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Original Research

Identifying Priority Protected Areas Based on Land-Water Coupling Ecosystem Services Assessment: A Case Study in the Shanghai Metropolitan Area, China

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Abstract

Identifying the important ecological areas for priority protection is critical to conducting the regional ecological security pattern. Taking a typical waterside area in Shanghai Metropolitan Area as a case study, this paper proposed a composite evaluating index framework of land-water ecosystem services (ESs) considering aquatic and terrestrial aspects, based on the ESs supply efficiency and multi-source data. We calculated the supply capacity of aquatic, terrestrial ESs, and land-water coupling degree respectively by quantitative evaluation model and coupling method to extract the vital ESs supply patches as the priority protected areas. Then some hierarchical control suggestions were put forward to determine the protected grades based on the landscape connectivity. The results showed that: (1) The total area of the priority protected areas was 263.37 km^2, accounting for 12.29% of the whole region, and was mainly distributed in northwest areas more than in the southeast areas. (2) The aquatic and terrestrial priority protected regions were identified with areas of 240.02 km^2 and 23.35 km^2 respectively through the land-water coupling analysis. (3) The ecological priority was divided into four grades. (4) The coincidence rate between the planned control line of the study area and priority protected areas was up to 81.12% and the non-coincident part could be used as the priority green spaces for urban planning in the future. The study provides a scientific model for the implementation of ecological space protection and restoration in regions around the metropolis in developing countries.

Keywords: ecosystem services, priority protected areas, coupling evaluation model, aquatic spaces, terrestrial spaces

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Introduction

Ecosystem services (ESs) refer to the goods, processes, and natural conditions provided by an ecosystem that is indispensable for human well-being and subsistence [1-3], including provisioning, regulating, supporting, and cultural service [4]. For the past years, rapid urbanization has transformed natural spaces into construction land dramatically, leading to the serious degradation of ESs capacity and an imbalance between the ESs supply and demand [5, 6]. This circumstance has caused a series of ecological risks, threatening both ecological security and sustainable economic development [7]. Thus, how to effectively and efficiently protect natural spaces and enhance the quantity and quality of ESs are of critical importance for spatial decisions under the background of land scarcity [8, 9].

In recent years, urban open and green spaces are continuously lost in rapidly developing regions [10], while the surge of the population with unhealthy urbanization has aggravated the mental and physical deterioration of people's daily environment [11,12]. Hence restoring natural spaces is urgent to meet people's environmental needs [13]. It has become a global trend to incorporate ecological network construction into the urban planning, alleviating environmental risks by the integration and connection of broken natural spaces [14, 15], especially in the areas with speedy population growth and environmental degradation, such as South Africa [16], Cuenca [17], Atakum [18] and Kolkata Metropolitan Area [19]. However, due to the limited land resources in China's rapidly urbanized areas [20], it is unrealistic to restore ecosystem function and resist ecological risks by increasing natural spaces on a large scale [21]. In order to maximize the utilization efficiency of the existing natural resources [22], patches providing important ESs should be established as the priority protected areas to prevent the further damage to the regional ecosystem function caused by the blind expansion of construction land and the pollution from human activities [23].

The identification of priority protected areas that can provide sufficient ESs is the core of ecological security pattern zoning and planning, and the source of much difficulty in the practical application of ESs theory. Previous studies primarily focused on the protection of biodiversity [24, 25], leading a large number of scholars to conduct in-depth research from the perspectives of landscape network [26], green infrastructure [27], ecological control line, and ecological risks [28], and then gradually turned to the study of ecosystem services value (ESV) [29-31]. In recent years, ESs assessment and mapping have become effective tools to support ecological function evaluation and ecological importance identification of ecological spaces [32]. The spatial representation of ES assessment results can show how the assessed value changes spatially [33] and reflect which areas should be retained preferentially or be included as key patches in the ecological network due to the high ESs supply [34-36]. In addition, the regional priority protected areas are supposed to play an effective and relatively more efficient role in the ecological protection of the whole region. The identification of priority protected areas mainly includes three modes as follows: 1) direct identification based on the existing protection spaces or land use status [37]; 2) selecting based on morphological spatial pattern analysis (MSPA) and combined with the patch function evaluation [38, 39]; 3) constructing multi-angle composite evaluating index systems of ESs importance, ecological sensitivity or ecological stability [40-42].

The primary problem in identifying high-supply ESs priority protected areas is the quantitative ESs assessment. At present, the application of evaluation formulas and models for terrestrial ESs is relatively mature [43-45]. Nevertheless, most studies of ESs spatial planning and mapping mainly focused on large magnitude terrestrial spaces or sites with few aquatic areas [46, 47]. They attached importance to the calculation of fixed environmental parameters based on the spatial pattern [48, 49], ignoring different types of dominant ES among different regions [50]. These traditional evaluation methods failed to link the prominent ecological risks in rapidly urbanized areas [51], which could not reflect the specific ecological value of the regional aquatic ecosystem. Actually, the aquatic ecosystem plays a pivotal role in ESs assessment [52, 53]. Neglecting the ESs provided by water spaces will affect the analysis of the overall evaluation results, resulting in insufficient guidance for their practical application [54].

Given the above research gaps and the need to protect the whole land and water spaces in rapidly urbanized areas, a large number of developing countries are realizing that the accurate identification of priority protected areas has become the primary problem in ecological protection. They took relevant measures to delimit the spaces prohibited from development and construction [55, 56], ensuring the integrity of critical ecosystems and the effective ESs supply. However, in general, the identification method of urban ecological spaces guided by the regional key ESs functions is still under trial and exploration. Therefore, taking a typical waterside area in Shanghai Metropolitan Area as an example, this study proposes a novel composite ESs assessment approach to identify the ecological priorities based on land-water coupling modeling, extracting the vital ESs supply patches as the priority protected areas of the study area. The objective of this study is to quantify the ESs supply efficiency by constructing a new land-water coupling ESs assessment framework, so as to identify the spatial priority of rapidly urbanized areas more clearly and accurately. Meanwhile, our research can provide a reference for the protection and restoration of urban ecological spaces.

Material and Methods

Methodological Framework of Land-Water Coupling ESs Assessment

This study generates a technical path of the composite ESs evaluating system considering both aquatic and terrestrial aspects, which is suitable for the rapidly urbanized areas in developing countries. In view of summarizing the typical ecological risks, we selected the regional key ESs to construct quantitative evaluation models, and calculated the supply capacity of aquatic and terrestrial ESs respectively. Based on the coupling model, the important ESs patches with high land-water coupling degree are extracted, and the priority protected areas are identified through the minimum area threshold. Finally, according to the landscape connectivity, the priority protected areas are divided into four grades with different hierarchical control strategies (Fig. 1).

Study Area

Shanghai Metropolitan Area is one of the most developed and the most strongly urbanized regions with a distinctive water-land environment in China [57]. The study area is a typical waterside area at the junction of Jiangsu, Zhejiang and Shanghai (30°45'-31°17'E, 120°21'-121°19'N), whose administrative divisions include Qingpu, Wujiang and Jiashan, covering an area of 2143 km^2 (Fig. 2). With flat terrain, dense lakes and rivers, and abundant waterside villages, the study area provides necessary ESs to the Shanghai Metropolitan Area and is an important ecological buffer for the transition from Taihu Lake to rapidly urbanized areas.

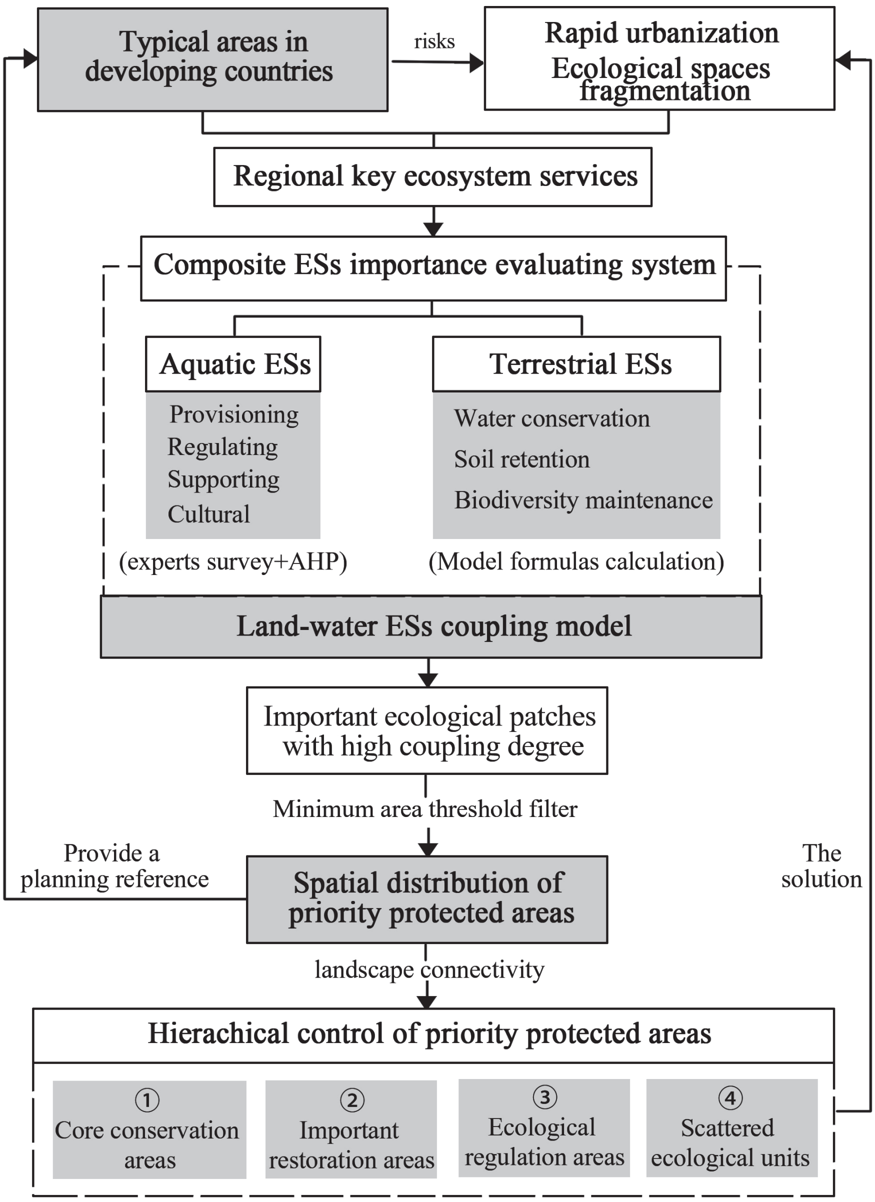

Fig. 1. Integrated assessment framework of land-water coupling ESs.

With the process of economic reform and opening up, the proportion of construction land in the study area has been increasing from 12.27% to 29.42% over the past 18 years, resulting in the severe loss of the traditional water network [58], which still accounts for 20.45% of the total area. Meanwhile, typical ecological risks caused by the extensive economic development mode in small town clusters should be mitigated urgently, such as ecological patch fragmentation, lower landscape connectivity, serious flood disasters, increased pollution emission, and wetland environment degradation [59, 60]. These environmental problems have become key factors restricting economic development and destroying the distribution of ecological spaces in the study area.

Data Sources and Processing

The data used in this study mainly include meteorological data, ecosystem-type data, earth surface evapotranspiration data, soil data, elevation data (DEM), normalized differential vegetation index (NDVI), mean perennial net primary productivity (NPP), the land-use/land-cover (LULC) and road network distribution of study area (Table 1). Since some data could not obtain the latest version, we used the data sets of different years (2015 and 2018, respectively). In order to reduce the uncertainty of the results caused by the fluctuation of the above indicator values in 2015/2018, the data (including soil seepage capacity, NDVI, and evapotranspiration, et al.) that did not need to be put into the evaluating formulas were standardized to a

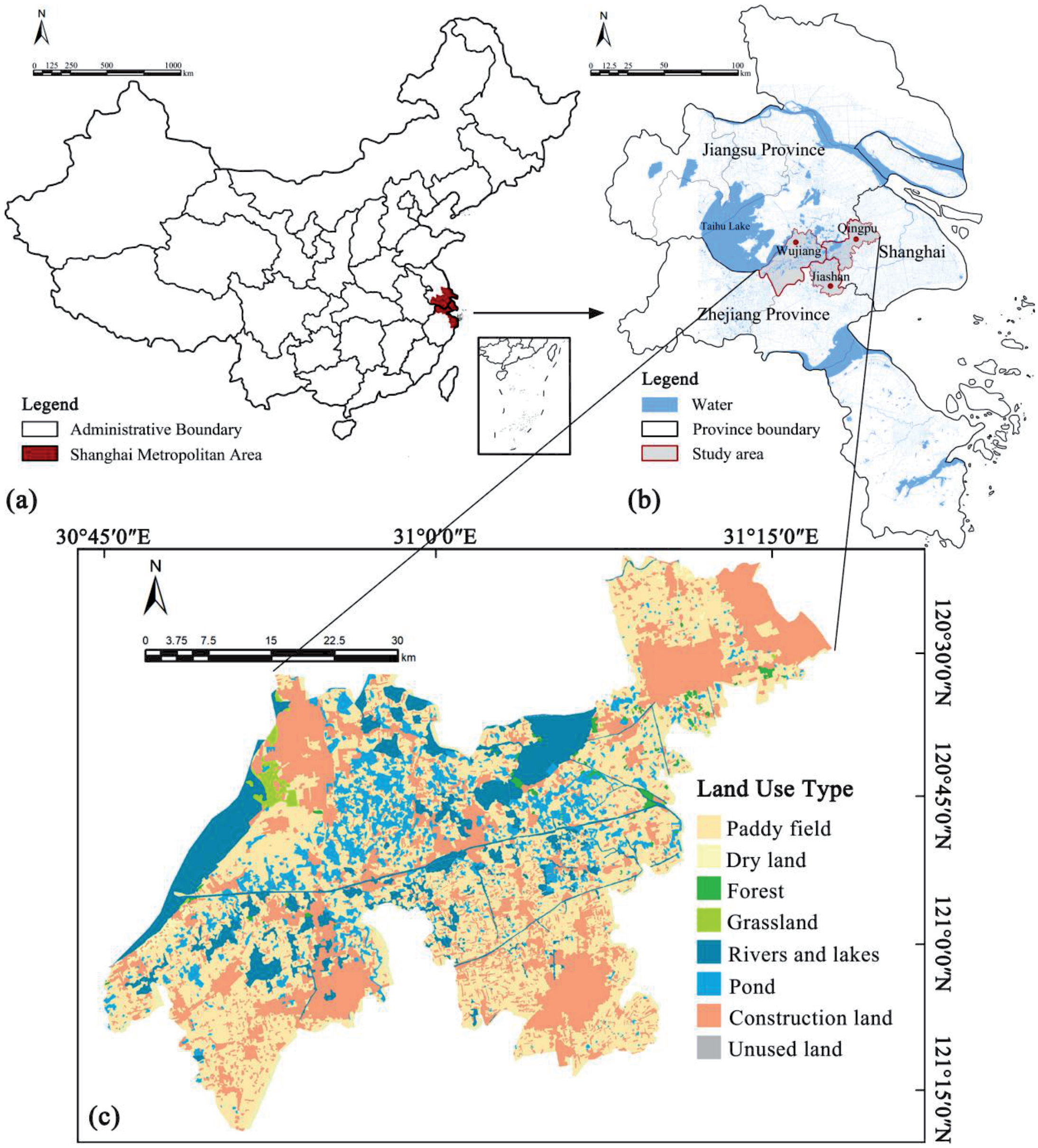

Fig. 2. The geographical location of the study area: a) geographical location of Shanghai Metropolitan Area; b) location map of the study area; c) land use type of the study area.

Table 1. Data sources and basic information.

Data Set	Time	Accuracy	Source
Meteorological data	2015	500m	China Meteorological Data Sharing Service System (http://data.cma.cn)
Ecosystem type data	2015	-	Remote Sensing Survey and Assessment Result of National Ecological Status
Earth surface evapotranspiration data	2015	1 km	Website of Science and Technology Resources Service System of Chinese National Ecosystem Research Network(http://www.cnern.org.cn/)
Soil data	2015	1 km	National Tibet Plateau Data Center 1: 1,000,000 China Soil Data Set(http://data.tpdc.ac.cn/)
Elevation data	2018	30 m	Geospatial Data Cloud DEM Data Set(http://www.gscloud.cn/)
NDVI data	2015	1 km	Geospatial Data Cloud (http://www.gscloud.cn/)
NPP data	2015	250 m	Geospatial Data Cloud (http://www.gscloud.cn/)
LULC data	2018	30 m	Institute of Geographic Sciences and Natural Resources Research, CAS(http://www.igsnrr.ac.cn/)
Road data	2018	-	Geospatial Data Cloud (http://www.gscloud.cn/)

value between 0-1 for the subsequent assessment, while the other data were directly used in the calculation. All the raw image data were processed with the ArcGIS 10.7 platform for projection correction and boundary cropping.

Identification of Regional Key ESs

Regional key ESs are defined as the ES types that play a significant leading role and have a great impact on other services in a specific environment and scale [61]. In this paper, we have chosen the aquatic ESs as regional key ESs mainly based on the following criteria: As a national water conservation space [62], the study area has prominent geomorphological characteristics of the waterside environment, with water area accounting for more than 20% of the total area [63], which have a major influence on the ecological security pattern. Therefore, we evaluated the importance of aquatic ESs supply by constructing a land-water coupling ESs evaluating system to improve the accuracy and comprehensiveness of ecological space identification.

Composite ESs Importance Evaluating System

Aquatic ESs Importance

According to the existing studies [64,65] and the classification plan for ESs in the UN Millennium Ecosystem Assessment [66], we identified 6 services and 13 aquatic ESs supply evaluation index factors to construct the aquatic ESs importance evaluating system, including water supply (WS) in the provisioning service, flood regulation (FR) and water purification (WP) in the regulating service, aquatic biodiversity maintenance (ABM) in the supporting service, cultural landscape resources (CLR) and recreation potential (RP) in the cultural service.

We invited 12 experts to conduct a questionnaire survey, whose research fields include landscape ecology, ESs assessment and mapping, urban ecological design, and sustainable landscape. According to the experience and preferences of experts in relevant fields, the relative importance of each ESs factor to the study area was determined based on Analytic Hierarchy Process and used as the weights in the evaluating model (Table 2). The individual indicator was divided into five ranks in the evaluating model, then the rank values were transferred into ArcGIS 10.7 to map the spatial distribution of aquatic ESs assessment results in the study area (detailed evaluation criteria of ranks and questionnaire design are shown in the Supplementary Materials).

Among them, the habitat quality indicator adopts the biodiversity module in InVEST model [35], which is calculated as follows:

$$Q_{xj} = H_j[1-(\frac{D_{xj}^z}{D_{xj}^z + k^z})] \quad (1)$$

$$D_{xj}^z = \sum_{r=1}^{R}\sum_{y=1}^{Yr}(\frac{\omega_r}{\sum_{r=1}^{R}\omega_r})r_y i_{riy}\beta_i S_{jr} \quad (2)$$

where Q_{xj} is the habitat quality index of the grid x in land use and land cover j; D_{xj} is the habitat stress level of the grid x in land use and land cover j; H_j is the habitat suitability of land use and land cove j; k is half-saturation constant; z is a normalized constant, for which the default parameter of the model is 2.5; r is the threat factor; R is the number of threat factors; Y represents the number of grid cells; ω_r is the weight of r whose value is 0 or 1; i_{riy} represents the influence of r from grid y on habitat in the grid i; β_i is the level of accessibility; and S_{jr} is the sensitivity of LULC type j to r.

Table 2. Classification and weight of aquatic ESs importance assessment.

Benchmark layer A	Weight	Benchmark layer B	Weight	Index layer (unit)	Weight
Provisioning service	0.4961	WS	0.4961	Soil seepage (%)	0.0811
				Production land types	0.2677
				Distance from drinking water sources (m)	0.1473
Regulating service	0.2121	FR	0.1767	Water areas (km^2)	0.0809
				Areas of impermeable surfaces (km^2)	0.0223
				Flood inundation scope	0.0735
		WP	0.0354	NDVI (%)	0.0236
				Distance from wetland (m)	0.0118
Supporting service	0.1915	ABM	0.1915	Habitat quality	0.1596
				Distance from biodiversity maintenance areas (m)	0.0319
Cultural service	0.1003	CLR	0.0752	Distance from waterside historical remains and traditional villages (m)	0.0752
		RP	0.0251	Distance from historical waterway recreation (m)	0.0201
				Number of visual river and lake landscapes	0.0050

Terrestrial ESs Importance

The study area located in the Middle-Lower Yangtze River Plain without a coastline is not closely related to wind prevention, sand fixation, and coastal protection services. Therefore, based on the characteristics of the regional ecological environment, we constructed the evaluating model for quantitative assessment with three services including water conservation (WC), soil retention (SR), and terrestrial biodiversity maintenance (TBM).

Water conservation (WC) service is calculated by the water-balance equation [67]. The equation is:

$$WC = \sum_{i=1}^{j} P_i - R_i - ET_i) \times A_i \times 10^3 \quad (3)$$

$$R = P \cdot \alpha \quad (4)$$

where *WC* represents the water conservation index; P_i is the average annual precipitation factor; R_i is the surface runoff factor; ET_i is the surface evapotranspiration factor; A_i is the ecosystem area; *i* is the serial numbers of ecosystem types; *j* is the total ecosystem types; *P* is the average annual precipitation; *a* is the average surface runoff coefficient determined by ecosystem type.

Soil retention (SR) service applied the Universal Soil Loss Equation (RUSLE) model to simulate soil erosion, and SR is calculated using the following equation [68]:

$$SR = A_p - A_r = R \times K \times L \times S \times (1 - C) \quad (5)$$

$$R = \sum_{i=1}^{12} (\beta \cdot 10^{(1.5 \times \log(p_i^2 / p) - 0.8188)}) \quad (6)$$

$$K = -0.01383 + 0.51575 K_{EPIC} \times 0.1317 \quad (7)$$

where *SR* denotes the amount of soil retention; represents potential soil erosion while A_p represents actual soil erosion; *R* is the rainfall erosion factor; *K* is the soil erodability factor; *L* and *S* represent the topographic factor (slope length and gradient); *C* denotes vegetation coverage factor; p_i and *p* represent average monthly precipitation and average annual precipitation, respectively; β is the parameter that 0.3937 in warm seasons and 0.3101 in cold seasons; K_{EPIC} is the soil erodability factor before correction.

Terrestrial biodiversity maintenance (TBM) service took the biodiversity maintenance service capability index as the evaluation index, and the calculation formula is as follows:

$$TBM = NPP_{mean} \times F_{pre} \times F_{tem} \times (1 - F_{alt}) \quad (8)$$

where TBM represents terrestrial biodiversity maintenance service capability index, NPP_{mean} is the mean perennial net primary productivity, F_{pre} is the average annual precipitation factor, F_{tem} is mean perennial temperature factor, and F_{alt} is the altitude factor.

Identification of Priority Protected Areas Based on the Coupling Model

The coupling refers to the interaction and influence between two or more systems. and the coupling degree represents the extent of interaction between systems [69]. Coupling analysis has been widely adopted to investigate the relationships between urbanization and ESs [70, 71]. In this study, to better reflect the extent of interaction between the terrestrial and aquatic ecosystems based on the results of ESs importance evaluation, a land-water ESs coupling model is constructed. The formula is:

$$C = 2\sqrt{\frac{U_1 \times U_2}{(U_1 + U_2)^2}} \tag{9}$$

where C denotes the coupling degree ($0 \le C \le 1$), while U_1 and U_2 are the normalized aquatic and terrestrial ESs importance assessment index ($0 \le U_1 \le 1$, $0 \le U_2 \le 1$), respectively. The patches with a high coupling degree ($0.8 \le C \le 1$) of terrestrial and aquatic ESs were selected as the ecological patches for priority protection.

The habitat patches can only impact the ecological security pattern and migration circulation of species under a certain scale and continuous space [72]. Referring to the results of previous studies and island biogeography theories [73], the species richness of patches rises with the increase of patches area [74]. The famous Species-area Equation was proposed as follows [75]:

$$\log S = z \cdot \log A + \log C \tag{10}$$

where S is the species richness, A is patches area, and C and z represent constants. The theoretical value of z is 0.263, often between 0.18 and 0.35, while the change of C value reflects the influence of geographical location on the species richness.

Therefore, the minimum area threshold of ecological patches is determined by analyzing changes in the number of important patches and the proportion to the total study area. Then we further calculated the proportion of species richness in each threshold compared with the situation of retaining all ecological patches. The fragmentary patches whose area is less than the threshold are removed, while the concentrated small patches are combined and processed properly to obtain the final scope of priority protected areas.

Hierarchical Control of Priority Protected Areas Based on Landscape Connectivity

Based on the Conefor 2.6.2 software platform [76] and previous studies [77, 78], 800m is finally selected as the optimal migration threshold upon comparison among 11 groups of 100-2000m distance thresholds. The connectivity probability is set as 0.5, while the landscape coincidence probability (LCP), possible connectivity (PC), and other indices are used for landscape connectivity evaluation of priority protected areas. The priority protected areas are divided into four grades according to the results, putting forward hierarchical control framework.

Results

Comprehensive Assessment of Aquatic ESs Importance

The results of aquatic ESs importance assessment obtained with the AHP method were shown in Fig. 3, and the area of ecological patches evaluated to be superior is 272.50 km^2, which accounts for 12.72% of the total study area. Upon the index layer map stacking, high-supply areas of ESs were mainly concentrated in large lakes like Taihu Lake and Yuandang-Dianshan Lake, the junction between Jiashan and Qingpu, and the southwest of Wujiang. These areas had higher ecological quality due to the large patch size and the relative distance from densely populated urban living areas. The situation in low-supply ESs areas was roughly consistent with the construction spaces scope (Fig. 3e).

Among them, the provisioning service was mainly affected by two drinking water sources close to Taihu Lake and Changbaidang (Fig. 3a). The regulating service was strongly related to the area of aquatic patches, and the broken patches in the southeast had relatively low importance (Fig. 3b). In the supporting service, Dianshan Lake area played a leading habitat role, while low-supply areas included most of the cultivated land and built-up spaces (Fig. 3c). In addition, the high-supply areas of cultural service reflected regions with abundant waterside cultural landscape resources such as historical remains, traditional villages, and historical waterways (Fig. 3d).

Comprehensive Assessment of Terrestrial ESs Importance

The results of the terrestrial ESs importance assessment were shown in Fig. 4. The area of ecological patches evaluated to be superior is 34.31 km^2, which only accounts for 1.60% of the total study area. Compared with important ecological patches in the aquatic area, the spatial distribution of terrestrial high-supply areas was mainly concentrated in the southeast and had a relatively scattered spatial pattern which was basically distributed in the suburbs. Owing to the less vegetation coverage and lower evapotranspiration than farmland and forest in the suburbs and the permeability of natural soil is almost the same as that in the more peripheral cultivated land environment, while the surface run-off is relatively low, the suburbs can retain more rainfall after raining. The low-supply areas were mainly concentrated in the internal scope of urban areas and the perimeter zones around large lakes (Fig. 4d).

Among them, the high-supply areas of WC service were distributed in the suburbs close to the cities and towns, while the low-supply areas were concentrated in the northwest of Wujiang and the regions around Taihu Lake (Fig. 4a). The overall SR service spatial distribution was bounded by the Taipu River, showing

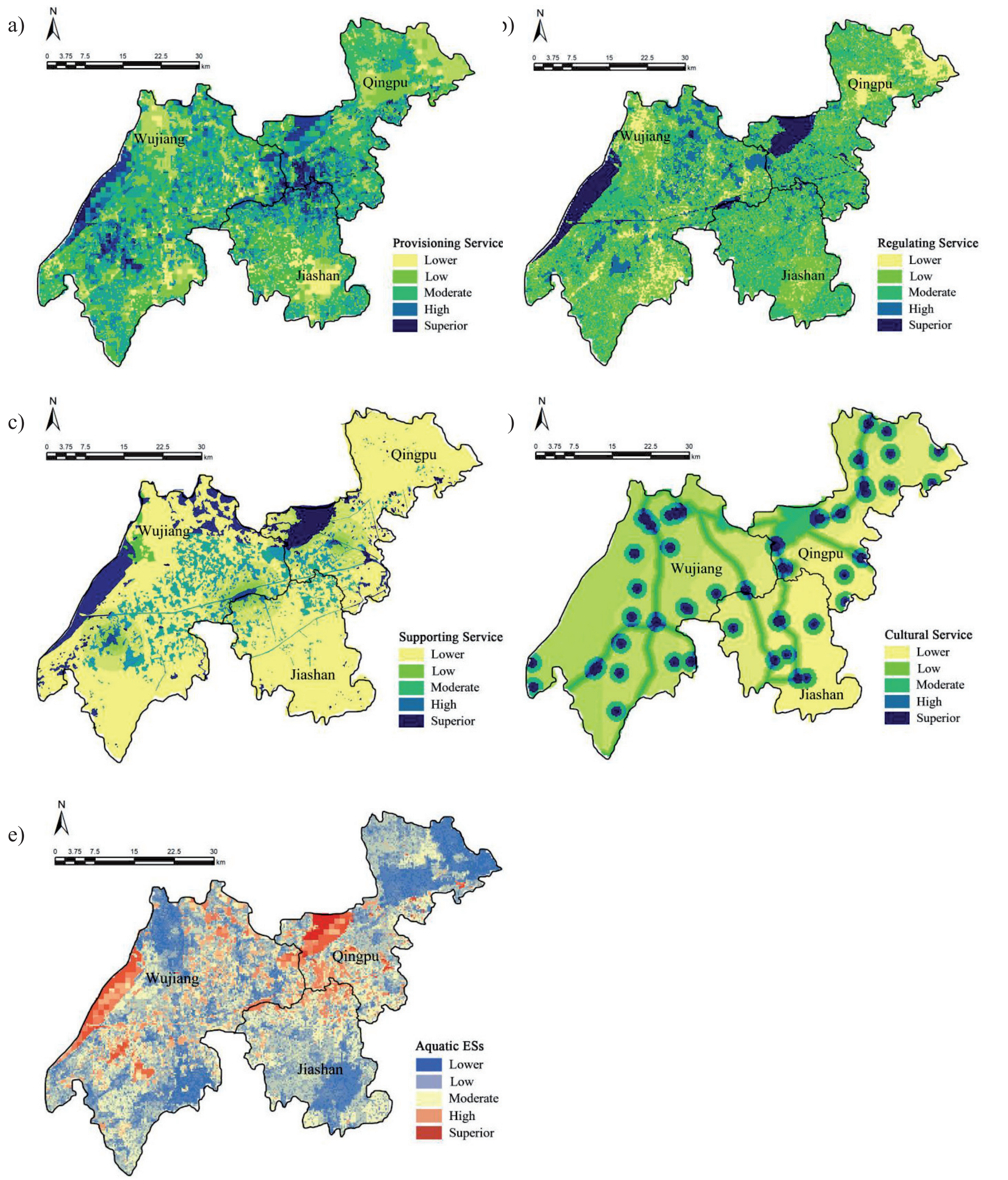

Fig. 3. Results of aquatic ESs importance assessment: a) provisioning service; b) regulating service; c) supporting service; d) cultural service; e) aquatic ESs.

an ecological pattern of "high in the northwest, low in the southeast" (Fig. 4b). The high-supply areas of BM service were mainly located in the south of Wujiang and the junction between Jiashan and Qingpu. Due to the NPP factor being NoData in both water areas and construction spaces, the low-supply areas of TBM were located within these two types of underlying surfaces (Fig. 4c).

Priority Protected Areas Filter and Identification

Results of Land-Water Coupling Degree and Minimum Area Threshold

Summarizing the results of terrestrial and aquatic ESs assessment, we obtained the spatial layout of land-water ESs coupling degree by constructing the coupling

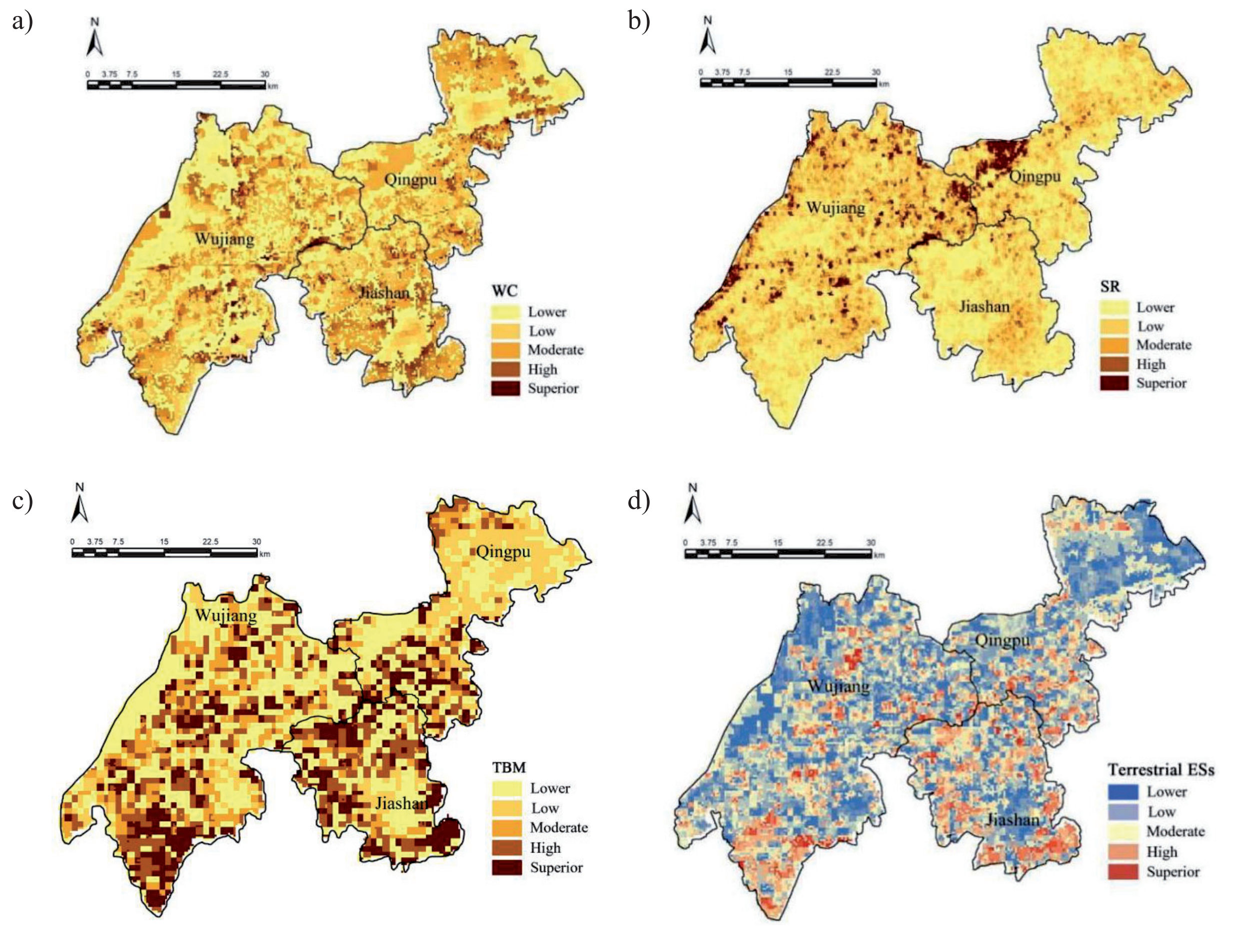

Fig. 4. Results of terrestrial ESs importance assessment: a) water conservation service; b) soil retention service; c) terrestrial Biodiversity maintenance service; d) terrestrial ESs.

degree model (Fig. 5a). The important ecological patches with high coupling degree ($0.8 \leq C \leq 1$) were selected and further screened according to the area threshold of patches. With the minimum area threshold of the region increased, patches area and the retained species richness decreased. When the minimum area threshold was set between 0-1 km^2 at an interval of 0.1 km^2, the percentage of patches areas to total study

Table 3. Changes in the number and area proportion of patches to the total study area.

Minimum area threshold/m^2	Number of patches	Retained patches areas/m^2	Percentage of total study area/%	Percentage of retained species/%
0	519	311.50	14.54	100.00
0.1	248	297.66	13.89	98.64
0.2	154	283.71	13.24	97.23
0.3	119	275.18	12.84	96.34
0.4	80	263.37	12.29	95.07
0.5	70	256.47	11.97	94.32
0.6	63	252.53	11.78	93.88
0.7	56	247.92	11.57	93.36
0.8	51	244.23	11.40	92.94
0.9	44	238.33	11.12	92.26
1.0	40	234.49	10.94	91.81

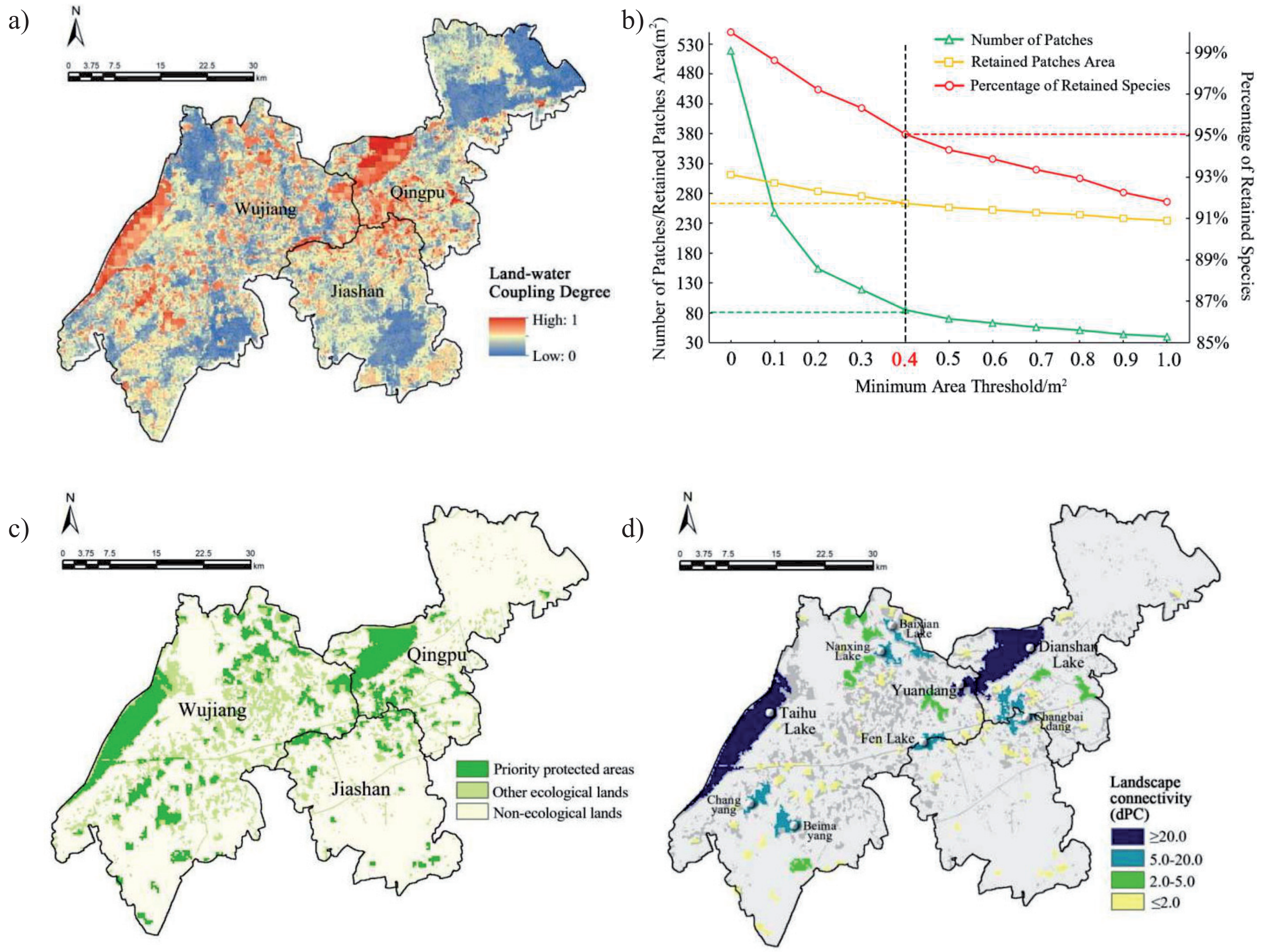

Fig. 5. Results of priority protected areas identification: a) land-water ESs coupling degree; b) changes in the minimum area threshold and the percentage of retained species; c) spatial distribution of priority protected areas; d) landscape connectivity evaluation of priority protected areas.

area maintained between 10.94%-14.54%, while the percentage of retained species decreased from 100% to 91.81% (Table 3, Fig. 5b). Each index decreased rapidly at the threshold of 0-0.4 km^2 and changed little after 0.4 km^2. When the area threshold was 0.4 km^2, the number of species retained could reach more than 95% of retaining all the original patches. Therefore, the minimum area threshold was set to be 0.4 km^2, and the scattered fragmented patches with an area less than this threshold were removed to obtain the spatial distribution of priority protected areas in the study area.

Spatial Distribution of Priority Protected Areas

Upon the small fragmented patches were removed, 80 ecological patches were obtained in this typical waterside area in Shanghai Metropolitan Area as shown in Fig. 5c), with an area of 263.37 km^2 and a proportion to the total study area of 12.29% (including 1.09% for terrestrial spaces and 11.20% for aquatic spaces). In terms of land use types, there were wide gaps in priority protected areas between terrestrial and aquatic spaces, and terrestrial ecological patches were only sporadically distributed around the urban areas. In terms of spatial distribution, it mainly included Taihu Lake and Yuandang-Dianshan Lake, middle-sized lakes such as Beimayang in the south of Wujiang, Changyang, Fenhu Lake in the center of the study area, and other small contiguous lakes. Generally, it presents the spatial distribution characteristics of “North More and South Less, West More and East Less”.

Hierarchical Results and Control Suggestions of Priority Protected Areas

Based on the landscape connectivity analysis results, the conservation priorities were determined as four grades (Fig. 5d). The top priority zone (dPC>20.0) mainly included Taihu Lake and Yuandang-Dianshan Lake, which had a decisive impact on the regional ESs supply and ecological environment. The high priority zone (5.0<dPC≤20.0) had made great contributions to individual ES, but the patches in this zone were relatively broken. The moderate priority zone (2.0<dPC≤5.0) and the low priority zone (dPC≤2.0) were scattered in the study area, mainly concentrated

Table 4. Distribution statistics of conservation priorities.

Conservation priorities	Land use type	Number of patches	dPC mean	Area/m^2	Percentage of total protection spaces/%
Top priority	Water area, forest	2	41.20	125.08	47.49
High priority	Water area	6	7.20	51.13	19.41
Moderate priority	Water area, forest	9	2.90	30.20	11.47
Low priority	Water area, forest, grassland	63	0.73	60.97	23.15

in the west of the Wujiang High-tech Zone, northern Wujiang and the junction of three districts (Table 4).

Discussion

The Rationality of ESs Assessment Framework

Quantitative assessments of water-related ESs have traditionally focused on the benefits linked to direct water availability for humans [79]. Under this perspective, the terrestrial natural spaces with high vegetation coverage are regarded as the main water producers and savers, such as forest and grassland, which realize water supply and regulation through interception and transpiration [80, 81]. In contrast, the ecological role of the original water spaces and aquatic ecosystems that have been generated and maintained is often neglected in the calculation [82]. Therefore, specific indicators are necessary to incorporate the direct and indirect contribution of aquatic ecosystems into ESs assessment framework.

At present, most of the existing ESs assessment frameworks rarely consider the coupling evaluation of aquatic and terrestrial ESs equally, but rather treat aquatic ESs as part of terrestrial assessment. Their typical approaches include using water yield or water-balance models to represent water-related ESs [83, 84], evaluating ESs of different land use types through experts scoring [85], and selecting indicators from the classification framework of UN Millennium Ecosystem Assessment (e.g. food security, water supplement and biodiversity conservation) [86]. But in the present study, aquatic ESs had a separate evaluating index system. The supply capacity of aquatic ESs was characterized by mapping the environmental indicators that were water-related or had a potential influence on aquatic ecosystem, such as distance from wetland, flood inundation scope and areas of impermeable surfaces. As for the terrestrial part of ESs assessment, our methods were similar with the other studies, and then the aquatic and terrestrial evaluation results were standardized to the same dimension through the land-water coupling model. In addition, many previous studies only selected biophysical indicators for the ESs calculation [87], while rarely involved the socio-cultural indicators closely related to the regional social and economic status. Based on cultural characteristics of the study area, we evaluated cultural landscape resources (CLR) and regeneration potential (RP) through indicators such as distance from historical waterway, number of visual river and lake landscapes, which complemented the detailed evaluation of cultural services in the ESs assessment framework.

The assessment results provide a basis for adding composite surrogate indicators representing the aquatic ecosystem into the framework [88, 89]. The terrestrial priority protected areas were distributed seriously fragmented and basically in the suburbs, which could not reflect the natural features. Yet the aquatic part accurately reflected the distribution of lakes with important ecological value. It can be concluded that the land-water coupling ESs assessment framework can make up for the limitations of the traditional assessment formulas to some extent.

Priority Setting and Governance of Natural Spaces

In this paper, we consider implementing different control strategies for different grades of protected areas. The top priority zone with the highest connectivity index contains a large number of intact drinking water sources and wetlands. In addition, this zone has a high capacity to deliver recreation and water purification services, including two tourist attractions of Taihu Lake and Yuandang-Dianshan Lake that have a decisive impact on the regional ESs supply. Thus, any development and construction activities harmful to the environment should be prohibited, while the big lake patches should be protected as a waterside cultural core based on the local cultural landscape heritage. The high priority zone is the main space for ecological restoration, which not only provide important individual ESs but also connect the top priority zone and urban spaces to a certain extent. For this ecological location-critical zone, it is necessary to advance the integrity of patches and expand the scale of habitats by implementing measures for ecological restoration, river connectivity strengthening, and rural environment improvement. The patches of the moderate and low priority zones are relatively smaller and widely distributed, which can be assembled and integrated into larger patches at a regional scale. These patches would be used as stepping stones to connect the top priority zone and important ecological hubs in the study area,

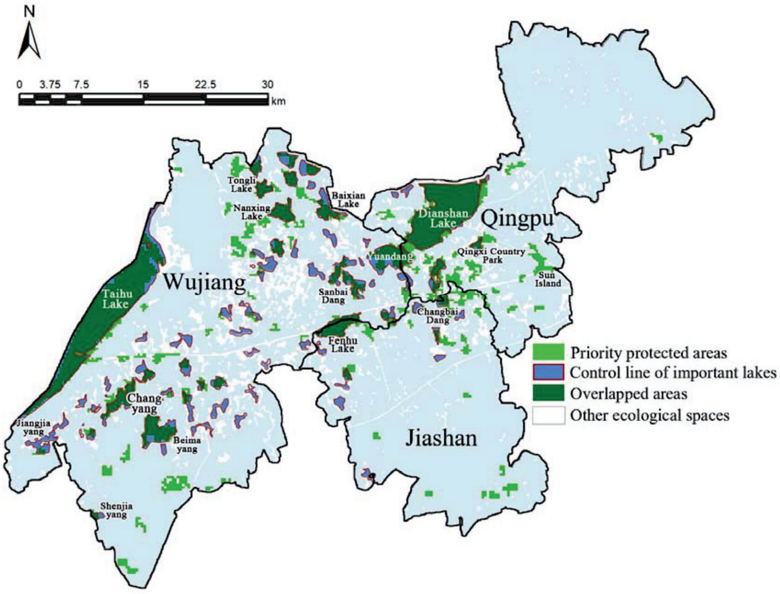

Fig. 6. Comparison of the important lake control line and priority protected areas.

establishing suburban greenbelts and wetland parks. In the rapidly urbanized areas like Shanghai Metropolitan Area, the governance of natural spaces needs detailed strategies according in accordance with priorities to address complex and diverse ecological risks. Our research results can provide spatial reference guidance for decisions on optimal natural resource management and environmental protection in future urban ecological network planning.

Reliability and Outlook of Urban Ecological Spaces Delimitation

Overlapping the priority protected areas with the control line of important lakes delimited, it can be found that 76 lakes including Taihu Lake, Yuandang-Dianshan Lake and Fenhu Lake are basically located within the scope of priority protected areas (Fig. 6). The spatial coincidence rate reaches 81.12%, indicating that the identification results are reliable. Moreover, the remaining 18.88% of the priority protection areas that do not coincide with the lakes control line are land areas with a high ESs coupling degree. The main components of these ESs are wetlands, forests and farmlands in suburbs, around important lakes or close to water sources. Due to the high proportion of farmland and the relatively small area of forest and grassland in the study area, according to the expected goal of increasing the forest coverage from 8.6% to 12% by 2035 proposed in the planning scheme of the study area [53], the non-overlapping areas in the priority protected areas can be used as the critical areas of land-water coupling ecosystem. These new green spaces will become the focus of future ecological construction in the study area, providing references for the site selection of ecological spaces such as forest parks and suburban greenbelts.

Since the influence of regional scale, data acquisition accuracy, and other aspects, there are certain limitations in the land-water coupling ESs evaluating system and key ecological sources identification methods in this paper. The future study can be conducted from the following aspects: 1) Exploring the quantitative evaluation methods of blue-green coupling infrastructure based on multi-source data. 2) Combined with the coordination between supply and demand, discussing the influence of synergistic or trade-off effects among different ESs on ecological spaces identification in specific scale areas.

Conclusions

Under the background of regional integration and rapid urbanization, optimizing the rational distribution of ecological spaces and identifying the priority protected areas [90] are the most important topics for regional green development and ecological civilization construction. This paper constructed a composite land-water coupling ESs evaluating system to assess both aquatic and terrestrial ESs importance in a typical waterside region of Shanghai Metropolitan Area, then effectively quantified the ESs coupling model, identifying and mapping the priority protected areas distribution pattern of high ESs supply. Finally the priority protected areas were divided into four grades with a hierarchical management framework based on the landscape connectivity. The results showed that 80 patches of the priority protected areas were identified with a total area of 263.37km^2, where the main distribution pattern is "North More and South Less, West More and East Less". Given the aquatic ESs were selected as regional key ecosystem services, we determined land and water priority protected areas through the land-water coupling analysis, respectively accounting for a total area of 1.09% and 11.20%. Compared with the existing planning scheme of the study area, the coincidence rate between the planned control line and priority protected areas is up to 81.12%, which illustrated the reliability and practicality of the assessment framework.

The results of this paper made the identification methods of priority protected areas more complete and comprehensive. Against the backdrop of regional ecological green integration development, the land-water coupling ESs assessment provides a reliable theoretical basis for the survival of waterside areas in the Shanghai Metropolitan Area. In addition, under the circumstance of sufficient farmland resources and extremely limited forest and grassland, identifying terrestrial patches as the green priority spaces can help decision-makers formulate economic and reasonable management strategies for the city park site selection and future urban smart growth. The study provides a scientific model for the implementation of ecological space protection and restoration with the purpose of further optimizing the regional ecological security pattern in other regions in China.

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Conflict of Interest

The authors declare no conflict of interest.

References

1. DAILY G.C. Nature's Services: Societal Dependence on Natural Ecosystems; Island Press: Washington. DC, USA, **1997**.
2. SANNIGRAHI S., CHAKRABORTI S., JOSHI P.K., KEESSTRA S., SEN S., PAUL S.K. KREUTER U., SUTTON P.C., JHA S., DANG K.B. Ecosystem service value assessment of a natural reserve region for strengthening protection and conservation. Journal of Environmental Management. **244**, 208, **2019**.
3. FU B., ZHANG L. Land-use change and ecosystem services: concepts, methods and progress. Progress in Geography, **33** (04), 441, **2014** [In Chinese].
4. FISHER B., TURNER R.K., MORLING P. Defining and classifying ecosystem services for decision making. Ecological Economics, **68** (3), 643, **2009**.
5. YANG D., YIN C., LONG Y. Urbanization and sustainability in China: An analysis based on the urbanization Kuznets-curve. Planning Theory, **12** (4), 391, **2013**.
6. DELPHIN S., ESCOBEDO F.J., ABD-ELRAHMAN A., CROPPER W.P. Urbanization as a land use change driver of forest ecosystem services. Land Use Policy, **54**, 188, **2016**.
7. LU L., WENG Q., GUO H, FENG S., LI Q. Assessment of urban environmental change using multi-source remote sensing time series (2000-2016): A comparative analysis in selected megacities in Eurasia. Science of the Total Environment, **684**, 567, **2019**.
8. EGOH B.N., REYERS B., ROUGET M., RICHARDSON D.M. Identifying priority areas for ecosystem service management in South African grasslands. Journal of Environmental Management, **92** (6), 1642, **2011**.
9. KAYA L.G., CETIN M., DOYGUN H. A Holistic Approach in Analyzing the Landscape Potential: Porsuk Dam Lake and Its Environs, Turkey. Fresenius Environmental Bulletin, **18** (8), 1525, **2009**.
10. CETIN M., ZEREN I., SEVIK H., CAKIR C., AKPINAR H. A study on the determination of the natural park's sustainable tourism potential. Environmental Monitoring and Assessment, **190** (3), **2018**.
11. CETIN M., SEVIK H. Evaluating the recreation potential of Ilgaz Mountain National Park in Turkey. Environmental Monitoring and Assessment, **188** (1), **2016**.
12. AKSOY T., DABANLI A., CETIN M., KURKCUOGLU M.A.S., CENGIZ A.E., CABUK S.N., AGACSAPAN B., CABUK A. Evaluation of comparing urban area land use change with Urban Atlas and CORINE data. Environmental Science and Pollution Research, **29** (19), 28995, **2022**.
13. ADIGUZEL F., SERT E.B., DINC Y., CETIN M., GUNGOR S., YUKA P., DOGAN O.S., KAYA E., KARAKAYA K., VURAL E. Determining the relationships between climatic elements and thermal comfort and tourism activities using the tourism climate index for urban planning: a case study of Izmir Province Tourism climate index for urban planning. Theoretical and Applied Climatology, **147** (3-4), 1105, **2022**.
14. XU L., HUANG Q., DING D., MEI M., QIN H. Modelling urban expansion guided by land ecological suitability: a case study of Changzhou City, China. Habitat International, **75**, 12, **2018**.
15. XU W. Research on innovation of urban ecological space in low-carbon Era. Annual National Planning Conference, Chongqing, China, **2010** [In Chinese].
16. NEL J.L., Le MAITRE D.C., ROUX D.J., COLVIN C., SMITH J.S., SMITH-ADAO L.B., MAHERRY A., SITAS N. Strategic water source areas for urban water security: Making the connection between protecting ecosystems and benefiting from their services. Ecosystem Services, **28**, 251, **2017**.
17. SERRA-LLOBET A., HERMIDA M.A. Opportunities for green infrastructure under Ecuador's new legal framework. Landscape and Urban Planning, **159**, 1, **2017**.
18. KILICOGLU C., CETIN M., ARICAK B., SEVIK H. Integrating multicriteria decision-making analysis for a GIS-based settlement area in the district of Atakum, Samsun, Turkey. Theoretical and Applied Climatology, **143** (1-2), 379, **2021**.
19. 1GHOSH S., CHATTERJEE N. D., DINDA S. Urban ecological security assessment and forecasting using integrated DEMATEL-ANP and CA-Markov models: A case study on Kolkata Metropolitan Area, India. Sustainable Cities and Society, **68**, 102, **2021**.

20. HYMAN J.B., LEIBOWITZ S.G. A general framework for prioritizing land units for ecological protection and restoration. Environmental Management, **25** (1), 23, **2000**.
21. XU W., SUN X., ZHU X., ZONG Y., LI, Y. Recognition of important ecological nodes based on ecological networks analysis: A case study of urban district of Nanjing. Acta Ecologica Sinica, **32** (04), 260, **2012** [In Chinese].
22. XU C., PU J., WEN B., XIA M. Potential Ecological Risks of Heavy Metals in Agricultural Soil Alongside Highways and Their Relationship with Landscape. Agriculture-Basel, **11** (8), 800, **2021**.
23. FAN M., SHIBATA H., CHEN L. Spatial conservation of water yield and sediment retention hydrological ecosystem services across Teshio watershed, northernmost of Japan. Ecological Complexity, **33**, 1, **2018**.
24. JENKINS C.N., PIMM S.L., JOPPA L.N. Global patterns of terrestrial vertebrate diversity and conservation. Proceedings of the National Academy of Sciences of the United States of America, **110** (28), 2602, **2013**.
25. PYKALAINEN J., KURTTILA M., HAKALISTO S. Evaluating potential protection areas by means of multi-attribute priority analysis for the Central Karelia Herbrich Forest Network pilot project in eastern Finland. Forest Landscape Restoration in Central and Northern Europe, **53**, 145, **2004**.
26. OPDAM P., STEINGROVER E., VAN ROOIJ S. Ecological networks: A spatial concept for multi-actor planning of sustainable landscapes. Landscape and Urban Planning, **75** (3-4), 322, **2006**.
27. WEI J., QIAN J., TAO Y., HU F., OU W. Evaluating Spatial Priority of Urban Green Infrastructure for Urban Sustainability in Areas of Rapid Urbanization: A Case Study of Pukou in China. Sustainability, **10** (2), 327, **2018**.
28. WANG Y., GAO J., ZOU C., XU D., WANG L., JIN Y. Identifying ecologically valuable and sensitive areas: a case study analysis from China. Journal for Nature Conservation, **40**, 49, **2017**.
29. SU S., XIAO R., JIANG Z., ZHANG Y. Characterizing landscape pattern and ecosystem service value changes for urbanization impacts at an eco-regional scale. Applied Geography, **34**, 295, **2013**.
30. WU K., YE X., QI Z., ZHANG H. Impacts of land use/land cover change and socioeconomic development on regional ecosystem services: the case of fast-growing Hangzhou metropolitan area, China. Cities, **31**, 276, **2013**.
31. WANG Z., CAO J. Assessing and Predicting the Impact of Multi-Scenario Land Use Changes on the Ecosystem Service Value: A Case Study in the Upstream of Xiong'an New Area, China. Sustainability, **13** (2), 704, **2021**.
32. NAIDOO R., BALMFORD A., COSTANZA R., FISHER B., GREEN R.E., LEHNER B., MALCOLM T.R., RICKETTS T.H. Global mapping of ecosystem services and conservation priorities. Proceedings of the National Academy of Sciences of the United States of America, **105** (28), 9495, **2008**.
33. NAHUELHUAL L., VERGARA X., KUSCH A., CAMPOS G., DROGUETT D. Mapping ecosystem services for marine spatial planning: Recreation opportunities in Sub-Antarctic Chile. Marine Policy, **81**, 211, **2017**.
34. BALVANERA P., DAILY G.C., EHRLICH P.R., RICKETTS T.H., BAILEY S., KARK S., KREMEN C., PEREIRA H. Conserving biodiversity and ecosystem services. Science, **291** (5511), 2047, **2001**.
35. MARTINEZ-HARMS M., BALVANERA P. Methods for mapping ecosystem service supply: a review. International Journal of Biodiversity Science Ecosystem Services & Management, **8** (1-2), 17, **2012**.
36. DE MONTIS A., CASCHILI S., MULAS M., MODICA G., GANCIU A., BARDI A., LEDDA A., DESSENA L., LAUDARI L., FICHERA C.R. Urban-rural ecological networks for landscape planning. Land Use Policy, **50**, 312, **2016**.
37. LIU H., YANG M., LI B., GUO S., GU X. Urban Green Corridor System Planning Based on Ecological Security–Taking Nanchang City as the Example. Chinese Landscape Architecture, **36** (04), 122, **2020** [In Chinese].
38. YU Y., YIN H., KONG F., WANG J., XU W. Scale effect of Nanjing urban green infrastructure network pattern and connectivity analysis. Chinese Journal of Applied Ecology, **27** (07), 2119, **2016** [In Chinese].
39. AN Y., LIU S., SUN Y., SHI F., BEAZLEY R. Construction and optimization of an ecological network based on morphological spatial pattern analysis and circuit theory. Landscape Ecology, **36** (7), 2059, **2021**.
40. CASTILLO-EGUSKITZA N., MARTÍN-LÓPEZ B., ONAINDIA M. A comprehensive assessment of ecosystem services: integrating supply, demand and interest in the Urdaibai Biosphere Reserve. Ecological Indicators, **93**, 1176, **2018**.
41. LIQUETE C., KLEESCHULTE S., DIGE G., MAES J., GRIZZETTI B., OLAH B., ZULIAN G. Mapping green infrastructure based on ecosystem services and ecological networks: A Pan-European case study. Environmental Science & Policy, **54**, 268, **2015**.
42. RAMYAR R., SAEEDI S., BRYANT M., DAVATGAR A., HEDJRI G.M. Ecosystem services mapping for green infrastructure planning-The case of Tehran. Science of the Total Environment, **703**, **2020**.
43. XIA H., YUE W., WANG T., WU T., CHEN Y. Theoretical thinking and practical scheme of "double evaluations" at provincial level: A case study of Zhejiang province. Journal of Natural Resources, **35** (10), 2325, **2020** [In Chinese].
44. LI X., YU X., WU K., FENG Z., LIU Y., LI X. Land-use zoning management to protecting the Regional Key Ecosystem Services: A case study in the city belt along the Chaobai River, China. Science of the Total Environment, **762**, 143, **2020**.
45. JIANG H., PENG J., DONG J., ZHANG Z., XU Z., MEERSMANS J. Linking ecological background and demand to identify ecological security patterns across the Guangdong-Hong Kong-Macao Greater Bay Area in China. Landsc. Ecology, **36** (7), 2135, **2021**.
46. HASSAN R., SCHOLES R., ASH N. Ecosystems and Human Well-being: Current State and Trends. Island Press, Washington, 165, **2005**.
47. BOITHIAS L., ACUÑA V., VERGOÑÓS L., ZIV G., MARCÉ R., SABATER S. Assessment of the water supply: demand ratios in a Mediterranean basin under different global change scenarios and mitigation alternatives. Science of the Total Environment, **470**, 567, **2014**.
48. GODDARD M.A., DOUGILL A.J., BENTON T.G. Scaling up from gardens: biodiversity conservation in urban environments. Trends in Ecology & Evolution, **25** (2), 90, **2010**.
49. WANG Y., SHEN J., XIANG W. Ecosystem service of green infrastructure for adaptation to urban growth: function and configuration. Ecosystem Health and Sustainability, **4** (5), 132, **2018**.

50. SWAFFIELD S. Empowering landscape ecology-connecting science to governance through design values. Landscape Ecology, **28** (6), 1193, **2013**.
51. MUNNS W.R., POULSEN V., GALA W.R., MARSHALL S.J., REA A.W., SORENSEN M.T., STACKELBERGZZ K. Ecosystem services in risk assessment and management. Integrated Environmental Assessment and Management, **13** (1), 62, **2017**.
52. BUKVAREVA E., ZAMOLODCHIKOV D., GRUNEWALD K. National assessment of ecosystem services in Russia: Methodology and main problems. Science of the Total Environment, **655**, 1181, **2019**.
53. GRET-REGAMEY A., WEIBEL B. Global assessment of mountain ecosystem services using earth observation data. Ecosystem Services, **46**, 101, **2020**.
54. FABER J.H., MARSHALL S., VAN DEN BRINK P.J., MALTBY L. Priorities and opportunities in the application of the ecosystem services concept in risk assessment for chemicals in the environment. Science of the Total Environment, **651**, 1067, **2019**.
55. CHEN D.S., PAN Y.Q., JIN X.L., DU H.Y., LI M.C., JIANG P.H. The delineation of ecological redline area for catchment sustainable management from the perspective of ecosystem services and social needs: A case study of the Xiangjiang watershed, China. Ecological Indicators, **121**, **2021**.
56. VIEIRA R.R.S., PRESSEY R.L., LOYOLA R. The residual nature of protected areas in Brazil. Biological Conservation, **233**, 152, **2019**.
57. SHI Y., ZHOU Y. The discussion and commentary on the study of megalopolis (metropolitan interlocking region). International Urban Planning, **24** (S1), 160, **2009** [In Chinese].
58. CHINA, N.B.O.S.O.T.P.S.R.O. China Statistical Yearbook (1978-2015). China Statistics Press, Beijing, China, pp. **2015** [In Chinese].
59. XU X., YANG G., TAN Y., ZHUANG Q., LI H., WAN R., SU W., ZHANG J. Ecological risk assessment of ecosystem services in the Taihu Lake Basin of China from 1985 to 2020. Science of the Total Environment, **554**, 7, **2016**.
60. AI J., SUN X., FENG L., LI Y., ZHU X. Analyzing the spatial patterns and drivers of ecosystem services in rapidly urbanizing Taihu Lake Basin of China. Frontiers of Earth Science, **9** (3), 531, **2015**.
61. PENG J., ZHAO H., LIU Y., WU, J. Research progress and prospect on regional ecological security pattern construction. Geographical Research, **36** (03), 407, **2017** [In Chinese].
62. CHINA, M.O.E.P., C.A.O.S. National Ecological Regionalization (Revised Edition). Available online: http://www.mee.gov.cn/gkml/hbb/bgg/201511/t20151126_317777.htm, **2015** [In Chinese]
63. SHANGHAI U.P.A.N.R.B., JIANGSU PROVINCE D.O.N.R.O., ZHEJIANG PROVINCE D.O.N.R.O. Draft of Overall Planning for National Space of Green Ecological Integration Development Demonstration Zone in Yangtze River Delta (2019-2035).http://ghzyj.sh.gov.cn/ghgs/20200617/970bdc96c4f8425c8ab0aa57438a6622.html, **2020** [In Chinese].
64. YU P., FENG M., LIU B., BAI S., GU S., CHEN Y. Demarcation and administration of watershed ecological protection red line considering the ecological security pattern: A case of the Qilu Lake watershed, Yunnan Province. J. Lake Science, **32** (01), 89, **2020** [In Chinese].
65. SHEN J., GUO X., WANG Y. Identifying and setting the natural spaces priority based on the multi-ecosystem services capacity index. Ecological Indicators, **125**, **2021**.
66. MILLENNIUM ECOSYSTEM ASSESSMENT. Ecosystems and Human Well-Being: Our Human Planet: Summary for Decision-makers. Island Press. Washington. DC. **2005**.
67. MINISTRY OF NATURAL RESOURCES. Guidelines on Resources Environment Carrying Capacity and National Space Development Suitability Evaluation (Trial). http://gi.mnr.gov.cn/202001/t20200121_2498502.html (**2020-01-19**) [In Chinese].
68. RENARD K.G. Predicting soil erosion by water: a guide to conservation planning with the revised universal soil loss equation (RUSLE). United States Government Printing, **1997**.
69. XIAO R., LIN M., FEI X., LI Y., ZHANG Z., MENG Q. Exploring the interactive coercing relationship between urbanization and ecosystem service value in the Shanghai-Hangzhou Bay metropolitan region. Journal of Cleaner Production, **253**, **2020**.
70. SUN Y., LIU S., DONG Y., AN Y., SHI F., DONG S., LIU G. Spatio-temporal evolution scenarios and the coupling analysis of ecosystem services with land use change in China. Science of the Total Environment, **681**, 211, **2019**.
71. TIAN Y., ZHOU D., JIANG G. Conflict or coordination? Multiscale assessment of the spatio-temporal coupling relationship between urbanization and ecosystem services: the case of the Jingjinji Region, China. Ecological Indicators, **117**, **2020**.
72. ZHANG Y., XU C., XIA M. Can land consolidation reduce the soil erosion of agricultural land in hilly areas? Evidence from Lishui District, Nanjing City. Land, **10** (5), 502, **2021**.
73. ZHAO S., MA Y., WANG J., YOU X. Landscape pattern analysis and ecological network planning of Tianjin City. Urban Forestry & Urban Greening, **46**, 126, **2019**.
74. WU J., VANKAT J. Island Biogeography: Theory and Applications; Academic Press: New York, USA, **2**, **1995**.
75. FU B., CHEN L., MA K., et al. Island Biogeography. Landscape Ecology; Science Press: Beijing, China, **3**, **2016**.
76. SAURA S., J TORNE. Conefor Sensinode 2.6: a software package for quantifying the importance of habitat patches for landscape connectivity. Environmental Modelling & Software, **24**, 135, **2009**.
77. WANG Y., PAN J. Building ecological security patterns based on ecosystem services value reconstruction in an arid inland basin: a case study in Ganzhou District, NW China. Journal of Cleaner Production, **241**, 118, **2019**.
78. DE MONTIS A., GANCIU A., CABRAS M., BARDI A., PEDDIO V., CASCHILI S., MASSA P., COCCO C., MULAS M. Resilient ecological networks: a comparative approach. Land Use Policy, **89**, 104, **2019**.
79. CASAGRANDE E., RECANATI F., RULLI M. C., BEVACQUA D., MELIA P. Water balance partitioning for ecosystem service assessment. A case study in the Amazon. Ecological Indicators, **121**, **2021**.
80. BRUIJNZEEL L.A. Hydrological functions of tropical forests: not seeing the soil for the trees? Agriculture Ecosystems & Environment, **104** (1), 185, **2004**.
81. HACKBART V.C.S., DE LIMA G.T.N.P., DOS SANTOS R.F. Theory and practice of water ecosystem services valuation: Where are we going? Ecosystem Services, **23**, 218, **2017**.

82. GAO J., LI F., GAO H., ZHOU C., ZHANG X. The impact of land-use change on water-related ecosystem services: a study of the Guishui River Basin, Beijing, China. Journal of Cleaner Production, **163**, S148, **2017**.
83. CHEN L., XIE G., ZHANG C., LIU C., CHEN C., WANG H. Ecosystem function and regionalization in the Lancang river basin. Resources Science, **35** (04), 816, **2013**. [In Chinese].
84. HOU Y., LI B., MULLER F., CHEN W. Ecosystem services of human-dominated watersheds and land use influences: a case study from the Dianchi Lake watershed in China. Environmental Monitoring and Assessment, **188** (11), 652, **2016**.
85. PENG J., WANG X., LIU Y., ZHAO Y., XU Z., ZHAO M., QIU S., WU J. Urbanization impact on the supply-demand budget of ecosystem services: Decoupling analysis. Ecosystem Services, **44**, **2020**.
86. LIU C., YANG, M., HOU Y., XUE X. Ecosystem service multifunctionality assessment and coupling coordination analysis with land use and land cover change in China's coastal zones. Science of the Total Environment, **797**, **2021**.
87. CORTINOVIS C., GENELETTI D., HEDLUND K. Synthesizing multiple ecosystem service assessments for urban planning: A review of approaches, and recommendations. Landscape and Urban Planning, **213**, **2021**.
88. ALAM M., DUPRAS J., MESSIER C. A framework towards a composite indicator for urban ecosystem services. Ecological Indicators, **60**, 38, **2016**.
89. BAGSTAD K.J., SEMMENS D.J., WAAGE S., WINTHROP R. A comparative assessment of decision-support tools for ecosystem services quantification and valuation. Ecosystem Services, **5**, 27, **2013**.
90. ZHOU D., XU Y., WANG Y., ZHOU K., LIU B., LI J., FAN J. Methodology and Role of "Double Evaluation" in Optimization of Spatial Development Pattern. Bulletin of Chinese Academy of Sciences, **35** (07), 814, **2020** [In Chinese].

Supplementary Materials

Table S1. Evaluation criteria of aquatic ESs importance.

ES Indicator	Value ranks and descriptions				
	Superior (9)	High (7)	Moderate (5)	Lower (3)	Low (1)
Soil seepage (%)	0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1
Production land types	Forest	Rivers Lakes	Grassland Paddy field	Dryland Unused land	Construction land
Distance from drinking water sources (m)	≤1000	1000-2000	2000-3500	3500-6000	≥6000
Water areas (km^2)	≥60	24-60	14-24	3-14	0-3
Areas of impermeable surfaces (km^2)	≤7	7-20	20-80	80-140	≥140
Flood inundation scope	Restricted navigable water level	10-year flood level	20-year flood level	50-year flood level	Other areas
NDVI (%)	0-22	22-44	44-56	56-80	≥80
Distance from wetland (m)	0	0-1000	1000-2000	2000-5000	≥5000
Habitat quality	Superior	High	Moderate	Low	Lower
Distance from biodiversity maintenance areas (m)	0	0-1000	1000-2000	2000-5000	≥5000
Distance from waterside historical sites and traditional villages (m)	≤200	200-500	500-1000	1000-2000	≥2000
Distance from historical waterway recreation (m)	0	0-200	200-500	500-1000	≥1000
Visibility of river and lake landscapes	Superior	High	Moderate	Low	Lower

S2. Design of experts' questionnaire:

Dear expert,

For the past years, rapid urbanization has transformed natural spaces into construction land dramatically, leading to the serious degradation of ecosystem services (ESs) capacity and imbalance between the ESs supply and demand. This circumstance has caused a series of ecological risks, threatening both ecological security and sustainable economic development. Thus, how to effectively and efficiently protect natural spaces and enhance the quantity and quality of ESs are of critical importance for spatial decisions under the background of land scarcity.

The study area is a typical waterside area at the junction of Jiangsu, Zhejiang and Shanghai (30°45'-31°17'E, 120°21'-121°19'N), whose administrative divisions include Qingpu, Wujiang and Jiashan, covering an area of 2143 km^2 (Fig. 2). Tthe study area provides necessary ESs for the Shanghai Metropolitan Area and is an important ecological buffer for the transition from Taihu Lake to rapidly urbanized areas. With the economic reform and opening up and the progress of rapid urbanization, the proportion of construction land in the study area has been increasing from 12.27% to 29.42% over the past 18 years, resulting in the severe loss of the traditional water network, which still accounts for 20.45% of the total area. Meanwhile, typical ecological risks caused by the extensive economic development mode in small town clusters should be mitigated urgently, such as ecological patches fragmentation, lower landscape connectivity, serious flood disasters, increased pollution emission, and wetland environment degradation. These environment problems have become key factors restricting the economic development and destroying the distribution of ecological spaces in the study area.

The purpose of this questionnaire is to determine the relative importance of each indicator in the aquatic ESs assessment to the study area. According to your experience, please take the 9-degree method to score each indicator based on its importance. The purpose of this questionnaire is to obtain more authoritative opinions and information. We guarantee that the data obtained will be used for academic research, and we promise to keep your personal information confidential.

Thank you for your support!

Below, please judge the importance of these ESs types and indicators in the study area, and assign the corresponding weight score:

- Scoring description:
  - —1: i and j are equally important.
  - —3: i is slightly more important than j.
  - —5: i is more important than j.
  - —7: i is much more important than j.
  - —9: i is absolutely more important than j.
  - —1/3: i is slightly less important than j.
  - —1/5: i is less important than j.
  - —1/7: i is much less important than j.
  - —1/9: i is absolutely less important than j.

- The importance of ecosystem services:

i : j	1	3	5	7	9	1/3	1/5	1/7	1/9
Provisioning service : Regulating service									
Provisioning service : Supporting service									
Provisioning service : Cultural service									
Regulating service : Supporting service									
Regulating service : Cultural service									
Supporting service : Cultural service									

- ESs importance—Regulating service:

Please evaluate the relative importance of the following two indicators for regulating service.

i : j	1	3	5	7	9	1/3	1/5	1/7	1/9
Flood regulation: Water purification									

● ESs importance—Cultural service:
Please evaluate the relative importance of the following two indicators for cultural service.

i : j	1	3	5	7	9	1/3	1/5	1/7	1/9
Cultural landscape resources: Recreation potential									

● ESs importance—Provisioning service—Water supply:
Please evaluate the relative importance of the following three indicators for water supply service.

i : j	1	3	5	7	9	1/3	1/5	1/7	1/9
Soil seepage : Production land types									
Soil seepage : Distance from drinking water sources									
Production land types : Distance from drinking water sources									

● ESs importance—Regulating service—Flood regulation:
Please evaluate the relative importance of the following three indicators for flood regulation service.

i : j	1	3	5	7	9	1/3	1/5	1/7	1/9
Water areas : Areas of impermeable surfaces									
Water areas : Flood inundation scope									
Areas of impermeable surfaces : Flood inundation scope									

● ESs importance—Regulating service—Water purification:
Please evaluate the relative importance of the following two indicators for water purification service.

i : j	1	3	5	7	9	1/3	1/5	1/7	1/9
NDVI : Distance from wetland									

● ESs importance—Supporting service—Aquatic biodiversity maintenance:
Please evaluate the relative importance of the following two indicators for aquatic biodiversity maintenance service.

i : j	1	3	5	7	9	1/3	1/5	1/7	1/9
Habitat quality : Distance from biodiversity maintenance areas									

● ESs importance—Cultural service—Recreation potential:
Please evaluate the relative importance of the following two indicators for recreation potential service.

i : j	1	3	5	7	9	1/3	1/5	1/7	1/9
Distance from historical waterway recreation : Number of visual river and lake landscapes									

Thank you very much for your help! Your valuable comments and suggestions are welcome to help us.

Table S3. Sources and application methods of aquatic ESs indicators.

ESs	Indicator	Source	Data Processing
WS	Soil seepage	National Tibet Plateau Data Center 1: 1,000,000 China Soil Data Set (http://data.tpdc.ac.cn/)	Selecting the seepage field of China Soil Data Set based on HWSD to characterize the indicator
	Production land types	LULC Data, Institute of Geographic Sciences and Natural Resources Research, CAS (http://www.igsnrr.ac.cn/)	Dividing the land use type into forest, grassland, paddy field, rivers and lakes, dry land, unused land and construction land to characterize the indicator
	Distance from drinking water sources	Division Scheme of Centralized Drinking Water Source Protection Areas in Jiangsu Province (http://sthjt.js.gov.cn/), Regulations of Zhejiang Province on the Protection of Drinking Water Sources (http://sthjt.zj.gov.cn)	Taking the spatial location of drinking water sources as the center, the buffer zones are analyzed to characterize the indicator. The radius of buffer zones is determined according to the protection scope of each water source.
FR	Water areas	LULC Data, Institute of Geographic Sciences and Natural Resources Research, CAS (http://www.igsnrr.ac.cn/)	Extracting water patches from land use data, calculating the area of water patches and grading it to characterize the indicator
	Areas of impermeable surfaces		Extracting urban built-up area patches from land use data, calculating the area of these patches and grading it to characterize the indicator
	Flood inundation scope	Prevention Plan for Excessive flood in Key Areas of Jiashan County (http://www.jiashan.gov.cn), Prevention Plan for Excessive flood of Jiangsu Province(http://jswater.jiangsu.gov.cn/), Prevention Plan for Excessive Flood in Taihu Lake (http://swj.sh.gov.cn/)	Counting the average value of restricted navigation, 10-year, 20-year and 50-year flood water levels in the study area as the threshold, and the space higher than the threshold altitude is successively screened through the raster calculator tool in ArcGIS based on DEM, so as to characterize the indicator
WP	NDVI	Geospatial Data Cloud (http://www.gscloud.cn/)	classifying by the natural breakpoint method to characterize the indicator
	Distance from wetland	Jiashan ecological protection red line(http://www.jiashan.gov.cn/), Wujiang ecological protection red line(http://www.wujiang.gov.cn/), Qingpu ecological protection red line(http://www.qingpu.gov.cn/)	Taking the spatial location of wetland as the center, the buffer zones are analyzed to characterize the indicator. The radius of buffer zones is determined according to the protection scope of each wetland patch
ABM	Habitat quality	Data sources and specific calculation methods can be found in the manuscript	
	Distance from biodiversity maintenance areas	Regional Planning of Ecological Space Management and Control in Jiangsu Province (http://www.jiangsu.gov.cn/), List of Nature Reserves in Shanghai (https://lhsr.sh.gov.cn/)	Taking the spatial location of biodiversity maintenance areas as the center, identifying the buffer zones to characterize the indicator
CLR	Distance from waterside historical remains and traditional villages	Draft of Overall Planning for National Space of Green Ecological Integration Development Demonstration Zone in Yangtze River Delta (2019-2035)	Taking the spatial location of waterside historical remains and traditional villages as the center, identifying the buffer zones to characterize the indicator
RP	Distance from historical waterway recreation	Draft of Overall Planning for National Space of Green Ecological Integration Development Demonstration Zone in Yangtze River Delta (2019-2035)	Taking the spatial location of historical waterway as the center, identifying the buffer zones to characterize the indicator
	Number of visual river and lake landscapes	LULC Data, Institute of Geographic Sciences and Natural Resources Research, CAS (http://www.igsnrr.ac.cn/)	The distance between each grid and the nearest water area is generated by the Euclidean Distance tool of ArcGIS, and then the Viewshed Analysis tool is used to calculate the number of rivers and lakes landscapes that can be viewed within the visual range of each grid

S4. Detailed results of aquatic ESs importance assessment

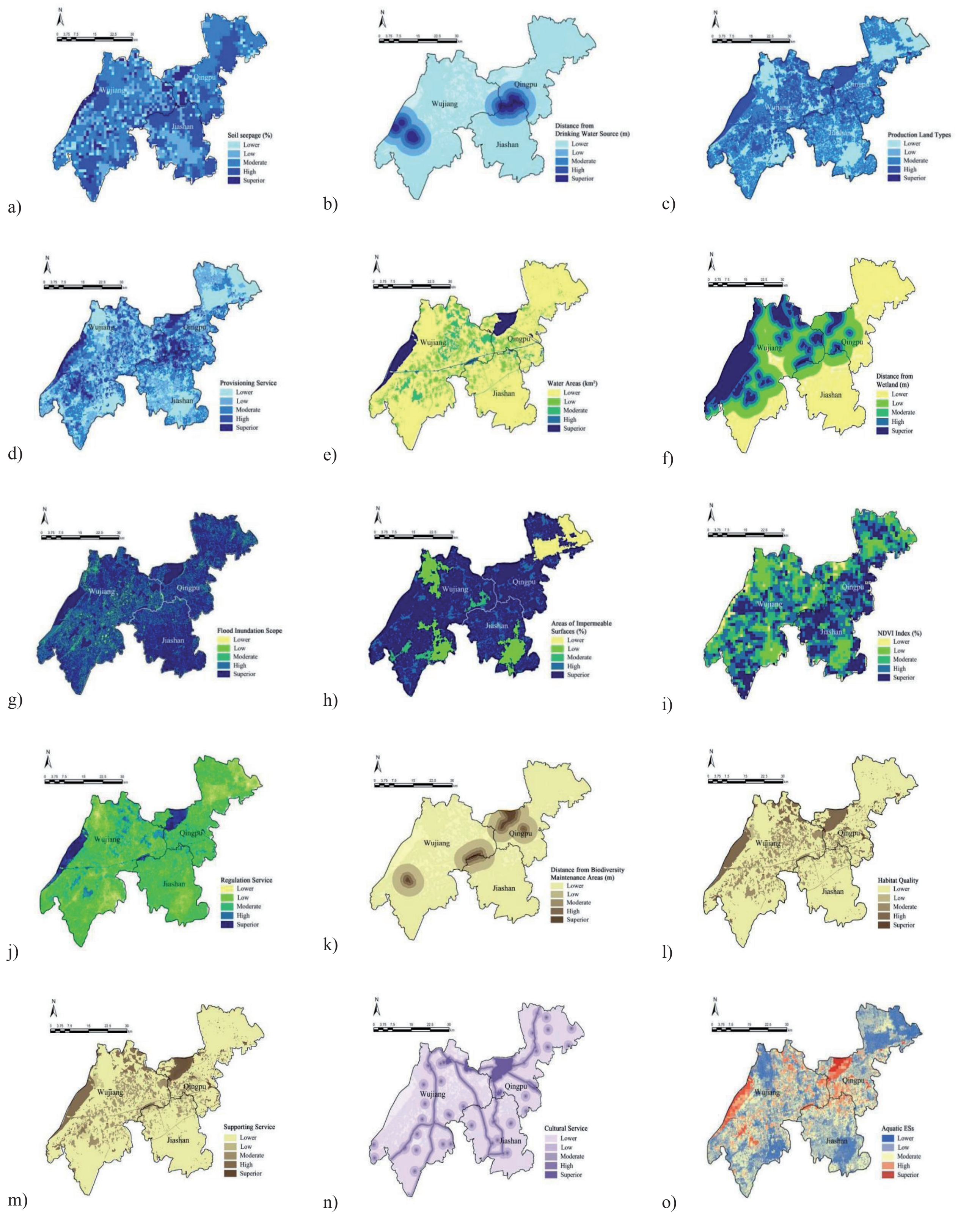

Fig. S4. Results of aquatic ESs importance assessment: a) soil seepage; b) distance from drinking water source; c) production land types; d) provisioning service; e) water areas; f) distance from wetland; g) flood inundation scope; h) areas of impermeable surfaces; i) NDVI index; j) regulating service; k) distance from biodiversity maintenance areas; l) habitat quality; m) supporting service; n) cultural service; o) aquatic ESs.