamic changes and recovery capabilities of wetland landscapes under different pressures. These studies have provided scientific foundations for wetland conservation and management, promoting the sustainable development of wetland landscape structural health. For example, to better understand the cumulative effects of urbanization and climate change on watershed runoff, a conceptual hydrological model (Model for Evaluating the Transfer and Quality of Water in Catchments or METQ) was employed to examine the response of watershed runoff from Lake Usma, located in the Kurzeme region of Latvia, to urbanization and climate change [73]. The study showed that very high watershed runoff events are more notably related to rain events than to snowmelt and that urbanization strongly influences extreme watershed runoff levels.

In China, research on the health of wetland landscape structures and patterns focuses mainly on landscape spatial differences [68], landscape functional classification [67], and evaluation systems [69]. To reveal the functional characteristics of wetland landscapes, Li et al. [67] also included social and economic sustainability (i.e., the index of the structural elements of service function landscapes) and ecological sustainability (i.e., the index of the structural elements of ecological function landscapes) in landscape structural health evaluation. In recent years, scholars have analyzed wetland landscape patterns and proposed wetland planning and construction strategies in response to changes in human habitats [46]. For example, to better understand the temporal changes in the landscape pattern of Yellow River Delta wetlands in China and the underlying factors, a series of five Landsat images from 1976 to 2016 were used to show that with increasing intensity

of human activities, the number of landscape types in the study area increased, patches became dispersed and more fragmented, and the entire landscape became more complex. It was concluded that human activities were the main force driving changes in the Yellow River Delta, which provides fundamental data for future landscape planning and construction in the region [74]. Similar studies were also conducted to obtain the characteristics of landscape pattern changes and their drivers in the wetlands of Henan Province, China, from 1980 to 2015 [75]. Regarding coastal wetlands, scholars have also applied GIS and RS technologies and have constructed a comprehensive evaluation system for the ecological health of coastal wetland ecosystems, including 14 evaluation indicators based on the driving force–pressure–state–response–regulation framework, to evaluate the ecological health of Liaodong Bay coastal wetlands in China [76]. Additionally, Yu et al. [77] used aerial image interpretation data and FRAGSTATS landscape pattern index calculation and analysis software to analyze landscape pattern indices such as patch area, number, fragmentation, and connectivity in the Nansihu Wetland in Shandong, China, to evaluate the ecological health of the wetland ecosystem. Furthermore, combining information derived from RS data with the pressure–state–response (PSR) model, researchers have analyzed the dynamic changes in the landscape pattern of coastal wetlands in Jiangsu, China, from 1992 to 2009 and evaluated the applicability of the AHP and Delphi methods, regional ecological security status, and trends in change [50].

Table 3. Summary of the research progress in the structural health of wetland landscapes after 2000.

Period	Focus	Methods	Key Applications	References
2000–2005	Landscape pattern analysis	Remote sensing, GIS, landscape metrics	Examination of changes in wetland landscape patterns and their effects on ecological processes and species	[71,72]
2005–2010	Hydrological connectivity and wetland functioning	Field measurements, hydrological modeling, network analysis	Exploration of the relationship between hydrological connectivity, wetland functions, and landscape structure	[78–80]
2010–2015	Landscape restoration and resilience	Ecological restoration, remote sensing, landscape modeling	Investigation of the effectiveness of landscape restoration in enhancing wetland structural health and resilience	[50,67,76,77]
2015–2022	Climate change impacts on the wetland landscape structure	Climate modeling, remote sensing, data analysis	Assessment of the vulnerability of wetland landscapes to climate change and identification of adaptation strategies	[73]

5.2. Functional Health

At present, studies on wetland landscape functional health worldwide mainly include ecological and social functions (refer to Table 4). Among them, research on ecological functions focuses mainly on the regulation and production capacity of wetland landscapes. For example, previous studies addressing the assessment of the cumulative effects of wetland ecological functions (including flood storage, water quality, and life support) have suggested that the contributions of a particular wetland to the landscape functions within a given watershed or region are determined by its intrinsic characteristics, such as size,

morphology, type, percentage of organic matter in sediment, and hydrologic regime, as well as by extrinsic factors, i.e., the context of the wetland in the landscape mosaic. Furthermore, any assessment of cumulative effects must account for the relationship between these intrinsic and extrinsic attributes and overall landscape functions [81]. Li et al. [67] selected evaluation indicators such as patch area, patch fragmentation, and patch diversity for ecological protection, as well as corridor area, corridor perimeter, and corridor connectivity for ecological protection, and extensively analyzed the spatial heterogeneity of the ecological sustainability in the Xixi Wetland, China. To better utilize the ecological functions of wetlands (or nature reserves), Kong et al. [82] examined ecological function changes (natural and human factors) in the Heihe Wetland National Nature Reserve, Zhangye, China, and found that temperature increase is one of the driving forces of wetland ecosystem environmental changes, while the increase in population, expansion of cultivated land, and sustained rapid development of the economy are the main driving forces of wetland ecosystem environmental degradation. Moreover, scholars have used software packages such as FRAGSTATS, ENVI, and Arc-Map to study the landscape ecological functions of the Zoige Wetland Nature Reserve, and it has been found that the changes in wetland landscape patterns and ecological functions are mainly due to the comprehensive effects of the natural environment and human activities, but human activities play a dominant role [83,84]. Numerous studies have shown that the premise of wetland degradation is the vulnerability of the natural environment, and the main driving factor causing wetland degradation is still human activity [82,85]. Interestingly, attention has also been given to the landscape function of geographically isolated wetlands (GIWs). Studies have demonstrated that GIWs form complexes with other water bodies on a regional scale, creating spatial and temporal heterogeneity characteristics in terms of time, flow paths, and scale of network connectivity. At the same time, the lower hydrological connectivity with downstream waters and restricted biological connectivity with other landscape elements can enhance certain functions of GIWs and enable others, while maintaining landscape functions requires the preservation of the continuity of the entire wetland (including GIWs).

In terms of the wetland landscape ecological service value, Johnson et al. [86] applied WETLANDSCAPE (WLS) model predictions to show that the prairie wetland complex in the central prairie pothole region (PPR) of North America exhibits significantly reduced water volumes, shorter hydraulic cycles, and reduced vegetation dynamics, portraying the future PPR as a much less resilient ecosystem. Wang et al. [87] adopted the key protected wetlands in the Yellow River Basin as the research object, included 16 indicators of wetland ecological service functions, protection function, and resource functions in the wetland evaluation index system and demonstrated and proposed priority and protection strategies for the important wetlands in the Yellow River. In terms of the ecological service value of wetlands, scholars have extensively studied the ecosystem service values of wetlands such as the Nanhé National Wetland in Guangyuan, Sichuan, China [88], Hangzhou Bay National Wetland in Zhejiang [89], and Chanba National Wetland in Xi'an [90], which could help to assess the importance of wetland ecological functions and health more intuitively. For example, Chen et al. (2018) adopted the Nanhé National Wetland in Sichuan as a research object and included 13 indicators of the ecological process value, social and cultural value, and future potential value in their ecosystem service value assessment system using the market price method, shadow price method, and contingent valuation method [88].

Table 4. Main elements of the study of wetland landscape functions after 2000.

No.	Research Direction	Research Content	Wetland Types	References
1	Water purification function	Assessment of the water purification efficiency, optimization of wetland treatment systems, etc.	Lakes, rivers	[89,91]
2	Biodiversity conservation function	Species diversity survey and monitoring, establishment and management of protected area networks, etc.	Marshes, estuaries, lakes, rivers	[82,92–94]
3	Carbon storage and climate regulation function	Estimation of carbon storage, studies on greenhouse gas emissions, research on wetland climate regulation effects, etc.	Marshes, coastal wetlands, lakes, rivers	[68,86,88,95–98]
4	Water resources regulation function	Simulation and prediction of the water balance, research on sustainable water resource management strategies, etc.	Lakes, rivers, marshes	[34,82,83]
5	Flood control function	Flood simulation and warning research, flood management and disaster reduction strategies, etc.	Estuarine wetlands, marshes, rivers	[83]
6	Nutrient cycling function	Research on nutrient dynamics, nitrogen and phosphorus cycling and transformation in wetland ecosystems, etc.	Estuarine wetlands, marshes, coastal wetland	[99,100]
7	Disaster risk reduction function	Research on the buffering and regulating effects of wetlands on natural disasters, risk assessment and management, etc.	Estuarine wetlands, marshes, lakes, rivers	[82]

5.3. Process Health

Landscape process research is one of the most important components of wetland landscape health assessment studies. Wetland landscape ecological processes refer to the interactions between wetland landscape elements, including energy flow, nutrient flow, and species flow, which mainly encompass physical, biological, and geochemical processes [101]. Among them, physical process research mainly includes wetland hydrological mechanisms, sedimentation processes affected by vegetation, and pre- and post-development regional heat balance aspects [102]. Biological processes primarily include wetland species ecological adaptation, organic matter accumulation and decomposition, wetland nutrient structure, material flow, and energy flow [103,104].

Currently, chemical process research has become the most important direction of current wetland water and soil research. For example, Hu et al. [101] reviewed the research on wetland ecological processes at the landscape scale worldwide, focusing mainly on hydrological processes and biogeochemical processes. This study direction mainly includes the flow, cycling, and transformation processes of wetland nutrients such as nitrogen (N), phosphorus (P), potassium (K), and other elements [105], the wetland greenhouse gas (CO₂) cycling mechanism and its contribution to changes in carbon (C), N release, and other factors, and the absorption, accumulation, and transformation of heavy metals in wetlands [106]. However, due to the lack of comprehensive research on the physical, chemical, and biological processes of the regional water ecological environment, it is difficult to reveal the interaction mechanisms of wetland system components such as the CO₂ partial pressure ($p\text{CO}_2$), CO₂ flux ($F\text{CO}_2$), and biogeochemical element cycling metabolism, as well as the dynamic feedback mechanism between wetland system components and the overall wetland system [107].

Water, as the most active and fundamental landscape element of wetlands, has always been considered the most critical factor in maintaining the health of wetland ecosystems. Moreover, as the most important environmental factor in wetland habitats, suitable water quality is a prerequisite for the health of other ecological processes in wetlands. Studies have shown that the most basic driving process (or mechanism) of wetland formation, development, and evolution entails hydrological processes [3]. Currently, the academic

community generally recognizes that hydrological processes are the most important characteristic of wetland ecosystems, which determine the environmental factors that shape and drive the evolution of wetlands [108–111]. Therefore, using ecohydrology to study the interaction and feedback mechanisms between wetland ecosystems and hydrological processes has become a focus and hotspot in wetland research in recent years.

5.3.1. $p\text{CO}_2$ and $F\text{CO}_2$

Although the area of inland freshwaters is relatively small, they constitute one of the most critical parts of global carbon cycling [112–114]. Previous studies have demonstrated that CO_2 in inland freshwaters (such as wetlands, rivers, and reservoirs) is often in a supersaturated state relative to that in the atmosphere, indicating that the net carbon efflux is released from aquatic ecosystems into the atmosphere through the water–air interface [109,115,116]. According to recent estimates of the global surface area of lakes or wetlands [117], the total CO_2 emissions originating from inland lakes reach approximately 0.5 Pg C yr^{-1} , of which approximately 60% stems from freshwater lakes [8,9,103] and 40% stems from salt lakes [118]. Compared to the total carbon emissions originating from continents into oceans (approximately 0.9 Pg C yr^{-1}) [95], the CO_2 emissions stemming from lakes and wetlands are undoubtedly an important component of the continental carbon balance.

Numerous studies have shown that the two most important indicators of carbon cycling in wetlands are $p\text{CO}_2$ and $F\text{CO}_2$, with $F\text{CO}_2$ typically based on the water surface $p\text{CO}_2$ [95,118,119]. Research has indicated that $p\text{CO}_2$ in aquatic systems can fluctuate in space and time, possibly influenced by multiple factors such as pH [120,121], water temperature [122,123], and nutrient status [124,125]. Currently, CO_2 oversaturation has been observed in most lakes and reservoirs worldwide, driven either by the imbalance between the net ecosystem production and net heterotrophy [99] or by the input of high concentrations of dissolved inorganic carbon (DIC) in surface water [126]. Few autotrophic lake ecosystems have been reported worldwide to function as net CO_2 sinks [103,112,127]. Cole et al. (1994) reported that less than 10% of the $p\text{CO}_2$ levels in 1835 lakes worldwide occurred within $\pm 20\%$ of the atmospheric equilibrium, while over 80% occurred in a state of supersaturation [8]. In the studied lakes, the estimated values of CO_2 evasion were collected mostly on a weekly to seasonal basis, which may overlook the daily variations in $p\text{CO}_2$ and CO_2 flux. Currently, there is still a large gap in research on the influence of the diurnal $p\text{CO}_2$ variation on CO_2 evasion estimates. For example, the daily concentration of inorganic carbon (IC) in a productive lake in northwest England ranged from 4 to $63 \text{ mmol} \cdot \text{m}^{-3}$, while the diurnal variation in $p\text{CO}_2$ in a nonproductive lake in northern Sweden was relatively low [128]. Our previous study also showed that throughout the study period (from November 2017 to June 2018), using the carbonate equilibrium model (refer to Section 6.4), a clear daily decreasing trend in $p\text{CO}_2$ and $F\text{CO}_2$ could be observed in a subtropical shallow lake in Louisiana, USA, with daily $p\text{CO}_2$ values ranging from 154 to $1698 \text{ } \mu\text{atm}$ and daily $F\text{CO}_2$ values ranging from -43 to $284 \text{ mmol m}^2 \text{ h}^{-1}$. The mean $p\text{CO}_2$ at 7:00, 10:00, 14:00, and 17:00 CST of the day was 945, 934, 445, and $374 \text{ } \mu\text{atm}$, respectively, while the mean $F\text{CO}_2$ was 77, 88, 14, and $-2 \text{ mmol m}^2 \text{ h}^{-1}$, respectively. The relationships between $p\text{CO}_2$ and environmental factors suggest that solar radiation and water temperature are the main factors driving the dynamics of $p\text{CO}_2$ and $F\text{CO}_2$ in lake water. Lake $F\text{CO}_2$ dynamics is the main factor. Because of the large daily variability in $p\text{CO}_2$ and thus the higher CO_2 evaporation at night, we suggest that current regional and global estimates of CO_2 evaporation may be grossly underestimated [129]. In addition, similar studies have been conducted in University Lake, Louisiana, USA [130], and Qinglonghu Lake, Chengdu, Sichuan, China [131]. Considering the large amount of metabolized carbon in wetlands such as lakes and reservoirs, a more scientifically reasonable way of carbon flux quantification is needed to help better understand global carbon cycling.

In recent years, there have been increasing studies on the estimation of freshwater CO_2 emissions at regional and global scales [95,112,132], but these estimates still contain

significant uncertainties. The high variations in CO₂ evasion may be partially due to differences in geographical regions resulting in differences in temperature and solar radiation [133]. For example, Arctic tundra data collected from upstream Alaska mountains show an average CO₂ flux of 5.1 $\mu\text{mol}\cdot\text{m}^2\cdot\text{s}^{-1}$, while in regions such as the Mediterranean, Morales-Pineda et al. (2014) found that the average CO₂ emission rates in two reservoirs in Spain, Guadalquivir and Bornos, ranged from 5.6 to 34.7 $\mu\text{mol}\cdot\text{m}^2\cdot\text{s}^{-1}$ [134]. Shao et al. (2015) also found that the CO₂ flux in western Lake Erie in the humid continental climate region of North America exhibited strong diurnal variations (ranging from 26.0 to 56.7 $\mu\text{mol}\cdot\text{m}^2\cdot\text{s}^{-1}$), while in Lake Kuivajarvi in northern Finland, the daily average CO₂ flux reached only 0.7 $\mu\text{mol}\cdot\text{m}^2\cdot\text{s}^{-1}$ with no apparent diurnal variation [97].

In addition, the uncertainty in CO₂ flux estimates on regional or global scales may be due to the limitations of the estimation methods [135]. Currently, the CO₂ emissions from water into the atmosphere are mainly calculated based on *p*CO₂ values estimated from the water alkalinity, pH, and temperature [8,98], which is not an accurate approach. One of the greatest problems is the *p*CO₂ estimation accuracy. Therefore, to reduce the uncertainty in CO₂ flux estimates, strengthening the research on *p*CO₂ variability is a key step in achieving reliable estimation of lake CO₂ emissions, and all relevant factors that contribute to data dispersion and variation must be constrained.

5.3.2. Elemental Chemistry

In recent years, with the intensification of human activities and rapid socioeconomic development, various organic and inorganic compounds have freely entered the water in different types of wetlands worldwide. Therefore, when studying the aquatic ecological processes in wetlands, relying solely on indicators such as the chemical oxygen demand (COD), DIC, and dissolved organic carbon (DOC) is no longer sufficient to effectively reflect the inherent properties of aquatic ecosystems [112,125]. Therefore, the application of biogeochemical theory and methods to study the physical, chemical, and biological processes, dynamic mechanisms, and the relationship between wetland ecosystem processes and functions has become an active research topic in wetland science worldwide [136,137].

Currently, research worldwide focuses on restoration mechanisms considering degraded wetlands, such as pollution prevention, pollution control, pollution treatment, and pollution removal. Many scholars have studied the transfer, transformation, and cycling processes of wetland chemical elements, such as major elements (C, P, N, S, etc.), trace elements, heavy metals (cadmium/Cd, arsenic/As, lead/Pb, and mercury/Hg), and the main elements of eutrophication (N, P, C, and S) [138]. For example, scholars have developed a research method for the healthy water environment of wetland landscapes based on the status and processes of the water environment (including total phosphorus/TP and total nitrogen/TN) in the Xixi Wetland in China, indicating that the water environment is generally below the subhealthy level [67,68]. Gao et al. [92] studied carbon mineralization and nitrogen fixation in mountain wetland soils, indicating that wet–dry cycles could impact the mineralization of carbon and nitrogen, suggesting that climate change may affect the carbon pool of mountain wetland soils by altering water and litterfall. Kania et al. [139] characterized the retention of major elements and trace metals and their potential release under extreme pH conditions from surface sludge sediments in French vertical flow constructed wetlands (VFCWs) under conventional operational conditions. Previous results have shown that most complex and humified dissolved organic compounds can be released under alkaline conditions. Lu et al. [138] collected surface soils (0–10 cm) from developed wetlands and ditch wetlands in the Nansha District of the Pearl River Delta in China to reveal heavy metal (As, Cd, Pb, zinc/Zn, and copper/Cu) pollution in the sampled soil within the cultivation period from 100 years ago to the past 10 years. Moreover, our previous studies on water samples collected in the upper, middle, and lower reaches of the Funan River in Chengdu, Sichuan, China, showed that two metals, namely, chromium and cadmium, affected the water quality, probably due to the interaction

of nutrients and metals caused by the various land use types, industrial activities, and hydrodynamic conditions [140].

Therefore, as the most crucial material flow in wetland landscapes, monitoring the ecological process of water flow is an indispensable monitoring task in wetland landscape research. Moreover, wetland water environmental health usually includes both water environment status health and process health, which are key landscape processes in wetland ecosystems. Although most existing research on wetland or watershed environmental processes is empirical and has not yet reached a systematic and sustained level, the accumulation of basic information could form the foundation for the development of landscape ecology principles in the future. Since the elements and topics included in wetland landscape process health are very complex, selecting the most representative key processes as the research object can help to evaluate the health status of wetland landscape processes more effectively.

6. Evaluation Methods of the WLEH

In recent years, research on the ecological health of wetland landscapes has focused mainly on quantitative studies, thereby using models to calculate evaluation indicators to determine whether the research object meets the WLEH requirements [46]. At the same time, the use of 3S technologies such as RS, GIS, and global positioning system (GPS) and new research software technologies to obtain spatial images and data is increasingly valued by scholars. However, due to the complex and diverse factors that affect wetland ecosystems and the uncertainty in indicator selection, it is difficult to establish a generally accepted landscape health evaluation system. Currently, landscape health evaluation methods mainly include three aspects: the indicator species method, the ecological integrity evaluation method, and the conceptual model indicator system method.

6.1. Indicator Species Approach

In this method, the health status of an ecosystem is described by the quantity, biomass, productivity, structural indicators, and functional indicators of key species, unique species, indicator species, endangered species, and environmentally sensitive species [141]. In previous studies, fish [142] and benthic communities in estuaries [143] have been employed as indicator species for WLEH evaluation. For instance, Stewart and Schriever [5] investigated the relative effects of environmental and spatial factors on the beta diversity of aquatic macroinvertebrate assemblages across 36 interdunal wetlands from five freshwater dune complexes in two eco-regions spanning a latitudinal gradient across Lake Michigan. Other researchers have also studied the potential utility of aquatic invertebrate communities as indicators of the wetland restoration status in the Sanjiang Plain in northeastern China [144] and the paucity of plant species in a Danish wetland 17 years after restoration [4].

6.2. Ecological Integrity Assessment

This method mainly includes physical, chemical, and biological integrity aspects of wetland ecosystems. Among them, physical integrity involves the selection of evaluation indicators from aspects such as stream physical habitats, riparian zone habitats, sediment properties, and channel integrity, aiming to reflect the ecological integrity of streams from a physical habitat perspective. Studies have shown that the content of chemicals in water and soil significantly affects the integrity of ecosystems. Therefore, chemical integrity is usually evaluated using water quality and soil indicators. Biological integrity evaluates the health of ecosystems through species surveys. For example, the IBI can be adopted to analyze changes in the composition, distribution, abundance, sensitivity, tolerance, endemism, and introduced species of fish communities to evaluate the health status of water ecosystems [145–147].

6.3. Conceptual Model Evaluation

The conceptual models for landscape health assessment include three types: the vigor–organization–resilience (VOR) model, the PSR model, and the ecological feature–function–socioeconomic (EFFS) model.

6.3.1. VOR Model

The VOR model was defined as an EH diagnosis model at the International Ecosystem Health Conference in 1999 [23,30]. The VOR model can be expressed as:

$$HI = V \times O \times R \quad (1)$$

where *HI* denotes the health index, and *VOR* denotes the indices of vigor (*V*), organization (*O*), and resilience (*R*) of the ecosystem. Specifically, the following applies:

The vigor index measures the rates of material production and energy circulation in the ecosystem, from solar energy to plants and animals to social products or other services, using the total amount or efficiency of ecosystem material production and energy fixation. In wetland water environments, vigor mainly refers to the ability of various water quality indicators to reach balance and stability while maintaining high elasticity [148].

The organization index reflects the optimization ability of the ecosystem structure and function, measured by the combination of ecological structure and functional characteristics. In wetland water environments, the organizational structure includes the values of various water quality indicators and the coordination between them.

Resilience is the ability of the ecosystem to resist or rebound from stress. In wetland water environments, resilience refers to the ability of the water environment to recover from a poor state in the process of change to a general level.

For example, under the traditional VOR framework, spectral index analysis, landscape theoretical ecological models, and spatial measurements have been used to construct subindices for RS-based diagnosis of the regional EH using RS datasets. Moreover, landscape heterogeneity (LH), landscape connectivity (LC), shape characteristics of forest patches (CS), and connectivity of forest patches (CC) have been adopted as the main factors to calculate the organization index, thus constructing a framework to address the problem of measuring the dynamic evolution process and characteristics of the regional EH [149]. Studies have also been conducted to assess the EH of wetlands in the Rarh district of the Murshidabad district using the VOR model with the help of bathymetry, landscape matrix, and land use and land cover (LULC) data [148]. It was revealed that the rapid growth in agricultural land and the expansion of urban areas are responsible for the deterioration in the ecological health of wetland landscapes.

6.3.2. PSR Model

The PSR model was jointly proposed by the Organization for Economic Cooperation and Development (OECD) and the United Nations Environment Programme (UNEP) in the late 1980s. This model includes three indicators: the pressure (P) indicator to indicate the causes of ecological environment degradation, the status (S) indicator to measure the changes in landscape due to human activities, and the response (R) indicator to reveal the efforts made by society to reduce environmental pollution and resource consumption.

Currently, there are many cases involving the use of the PSR model to study the health of landscape ecosystems, most of which are large-scale assessment studies based on 3S technology. For example, Das et al. [150] explored the health status of wetland ecosystems at the block level in the Murshidabad district of India in 2013 and 2020 using the PSR model. In addition, scholars studied a typical wetland area in the Momo National Protection Area and used the PSR model and mathematical methods based on disaster incremental theory to improve model parameters. They evaluated the ecological security status of the study area from 2000 to 2020 using GIS-based methods [151]. Coastal ecosystems in particular are being degraded worldwide due to resource pressures and global climate change. Previous studies

examining the health of coastal wetland ecosystems in the Sundarban Biosphere Reserve (SBR), India, involving PSR model application have shown that ecosystem fragmentation and human disturbance are the two dominant factors contributing to the decline in the health of SBR wetlands over the past two decades, and the results of this study may help in the development of management policies for coastal wetland ecosystems [152].

6.3.3. EFFS Model

The EFFS model is a method for evaluating ecosystem health by selecting evaluation indicators from the aspects of system ecological features, function integration, and socioeconomic environment [153]. In recent years, this model has been widely applied to evaluate the health of wetland ecosystems. For instance, this EFFS model was employed to assess freshwater wetland EH in China's Poyang Lake region [62]. In this study, ecological characteristics (e.g., water quality, vegetation cover, and biodiversity), as well as socioeconomic factors affecting wetland ecosystems (e.g., land use change and human activities), were selected to identify the major threats to wetland ecosystems and propose strategies to mitigate these threats. With the help of this model, it has also been found that the wetland ecosystems on the Tibetan Plateau are facing multiple threats, thereby selecting ecological characteristics of wetlands, such as soil quality, vegetation cover, and water quality, as well as assessing socioeconomic factors influencing wetland ecosystems, such as human activities, and suggesting that wetland conservation and restoration should be prioritized to mitigate these threats [154].

This model provides a comprehensive and systematic approach for wetland ecosystem assessment, which accounts for the complex interactions among ecological, functional, and socioeconomic factors. By using this model, researchers can identify the major threats to wetland ecosystems and propose strategies to mitigate these threats, which can contribute to the sustainable management and conservation of wetland ecosystems.

6.3.4. Comparison of the VOR, PSR, and EFFS Models

The VOR model focuses on the natural resilience of wetland landscapes and the effects of human intervention [148,149], whereas the PSR model focuses on the pressures on wetland landscapes and the role of policy management [150,152,155]. Moreover, the EFFS model focuses on the effects of the characteristics and functions of wetland landscapes on socioeconomic systems and the impacts of socioeconomic factors on wetland landscapes [61,62,75,153] (refer to Table 5).

Table 5. Similarities/differences among the VOR, PSR, and EFFS models in wetland landscape ecological health.

Model	Overview	Emphasized Elements	Application to the WLEH
VOR	This model focuses on the vitality, organization, and resilience of wetland landscape ecosystems. It emphasizes the natural recovery capacity and the impacts of human interventions on wetland landscapes.	Wetland landscape vitality, organization, resilience	This model is used to study the recovery capacity and vulnerability of wetland landscapes by assessing biodiversity, ecological processes, and ecosystem functions.
PSR	This model describes the influences of human activities (pressure) on the state of wetland landscape ecosystems and considers the effects of policies and management responses (response) on the state of wetland landscapes. It emphasizes the pressure on wetland landscapes originating from human activities and the role of policies and management.	Wetland landscape pressure, state, response	This model is employed to assess the sustainability and ecological health of wetland landscapes by analyzing pressure sources, ecological states, and management responses of wetland landscapes.
EFFS	This model comprehensively considers the interaction between ecological characteristics, ecological functions, and socioeconomic factors in wetland landscapes. It emphasizes the impacts of wetland landscape characteristics and functions on the socioeconomic system and the influences of socioeconomic factors on wetland landscapes.	Wetland landscape ecological characteristics, ecological functions, socioeconomic factors	This model is used to evaluate the overall health and sustainable utilization of wetland landscapes by analyzing the relationships between ecological characteristics, ecological functions, and socioeconomic factors of wetland landscapes.

6.4. Calculation of Water–Gas CO₂ Parameters

6.4.1. Calculation of $p\text{CO}_2$

Studies have confirmed that the concentrations of HCO_3^- , CO_3^{2-} , H_2CO_3 , and dissolved CO_2 , which comprise IC in water, all depend on the pH, temperature, and ionic strength of water given aqueous solution equilibrium. Therefore, the carbonate equilibrium model was used to calculate the water–air $p\text{CO}_2$ based on the pH, HCO_3^- , CO_3^{2-} , K_h , and ions in water as follows [Equations (2)–(5)]:



$$K_{\text{CO}_2} = [\text{H}_2\text{CO}_3^*] [p(\text{CO}_2)] \quad (3)$$

$$K_1 = [\text{H}^+] [\text{HCO}_3^-] / [\text{H}_2\text{CO}_3^*] \quad (4)$$

$$K_2 = [\text{H}^+] [\text{CO}_3^{2-}] / [\text{HCO}_3^-] \quad (5)$$

where K_i is the equilibrium constant, calculated by Equations (6)–(8):

$$pK_{\text{CO}_2} = -7 \times 10^{-5} t_{\text{water}}^2 + 0.016 T + 1.11 \quad (6)$$

$$pK_1 = 1.1 \times 10^{-4} t_{\text{water}}^2 - 0.012 T + 6.58 \quad (7)$$

$$pK_2 = 9 \times 10^{-5} t_{\text{water}}^2 - 0.0137 T + 10.62 \quad (8)$$

where pK_{CO_2} , pK_1 , and pK_2 denote the negative logarithms of K_{CO_2} , K_1 , and K_2 , respectively, and t_{water} denotes the water temperature (°C). According to Henry's law, $p\text{CO}_2$ (μatm) can be calculated with Equation (9):

$$p\text{CO}_2 = [\text{H}_2\text{CO}_3^*] / K_{\text{CO}_2} = \alpha (\text{H}^+) \cdot \alpha (\text{HCO}_3^-) / (K_{\text{CO}_2} \cdot K_1) \quad (9)$$

where $\alpha (\text{H}^+)$ and $\alpha (\text{HCO}_3^-)$ denote the ionic activities of $[\text{H}^+]$ and $[\text{HCO}_3^-]$, respectively, which can be obtained with Equations (10)–(12):

$$\alpha (\text{H}^+) = 10^{-[\text{pH}]} \quad (10)$$

$$\alpha (\text{HCO}_3^-) = [\text{HCO}_3^-] \times 10^{-0.5\sqrt{I}} \quad (11)$$

$$I = 0.5([\text{K}^+] + 4[\text{Ca}^{2+}] + [\text{Na}^+] + 4[\text{Mg}^{2+}] + [\text{Cl}^-] + 4[\text{SO}_4^{2-}] + [\text{NO}_3^-] + [\text{HCO}_3^-]) \quad (12)$$

where I is the ionic strength.

6.4.2. Estimation of FCO_2

In previous studies, it has been determined that CO_2 diffusion across the water–gas interface is influenced by the difference in $p\text{CO}_2$ between the atmosphere and water, temperature, salinity, and wind speed. Accordingly, we used the hysteresis layer model (cf. ref. [156]) to calculate the water–gas FCO_2 :

$$\text{FCO}_2 = K_T K_H [p\text{CO}_2(\text{water}) - p\text{CO}_2(\text{air})] \quad (13)$$

where FCO_2 denotes the flux of CO_2 at the water–air interface ($\text{mmol m}^{-2} \text{h}^{-1}$), K_H denotes the solubility of CO_2 at a certain temperature ($\text{mol L}^{-1} \text{atm}^{-1}$), and K_T is the gas exchange rate of CO_2 (cm h^{-1}). K_H is influenced by the temperature, salinity, and pressure of water, as follows [14] (cf. [157]):

$$\ln K_H = A_1 + A_2 (100/T) + A_3 \ln(T/100) + S [B_1 + B_2 (T/100) + B_3 (T/100)^2] \quad (14)$$

where the constants A_1 , A_2 , A_3 , B_1 , B_2 , and B_3 can take values of $[-58.0931]$, $[90.5069]$, $[22.2940]$, $[0.027766]$, $[-0.025888]$, and $[0.0050578]$, respectively, based on previous studies. Moreover, S and T denote the salinity (‰) and Kelvin temperature (K), respectively. Studies

have shown that the salinity (S) is negligible when targeting freshwater lakes, reservoirs, or wetlands (freshwater) [130]. Therefore, Equation (14) can be simplified as Equation (15).

$$K_H = e^{[A_1 + A_2(100/T) + A_3(T/100)]} \quad (15)$$

Furthermore, K_T was converted from the normalized Schmidt number 600 (K_{600}) according to Equation (16) [158]:

$$K_T = K_{600} \times \left(\frac{600}{Sc_{CO_2}} \right)^n \quad (16)$$

where n is the Schmidt number exponent that depends on the surface state of water. Moreover, n is 0.50 when the wind speed exceeds 3.7 m s^{-1} and 0.75 when the wind speed is lower than 3.7 m s^{-1} [159]. Based on the findings of Cole and Caraco [160], the Schmidt number is 0.67 under normal circumstances. $[Sc_{CO_2}]$ denotes the Schmidt number of CO_2 at a given temperature (t) and was calculated using Equation (17):

$$Sc_{CO_2} = 1742 - 91.24 t + 2.208 t^2 - 0.0219 t^3 \quad (17)$$

where the values of the coefficients were obtained from previous studies (Yang et al., 2019). The following Equation (18) was used to obtain the value of K_{600} :

$$K_{600} = 2.07 + 0.215 U_{10}^{1.7} \quad (18)$$

where U_{10} is the normalized wind speed (m s^{-1} ; ref. [160]) at a height of 10 m above the water surface at the time of sampling.

6.5. Integrated Multi-Indicator Evaluation

Due to the comprehensiveness and complexity of wetland evaluation indicators, the evaluation results are inevitably determined by multiple factors, such as the evaluation objects, objectives, indicators, and methods. Traditional evaluation methods cannot objectively and scientifically evaluate multiple factors, which may lead to large differences in the results obtained by different evaluation methods [6,154]. In recent years, multi-indicator integrated assessments of the ecological health of wetland landscapes have been increasingly applied. This approach aims to provide more comprehensive and accurate assessment results by collecting and analyzing multiple indicators, which can realize comprehensive assessment of all aspects of wetland landscapes [161]. This method can help identify problems and potential risks of wetland landscapes and provide a scientific basis for the formulation of effective conservation and management measures. In comprehensive multi-indicator evaluation of the ecological health of wetland landscapes, a series of suitable indicators must be selected to reflect the ecological status of wetland landscapes. These indicators can include the biodiversity index, water quality index, soil quality index, vegetation cover, and landscape connectivity. These indicators reflect the physical, chemical, and biological aspects of the wetland landscape and can be considered to quantify the ecological functions and health status of wetland landscapes [162].

In recent years, multi-indicator comprehensive evaluation has become a hot research topic in the field of wetland health assessment. Sun et al. [163] selected 27 ecological, social, and economic indicators for the Jiaozhou Bay wetland in Shandong Province, China, and established a PSR model. They then used the AHP and fuzzy comprehensive evaluation (FCE) methods to calculate the weight of each indicator and obtain the health index. In addition, Zhao et al. [164] proposed an indicator system for assessing the ecological health of the Shenzhen Futian mangrove wetland ecosystem in China using the PSR model. Additionally, they employed the AHP method to determine indicator weights and evaluate the system. These results demonstrated the applicability of the PSR model and AHP method in assessing the ecological health of mangrove wetlands, which could provide useful information for policymakers and environmental managers to make informed

decisions regarding conservation and management strategies. In addition, previous studies integrated the environmental salinity (based on the Baseline-Based Soil Salinity Index, or BSSI) and new vegetation elements (improved hyperspectral image-based vegetation index, IHSVI) combined with the use of the Mann–Kendall test and wetland ecological index (WEI)-Mann–Kendall analysis methods to determine the spatial and temporal changes in the ecological integrity of the Yellow River Delta, China, from 1991 to 2020 [151].

In conclusion, comprehensive multi-indicator evaluation is an effective method to systematically assess the ecological health of wetland landscapes by considering multiple landscape aspects and to provide scientific support for wetland conservation and management [165]. However, researchers must carefully choose appropriate evaluation methods and indicators based on the specific characteristics of the wetland ecosystem under evaluation. Therefore, combining two or more evaluation methods into a new evaluation method has become a research hotspot in the field of wetland health, but different multi-indicator comprehensive evaluation methods provide different advantages, disadvantages, and application scopes, as shown in Table 6.

Table 6. Summary of the comprehensive evaluation methods for wetland health assessment.

Evaluation Method	Selection Advantages	Selection Disadvantages	Application Notes	References
Entropy weighting method	Higher accuracy and objectivity than subjective assignment methods	Limitations when evaluating indicators with low variations and high concentrations	Used for indicators that do not significantly contribute to the evaluation results and can better explain the results obtained	[166]
Delphi method	Simple process and easy-to-use conclusions	Highly subjective, time-consuming, difficult to converge conclusions	For probabilistic estimation of nontechnical elements that cannot be quantitatively analyzed	[167]
Hierarchical analysis method	Simple and straightforward, relatively reliable and practical, with small errors	Highly influenced by human factors, more subjective, and not too many factors for subject evaluation	Higher accuracy and reliability when combined with the Delphi and fuzzy mathematical methods	[94,168]
Fuzzy integrated evaluation method	Scalability with multiple levels of solutions based on different possibilities	Affiliation and synthetic operator determination are subjective, and the model is not self-validating	Suitable for a wide range of nondeterministic problems	[11,148]
Projection tracing method	An exploratory approach to data analysis	Quite computationally intensive and complex	Suitable for nonlinear, nonnormal, high-dimensional data	[169]
Landscape development intensity method	Less input based on remote sensing imagery, thematic maps of the study area, topographic maps, etc.	Low evaluation accuracy and neglect of the impact of land use types outside the depicted area	Suitable for evaluating the health of wetlands at the large landscape and regional levels	[58]
Rapid assessment method	Lower investments in capital and labor	The selection and assignment of indicators are subjective, and the evaluation results cannot be directly used for decision-making	Suitable for evaluating individual wetlands or a small number of wetlands	[91]
Backward propagation neural network	Nonlinear mapping capability and self-learning, self-organizing, and self-adaptive capabilities	Weak physical foundation, poor network outreach, large number of training samples required for application	Suitable for managing large, complex nonlinear systems	[170]
Support vector machine	Algorithm science, high model interpretation and predictive power	No universal solution to nonlinear problems, and kernel functions must be carefully chosen to manage these problems	Use in case of a small sample size	[171,172]

7. Conclusions and Outlook

In summary, research on the ecological health of wetland landscapes should include two study levels. First, based on the study of the health status of wetland landscapes, emphasis should be placed on maintaining the ecological condition of wetland landscapes, thereby satisfying their ecological processes. This mainly includes the completeness of the basic elements of wetland landscapes, the rationality of their structure, the performance of their landscape functions, the resilience, balance, and recovery ability of wetland landscapes, etc. Second, wetlands, as a part of social and economic development, should provide the ability to meet certain operational management requirements. Therefore, based on the basic theories of landscape ecology and from the perspectives of indicator systems, research dimensions, and interdisciplinary integration, studying the essential attributes or key ecological stages of the landscape ecological structure, function, and process may be more effective and scientific in revealing the ecological health status of wetland landscape ecosystems and providing scientific references for the restoration, repair, protection, and operational management of wetlands.

- (1) Indicator system. Due to the diversity of the constituent elements, influencing factors, and evaluation scales of wetland ecosystems, there exists uncertainty in the selection of evaluation indicators, and there are no established evaluation criteria [173,174]. Therefore, it is urgently necessary to formulate standards and norms for the selection of evaluation indicators, to design corresponding benchmarks and thresholds based on the characteristics of different wetlands, and to construct an accurate and reasonable evaluation indicator system to scientifically evaluate the ecological health status of wetland landscapes.
- (2) Research dimensions. In existing studies, the temporal scale is focused mostly on LEH research during a specific year, and the results can hardly reflect the dynamic changes and evolution trends of wetland health. Therefore, in the future, the temporal scale can be expanded, and the dynamic changes in WLEH can be more closely studied [175]. In empirical research, mathematical models can be established between indicator and wetland changes to assess the wetland health status more accurately. In addition, spatial scales can be overlaid to compare the WLEH among different spatial scales, yielding the more accurate and specific evaluation results.
- (3) Interdisciplinary integration. Wetland ecosystems are complex and diverse systems that are highly susceptible to human activities. In addition to relying on the theories and methods of ecology, geography, statistics, and other disciplines, WLEH research should introduce theories and methods obtained from social science research to ensure more comprehensive and integrated results.

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