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Review

Implementation of Diversified Ecological Networks to Strengthen Wetland Conservation

The notion that the conservation of wetlands in the world is too limited has gained a universal consensus because of the conflicts between their great value and the drastic decline in their quantity and quality. To mitigate these conflicts, ecological networks have integrated the hydrologic and biological connectivity of ecosystems. The basic elements of ecological networks, patches, and corridors, have been extracted to reflect the attributes of the hydrologic and biological connectivity of ecosystems. This paper reviews recent applications of network approaches to ecological conservation, focusing on their application in wetland ecosystems, and proposing a new perspective for wetland conservation. This review is limited to four aspects: first, the linkages between wetlands and ecological networks are determined by reviewing the development both of them; second, the two types of connectivity and their application that can be obtained from graphs or network models are discussed; third, common network analysis approaches, which can provide a theoretical basis to explore the optimal relationship between network structure and function, are summarized; finally, this paper presents the configuration and convergence characteristics of different types of wetland networks at multiple spatial scales. At the conclusion, suggestions for further work are presented.

Keywords: Ecosystem connectivity; Ecosystem conservation; Multiple scales; Wetland network

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1 Introduction

Wetlands are highly valuable because their functions can provide several direct and indirect benefits, such as shelter and food, to diverse flora and fauna, including human beings [1, 2]. However, wetlands are becoming one of the most degraded ecosystems on earth [3]. More than 50% of global wetlands have already been destroyed as a result of various human and natural causes, including drainage for agriculture and forestry; exploitation for industrial, agricultural, and commercial development; filling for solid-waste disposal; water pollution from industrial and agricultural activities; sea-level rise; and erosion and biotic effects [4–12]. In some densely populated regions in Europe, North America, and portions of Oceania and East Asia, over 80% of wetlands have been lost or degraded [5, 13]. This magnitude of loss or degradation clearly indicates the urgent need and great importance to conserve wetlands [3]. In fact, the great ecological, commercial, and socio-economic importance of wetlands has been recognized by many countries; however, the trend of wetland destruction has not yet been completely reversed [3, 14]. Traditional wetland conservation approaches may be based on ecological processes of individual wetlands and ignore the fact that the dispersion function (connectivity) of wetlands is of primary importance to their conservation and restoration [3, 15]. However, wetland conservation and restoration can be taken as a systematic process that aims to maintain or re-establish the ecological functions of original wetlands and the links among their biotic and abiotic components [16–22].

Therefore, the significance of hydrologic and biological connections, as well as regional collaboration, to the conservation of wetland ecosystems can be evaluated by the principles of island biogeography theory and landscape network theory [23, 24]. Based on the species–area relationship [25] and wetland conservation greenway [26], species can spread throughout the wetland systems for foraging, rest, and shelter. Wetland systems with water and corridors are usually taken as wetland networks in reference to a network system consisting of various wetland types (wetland corridors: channels, ditches, and small streams; and wetland patches: e.g., ponds, lakes, and reservoirs) that are interconnected by their hydrology and biology. Wetland networks are currently taken as protected areas that can improve the connectivity for the ability of species to move and occupy new habitats [26–28]. Therefore, a river wetland network is examined by graph-theoretic approaches to search for key segments for fish conservation [29]. River wetland networks are becoming more fragmented because of the disruption to their natural hydrologic connectivity (e.g., due to dams, reservoirs, and water abstraction) and the loss of aquatic biodiversity is obvious. Fortunately, Erös et al. [29] presented a simple and effective method by which managers can maintain connectivity of valuable segments

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Abbreviations: **FW**, food webs; **RN**, river networks; **WN**, water allocation network

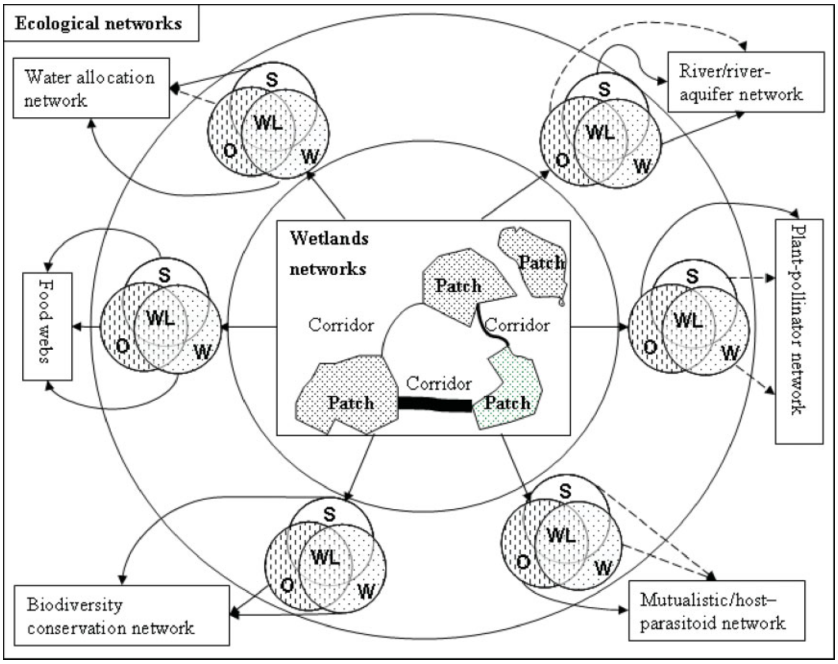

Figure 1. Illustration of the linkages between wetland and ecological networks. WL, W, S, and O represent wetlands, water, hydromorphic soil, and organisms, respectively. Water, hydromorphic soil, and organisms are the three elements of wetlands. The solid lines represent the direct linkages between each element and ecological networks, and the dotted lines are the indirect linkages. The thicknesses of the lines in the wetland network represent its attributes, e.g., the water flow or the movement ability of species.

that are more upstream in the river wetland network instead of maintaining the connectivity of all of the segments.

Most studies of wetlands, as mentioned above, imply that wetland conservation requires a perspective that focuses on the spatially integrated structure of wetland ecosystems. This structure can be designed by using the available theory and empirical knowledge of ecological networks [30]. The notion of the ecological network comes from the practices of land-use planning, the initial aim of which is the conservation of nature and biodiversity at the landscape scale where habitats are subjected to high fragmentation as a result of economic development [31]. Ecological network design provides appropriate opportunities for sustainable development that enables species' populations, including humans, to survive [31, 32]. The idea of an ecological network was first put forward in 1976, but the idea was not widely applied until the 1990s after gaining people's attention and increasing in feasibility [33]. Researchers of ecological networks have started to maintain the ecological consistency of an inner network by providing ecological connectivity across the ecosystem, landscape, and regional scales to restore degenerated ecosystems and protect biodiversity. For example, Smith [34] examined the functions of ecological networks in controlling floods, cleaning water, and purifying air. Moreover, the planning and establishment of ecological networks as a means of creating spatially integrated landscapes and habitats is increasingly accepted as an appropriate approach for improving the ecological quality of natural ecosystems and protecting biodiversity [35–37]. Recently, the implication of ecological networks goes beyond the single objective of protecting biodiversity [38, 39] and conservation strategies have been focused on the conservation of potential ecological corridors for the movement of multiple species among habitats as well [40, 41].

2 Linking wetlands with ecological networks

Ecological networks usually consist of core areas (nodes), corridors (natural and/or artificial linkages), and buffer zones and can be subdivided into many broad types (Fig. 1). With the help of connectivity (e.g., by corridors), materials, and resources can be transferred within and among habitats in ecological networks by wind, water, animal, and human vectors [42, 43]. This transference and/or dispersal will improve the ecological quality of terrestrial and aquatic ecosystems and help to protect their biodiversity [40]. The application of the emerging framework, i.e., used for conservation planning in ecological networks is likely an ideal tactical and strategic decision-making framework for the conservation and restoration of wetlands [44, 45]. This framework is usually called the "wetland network" in wetland conservation [45]. It is well known that the wetland patches within the network are composed of three fundamental elements: water, organisms, and hydromorphic soil (Fig. 1). It is not difficult to infer that the dynamics of the three elements are also closely related to the different types of ecological networks, which are driven by hydrologic and biological connectivity. Therefore, the nodes of a wetland network are considered wetland patches and the connectivity between nodes are indicated by ecological corridors (e.g., river channels and greenways).

Previously, much of the research on wetland networks has concentrated on single elements of wetlands [29, 46, 47], key sites for the most rare habitats and species [48, 49], and the structural and functional elements of wetland networks [50, 51]. All of these studies facilitate the development of ecological networks in wetlands. However, the use of the ecological network framework for conserving wetland biodiversity and improving wetland ecosystem services has not been adequately studied. The reasons include the structural and functional complexity of wetlands and the multi-level management strategies and different operation strategies in practice for wetlands. Therefore, the wetland network framework is employed to conserve wetland biodiversity [29] and improve wetland ecosystem services [50–52]. Wetland networks not only include networks with hydrologic linkages, such as river networks (RN) and water allocation networks (WN), but also networks with biological linkages, such as food webs (FW), plant–pollinator networks, and mutualistic/host–

parasitoid networks (Fig. 1). Unfortunately, these linkages weaken or disappear as a result of wetland network fragmentation caused by rapid urban sprawl and water shortages. Actions including the establishment and/or restoration of linkages between isolated wetland patches through an increase in ecological connectivity can strengthen the linkages and facilitate the ecological functions of wetlands [53]. In this paper, two modes of connectivity in wetland networks are discussed: hydrologic and biological linkages, each of which has different implications for wetland conservation.

2.1 Wetland networks with hydrologic linkages

2.1.1 Water allocation networks

The design of WN originates from developments in mathematical programming since the 1980s aimed at improving water allocation processes, reducing freshwater consumption, and wastewater generation and maximizing wastewater reuse in industries [54–56]. Under this circumstance, the WN can be divided into a water utilization network and an effluent treatment network. Later, the optimization of methodologies for managing WN were further applied to the allocation of agricultural water use, municipal water use, ecological water use, and even the water use of society as a whole [57]. The focus of WN design has also changed from simply reducing freshwater consumption to jointly conserving water resources and improving energy performance [56, 58, 59].

It is believed that reasonable WN should not only increase the economic benefits of water resource but also maximize their social and, especially, ecological benefits. For wetland networks, the design of an optimal WN is supposed to rely on a thorough understanding of the ecological water requirements of the main structural and functional groups. The ecological water requirements for wetland ecosystems refer to the water regime required to maintain the natural growth of wetland habitats, protect biodiversity, sustain human activities, and improve environmental quality. Hence, the water regime determined by the ecological water requirements can be used as the foundation for the establishment of a WN [60]. Another WN, water use systems, consists of the water exchanges among a number of activities that transfer water between different river segments that allow a river network to function at the basin scale [52, 61]. Once a WN for an ecological water requirement is established, a corresponding energy and materials exchange network can be developed. This network has an optimal network configuration that minimizes energy consumption and maximizes cost-effectiveness and affordable water allocation.

2.1.2 River network

Water flows dominantly influence river morphology and water acts as a medium that can link rivers and landscape elements [62]. Rivers with adjacent water areas form RN that contain abundant biotic and abiotic factors, especially endemic species [63]. The biodiversity of RN has been severely threatened by natural variation and human activities [64, 65]. When RN are considered from a linear perspective across ecological networks, the management of this river network structure can help to abate these threats [63]. The spatial structure of RN can be effectively described by a graph, which is composed of "edges" and "nodes"; these two components are river channels and confluences, respectively, in hydrologic terms [66].

Recently, a network-based approach has been employed by detecting and optimizing the river network structure to achieve more effective conservation of rivers [29, 52]. The hierarchical network pattern of a river network is one of the most fundamental patterns in a watershed [50, 51, 67]. River network structure strongly influences its ecological processes, including habitat connectivity [68], predator–prey interaction rates [69], and biological diversity [63]. For convenience, a RN is considered in a graph context in which the river segments correspond to links and the confluences between them correspond to nodes, which can be denoted on a graph consisting of a set of nodes and a set of links [29, 66]. In addition, a river network can be represented by a tree approach, with the river segments representing links or edges and the confluences between them corresponding to tree nodes, where loops never appear [70].

RN are usually connected to other types of wetlands (e.g., river headwaters, lakes, reservoirs, and/or marshes) by hydrologic connectivity. These wetland patches play a significant role in energy flow and material cycling. Therefore, wetland patches are introduced into the RN and a broader concept of nodes is proposed that considers patches of confluences, river headwaters, lakes, reservoirs, and/or marshes [52]. Following this concept, the function of a river network for drought and flood control can be improved by optimizing the structure of the network. Rivers can be taken as natural ecological networks that provide connectivity to species dispersal among different habitats and the riparian buffer zones of RN are typical elements of ecological networks [49]. Riparian buffer zones have been considered as buffer strips to trap non-point source pollution [71, 72] and as core habitats for the management of natural resources [73]. These buffer zones can increase longitudinal connectivity and biodiversity [73, 74]. However, few studies have incorporated riparian buffer zones into RN to address the implications of these buffer zones to the dynamics of the physical structure and ecological of a river network when planning basin water resource management.

2.2 Wetland networks with biological linkages

2.2.1 Food webs

FW can be simply denoted as linear trophic chains of primary producers, herbivores, and carnivores [75, 76]. Research concerning FW in an ecological ecosystem focuses on two aspects: the trophic level configuration and the material transfer within FW. For FW, the links are the movements of species and represent dispersal rates or likelihoods. Dunne et al. [77] suggested that it is important to explore the topological structure of FW and predict responses of functional ecosystems to structural changes from an applicable and conservation-based perspective. By examining the topological structure of 16 FW from a variety of ecosystems, they determined that the topologies of FW are consistent with patterns found within those small-world, scale-free networks. Due to the diversity of species in each trophic level and the complex interactions among different trophic levels, the configurations of FW generally have much higher complexity, measured as connectivity, compared to other networks [77]. Therefore, the configuration of a FW can also be defined as a dynamical system on an underlying graph with interconnected nodes and links [78]. Overall, for trophic chain configurations, an ecological network is a predator–prey interaction, which also includes flows of energy–matter transfers within a FW [79].

In addition, wetland ecosystems (especially in estuaries) feed abundant resources of flora and fauna [80]. However, these organisms might be exposed to higher levels of pollutants [81]. Pollutants that are assimilated by primary producers are available to herbivores and detritivores and, thus, can enter into and accumulate within FW [82, 83]. The biomagnification of inorganic pollutants in FW is more significant than that of organic pollutants [81, 82, 84, 85]. The accumulation of inorganic pollutants along the trophic chains in FW has been studied in estuarine ecosystems [81, 82]. However, frameworks that consolidate the key principles for biomagnification in FW by considering seasonal variations and regional differences are still lacking.

2.2.2 Biodiversity conservation networks

Stakeholders have acknowledged that the use of traditional conservation measures for an individual reserve may not be suitable to wetland sustainability in the long-term because of the inherent lack of consideration of the regional background. However, some species, such as birds and fish, have their own species distributions and migration routes and the connections among wetland reserves and the associated surrounding buffers provided by hydrologic and biological connectivity are essential for species' survival and ecosystem services [67]. In addition, a connected wetland network can effectively improve the ecological functions and facilitate adaptation to climate changes and human influences. Intense land use pressures also compel the establishment of efficient conservation networks that minimize the habitat and corridor requirements for protecting biodiversity [86, 87]. Under this circumstance, ecological conservation networks can be defined as systems of nature reserves and their interconnections that make fragmented natural systems coherent and can thus support increased biodiversity compared with the unconnected form. In an ecological network, the reserves are mostly multi-functional landscape structures [32].

Generally, these networks for the conservation of biodiversity are mainly composed of core areas, buffer zones, and ecological corridors [88]. All three components are connected to each other through ecological corridors, which will play a dominant role in biodiversity conservation by maintaining gene flow and facilitating species migration, dispersal, and recolonization [89]. The key objectives of biodiversity conservation are to identify the most important habitat patches [90], high valuable corridors [29], and keystone species [91] to maintaining biodiversity on broad scales. These patches, corridors, and species are more important than others for maintaining biodiversity in ecosystems and thus have a higher priority for conservation. Removing an element (patch, species, or corridor) to test the response dynamics of the rest of the network has been considered as an effective approach to identify these critical patches, species, and corridors [29, 90, 92]. Biodiversity conservation needs to pay more attention to the identification and conservation of important habitat patches, high valuable corridors and keystone species, and relatively less attention to rarity.

3 Existing approaches to ecological network analysis

Network analysis is an important methodology, i.e., commonly used in many research areas, including computer networks [93], social networks [94], and transportation systems [95]. Since the 1970s, network analysis has been applied in systems ecology. Hannon [96] first applied economic input–output analysis, which originates from the economic analysis of monetary flows, to investigate the ecological processes in an ecosystem. Since then, a suite of ecological network analyses, including trophic structure analysis, pathway analysis, and information analysis have been applied to holistically analyze environmental interactions [29, 79, 97–100]. Specifically, graph theory can efficiently describe the topology of an ecological network, which is treated as a system of interconnected nodes and links with the function of dispersal potential or frequency between patches [75, 101]. In fact, graph-theoretic models have been widely used in ecological network analysis in recent years (Tab. 1). These models have been applied not only to analyze the interactions between an ecosystem's structure and function and thus reveal the integrity and complexity of ecosystem behaviors [79, 102] but also to strengthen network functions by improving the topological structure of the network [50–52, 103].

The research focal points of ecological networks at different scales are listed in Tab. 2. Generally, ecological conservation and reserve creation have focused on a single function, such as improving water quality, strengthening biodiversity, or providing regional drought and flood control [50–52, 103, 139]. Systematic conservation planning for wetland ecosystems has been advocated to identify priority areas for conservation at multiple scales of wetland networks. Broad-scale changes, including climate change and habitat loss and fragmentation, are likely to affect the ecological functions of wetlands [140]. Biodiversity in wetlands is highly variable at different spatial scales [141]. The large network of national parks and reserves is believed to be a key factor to ensure the success of biodiversity conservation efforts [142].

4 Arrangement of wetland networks at different scales

Wetland systems exhibit a hierarchical organization in terms of their structure, function, space, time, and scale-specific variables and processes play important roles at each level of every hierarchical structure [50, 51, 143]. To be specific, the basic system of wetland structure (the biotic and abiotic webs of which nodes are elements, such as vegetations and soils) and the different states of ecological processes (the dynamics of transformation of matter or energy) at various scales can greatly influence the functional performance of wetland ecosystems at each hierarchical level [139, 144]. This section focuses on the consideration of wetland networks at different spatial scales (the local, regional, and river basin and trans-basin scales) and then the connections and distinctions among the structural, ecological characteristics as well as the functional performance of wetland networks are reviewed. Due to the connectivity among resources, energy, and information in social, physical, and biological systems, the environmental stresses induced by human activities will influence wetland networks at all spatial scales (Fig. 2).

However, the responses of wetland networks to various human activities on different spatial scales will vary as a result of the spatial variations in structural patterns and functional performances influenced by the inconsistent internal processes that play a leading role in the system model of each hierarchical scale (Fig. 2). The magnitude of these projected physical changes and their subsequent impacts on wetlands, including abiotic factors such as wetland hydrology and geomorphology and biotic factors such as the species distribution patterns of population and biological processes, in a wetland net-

Table 1. Common graph-theoretic models applied to ecological networks, which can be denoted as a graph, consisting of a set of nodes and a set of links

Index	Description and selected references	Application fields
Structural		
Node degree	Number of neighboring nodes directly connects to a node [104–109]	FW; BN
Weighted degree	Sum of weights on the links fitting to the analyzed patch [104]	BN
Area index	Area of largest habitat patch divided by the area of the largest component [110]	FW; BN; RN; WN
Shortest path	The sum of the weights of its constituent links is minimized [62, 97, 111]	FW; BN; RN; WN
Network diameter	The ''longest shortest path'' between the two most distant patches in a network [110, 112, 113]	FW; BN; RN; WN
Characteristic path length	A network attribute measures the average shortest path length over the network [44, 101]	FW; BN
Gamma index	The ratio of the number of links in a network to the maximum number of links possible [52, 53]	RN; BN
Alpha index	The number of loops present divided by the maximum number of loops possible [52, 53]	RN; BN
Clustering coefficient	The ratio of the number of links among the nodes within its neighborhood divided by the total number of links that could possibly exist among them [94, 104–106]	FW; RN; BN
Betweenness centrality	Quantifies how frequently a node *i* is on the shortest paths between every pair of nodes *j* and *k* [66, 104, 105, 110, 114–117]	FW; BN; RN; WN
Information centrality	The relative drop in the network efficiency caused by the removal of the node from the network [104, 118]	FW
Closeness centrality	How long the shortest path is from a given node to all others [104, 114, 116, 117]	FW; BN
Redundancy	Ratio of least cost distance to effective resistance distance [119]	BN
Harary index	Sum of the inverse values of the topological distance between every two patches. If two patches belong to different components, their topological distance is infinity (a component is defined as a set of patches that can be reached from each other through existing links) [120–122]	BN
Area-weighted flux	Sum of the products of the direct dispersal probability between each pair of nodes and the attributes of those nodes *i* and *j* [112, 113, 123]	BN
Integral index of connectivity	Integral index of connectivity calculates from the attributes of the patches and the topological distances between them. It takes into account the connected area existing within the patches, the estimated dispersal flux between different patches and their contribution as stepping stones or connecting elements that uphold the connectivity between other patches [29, 92, 122, 124]	BN; RN
Probability of connectivity	The probability that two points randomly place within the landscape fall into habitat areas that are reachable from each other (interconnected) given a set of *n* habitat patches and the links (direct connections) among them [108, 121, 123–125]	BN
Traversability	Diameter of the largest component of the graph based on weighted distances [112, 113, 126]	BN
Functional		
Community importance	The percentage of other species lost from the community after its removal, we can illustrate this assumption by plotting, for a hypothetical community, the relative community importance of each species [109, 127, 128]	BN, FW
Interaction strength index	The sum of all resulting relative changes in the system [the total absolute relative changes in all but the removed group (species)] [109, 128, 129]	BN, FW
Community longevity support	The sum of the opposite (sign) of the real value of the predicted change of each affected group (species) multiplied by its longevity [128]	BN, FW
Keystone index	Keystone index is the Interaction strength index divided by the present of the system's overall living biomass represented by group (species) *i* before it was removed [128]	BN, FW

Nodes are the basic element of a graph, the object of interest; pathes are a sequence of consecutive edges in a network that join any two nodes. WN, water allocation network; RN, river networks; FW, food webs; BN, biodiversity conservation network.

work vary regionally [145]. To arrange wetland networks at different scales, four key principles have been presented to design ecological networks for the representation and persistence of biodiversity: (1) selecting ecosystems of high ecological integrity, (2) incorporating connectivity, (3) incorporating areas important to population persistence, and (4) identifying additional natural processes [146].

4.1 Local scale

Wetland networks isolated at the local scale are usually distributed across a catchment area smaller than 100 km^2. This type of network is an open system, characterized by administrative rather than physical boundaries. The elements that comprise the wetland networks, such as patches, corridors, and species, are significantly separated and controlled by the surrounding factors (e.g., surrounding habitats) [140]. The isolation between wetland elements will undoubtedly reduce the hydrologic connectivity, which further disturbs the water cycle of a locally isolated wetland network. Once any hydrologic change, including either a higher frequency of extreme rainfall or continual drought events, occurs within the local wetland network, the ecological processes of the affected wetland network will be substantially influenced at first [147, 148] and the species

Table 2. General themes in the literature relating to multiple scales of ecological networks

Ecological network types	Typical research questions	Analytical tools	Ecological process	Spatial scales	Selected references
River network	How landscape influences on river network integrity? Which the factors do regulate denitrification at river network scales?	Field observations, aerial photograph interpretation, and geographic information system; models	Dispersal and migration; removal	Local and regional scales	[130–132]
Food webs	How body-size effects in food webs through a scale of ascending complexity? How to characterize patch-scale variability in food-web attributes?	Field observations, metabolic, and genetic theory, niche models	Adaptation, individual and inter-species interactions	Local and regional scales	[133–135]
Biodiversity conservation network	How multi-scale affect the natural resource management? How productivity influences species diversity in marine systems? How much biodiversity is preserved in different scales?	Systems analysis and models, remote sensing, regression analyses, field observations, and models	Adaptation, dispersal, migration, and species interactions	Local, regional, and trans-basin scales	[86, 136–138]
Wetland networks	What role of wetland scales play in Flow attenuation, sediment storage and Pollutant removal?	Systems analysis and models	Storage and removal	Local and regional scales	[50, 51]

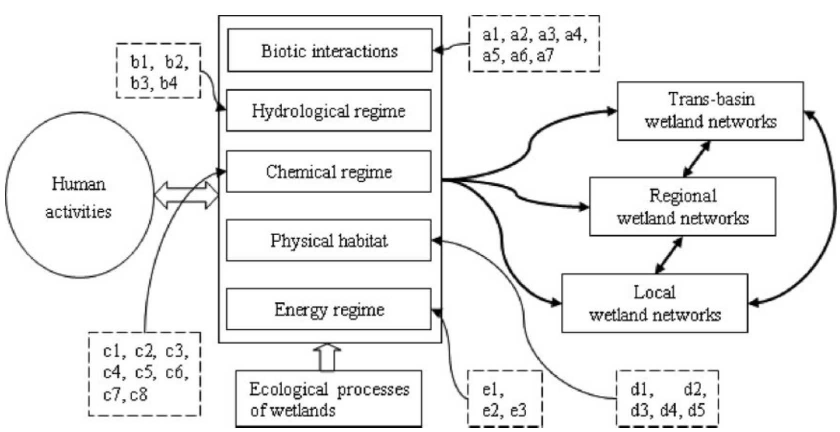

Figure 2. Conceptual relationships between the biological, physical, and chemical processes for multiple scales of wetland networks and considering the influence of human activities. The dotted boxes represent factors that can affect the biological, physical, and chemical processes operating within wetland networks. (a1–a7) Represent the biotic structure and composition, competition and predation, disease and parasitism, mutualism, feeding, reproduction, and production, respectively; (b1–b4) Represent the ground water regime, soil moisture regime, surface inundation regime, and surface flow regime, respectively; (c1–c8) Represent the radioactivity, pH, temperature, dissolved gases, dissolved minerals, organic compounds, turbidity, and salinity, respectively; (d1–d5) Represent the woody debris, riparian canopy, geomorphology, connectivity, and sediment/soil regime, respectively; and (e1–e3) Represent the organic mater inputs, sunlight, and natural thermal discharges, respectively.

composition and/or metapopulation structure may also be altered as longer-term and further responses unfold [149]. For example, extreme rainfall often causes serious water loss and soil erosion, which can bring about the replacement of perennial, local species by invasive species and lead to the further degradation of the biodiversity of a locally isolated wetland network [150, 151].

In fact, wetlands that are fragmented at the local scale are usually more susceptible to human-induced pressures because of the poor connectivity for the movement of water and organisms, which, in turn, reduces the regulatory ability of wetland networks at the local scale when facing the problems associated with climate change, pollution, and biodiversity degradation induced by human activities [140, 152]. However, such isolation may also prevent the dissemination of pollutants or infectious diseases [153]. The geometric structure of a wetland network (river network) isolated at the local scale is often displayed as a tree, which implies that the network may become unconnected after being interrupted because there is only one path from one confluence to another in a binary tree [70]. Therefore, the water cycle of a locally isolated wetland network may be disturbed by changes in the major sources of water to wetlands and flow paths. This poor hydrologic connectivity can further alter the species populations' patterns and processes by determining the level of biotic interaction between wetland species, including competition, predation, and parasitism (Fig. 2).

Johnston et al. [154] and Hogan et al. [155] verified that both constructed wetlands and semi-natural wetlands have a high and long-term capacity to remove nutrients from through-flowing water at the local scale. Therefore, in terms of water purification, restoring wetland ecosystems at the local scale is a good option. However, once excessive nutrient loads (beyond a critical value) enter a wetland ecosystem isolated at the local scale, the wetland will undergo sudden, drastic changes, including a shift in species dominance and species composition [156–158]. Nutrient-enriched wetland ecosystems can often lose species at the local scale and exhibit drastic changes in nutrient cycling rates, both of which will in turn enhance the biodiversity degradation of the local wetland network [159]. In summary, wetland ecosystems are quite vulnerable to both climate change and pollution inputs when isolated at the local network scale. Therefore, the management of wetland resources from the perspective of a greater spatial scale should be implemented considering the fact that the local-scale gradients are often related to regional patterns in climate, atmospheric chemistry, resource quality and quantity (e.g., water and nutrients), and land use [43]. However, there is the potential management problem of crossing administrative boundaries when attempting to protect and manage wetland resources across different local scales, which will influence the prompt and effective implementation of management measurements.

4.2 Regional and river basin scales

The extent of coverage of wetland networks connected quality at the regional and basin scale promotes a greater feasibility in terms of maintaining ecological integrity and habitat than possible when isolated at the local scale because wetland networks will connect more information and elements at larger scales [144]. Wetland networks connected at the regional and river basin scale, which are often closed systems with physical borders, are mainly distributed across an area from a few hundred to several hundred square kilometers. The wetland resources of a regional-scale wetland are often distributed across administrative boundaries; therefore, the management of wetland resources at this scale requires collaboration among the representative administrative departments of each province/municipality. The implementation of management programs for wetland ecosystems should guarantee the integration of wetland resources at the regional scale.

Generally, the larger the scale of the wetland network considered is, the greater the degree of heterogeneity of environmental factors. According to Wang et al. [160], such heterogeneous distributions will strengthen the robustness of the network; i.e., the wetland network can be more resilient to random disturbance or interruption at the regional scale. For example, when any wetland resources encounter the problem of continual drought locally, the integrated and connected regional wetland network can rapidly transfer water from other wetland ecosystems within the region that have a water surplus [43, 52, 161]. In contrast to locally isolated wetland ecosystems, the river basin can be considered as a network that can transfer materials, organisms, and information across the region by connecting adjacent and non-adjacent areas [43]. Such a capacity to maintain natural processes via the connectivity of a wetland network is essential to the viability of many aquatic organisms at the regional scale [161, 162]. This process might provide an explanation as to why higher productivity regions contain fewer local species and more regional species [141].

In reality, the more integrated wetland elements of the regional- or river basin-scale wetland not only maintain species diversity but also help to maintain the species composition of wetland communities in a more stable state, which often varies greatly in wetland networks that are isolated a local scale [139]. In terms of the responses of wetland ecosystems at the river basin scale to eutrophication, Verhoeven et al. [159] suggested that wetlands in river basins have a high potential for nutrient retention as long as the wetland habitat accounts for at least 2–7% of the total basin area. Chase and Leibold [141] also found that eutrophication may increase regional species diversity but decrease local species diversity. In addition, the spatial scale at which wetlands are studied can also influence the relationship between productivity and species richness [141, 163]. There are the linear relationships at the river basin scale, while a hump-shaped relationship can occur at the local scale [146]. In summary, the favorable structural and functional connectivity of the wetland network at the regional and river basin scale exhibits a stronger hierarchy, self-organization, and stability compared with a locally isolated wetland network. Therefore, a wetland network, i.e., connected at the regional and river basin scale will always be more resilient to the influence of human activities, pollution, and biodiversity crises.

4.3 Trans-basin scale

Ecological conservation, especially in wetlands is being focused on larger scales, where contain more landscape heterogeneity that provides more suitable habitats for propagation [113, 164]. However, habitats fragmentation, which will disconnect the hydrologic and biological linkages in wetland systems, is usually treated as one of major cause of biodiversity loss and function degradation of wetlands. Therefore, the loss of linkages between wetland patches should be reconnected at the trans-basin scale, which facilitates the spread of propagation among wetlands and improves biodiversity. These linkages and wetland patches are two basic components of wetland network, which is in great demand in order to maintain regional ecological sustainable development and improve the suitable habitats for propagation including human beings. A wetland network that connects the patches by linkages is mainly established through the efforts of the human population to reallocate water resources. Wetland networks often span through thousands of kilometers at the trans-basin scale, with a physical rather than administrative border. Some efforts have tried to unite the pre-separated hydrologic units in different river basins through natural or constructed wetland corridors (channels) to integrate the isolated network elements of different regions.

Through these continual hydrology-driven connections, wetland networks connected at the trans-basin scale can effectively regulate the water balance between different regions. Wetland networks have been used to meet the ecological water demands of different fauna and flora, mitigate the drought impacts of water-deficits in hydrologic units, and reduce the flood risk of water-surplus hydrologic units throughout trans-basin wetland networks and further maintain regional climate balance [52, 63, 165, 166]. However, considering the potential impacts of diverting one basin's freshwater into another basin to correct the spatial and temporal imbalance of water availability and demand, scientists have highlighted the importance of determining a reasonable flow downstream of the diversion point in order to meet the environmental and other long-term water needs of the water-exporting river basin [161, 167]. In terms of pollution concerns, water transfer between different river basins, the main driver for the establishment of wetland networks at the trans-basin scale, can dilute pollution through a large volume of water input, but on the other hand, water transfers may worsen the water quality of lakes or reservoirs through the introduction of chemicals and biotas from other wetland ecosystems [168, 169].

The extremely large-scale and continuous activity occurring across river basins provides the physical basis for more numerous ecological systems, which will contribute to the biological diversity of the entire region. Because a wetland network connected at the trans-basin scale often passes through several administrative boundaries and even river basin borders, the management of wetland networks at the trans-basin scale requires a more intensive demand for the cooperation between administrative departments from different provinces, cities, and municipalities to establish a multi-disciplinary management mechanism that involves physical, social, economic, and environmental components [170].

5 Concluding remarks

The wetland functions influence almost every aspect of the human population and the associated ecosystems. Overall, the importance of wetland conservation has reached a universal consensus. The application of the network perspective to conserve wetlands has significant implications for the management of wetlands. The need for collaboration among stakeholders at many different scales to protect, restore, and monitor ecological resources and the services they provide and the implementation of the idea of ecological networks in the management of wetlands are paramount.

Future analyses of wetland networks could pay more attention to the parameterization and validation of graph models as well as the determination of management models that combine the advantages of different network analysis approaches to maximize the holistic functions of wetlands, including flood control and drought relief, water supply and purification, and ecological conservation. Empirical research on wetland networks should address increases in the understanding of wetland networks by combining qualitative and systematic quantitative approaches. To further improve the understanding of wetland networks, the responses of ecological functions to the spatial structures and spatiotemporal scales encompassed by these networks should be examined. More studies should investigate how to strengthen wetland network functions by improving the topological structures of wetlands.

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