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Identifying the Key Protection Areas of Alpine Marsh Wetlands in the Qinghai Qilian Mountains, China: An Ecosystem Patterns–Characteristics–Functions Combined Method

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Abstract: The alpine marsh wetlands in the Qilian Mountains of Qinghai (QMQ) are under constant threat from the effects of climate change and human activities. Identifying the key ecological protection areas (KEPAs) of marsh wetlands is the prerequisite for formulating protection strategies and executing spatial planning programs. The current study developed a novel method to identify the KEPAs of marsh wetlands by following the ecosystem pattern–characteristics–functions (EPCFs) combined method and the ecological source–ecological corridor–ecological node research paradigm. More specifically, an evaluation system for ecological resistance was constructed by integrating the drivers of EPCFs in the marsh wetlands. Additionally, the marsh wetland degradation disturbances were analyzed through the drivers of EPCFs incorporated with a field survey. The findings indicated the following: (1) The marsh wetlands had a total water yield of approximately 3.96×10^8 m^3. The soil conservation rate and habitat quality per unit area were calculated to be 52.92 $t \cdot hm^{-2} \cdot a^{-1}$ and 0.992, respectively, with higher values observed on the southern bank and lower values on the northern bank of the river in the QMQ. (2) The KEPAs for the marsh wetlands covered a total extent of 996.53 km^2 in the QMQ, encompassing 40 ecological sources, 39 ecological corridors, and 40 ecological nodes, predominantly located in the river source regions. (3) The KEPAs were restructured into an ecological framework comprising two ecological axes, four ecological belts, four ecological cores, and multiple nodes in the QMQ. In response to the factors contributing to the degradation of marsh wetlands, adaptive measures including prioritizing natural restoration, modifying grazing strategies, executing ecological restoration projects as a minimum, and designating protected areas have been recommended. This research could contribute to enhancing the efficiency of regional territorial planning and offer a theoretical foundation for improving the ecological protection framework of regional marsh wetlands.

Keywords: ecological conservation; ecosystem service functions; ecological resistance surface; alpine marsh wetlands; wetland eco-engineering

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1. Introduction

The alpine marsh wetland is a crucial and distinctive natural ecosystem located in the Qinghai–Tibetan Plateau, which has evolved to adapt to the high-altitude climate. As a

kind of typical wetland, marsh wetlands usually develop in areas with excessively moist soil, where marsh plants grow, where peat accumulates, or with gleyic characteristics. This ecosystem plays a vital role in regulating river and stream water sources, sequestering carbon, preserving biodiversity, and ensuring the sustainability of alpine animal husbandry in the plateau [1–4]. Unfortunately, the degradation of the marsh wetlands and their continual reduction in size have been observed in recent years due to the impacts of climate change and human activities [4–8]. Moreover, the fragile natural ecosystem in the Qilian Mountains, coupled with its limited ability to self-repair, accentuates the importance of addressing these issues promptly. The deterioration of the marsh wetlands is predicted to alter the regional landscape, significantly diminish its biodiversity, and reduce its ecosystem services, ultimately disrupting the ecological balance of the region [9–12]. Therefore, there is a critical need to enhance the structure and functionality of the ecosystem by designating protected areas for the marsh wetlands, implementing eco-friendly restoration techniques, and executing sustainable development initiatives [13,14].

In light of the growing significance of wetland ecological conservation and sustainable development, these topics have emerged as pivotal areas of global research. Several associated concepts, including wetland eco-engineering, wetland ecological security patterns, and wetland nature reserves, have recently garnered substantial attention [15,16]. The process of identifying or delineating ecological conservation areas typically adheres to fundamental principles such as holistic regional assessment, comprehensive procedural evaluation, and the inclusion of all elements. An index system has been developed by integrating regional characteristics and follows the ecological source–ecological corridor–ecological node research paradigm [17–21]. This methodology encompasses tasks such as identifying ecological sources, constructing ecological resistance surfaces, and extracting ecological corridors along with ecological nodes. The ecological source areas form the foundation of establishing the key ecological protection areas (KEPAs) [22]. Past research has frequently utilized indicators such as the importance of ecosystem services, ecological sensitivity, and landscape connectivity to evaluate ecological processes or functions [23–25]. These methods have primarily identified key areas providing ecosystem functions as ecological sources [26]. Nevertheless, relatively few studies have concentrated on the integrated application of various assessment models, with a predominant focus on evaluations encompassing all ecosystem types within a region [27–29]. There have been comparatively fewer research efforts dedicated to the conservation of marsh wetland ecosystems [30–33].

Ecological corridors serve as crucial pathways that facilitate species' migration and the flow of ecological processes. These corridors act as linear connectors linking various ecological sources [34], offering a solution to the fragmentation of ecological resources [35]. The extraction of ecological corridors often employs methods such as the minimum cumulative resistance (MCR) model [14], circuit theory [36], and the minimum cost distance model [37]. In particular, the MCR model, which is grounded in source–sink theory, is both adaptable and operationally effective for spatial expansion. This model has seen extensive application in creating ecological safety networks, including in areas like the Loess Plateau [38], the Ebinur Lake Basin [39], and the Poyang Lake urban agglomeration [40].

The simulation of ecological resistance surfaces is essential for identifying ecological corridors and facilitating the evaluation of migration difficulty in ecological flows. Presently, there are three main categories for modeling ecological resistance surfaces: expert experience methods, revised estimation methods, and indicator evaluation methods [41]. Expert empirical methods tend to be highly subjective [42]. Accuracy in adjusting factors such as terrain relief, population density, and night light in revised estimation methods can be challenging to maintain [43]. Furthermore, a universal assessment system for indicator evaluation methods has yet to be established [20]. The marsh wetland ecosystem is intricate, with its landscape configuration, structural traits, ecological roles, and various ecological processes being interlinked, underscoring the system's comprehensive nature. Previous research has predominantly focused on wetlands' ecological conservation and restoration from biodiversity, landscape connectivity, and ecological restoration resistance

standpoints [44–46]. Nonetheless, the interconnection between different elements of the wetland ecosystem is often overlooked. Several reference concepts and standard methods have been suggested for pinpointing key areas in territorial ecological protection. Consequently, further research is required to incorporate EPCF factors into the simulation of ecological resistance surfaces, ensuring alignment with the regional characteristics of marsh wetlands.

The Qilian Mountains in Qinghai (QMQ) hold significant importance as a water conservation region within the Yellow River Basin. Recognized as a critical biodiversity conservation area in China [47], it plays a vital role in the construction of ecological civilization and the protection of ecological security in the country. Nevertheless, the marsh wetlands in this region have been subjected to the dual challenges of natural environmental changes and anthropogenic activities over the past few decades. Climate change has led to glacier melting and increased precipitation, significantly affecting the marsh wetland ecosystem. Concurrently, human activities such as overgrazing and mining have impacted the wetlands' vegetation, soil, and permafrost hydrology, resulting in detrimental effects, including the proliferation of rodents (*Ochotona curzoniae* and *Myospalax baileyi*) and poisonous plants (*Stellera chamaejasme* and *Achnatherum inebrians*), which further exacerbate marsh wetlands' degradation [48,49]. This degradation causes several issues, including reduced vegetation coverage, declining soil nutrients, the disruption of ecological structure, and the potential loss of ecosystem function. Given that the QMQ is a key area for marsh wetland distribution, there is an urgent need to advance the ecological protection and restoration efforts of these wetlands.

Primarily, the goal of this research was the following: (1) To establish a system for assessing the ecological resistance and recognizing the KEPAs of marsh wetlands in the QMQ. (2) To assess the degradation and disruption factors impacting the marsh wetlands, and to offer adaptive reference strategies for safeguarding and restoring the ecological balance of these wetlands.

2. Materials and Methods

2.1. Study Area

The Qilian Mountains lie to the northeast of the Qinghai–Tibetan Plateau and cover an area of 34,200 km^2 in Qinghai (Figure 1). The climate in the Qilian Mountains is characterized as a continental alpine semi-humid mountain climate, displaying clear horizontal and vertical zonal differences. The mean yearly temperature ranges from −11.5 to 6.5 °C, while the annual precipitation varies between 141 and 640 mm, and the area receives approximately about 2100 h of sunshine per year. The terrain exhibits pronounced undulation on both the north and south sides, with landform types changing considerably from east to west. Major soil types in the region include felt soils, cold calcic soils, alpine frozen soils, and marshy soils. The area has a densely distributed river network, incorporating the Heihe River Basin (HH), the Datong River Basin (DT), the Tuole River Basin (TL), and the Shule River Basin (SL). The region's surface water resources total 6.02 billion m^3. The region's marsh wetlands are abundant, occupying 2778.24 km^2 in 2020. Hydrology, vegetation, and water-saturated soil are recognized as the three fundamental components of marsh wetlands. The alpine marshes are mainly found in the depressions, floodplains, and foothill discharge zones of the eastern Qilian Mountains, where the drainage is impeded and the soil permeability is poor. The vegetation of the alpine marsh wetlands is dominated by marsh meadows, with typical dominant species including *Carex capillifolia* (Decne.) S. R. Zhang, *Carex tibetikobresia* S. R. Zhang, *Carex alatauensis* S. R. Zhang, and *Blysmus sinocompressus* Tang and F. T. Wang. They often exhibit distinctive frost heave geomorphic features.

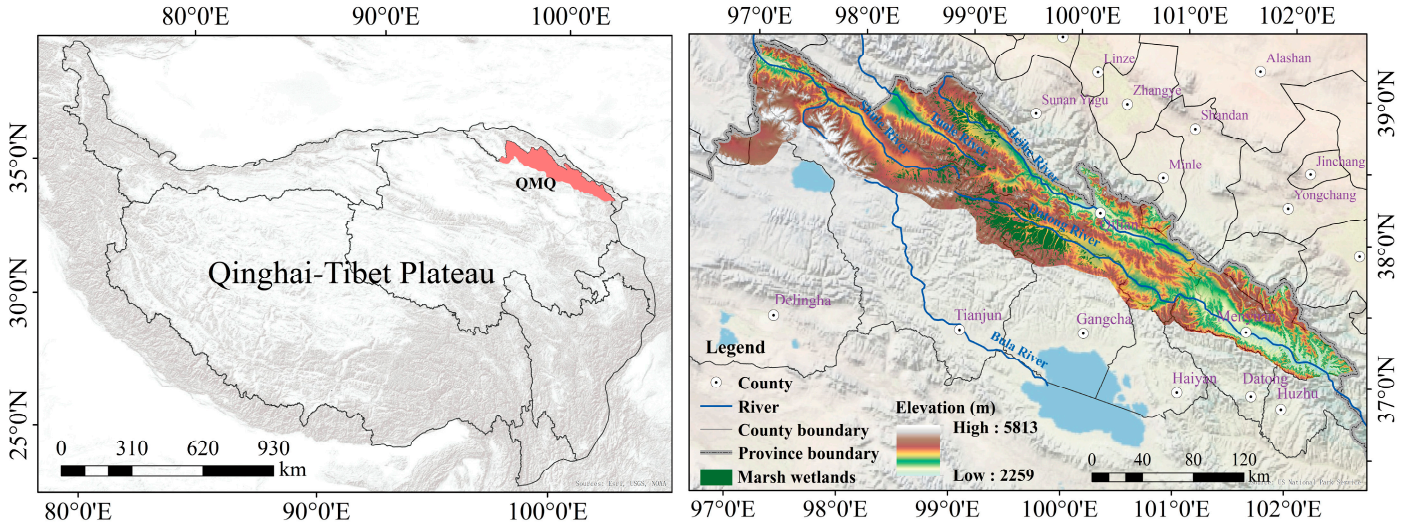


Figure 1. Overview of the study area.

2.2. Data Sources

Table 1 illustrates detailed information regarding the data utilized in this study. For all factors, the WGS84 coordinate system was implemented, and the year chosen was 2020. To facilitate modeling, the factors were resampled to raster cells with a spatial resolution of 30 m.

Table 1. Description of the data used in this study.

Variable Categories	Name (Abbreviation)	Resolution	Data Sources
Meteorological/ Hydrological	Monthly precipitation (PRE)	1 km	National Meteorological Information Center (http://data.cma.cn, accessed on 5 June 2024)
	Average monthly temperature (TEM)	1 km	National Meteorological Information Center (http://data.cma.cn, accessed on 5 June 2024)
	Annual evapotranspiration (EVP)	1 km	MOD 16A2 (https://ladsweb.modaps.eosdis.nasa.gov, accessed on 5 June 2024)
	Annual maximum temperature (AMNT)	1 km	National Earth System Science Data Center (http://www.geodata.cn, accessed on 5 June 2024)
Vegetation	Normalized difference vegetation index (NDVI)	30 m	Landsat 8 OLI (http://lpdaac.usgs.gov, accessed on 5 June 2024)
	Gross primary productivity (GPP)	500 m	MOD 17A3HGF (https://ladsweb.modaps.eosdis.nasa.gov, accessed on 5 June 2024)
Soil	Soil texture (clay/silt/sand)	1 km	Chinese Academy of Sciences (http://www.issas.ac.cn, accessed on 14 July 2024)
	Soil bulk density (BD)	1 km	HWSD (Harmonized World Soil Database)
	Soil organic carbon (SOC)	1 km	HWSD (Harmonized World Soil Database)
	Soil water capacity index (SWCI)	500 m	MOD09A1 V6 (https://ladsweb.modaps.eosdis.nasa.gov, accessed on 14 July 2024)
	Soil type (ST)	1 km	Chinese Academy of Sciences (http://www.issas.ac.cn, accessed on 14 July 2024)
Topographic	Digital elevation model (DEM)	30 m	SRTM (Shuttle Radar Topography Mission)
	Slope (SLOPE)	30 m	SRTM (Shuttle Radar Topography Mission)
	Topographic wetness index (TWI)	90 m	SAGA-GIS [50]
Human activity	Geomorphic type (POP)	1 km	Resource and Environmental Science Data Platform (http://www.resdc.cn, accessed on 14 June 2024)
	Human footprint index (HF)	1 km	National Tibetan Plateau/Third Pole Environment Data Center (https://data.tpdc.ac.cn, accessed on 14 July 2024)

2.3. Methods

Figure 2 illustrates the technical methodology for this research, which was primarily segmented into four main components: (1) Identifying ecological sources. Initially, using the spatial configuration of the marsh wetlands from the year 2020, the ecosystem service functions were evaluated employing the InVEST model as well as the Revised Universal Soil Loss Equation (RUSLE) model. Following this, the significance of comprehensive ecosystem service functions was categorized using a method that superseded equal

weighting. (2) The extraction of ecological corridors. Subsequently, an ecological resistance evaluation framework was established by integrating the drivers of the marsh wetlands' EPCFs. The ecological resistance surface was generated through the MCR model, and ecological corridors were delineated using the minimum cost distance model. (3) Constructing the KEPAs of the marsh wetlands. The points of intersection between the ecological sources and corridors were designated as ecological nodes, thereby forming the KEPAs for the marsh wetlands. (4) In the final phase, an analysis of the ecological disturbance factors contributing to the degradation of the marsh wetlands was conducted, followed by recommendations and strategies for adaptive management.

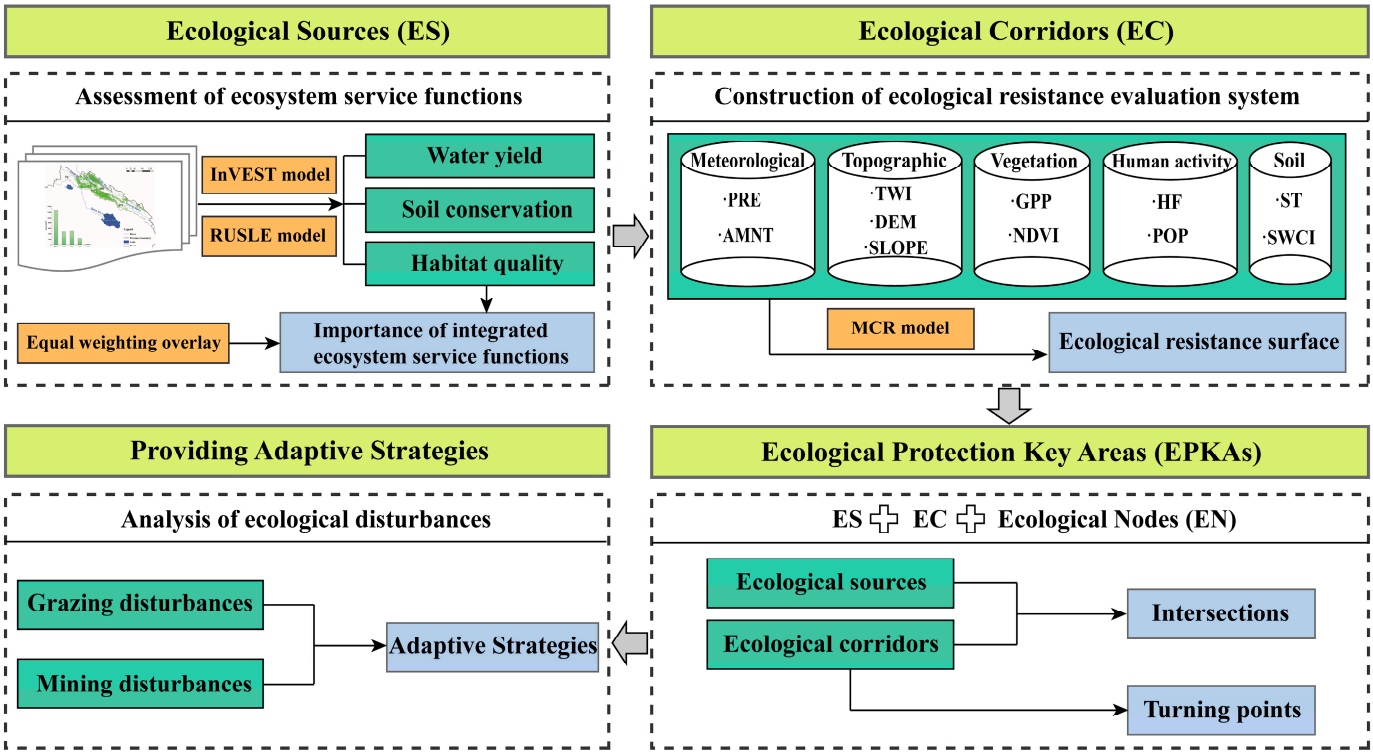


Figure 2. The research framework. Note: PRE, annual precipitation; AMNT, annual minimum temperature; TWI, topographic wetness index; DEM, digital elevation model; SLOPE, topographic slope; GPP, gross primary productivity; NDVI, normalized difference vegetation index; HF, human footprint index; POP, population density; ST, soil type; SWCI, soil water capacity index.

2.3.1. Identification of Ecological Sources

Ecological patches, as crucial components of the regional ecological system, have a key role in enhancing ecological processes, ensuring ecological stability, and improving ecosystem services [51]. Our study focused on two main criteria for identifying ecological patches: the combined ecosystem service capabilities of the marsh wetlands and the overall patch size.

(1) Evaluation of ecosystem service functions

Ecosystem service functions encompassed water yield, soil conservation, and habitat quality. For the assessment of water yield from marsh wetlands in the QMQ region, we employed the Water Yield module from the InVEST model. This module operates on the foundation of Budyko's coupled hydro-thermal equilibrium hypothesis, as articulated by Zhang et al., to estimate total annual water yield [52]. Regarding soil conservation, we utilized the RUSLE model, which calculates soil conservation by deducting the actual soil erosion amount from the potential soil loss. Habitat quality was assessed using the InVEST model's Habitat Quality module, which assigns habitat quality scores between 0 and 1 based on land use and threat source data; higher scores denote superior habitat quality. We

constructed habitat quality parameters by simultaneously considering various threat source data including urban areas, construction zones, agricultural fields, roads, and unused land. Table 2 provides detailed evaluation methods.

Table 2. Evaluation methods of ecosystem service functions.

Ecosystem Service Functions	Models	Formulas	Parameters
Water Yield	The Water Yield module of the InVEST model	$Y_{ij} = (1 - \frac{AET_{ij}}{P_i}) \times P_i$	Y_{ij} is the annual water yield of the study area (mm); AET_{ij} is the annual average actual evaporation of each raster i on a land use type j (mm); P_i is the average annual precipitation (mm).
Soil Conservation	The Revised Universal Soil Loss Equation (RUSLE)	$SC_i = R_i \times K_i \times LS_i \times (1 - C_i \times P_i)$	SC_i is the actual soil conservation ($t \cdot hm^{-2}$); R_i *is* rainfall erosivity factor ($MJ \cdot mm \cdot hm^{-2} \cdot h^{-1} \cdot a^{-1}$); K_i is the soil erodibility factor ($t \cdot hm^2 \cdot h \cdot hm^{-2} \cdot MJ^{-1} \cdot mm^{-1}$); LS_i is the slope length and slope factor; C_i is the vegetation cover management factor; P_i is the factor of water and soil conservation measures.
Habitat Quality	The Habitat Quality module of the InVEST model	$Q_{ij} = H_j \left[1 - \frac{D_{ij}^z}{D_{ij}^z + k^z}\right]$	Q_{ij} is the habitat quality of each raster i; H_j is the habitat suitability of a land use type j; D_{ij} is the habitat degradation degree of each raster i; k is the semi-saturation constant 0.5.

(2) Significance of integrated ecosystem services

Using model assessment, we acquired a raster map depicting the function of ecosystem services within the marsh wetlands. The map was processed with the Raster Calculator in ArcGIS 10.8 software to normalize the data, and we calculated cumulative service values by ranking each function from highest to lowest. We designated the values that represented 50% and 80% of the cumulative ecosystem service functions as key thresholds for classification. Ultimately, we categorized the ecosystem service functions into three levels and allocated scores to each level (Table 3).

Table 3. Grading of ecosystem service assessments.

Importance Levels	Cumulative Service Value Ratio	Grading Criteria	Integrated Ecosystem Service Scores
Generally important	20%	2	0~6
Important	30%	3	7~9
Extremely important	50%	5	10~15

(3) Extraction of ecological sources

In order to prevent the singular nature of the ecosystem service roles and the fragmentation of the marsh wetland landscapes, we combined the three ecosystem service functions with equal weight to derive and identify their highly significant levels. Subsequently, the spatial distribution pattern of the marsh wetlands was overlaid to extract patches exceeding an area of 10 km^2. Ultimately, the ecological sources of the marsh wetlands in the QMQ were determined.

2.3.2. Identification of Ecological Corridors

Ecological networks are systems of nature reserves and their interconnections, which make fragmented natural systems coherent and thus support more biodiversity than non-

connected forms, including core areas, buffers, and corridors [53–55]. Ecological resistance inhibits the flow of materials, energy, and information among various ecological elements, processes, or functions from the ecological source via the ecological corridor [56]. Ecological corridors serve as vital pathways for the migration and diffusion of species or ecological flows, facilitating connections between the linear components of ecological sources [34,57]. To identify ecological corridors, it is essential to construct a surface representing ecological resistance.

(1) Construction of ecological resistance surface

Given the intricacies of the geographical landscape and the pronounced zonal variations in the marshes in the QMQ, we thoroughly examined the factors driving the formation and distribution of marsh wetlands [58], the changes characteristic of degraded marsh wetlands [59], and the factors influencing ecosystem service functions [60]. To this end, we developed an evaluation system for ecological resistance (Table 4). Subsequently, the ecological resistance evaluation indices were normalized in both positive and negative manners, and the significance of the indicators was established by integrating expert scoring with the analysis hierarchical process (AHP). In conclusion, we computed the comprehensive ecological resistance surface based on the superposition of the weights. Tables A1–A6 show the consistency tests and resistance factor weights.

Table 4. The evaluation system for the ecological resistance of the marsh wetlands.

Resistance Categories	Resistance Factors	Weights	Direction
Meteorological/Hydrological	PRE	0.299	−
	AMNT	0.043	+
Topographic	TWI	0.139	−
	DEM	0.262	+
	SLOPE	0.049	+
Vegetation	GPP	0.076	−
	NDVI	0.038	−
Human Activity	HF	0.039	+
	POP	0.019	+
Soil	ST	0.012	+
	SWCI	0.025	−

Note: PRE, annual precipitation; AMNT, annual minimum temperature; TWI, topographic wetness index; DEM, digital elevation model; SLOPE, topographic slope; GPP, gross primary productivity; NDVI, normalized difference vegetation index; HF, human footprint index; POP, population density; ST, soil type; SWCI, soil water capacity index.

(2) Extraction of ecological corridors

Utilizing the MCR model [61,62], input data included ecological sources and ecological resistance surfaces. The Cost Connectivity tool within ArcGIS 10.8 software was employed to determine the potential ecological corridors representing the least costly pathways. Subsequently, these corridors were filtered based on their significance. The algorithm of the model is detailed as follows:

$$M = f_{min} \sum_{j=n}^{i=m} (D_{ij} R_i) \quad (1)$$

where M represents the minimum cumulative resistance value; f_{min} denotes the unspecified function that indicates the positive relationship between the minimum cumulative resistance and ecological processes; D signifies the spatial distance from the ecological source j to the landscape i; and R_{ij} is the resistance coefficient of the landscape i to the ecological process.

2.3.3. Identification of Key Areas for Ecological Protection

Ecological nodes typically represent point landscape features that play a crucial role in preserving the ecosystem services of a given region [63]. The junctions or pivotal locations where ecological corridors meet ecological sources are considered ecological nodes. To conclude, the findings related to ecological sources, corridors, and nodes were utilized as EPCAs for marsh wetlands in the QMQ.

3. Results

3.1. Evaluation of Ecosystem Service Functions and Ecological Sources of Marsh Wetlands

Figure 3 illustrates that the total water yield reached 3.96 × 10^8 m^3 in the QMQ, with higher yields observed in the upstream regions of the DT and HH, while lower yields were found in the downstream regions of the SL and TL. This distribution demonstrates a pattern of greater values on the southern bank compared to the northern bank of the river, mirroring the rainfall distribution characteristics in the area [64]. The soil conservation per unit area in the marsh wetlands was recorded as 52.92 $t \cdot hm^{-2} \cdot a^{-1}$, with its spatial distribution pattern aligning with that of the water yield. The regions of high value were primarily located on the southern riverbank, attributable to the presence of dense drainage systems, ample precipitation, extensive vegetation cover, and gradual slope variations that facilitate soil retention. The average habitat quality per unit area within the marsh wetlands was measured as 0.992, exhibiting no notable spatial variation.

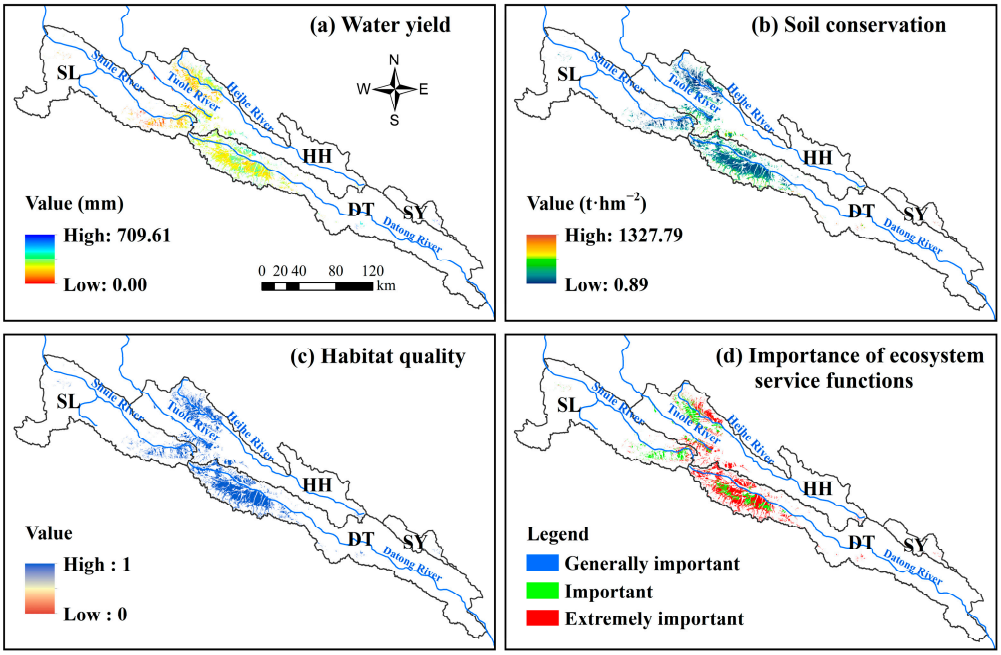


Figure 3. Spatial distribution and importance of ecosystem service functions in QMQ.

Table 5 illustrates that the overall ecosystem service function of marsh wetlands in the QMQ was favorable, with approximately 70% of the region classified as at an extremely important level, 30% categorized as important, and the smallest portion as generally important. The DT exhibited the most extensive areas rated as extremely important (1272.41 km^2), followed by the HH, which made up around 61.87% of the entire marsh wetlands' area in the QMQ.

Table 5. Proportion of area within various classifications of integrated service function of marsh wetlands.

Level	QMQ	DT	HH	SL	SY
Generally important	0.01	0.00	0.01	0.04	0.00
Important	30.50	20.02	38.13	65.30	0.00
Extremely important	69.49	79.98	61.87	34.67	100.00
Areas (km^2)	2778.24	1590.91	893.11	290.74	3.49

Note: QMQ refers to the Qilian Mountains of Qinghai; DT represents the Datong River Basin; HH denotes the Heihe River Basin; SL is the Shule River Basin; and SY signifies the Shiyang River Basin.

According to the principle of integrated ecosystem service functions, which are of critical significance, and considering only patches exceeding 10 km^2, a total of 40 ecological sources were identified (Figure 4). These sources collectively span an area of 996.53 km^2, representing 35.87% of the overall marsh wetland area in the QMQ. Notably, the largest ecological sources are found in the DT, encompassing 729.97 km^2, which constitutes 73.25% of the total ecological sources within the QMQ. The spatial distribution of these ecological sources includes Muli Town, Jiermeng Town, Quanji Town, and Yikewulan Town, situated in the upper DT region, along with Yanglong Town, in the upper HH region, and Suli Town, located in the lower SL region. Due to the availability of ample water resources, a low human population density, and minimal disturbances to the marsh wetlands, these specific areas are recognized as vital ecological sources for the marsh wetlands in the QMQ.

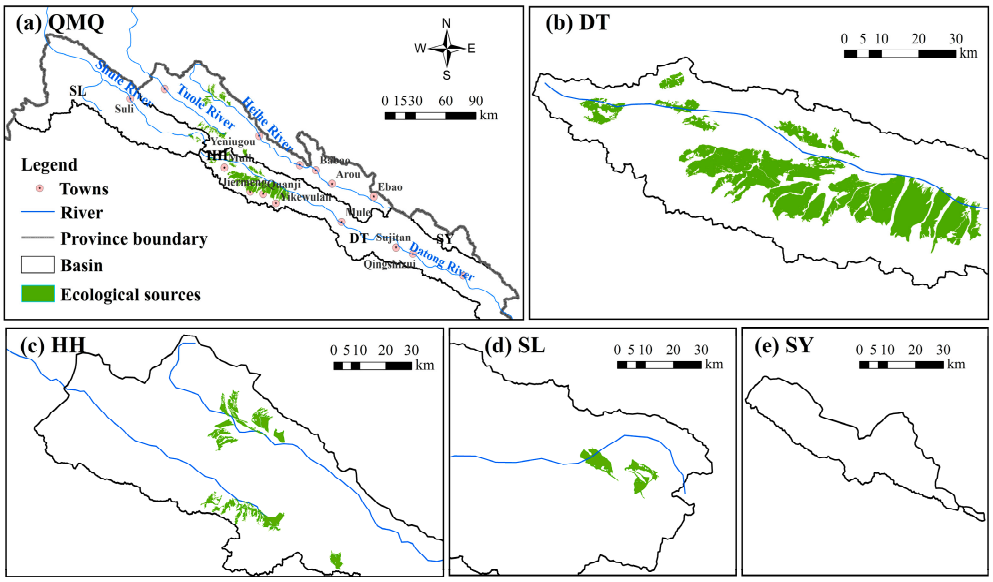


Figure 4. Spatial distributions of marsh wetlands' ecological sources in QMQ.

3.2. Spatial Patterns of Ecological Resistance Surface and Ecological Corridors

Figure 5 illustrates the spatial distribution of ecological resistance surfaces and ecological corridors within the marsh wetlands. The values for the ecological resistance ranged from 0 to 0.68 (Figure 5a). In the QMQ, the development areas of the marsh wetlands correspond to the regions of low ecological resistance, facilitating the migration and dispersal of organisms. Additionally, regions sustaining crucial ecosystem services were also identified as areas exhibiting high ecological security. The high ecological resistance areas are predominantly located in the northwestern region of the SL and HH, where the presence of significant mountain ranges (the Tuole and Shule Mountains) can considerably hinder biological flow transmission. As depicted in Figure 5b, a total of 39 ecological corridors were identified in the QMQ, collectively extending over 505.85 km^2, including 14 ecological corridors spanning 266.13 km^2 that were derived from the DT. These ecological corridors

play a vital role in linking ecological sources characterized by distinct spatial distributions, with notably long corridors crossing the basin.

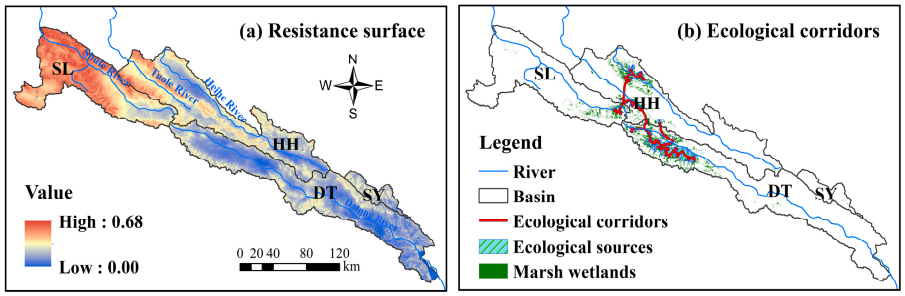


Figure 5. Ecological resistance surface and corridors of marsh wetlands in QMQ.

3.3. Identification of Key Ecological Protection Areas of Marsh Wetlands

Figure 6 illustrates the KEPAs of marsh wetlands in the QMQ. Besides the previously identified ecological sources and corridors, a total of 40 ecological nodes were extracted, which collectively form the KEPAs of the marsh wetlands in the QMQ. These ecological nodes are primarily concentrated in the upper reaches of the DT, enhancing the migration of wetland organisms and significantly supporting the expansion of the marsh wetlands' sources as well as the connectivity of corridors within the QMQ. The biological connections among ecological sources rely on these nodes. For nodes that are spatially separated, they are also the most probable stopover points for organisms during their migration. Thus, protecting these nodes and enhancing the ecological connectivity of the marsh wetlands should be prioritized.

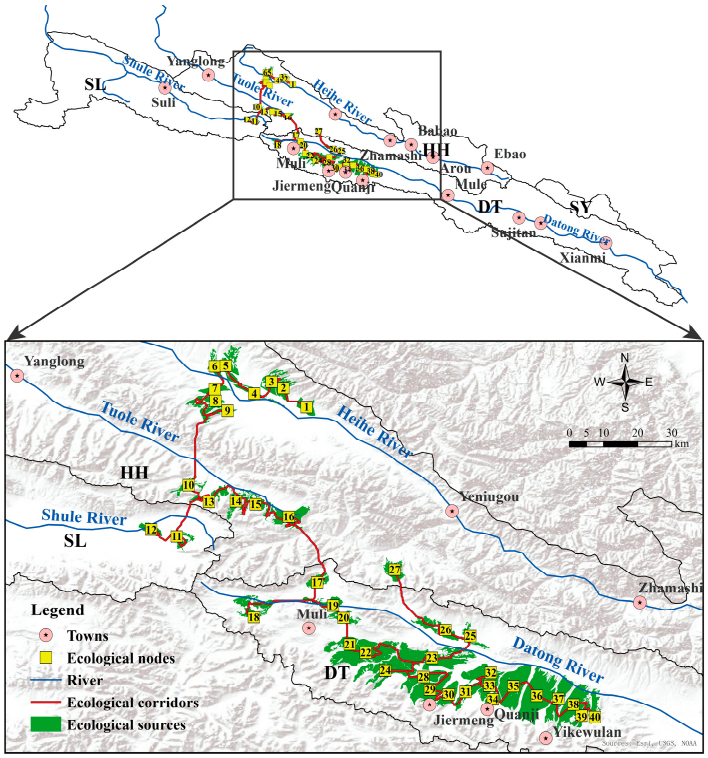


Figure 6. Key ecological protection areas of marsh wetlands in QMQ.

4. Discussion

4.1. Advantages of Constructing Ecological Resistance Surfaces in Marsh Wetlands

Ecological resistance surfaces reflect how the spatial heterogeneity of landscapes influences the movement of ecological flows [39]. Some researchers have directly applied values to these resistance surfaces according to land use type [42], which makes it difficult to reflect differences within the same type of ecosystem and introduces significant subjectivity. Additionally, certain studies have incorporated spatial factors to adjust the ecological resistance associated with land use types, including characteristics such as topographic relief, slope, and vegetation cover [43]. Some studies have identified urban ecological security patterns by considering the type of land use, the normalized difference vegetation index (NDVI), distance from residential area, distance from water source, elevation, slope, and the degree of soil erosion to construct ecological resistance surfaces [65]. However, this approach poses challenges in adequately ensuring the modification degree of the influencing factors on the ecological resistance of various land use types.

Informed by the concept of EPCFs related to marsh wetlands, we constructed an ecological resistance evaluation system (Figure 7). The system considers the driving forces of the formation and distribution of these wetlands, the alterations in the characteristics of the degraded marsh wetlands, and the factors of the ecosystem service functions. This section on evaluation indicators was guided by several criteria: (1) Research conducted by Wang et al. (2024) indicated that meteorological conditions and topography are critical determinants in the formation and distribution of marsh wetlands in the QMQ, with vegetation and soil acting as secondary factors [58]. Additionally, the cumulative impact of anthropogenic activities on marsh formation and distribution surpasses that of soil factors. (2) Findings from Wang et al. (2022) showed that the wetlands' water yield is predominantly influenced by the PRE, while their soil conservation is primarily dictated by the NDVI; furthermore, the habitat quality has faced increasing disturbances from the HF, particularly from the POP [60]. (3) A field survey and experimental analysis revealed (Figure A1) that the marsh wetlands are undergoing severe aridification and an inverse successional trajectory driven by hydrological conditions [66], resulting in diminished soil nutrients and the reduced dominance of wetland plant species. In conclusion, we selected 11 indicators representing the EPCFs of the marsh wetlands, categorized into five groups: meteorology, topography, vegetation, soil, and human activities. According to the impact degree, the weights of these indicators were assigned via expert evaluation and AHP methods, leading to the establishment of the ecological resistance evaluation system for the marsh wetlands. Thus, the system enables an objective and scientific approach to analyzing the ecological resistance surfaces constructed by this method.

4.2. Importance of Identifying Key Ecological Protection Areas of Marsh Wetlands

Identifying KEPAs is of significant importance for the scientific management and effective restoration of regional marsh wetlands [67]. The QMQ serves as a representative area for marsh wetland distribution. However, the natural environmental conditions are characterized as "high, cold, and dry" in the QMQ, resulting in a simpler structure and function of marsh wetlands in this habitat. When exposed to external disturbances, their limited ability for self-regulation and recovery often results in alterations to landscape patterns, which can severely impact hydrological conditions, soil properties, and plant communities, ultimately diminishing ecosystem functions. Utilizing the research framework of ecological sources, corridors, and nodes, we identified the KEPAs of marsh wetlands within the QMQ, considering the drivers of the EPCFs of these wetlands. The KEPAs play a significant role in sustaining the stability of ecological processes and providing beneficial ecosystem services in the QMQ.

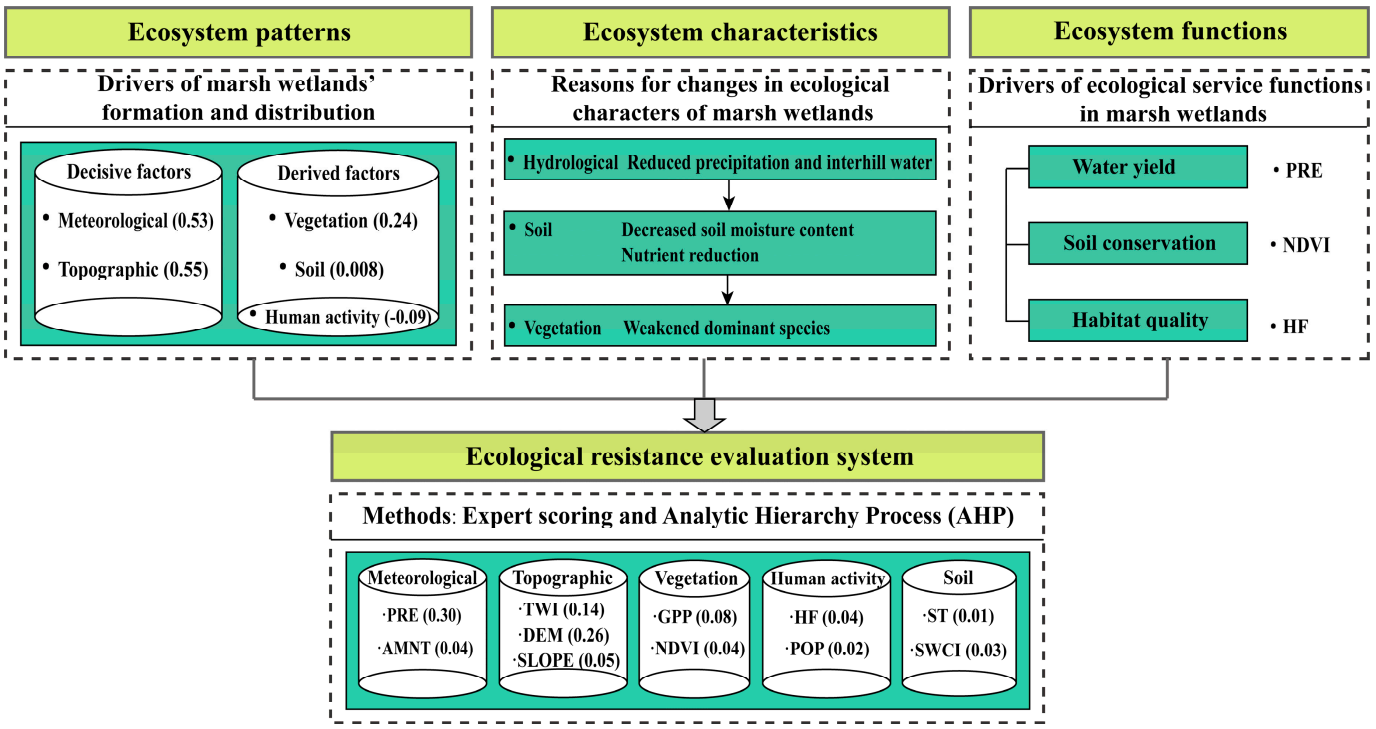


Figure 7. Rationale for constructing ecological resistance evaluation system for marsh wetlands. Note: PRE, annual precipitation; AMNT, annual minimum temperature; TWI, topographic wetness index; DEM, digital elevation model; SLOPE, topographic slope; GPP, gross primary productivity; NDVI, normalized difference vegetation index; HF, human footprint index; POP, population density; ST, soil type; SWCI, soil water capacity index.

Based on the aforementioned Section 3.3, we optimized the KEPAs of the marsh wetlands. Figure 8 shows the optimized ecological framework within the QMQ's marsh wetlands. This framework encompasses two ecological axes, four ecological belts, four ecological cores, and various ecological nodes, collectively forming a well-structured spatial layout system. The four ecological cores comprise the upper reaches of the HH, the lower reaches of the TL, the lower reaches of the SL, and the upper reaches of the DT. This extended ecological axis links the four townships of Muli, Jiermeng, Quanji, and Yikewulan, located within the DT, establishing a relatively smooth ecological network channel. These findings contribute to optimizing the regional spatial territory, sustaining a robust ecological security pattern, and offering theoretical guidance for enhancing the ecological protection system of the marsh wetlands.

4.3. Adaptive Strategies

Regarding management strategies, most of the current programs are put forward based on familiarity with the area, but they lack solid theoretical backing [23,68]. This research proposes adaptive management strategies that integrate the specific environmental features of the region, which can address the limitations of subjective management plans and enhance the precision of the protection strategies. According to observation from field surveys and remote sensing images (Figure A1), the marsh wetlands at the origins of the HH and SL are experiencing slight degradation. This is primarily due to the prolonged use of these areas as summer pastures, leading to meadow status at the edges of the marsh wetland patches as well as the obvious nibbling of plants and noticeable grazing of vegetation. Overall, the marsh wetlands in the DT remain undegraded; however, the wetlands in Muli have decreased in size due to coal mining and excavation activities, which have reduced the marshes' areas, contributed to the drying of nearby wetlands, and destroyed the wetlands' water conveyance system. According to the World Conservation

Union–Conservation Measures Partnership (IUCN-CMP) classification of direct threats to biodiversity (version 1.1), marsh wetlands are threatened by agriculture, aquaculture, energy production, and mining [69]. In response to the disturbance of grazing and mineral extraction (Figure 9), it is essential to formulate measures tailored to local conditions, as this approach is an effective means to prevent marsh wetland degradation.

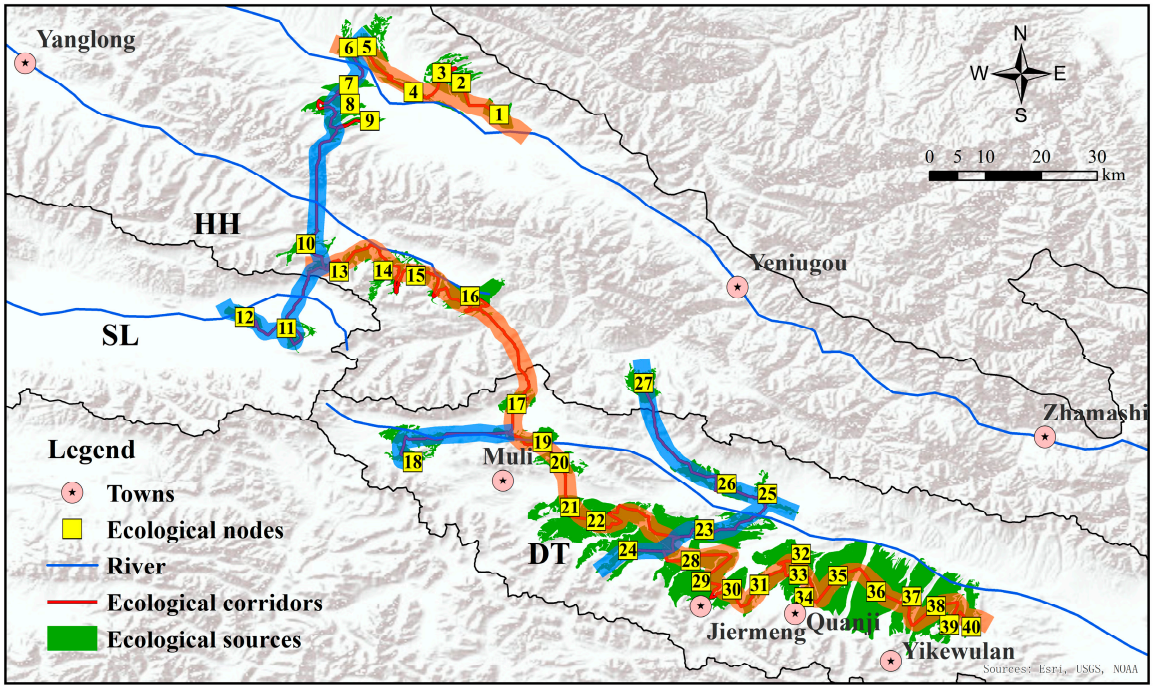


Figure 8. Ecological framework of marsh wetlands in QMQ.

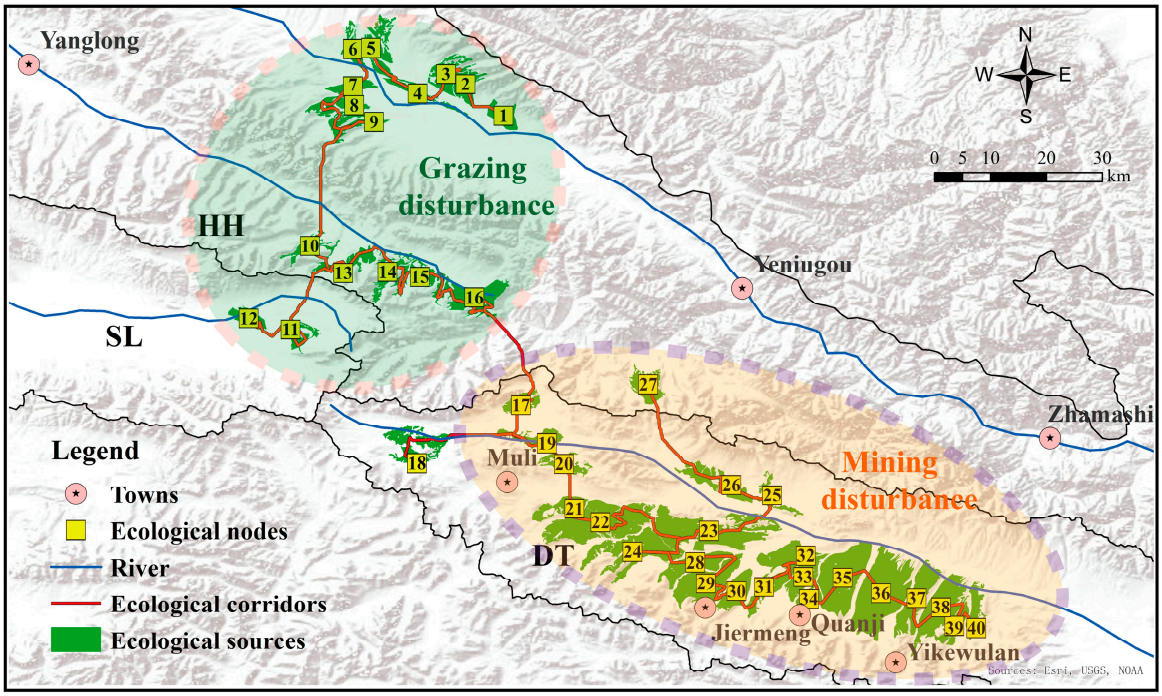


Figure 9. Ecological disturbance factors of marsh wetlands.

Considering the adaptive strategies for grazing disturbances in the marsh wetlands, prioritizing natural restoration, modifying grazing techniques, and strictly regulating the livestock capacity of the wetland pastures are proposed. Grazing should be organized based on grass availability, and conflicts between livestock and grass should be effectively mitigated by altering the grazing system and methods. This aims to harmonize human activities with biodiversity. Concurrently, it is important to limit tourism development initiatives, reinforce fencing, adopt rotational grazing or seasonal livestock management, and create artificial grasslands to alleviate stress on the natural grasslands. Regarding the adaptive strategies for mining disturbances in the marsh wetlands, carrying out ecological restoration projects at mines is recommended to enhance the ecological environmental conditions and improve both the quality and functions of the wetland ecosystem. This could be achieved through vegetation restoration, soil rehabilitation, and landform modification. Additionally, it is suggested that the DT's marsh wetlands should be designated as part of the Qilian Mountains National Park (Qinghai) (Figure 10), with a ban on their development and use. Community members can directly participate in the conservation of biodiversity in the marsh wetlands, such as monitoring species and recording ecological changes. At the same time, it is also possible to teach residents wetland protection knowledge and skills through organizing lectures, exhibitions, practical activities, etc., to improve their environmental awareness and participation. In addition, the introduction of social capital can provide financial support, technical assistance, and management experience for wetland protection. This comprehensive protection model emphasizes multi-party participation, collaboration, and joint efforts to promote the development of wetland conservation.

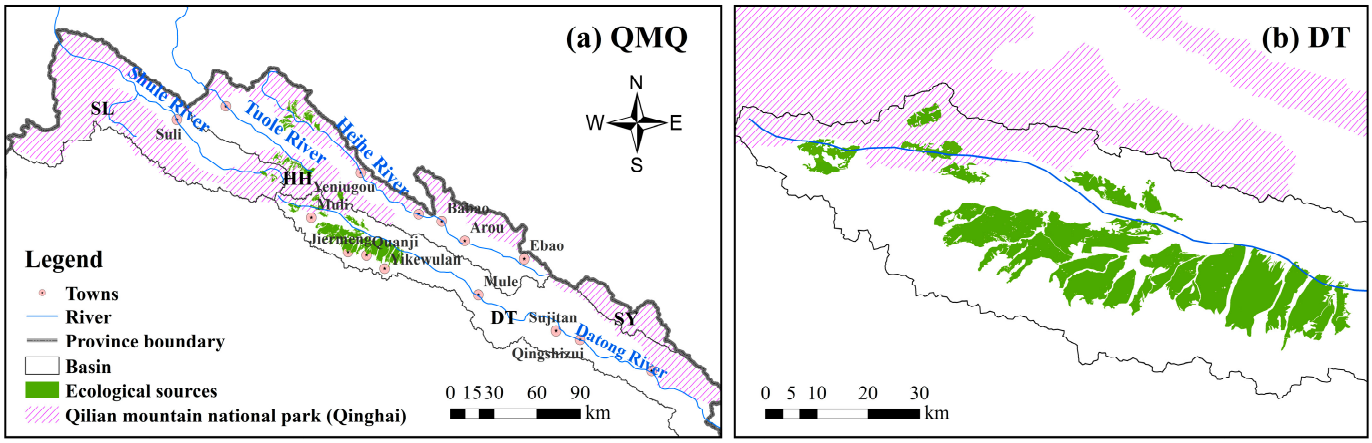


Figure 10. Reference for the delineation of the marsh wetland conservation area.

4.4. Limitations

Firstly, this study focused on modeling only three ecosystem service functions—water yield, soil conservation, and habitat quality—while neglecting carbon storage, windbreak, sand fixation, and biodiversity, resulting in an incomplete evaluation of wetland ecosystem service functions. Additionally, the contiguity of the spatial structure of the marsh wetlands, is the basis for promoting the connectivity of ecological processes and functions, such as species migration, gene exchange, energy flow, and material cycling [70,71]. This research failed to establish a distance threshold for wetland ecological sources. Connectivity between ecological sources is absent when the distance between these sources exceeds that of biological diffusion or migration. Lastly, the impact of the width of ecological corridors and the quantity of ecological nodes on ecosystem functions warrants further exploration.

5. Conclusions

Based on the research paradigm of ecological sources, corridors, and nodes, the KEPAs of marsh wetlands were identified and adaptive strategies for marsh wetland degradation were proposed, combined with the drivers of EPCFs, which are valuable for implementing ecological protection projects and delineating ecological security patterns. The conclusions are as follows:

(1) The water conservation, soil conservation, and habitat quality functions of the marsh wetlands in the QMQ in 2020 were simulated using the InVEST and RUSLE models. The overall ecosystem service function was good, with nearly 70% of the area at the extremely important level.

(2) The KEPAs of marsh wetlands in the QMQ included 40 ecological sources with a total area of 996.53 km^2, 39 ecological corridors, and 40 ecological nodes, which are spatially concentrated in the upper reaches of the DT and the HH. Based on the identification results of the KEPAs, the ecological network system of "two ecological axes, four ecological belts, four ecological cores, and multiple nodes" was proposed.

(3) The internal ecological interference of the KEPAs for wetland ecological protection in the marsh wetlands was highlighted by constructing the ecological resistance evaluation system. In response to the two types (grazing and mineral mining) of interference in the degraded marsh wetlands, it is proposed that natural restoration should be the main approach for marsh wetlands in the source areas of the HH and SL. Grazing strategies should be adjusted to effectively alleviate the conflict between livestock and grass and coordinate the relationship between human activities and biodiversity. In addition, the implementation of mining ecological restoration projects and regulatory measures, such as the delineation of protected areas in the source areas of the DT, have improved the ecological environment and enhanced the quality and function of the regional ecosystem.

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Appendix A

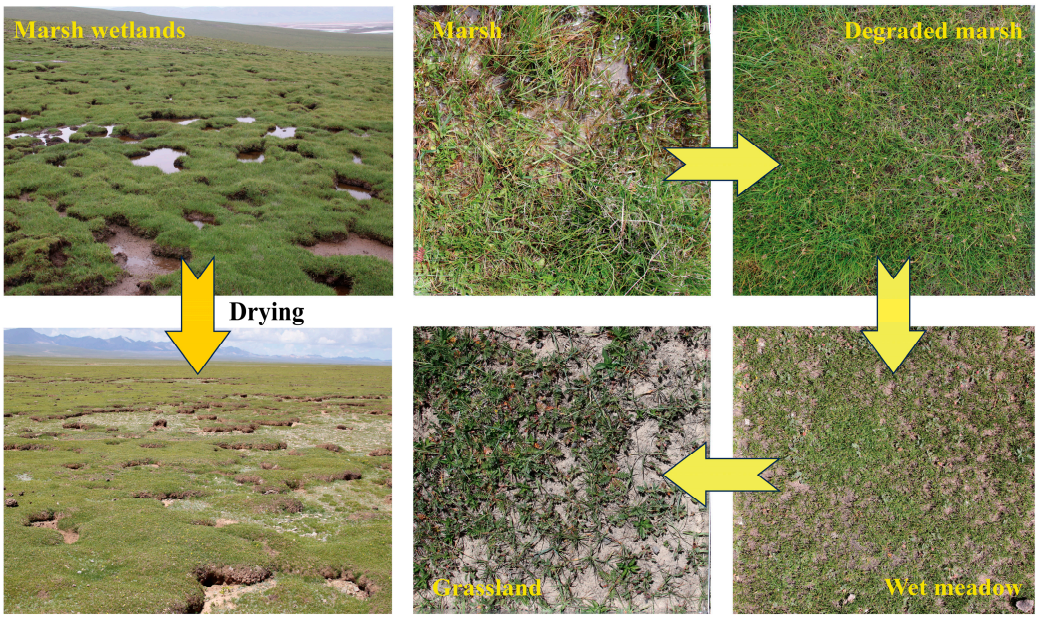


Figure A1. Degradation and aridification of marsh wetlands in QMQ.

Table A1. Consistency tests and indicator weights for marsh wetlands.

Marsh Wetlands	Meteorological/ Hydrological	Vegetation	Human activity	Soil	Topographic	Weight
Meteorological/ Hydrological	1.0000	5.0000	6.0000	8.0000	0.5000	0.3413
Vegetation	0.2000	1.0000	3.0000	4.0000	0.2000	0.1139
Human Activity	0.1667	0.3333	1.0000	2.0000	0.1667	0.0579
Soil	0.1250	0.2500	0.5000	1.0000	0.1250	0.0371
Topographic	2.0000	5.0000	6.0000	8.0000	1.0000	0.4498

Note: Consistency ratio, 0.0480; λ_{max}, 5.2152.

Table A2. Consistency tests and indicator weights for topographic elements.

Topographic	TWI	DEM	SLOPE	Weight
TWI	1.0000	0.5000	3.0000	0.3090
DEM	2.0000	1.0000	5.0000	0.5816
SLOPE	0.3333	0.2000	1.0000	0.1095

Note: Consistency ratio, 0.0036; λ_{max}, 3.0037; TWI, topographic wetness index; DEM, digital elevation model; SLOPE, topographic slope.

Table A3. Consistency tests and indicator weights for meteorological/hydrological elements.

Meteorological/Hydrological	PRE	AMNT	Weight
PRE	1.0000	7.0000	0.8750
AMNT	0.1429	1.0000	0.1250

Note: Consistency ratio, 0.0000; λ_{max}, 2.0000; PRE, annual precipitation; AMNT, annual minimum temperature.

Table A4. Consistency tests and indicator weights for vegetation elements.

Vegetation	GPP	NDVI	Weight
GPP	1.0000	2.0000	0.6667
NDVI	0.5000	1.0000	0.3333

Note: Consistency ratio, 0.0000; λ_{max}, 2.0000; GPP, gross primary productivity; NDVI, normalized difference vegetation index.

Table A5. Consistency tests and indicator weights for human activity elements.

Human Activity	POP	HF	Weight
POP	1.0000	0.5000	0.3333
HF	2.0000	1.0000	0.6667

Note: Consistency ratio, 0.0000; λ_{max}, 2.0000; POP, population density; HF, human footprint index.

Table A6. Consistency tests and indicator weights for soil elements.

Soil	ST	SWCI	Weight
ST	1.0000	0.5000	0.3333
SWCI	2.0000	1.0000	0.6667

Note: Consistency ratio, 0.0000; λ_{max}, 2.0000; ST, soil type; SWCI, soil water capacity index.

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