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Using Ecosystem Services to Inform Sustainable Waterfront Area Management: A Case Study in the Yangtze River Delta Ecological Green Integration Demonstration Zone

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Abstract: Ecosystem service assessments are crucial for sustainable water area management. Previous studies and actions on waterfront area management often emphasized merely the saving and use of water resources per se, ignoring the safeguarding of hydrological source ecosystems and assurance of sustainable provision capacity of water supplies. Using the Yangtze River Delta Ecological Green Integration Demonstration Zone (demonstration zone) as an example, this study integrated ecosystem service assessment into waterfront area management in an urbanizing region. We evaluated and mapped four ecosystem services—carbon sequestration, water purification, stormwater regulation and climate regulation—in the demonstration zone in 2020. We examined ecosystem service quantities, spatial distributions and economic values to inform policy balancing development and the environment. Our results show that ecosystem services provide significant benefits to waterfront areas: the zone furnished substantial ecosystem services, sequestering 544,900 tons of atmospheric carbon dioxide (USD 2.03 million), eliminating the total material quantities of nitrogen and phosphorus pollution of 47,700 tons and 13,900 tons (USD 66.31 billion and USD 20.17 billion, respectively), and retaining over 467.48 million cubic meters of stormwater runoff (USD 1756.35 million) and total material quantity of climate regulation amounts to 65.13 billion kilowatt hours (USD 5.10 billion). However, these service provisions varied spatially. Wujiang District provided the most ecosystem services overall, while Qingpu District had the highest per-unit intensities in stormwater regulation. Policy, planning and action should consider ecosystem providing security and prosperity. Managing the trade-offs between development and environment, reducing risks and cultivating resilience necessitates safeguarding ecosystem service potential.

Keywords: ecosystem services; waterfront area management; Yangtze River Delta; green development; Integration Demonstration Zone

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1. Introduction

Ecosystem services are the benefits that people obtain from ecosystems [1]. These include provisioning services, such as food and water; regulating services, such as flood and disease control; cultural services, such as recreational and spiritual benefits; and supporting services, such as nutrient cycling [2]. The assessment of ecosystem services is important because it helps to quantify the benefits that ecosystems provide to society [3,4]. This can inform decision making on the management and conservation of ecosystems [5–7]. The waterfront area refers to the zone interfacing with land and water, encompassing riverbanks, lake shores and coasts [8,9]. The management of waterfront areas is imperative as it serves in safeguarding aquatic environments by improving water quality and protecting wetlands via spatial planning and regulation [10]. enables infrastructure and vegetation to absorb flood crests and mitigate surface runoff [11], provides valuable economic and social functions, which necessitate prudent land-use planning [12], and facilitates research on the interactions between terrestrial and aquatic systems [13]. While waterfront area management focuses more on the environment, ecosystems and integrated use, water area management centers on water resources [14]. Overall, ecosystem-based management of waterfront areas is conducive to sustainability [15]. Ecological infrastructure refers to nature-based structures that provide ecosystem services to support human well-being [16]. Urban wetlands and green spaces, functioning as ecological infrastructure in urban areas, deliver a wide range of benefits [17]. However, changes to their structure and function due to urbanization may precipitate decreased species richness, owing to habitat loss and fragmentation [18]; degraded water quality, resulting from altered hydrology and nutrient inputs [19]; an increased heat island effect, attributable to reduced evapotranspiration [20]; and increased air pollution, arising from expanded impervious surfaces and traffic emissions [21]. The integration of ES assessment can provide valuable information for decision makers to develop and implement effective waterfront-areas-management policies [22–25]. By understanding the value of ES, decision makers can prioritize conservation efforts and allocate resources more effectively [26–28].

The Yangtze River Delta region is embroiled in a relentless struggle to reconcile the rapacious thirst for water from its breakneck economic expansion by safeguarding its water ecosystems, which are acutely imperiled by such untrammeled growth [29]. Once endowed with water resources of an abundance scarcely imaginable today, a mere fraction (a fifth) per capita now remains due to the agricultural and industrial march. Compounding its dire hydrological straits, a staggering sixty percent of surface-water-monitoring stations unveil water quality so poor as to pose existential threats to both human well-being and the environment alike [29,30]. Hence, the conundrum of how to deploy water usage and steward water resources has emerged as a restriction on this region's sustainable development.

Improved insights into the interplay between hydrological processes and ecosystems are key to surmounting these challenges. As a result, ecosystem services are introduced, which act as a scientific compass by which to systematically gauge how human activities impinge upon the environment and water resources alike and, in turn, how perturbations to ecosystem services reverberate through human well-being [31,32]. Quantifying ecosystem services would point to ecologically sustainable water use limits, minimizing the trade-offs between economic spoils and ecological resilience [33,34]. Ecosystem-based management has gained currency as an innovative approach to water stewardship worldwide [35,36]. However, in the past, research and practices on waterfront areas regulation and management tended to focus only on the conservation and utilization of water resources themselves while neglecting the maintenance of aquatic-source area ecosystems and the protection and enhancement of the sustainable supply capacity of water resources.

This study seeks to assay the multiple ecosystem services underpinning the Yangtze River Delta Ecological Green Integration Demonstration Zone (demonstration zone) launched in 2018, embracing one district in Shanghai, one county in Jiangsu and one county in Zhejiang Province. Envisaging a green development model that strikes a balance between economy, society and ecology, waterfront area management has been recognized as key to its sustainable growth [37,38]. We singled out four services pivotal to this study: carbon sequestration, rainstorm runoff regulation, climate regulation and water purification. By integrating biophysical and economic modeling, we quantify their supplies and values.

This paper addresses the three questions: What are the supplies and economic values of these services in the demonstration zone? How are these services spatially arrayed, and where do priorities for their conservation lie? The outcomes would provide scientific inputs for balancing the trade-offs between development and environment, diminishing risks from both water scarcity and contamination, and cultivating resilience and sustainability.

This study propounds an innovative deployment of ecosystem services to undergird the integrated management of water, ecology and economy in this demonstration zone. The insights gleaned herein stand to benefit both science and practice on ecosystem solutions for regions under intensive human pressures.

2. Materials and Methods

2.1. Study Area

This study selects the Yangtze River Delta Ecological Green Integration Demonstration Zone as the object of inquiry. In November 2018, the central government established the demonstration zone over 2400 km^2 spanning the Shanghai Qingpu District, Jiangsu Wujiang District and Zhejiang Jiashan County. Among these, the Early Launch District spans 660 km^2, and the Coordination District 450 km^2. Demanding ecological environment protection and restoration be accorded top priority, the aim is to construct three new highlands of 'ecological value', 'green innovation and development' and 'green livability', centering on 'One River, Three Lakes' (Taihu River, Fen Lake, Dianshan Lake, Yuandang Lake), comprehensively harnessing the ecological environment and sculpting an aesthetically optimized, harmonious ecological expanse.

Riven by administrative divisions, the local river and lake environments within the region have fallen under the shadow of pollution from various local sources as well as influenced by the water quality of upstream inflows [37,39]. The Shanghai region's water environment is prey not only to the water quality of Taihu Lake's upstream inflows but also to that of the Taihu River as it winds through Jiangsu's Wujiang and Zhejiang's Jiashan downstream, and the water quality of flows seeping from Jiangsu's Kunshan through Dianshan Lake, manifesting as the undesirability of river and lake environmental facets and instability in water quality—a far cry from the requirements stipulated in the 'Overall Plan for the Yangtze River Delta Ecological Green Integration Demonstration Zone'.

2.2. Data Collection

Spatial–temporal ecological data and social statistics data of the study area were collected for ES assessment (Table 1):

Table 1. Data Collection.

Data	Time	Resolution	Type	Source
Land cover/use	2020	30 m	Spatial data: Raster	Resources and Environmental Scientific Data Centre (RESDC) of the Chinese Academy of Sciences (CAS) (https://www.resdc.cn/) (accessed on 1 June 2022)
The Digital Elevation Model (DEM)	/	30 m	Spatial data: Raster	Geospatial Data Cloud (http://www.gscloud.cn/) (accessed on 1 June 2022)
Daily rainfall, temperature, evaporation data of each station in the study area	2020	/	text	Resources and Environmental Scientific Data Centre (RESDC) of the Chinese Academy of Sciences (CAS) (https://www.resdc.cn/) (accessed on 1 June 2022)
Soil type map	/	/	Spatial data: Raster	Resources and Environmental Scientific Data Centre (RESDC) of the Chinese Academy of Sciences (CAS) (https://www.resdc.cn/) (accessed on 1 June 2022)
Normalized Difference Vegetation Index (NDVI)	2020	30 km	Spatial Data Raster	Resources and Environmental Scientific Data Centre (RESDC) of the Chinese Academy of Sciences (CAS) (https://www.resdc.cn/) (accessed on 1 June 2022)

Table 1. *Cont.*

Data	Time	Resolution	Type	Source
Ecosystem services model parameters	/	/	Document	Technical specification for accounting gross ecosystem product ofZhejiang: (http://zjamr.zj.gov.cn/art/2020/9/29/art_1229047334_58814039.html) (accessed on 1 June 2022); Technical specification for accounting national ecological product valuation(https://www.ndrc.gov.cn/xwdt/ztzl/jljqstcpjzsxjz/gzdt/202301/t20230120_1347277_ext.html) (accessed on 1 December 2022)
Grade of precipitation				Grade of precipitation GB/T 28592-2012: https://max.book118.com/html/2018/1028/8136000107001130.shtm (accessed on 1 June 2022)
Yangtze River Delta Integration Zone Plan	2019/2023	/	Document	Local academic institutions and governments

For ecological space types classification, land use and land cover (LULC) data in 2020, with a spatial resolution of 30 m, were collected by the Resources and Environmental Scientific Data Center (RESDC) of the Chinese Academy of Sciences (CAS) (https://www.resdc.cn/) accessed on 6 June 2022. The ecological space types are classified into nine categories: forest, grassland, marsh land, lake, reservoir/pond, river, paddy field, rainfed cropland and built-up land, with the area of 11.77 km^2, 19.07 km^2, 3.70 km^2, 255.09 km^2, 218.50 km^2, 34.51 km^2, 1128.66 km^2, 16.28 km^2 and 725.77 km^2. The spatial distribution of these types is shown in Figure 1. The paddy field has the highest proportion of area (46.77%), followed by built-up land (30.07%).

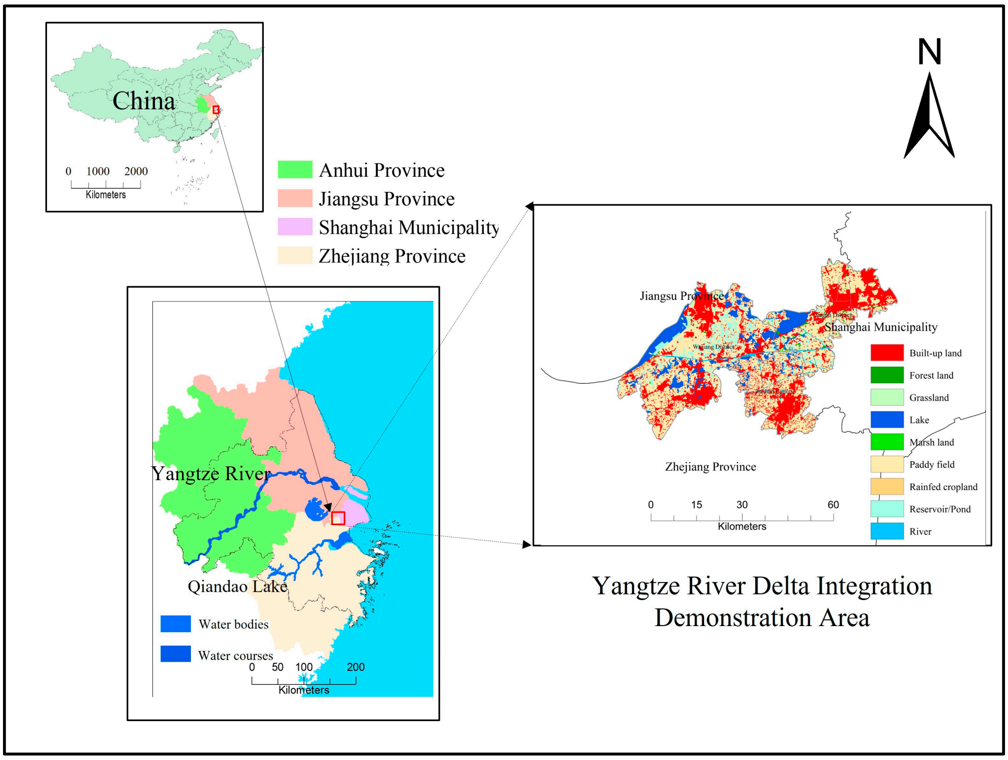

Figure 1. The location and land cover/use of the Yangtze River Delta Integration Demonstration zone.

2.3. Ecosystem Services Evaluation and Valuation

In this study, the quantitative assessment of ES was based on widely used ES assessment methods and standardized procedures according to Ouyang et al. [22] and the technical specifications for accounting national ecological product valuation (https://www.ndrc.gov.cn/xwdt/ztzl/jljqstcpjzsxjz/gzdt/202301/t20230120_1347277_ext.html) (accessed on 1 December 2022). The following results were calculated using the Intelligent Urban Ecosystem Management System (IUEMS)(https://www.iuems.com/eco/index.html) (accessed on 1 June 2022) and InVEST 3.12 model (https://naturalcapitalproject.stanford.edu/software/invest) (accessed on 1 June 2022).

(1) Carbon sequestration service

This ecosystem service refers to the ecosystem's function in absorbing carbon dioxide and synthesizing organic matter through photosynthesis, and storing carbon in plants and soil, reducing the concentration of carbon dioxide in the atmosphere. The service is calculated using a fixed carbon rate method, which uses data on ecological space types and fixed carbon rates for different ecosystems (Table 2).

Table 2. Carbon Sequestration Rates in Ecosystems.

Eastern Subtropical Evergreen Broad-Leaved Forest Zone	Aboveground Carbon Sequestration Rate	Soil Carbon Sequestration Rate
Forest	0.8150	0.2130
Shrubland	0.8150	0.2130
Grassland	0.0000	0.0240
Cropland	0.8150	0.2130
Wetland_Lake wetland	0.5667	0.0000
Wetland_Salt marshes	2.3562	0.0000

The calculation formula used to determine the total fixed carbon amount is:

$$Q_{tCO_2} = M_{CO_2}/M_C \times (FCS + GSCS + WCS + CSCS) \tag{1}$$

where Q_{tCO_2} represents the total fixed carbon amount in t CO_2/a, M_{CO_2}/M_C is the ratio of carbon to carbon dioxide, and FCS, GSCS, WCS, and CSCS represent the fixed carbon amount of forests, grasslands, water bodies and croplands, respectively.

The ecosystem service value is estimated using a market value method, which uses data on carbon trading prices. The calculation formula used to determine the value of fixed carbon is:

$$V_{Cf} = Q_{tCO_2} \times C_{CO_2} \tag{2}$$

where V_{Cf} represents the total value of fixed carbon, Q_{tCO_2} represents the total fixed carbon amount in t CO_2/a, and C_{CO_2} represents the carbon trading price. The market value calculation for fixed carbon entails multiplying the total fixed carbon amount with the carbon trading price to determine the value.

(2) Rainstorm runoff regulating service

This ecosystem service refers to the ecosystem's function in regulating storm runoff and reducing flood peaks by infiltrating and retaining rainfall through vegetation and water bodies. The physical amount of stormwater regulation service can be calculated using a grid-based model [40,41]:

$$C_{vfm} = \sum_{i=1}^{n} (P_i - R_{fi}) \times A_i \times 10^3 \tag{3}$$

In this formula, C_{vfm} represents the total value of fixed stormwater regulation services, P_i represents precipitation in the ith area, R_{fi} represents runoff in the ith area, and A_i represents the area of the ith region (Table 3). The summation notation represents the sum of all areas in the given region. The value is then multiplied by a factor of 10^3 to express the value in terms of currency.

Table 3. Curve number values of runoff.

Curve Number	Land Cover Type
2.00	Broadleaf forest
9.37	Shrubland
0.00	Marshes
0.00	Lake
0.00	Reservoir/Ponds
0.00	River
34.7	Paddy fields
46.96	Rainfed croplands
100.00	Impervious surface
100.00	Bareland

Using the replacement cost approach, which involves assessing the construction and operation costs of reservoirs, to calculate the flood regulation and storage value of the ecosystem, the ecological system's flood regulation and storage value (V_{fm}) can be calculated using the formula:

$$V_{fm} = C_{fm} \times (C_{we} + P_{we} \times D_r) \tag{4}$$

where C_{fm} represents the ecological system's ability to regulate and store floodwater in cubic meters per year, P_{we} represents the project cost per unit capacity of reservoirs in CNY per cubic meter, C_{we} represents the annual operating cost per unit capacity of reservoirs in CNY per cubic meter per year, and Dr represents the annual depreciation rate of reservoirs.

(3) Climate regulation service

This ecosystem service refers to the ecosystem's function in regulating local climate by affecting temperature and humidity through evapotranspiration and albedo processes. The physical amount of climate regulation services is evaluated by choosing the total energy consumed by the ecological system through evapotranspiration as the evaluation index. It should be noted that, in order to accurately calculate the value of climate regulation services, the energy consumption associated with evapotranspiration is replaced by the equivalent energy required for air conditioning.

The formula for calculating the total energy consumed through evapotranspiration is:

$$E_{tt} = E_{pt} + E_{we} \tag{5}$$

$$E_{pt} = \sum_{i}^{n} EPP_i \times S_i \times D \times 10^6 / (3600 \times r) \tag{6}$$

$$E_{we} = E_{wt} \times \rho_w \times q \times 10^3 / (3600 \times r) \tag{7}$$

where E_{tt} represents the total energy consumed by the ecological system through evapotranspiration in kilowatt-hours per year. E_{pt} represents the energy consumed by non-aquatic ecological systems through evapotranspiration in kilowatt-hours per year. $\sum_{i}^{n} EPP_i$ represents the heat consumed per unit area of the non-aquatic ecological system i in kilojoules per square meter per day. S_i represents the area of the non-aquatic ecological system i in square kilometers. D represents the number of days in which air conditioning was used to cool the indoor environment. r is the energy conversion efficiency of air conditioning, which is dimensionless. i represents the ith type of non-aquatic ecological system, with i = 1, 2, 3, ... , n, where n represents the total number of non-aquatic ecological systems. E_{we} represents the water evaporation from the water surface during the cooling period of air conditioning, in cubic meters per year. ρ_w represents the density of water in grams per cubic centimeter. q represents the latent heat of water, which is the amount of heat energy required to evaporate 1 g of water in joules per gram.

The climate regulation model was designed with full consideration of human society's need for the ecosystem's temperature regulation function. Therefore, the amount of environmental heat absorbed by evaporation and the transpiration of vegetation and wetlands in the study area was calculated when the average temperature exceeded a certain threshold. Moreover, to more intuitively express the value, the heat was then converted into electricity consumption that achieves the same cooling effect as air conditioning. The logical order of the entire model is not simply to calculate the absorption of heat by evaporation and transpiration when the air conditioner is turned on but to calculate the amount of heat absorbed by evaporation and transpiration when the average temperature exceeds a certain threshold. In this paper, the threshold value is 26 °C, which is a value used in many similar studies and is also the minimum cooling temperature recommended by the Chinese government for air conditioning.

This ecosystem service value is calculated using the replacement cost approach, which involves assessing the power consumption required for manually regulating temperature, which is used to calculate the climate regulation value of the ecosystem. The formula used to calculate the value of the ecosystem's climate regulation service is

$$V_{tt} = E_{tt} \times P_e \tag{8}$$

where V_{tt} represents the value of ecosystem's climate regulation services in CNY per year, E_{tt} represents the total energy consumed by the ecosystem in regulating temperature in kilowatt-hours per year, and P_e represents the local residential electricity tariff in CNY per kilowatt-hour.

(4) Water Purification: non-point source pollution purification

Water purification (non-point source pollution reduction): This service refers to the ecosystem's function in reducing non-point source pollutants such as nitrogen and phosphorus in water bodies through retention and transformation processes. The service is calculated using an export coefficient method, which uses data on land use types, pollutant export coefficients and water quality standards. The service value is estimated using a damage cost avoided method, which uses data on pollutant treatment costs.

The core equation used in the model for reducing non-point source pollution is the Revised Universal Soil Loss Equation (RUSLE). First, we applied the Revised Universal Soil Loss Equation (RUSLE) to calculate the soil retention amount in the study area, i.e., how much water and soil loss was reduced spatially. While the ecosystem performs the function in soil retention, it also avoids spatially soil pollutants forming non-point source pollution entering water bodies under precipitation conditions. Therefore, multiplying the soil retention amount by the content of various pollutants in the soil yields the non-point source reduction amount, i.e., the non-point source pollution reduction service toward different pollutants. In value calculation, we adopted the pollutant tax-fee method, referring to the pricing in the Zhejiang Provincial Standard «Technical Specifications for Accounting Gross Ecosystem Product (GEP)» for terrestrial ecosystems. The passage uses a more formal, objective tone with precise terminology to describe the model and calculations involved.

Physical quantity: the amount of non-point source pollution that is reduced is selected, that is, the amount of non-point source pollution formed by pollutants in the soil that is reduced while reducing soil erosion due to the role of the ecosystem, as the evaluation index of the physical quantity of non-point source pollution services for reducing the ecosystem.

$$Q_{dpd} = \sum_{i=1}^{n} Q_{sr} \times c_i \tag{9}$$

Q_{dpd}—reduction of non-point source pollution (tons per year);
Q_{sr}—soil retention (tons per year);
i—the number of pollutant species in the soil, i = 1, 2, . . . , n;
c_i—the net content of pollutants in the soil.

Value quantity: According to the reduction in non-point source pollution, the alternative cost method (i.e., soil pollutant treatment cost) is used to calculate the value of ecosystem reduction of non-point source pollution.

$$V_{dpd} = \sum_{i=1}^{n} Q_{dpdi} \times p_i \quad (10)$$

V_{dpd}—reducing the value of non-point source pollution (RMB per year);
Q_{dpdi}—reduction in various types of non-point source pollutants (tons per year);
p_i—unit treatment cost of Class I pollutants (CNY per ton).

3. Results

The demonstration zone evidenced substantial provisions of four pivotal ecosystem services in 2020: carbon sequestration, water purification, stormwater runoff regulation and climate regulation. These services rendered by the ecological infrastructures within the demonstration zone have attenuated the impacts of intensifying anthropogenic pressures and climate change, fortifying environmental resilience and sustainability in this rapidly developing region.

Carbon sequestration service extracted 544,900 tons of carbon dioxide, a greenhouse gas responsible for global warming, from the atmosphere. This considerable volume of sequestered carbon is valued at USD 2.03 million and has contributed significantly to mitigating climate change (Table 4). Marsh ecosystems, with their profuse vegetation and waterlogged conditions restricting aerobic respiration, were found to demonstrate the greatest potential for carbon sequestration compared to other ecological spaces (Figure 2).

Table 4. Carbon Sequestration Service of the 'two Districts and One County 'in the Yangtze River Delta Ecological Green Integration Demonstration Zone (2020).

	Qingpu District	Wujiang District	Jiashan County	Total
Physical Amount (tonnes)	148,700	278,400	117,900	544,900
Physical Amount per unit (tonnes/km^2)	222.19	224.90	232.53	/
Value (USD million-)	0.58	1.02	0.44	2.03

Note: USD 1 = CNY 6.8974 (http://www.mofcom.gov.cn/article/i/jyjl/e/202101/20210103034969.shtml) (accessed on 1 June 2022).

Of the total carbon sequestration capacity, the Wujiang District constituted the majority at 51.09%. Although marginally lower per unit area than Jiashan County's 232.53 tons/km^2, Wujiang District's larger expanse meant its greater overall contribution (Table 4).

Stormwater runoff regulation service retained and gradually discharged over 467.48 million cubic meters of stormwater runoff, equivalent to USD 1756.25 million (Table 5). The areas with higher supply intensities of stormwater runoff regulation are located in the northern parts of the 'two districts and one county', especially the northeast. In contrast, the southern regions demonstrate lower supply intensities (Figure 3). The spatial heterogeneity in stormwater runoff regulation capacities across the study area arises from several factors. Primarily, the precipitation amounts vary geographically, with heavier rainfalls concentrated in the north compared to the south. Secondly, the northern regions contain more water bodies, conferring greater capacities for mitigating extreme runoff events. Lastly, Dianshan Lake, in the junction of the three districts, demonstrates a particularly strong capability of attenuating stormwater impacts.

Wujiang District contributed 49.06% of the stormwater regulation capacity, while Qingpu County regulated 0.23 cubic meters/km^2, the highest per unit area (Table 5). Although superior to other areas in per unit physical quantity contained, this service's monetary value was dependent on the economic valuation of flood prevention and was hence variable. Forest ecosystems, with their complex structures and rooted vegetation, were most effective in stormwater regulation compared to other ecological spaces.

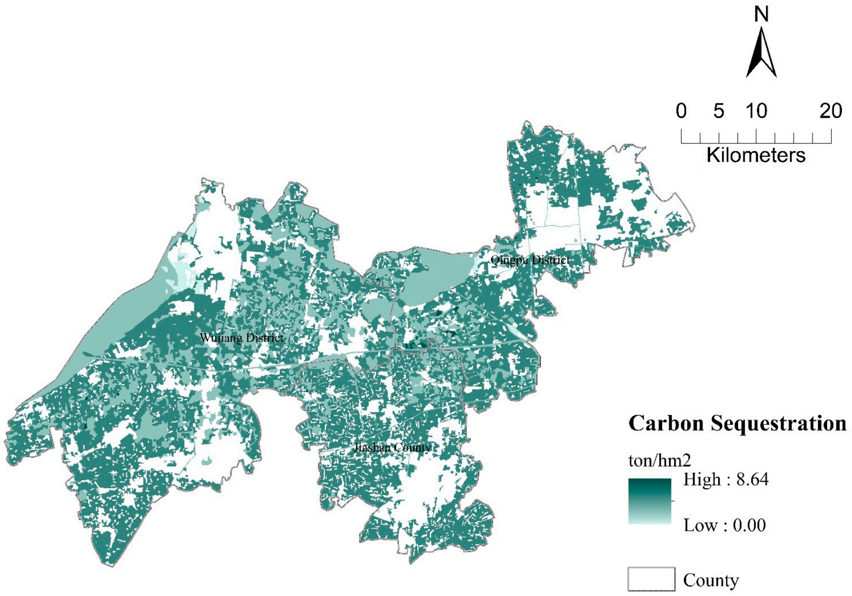

Figure 2. Spatial distribution of Carbon Sequestration Service in the Yangtze River Delta Ecological Green Integration Demonstration Zone (2020).

Table 5. Stormwater Regulating Service of the 'two Districts and One County 'in the Yangtze River Delta Ecological Green Integration Demonstration Zone (2020).

	Qingpu District	Wujiang District	Jiashan County	Total
Physical Amount (million m^3)	152.98	229.33	85.16	467.48
Physical Amount per unit (million m^3/km^2)	0.23	0.19	0.17	/
Value (USD million-)	574.77	861.51	319.96	1756.25

Note: USD 1 = CNY 6.8974 (http://www.mofcom.gov.cn/article/i/jyjl/e/202101/20210103034969.shtml) (accessed on 1 June 2022).

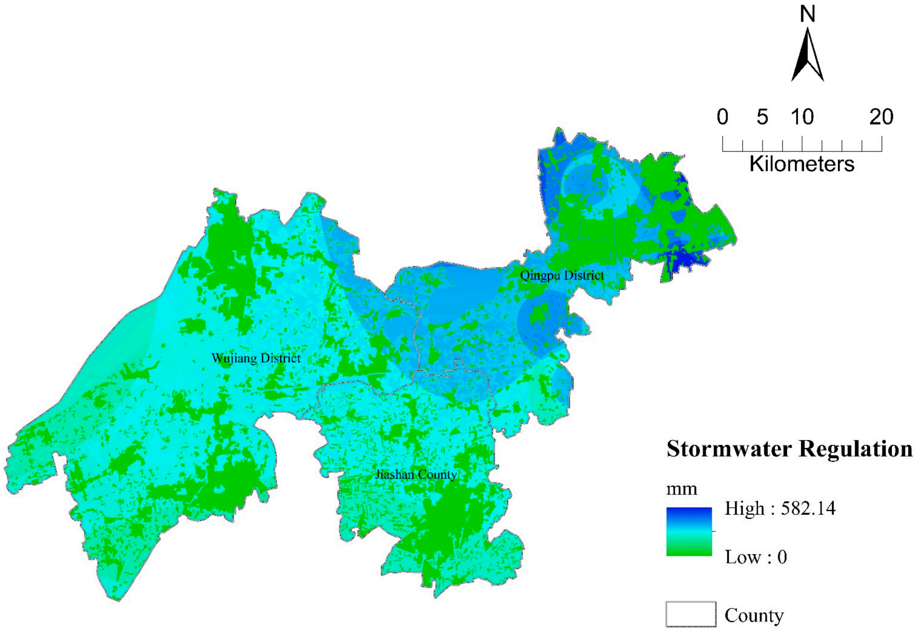

Figure 3. Spatial distribution of Stormwater Regulation Service in the Yangtze River Delta Ecological Green Integration Demonstration Zone (2020).

Owing to the relatively flat terrain and minor elevation differences in the 'two districts and one county' area, the supply intensities of non-point source pollution mitigation services exhibit little overall spatial variation across ecosystems (Figures 4 and 5). Areas with higher values are often distributed along roadsides, lake embankments, farmland ridges and other places with certain elevation differences.

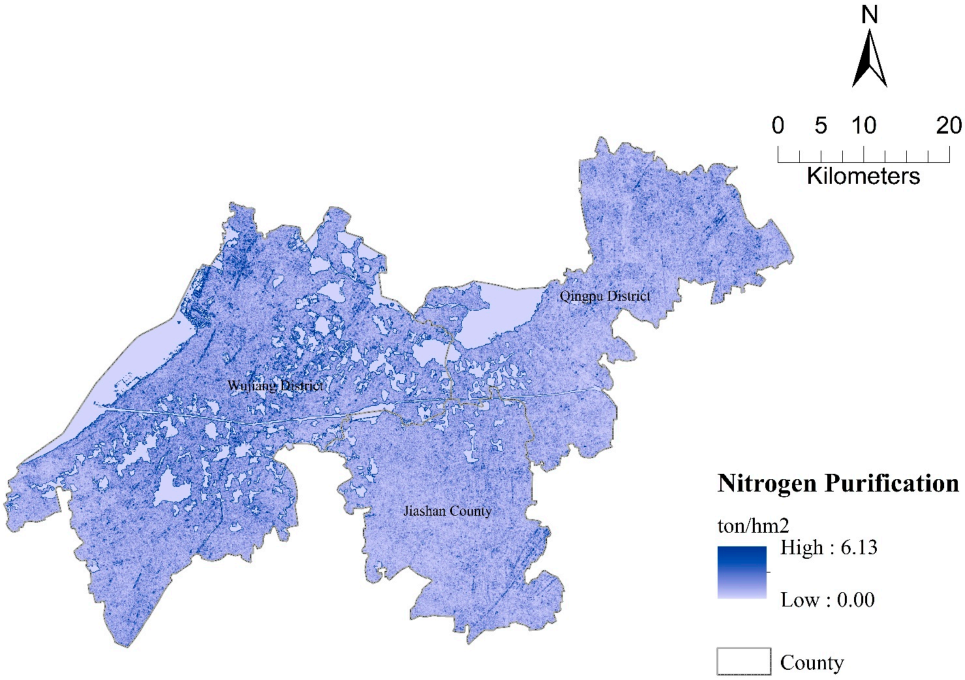

Figure 4. Spatial distribution of Nitrogen Purification Service (Water Purification) in the Yangtze River Delta Ecological Green Integration Demonstration Zone (2020).

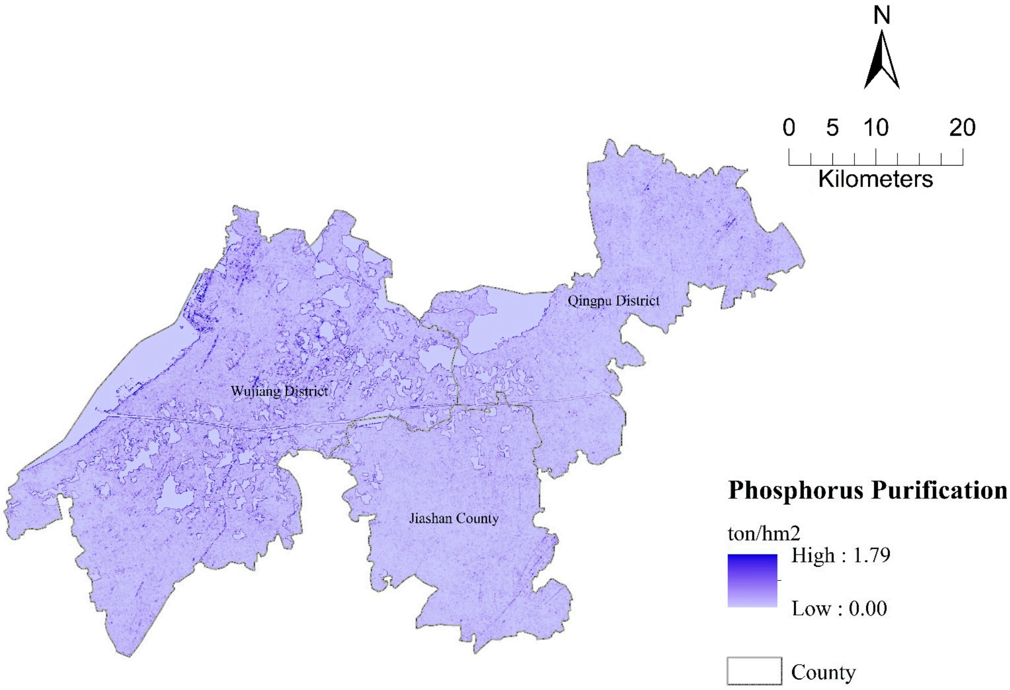

Figure 5. Spatial distribution of Phosphorus Purification Service in the Yangtze River Delta Ecological Green Integration Demonstration Zone (2020).

According to Tables 6 and 7, the total material quantities of nitrogen and phosphorus pollution load reduction services in the 'two districts and one county' area are 47,700 tons and 13,900 tons, valued at USD 66.31 billion and USD 20.17 billion, respectively.

Table 6. Water Purification Service (Total Nitrogen) of the ‘two Districts and One County ‘in the Yangtze River Delta Ecological Green Integration Demonstration Zone (2020).

	Qingpu District	Wujiang District	Jiashan County	Total
Physical Amount (tonnes)	10,600	28,900	8200	47,700
Physical Amount per unit (tonnes/km^2)	15.84	23.35	16.17	/
Value (USD million-)	14.66	40.20	11.46	66.31

Note: USD 1 = CNY 6.8974 (http://www.mofcom.gov.cn/article/i/jyjl/e/202101/20210103034969.shtml) (accessed on 1 June 2022).

Table 7. Water Purification Service (Total Phosphorus) of the ‘two Districts and One County ‘in the Yangtze River Delta Ecological Green Integration Demonstration Zone (2020).

	Qingpu District	Wujiang District	Jiashan County	Total
Physical Amount (tonnes)	3100	8400	2400	13,900
Physical Amount per unit (tonnes/km^2)	4.63	6.79	4.73	/
Value (USD million-)	4.50	12.19	3.48	20.17

Note: USD 1 = CNY 6.8974 (http://www.mofcom.gov.cn/article/i/jyjl/e/202101/20210103034969.shtml) (accessed on 1 June 2022).

The proportion of non-point source pollution reduction services in Wujiang District is the highest, reaching 60.57%. Similarly, the per capita material quantity is also the highest in Wujiang District, with 23.35 tons of total nitrogen and 6.79 tons of total phosphorus per square kilometer (Table 7).

Spatially, the northwestern and northern parts of the ‘two districts and one county’ area, with their contiguous water bodies, exhibit higher intensities (kilowatt hours/km^2) of climate regulation service provision (Figure 6). In contrast, the southern regions with agricultural land and impervious surfaces demonstrate lower intensities (Figure 6).

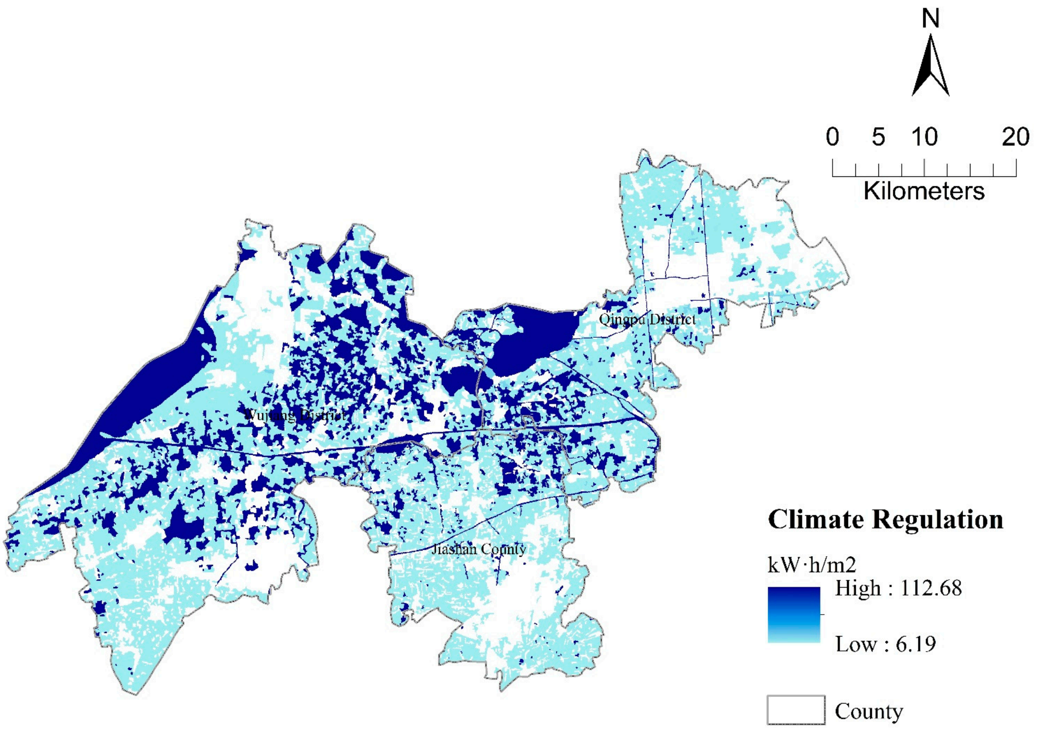

Figure 6. Spatial distribution of Climate Regulation Service in the Yangtze River Delta Ecological Green Integration Demonstration Zone (2020).

The total material quantity of climate regulation services in the 'two districts and one county' study area amounts to 65.13 billion kilowatt hours, valued at USD 5.10 billion (Table 8). Specifically, the Qingpu District accounted for 16.38 billion kilowatt hours, the Wujiang District 41.41 billion kilowatt hours, and the Jiashan County 7.34 billion kilowatt hours, which were worth USD 1.28 billion, USD 3.25 billion and USD 0.57 billion, respectively.

Table 8. Climate Regulation Service of the 'two Districts and One County 'in the Yangtze River Delta Ecological Green Integration Demonstration Zone (2020).

	Qingpu District	Wujiang District	Jiashan County	Total
Physical Amount (billion kilowatt hours)	16.38	41.41	7.34	65.13
Physical Amount per unit (billion kilowatt hours/km^2)	0.02	0.03	0.01	/
Value (USD billion-)	1.28	3.25	0.57	5.10

Note: USD 1 = CNY 6.8974 (http://www.mofcom.gov.cn/article/i/jyjl/e/202101/20210103034969.shtml) (accessed on 1 June 2022).

The proportion of climate regulation services in the Wujiang District was the highest, reaching 63.58% (Table 8). Similarly, the per capita material quantity was also the highest in the Wujiang District, about 0.03 billion kilowatt hours per square kilometer.

4. Discussion

4.1. Synthesis and Interpretation of Results

The outcomes of this inquiry reinforce the substantial contributions of ecological infrastructures within the demonstration zone in furnishing four pivotal ecosystem services: carbon sequestration, water purification, stormwater runoff regulation and climate regulation. These services were found to mitigate existential threats, safeguard regional security and support continued socioeconomic progress.

The spatial distribution differences observed in the study area for the four ecosystem services are influenced by climatic conditions, land cover and vegetation, topography, and human activities. Understanding these factors is crucial for effective land management and conservation efforts to optimize the provision of ecosystem services in the study area:

Climatic conditions: the variations in precipitation patterns and temperatures across the study area can influence the distribution of ecosystem services. Areas with higher rainfall and more moderate temperatures tend to have higher stormwater regulation and climate regulation services due to increased water storage and evapotranspiration rates.

Land cover and vegetation: the types and extent of land cover, including forests, wetlands, grasslands, and farmland, play a crucial role in determining the supply of ecosystem services. Forested areas generally exhibit higher carbon fixation rates as they have larger biomass and more efficient photosynthesis. Similarly, areas with denser vegetation cover have higher stormwater regulation and climate regulation services due to increased interception and transpiration.

Human activities and land Management: human activities, such as urbanization, agricultural practices, and land use changes, can significantly alter the distribution of ecosystem services. Urbanized areas and regions with intense agricultural practices often have reduced carbon fixation and stormwater regulation services due to the loss of natural land cover and increased impervious surfaces.

Topography: the elevation and slope of the terrain can impact the distribution of ecosystem services. Areas with steeper slopes and higher elevations tend to experience higher stormwater regulation services due to increased runoff and water storage capacity. Additionally, topographic variations can affect wind patterns, which, in turn, influence the distribution of climate regulation services.

Comparing our results with other studies on ecosystem service assessment and integration into water management reveals some common themes as well as some unique insights [42,43]. For example, many studies have highlighted the importance of considering multiple ecosystem services when making decisions about land use or resource management [44–46]. Our study adds to this body of literature by providing detailed data on specific ecosystem services in a particular region (the demonstration zone), which can inform local decision making.

At the same time, our study also highlights some unique challenges associated with integrating ecosystem service assessment into waterfront area management in rapidly urbanizing regions such as the Yangtze River Delta. Rapid urbanization can lead to loss or degradation of natural habitats which provide important ecosystem services [47–49]. This underscores the need for careful planning and management to ensure that urban development does not compromise essential ecosystem services [19,50].

In synopsis, ecological infrastructures were clearly substantial generators and providers of services that buffer societies and economies. However, the capacities and intensities of services varied spatially, necessitating area-specific strategies and highlighting the diversity of mechanisms through which nature benefits humanity.

4.2. Implications for Policy and Practice

The outcomes of this study bear important implications for policymaking and management within the demonstration zone and beyond. Recognition must be accorded to ecological infrastructures as natural assets underpinning regional sustainability and security. Accounting for nature's diverse contributions can help balance trade-offs between development and environmental integrity, diminish risks from resource scarcity and pollution, and cultivate resilience [24,51].

The results of this study have direct and indirect implications for ecosystem services conservation priorities in the demonstration zone:

Directly, the study identified specific areas within the demonstration zone that provide high levels of certain ecosystem services, such as carbon sequestration in marsh ecosystems and water purification in the Wujiang District. These areas could be prioritized for conservation efforts targeting the ecosystem services they provide. For example, marshes could be protected or restored to enhance carbon sequestration, while natural infrastructure in Wujiang District could be maintained to support water purification.

Indirectly, the study highlights the importance of considering multiple ecosystem services together in conservation planning. Focusing on single services in isolation may lead to unintended trade-offs in other services. The spatial heterogeneity in service provision indicates the need for tailored strategies across the demonstration zone. A comprehensive, integrated perspective can help determine how to maximize co-benefits across services through strategic conservation of ecological infrastructure.

Furthermore, the substantial economic values assigned to the quantified services in this study provide an economic incentive and justification for prioritizing ecosystem services conservation. Protecting natural capital that furnishes essential services on which human well-being depends can prove cost-effective compared to technological investments, in addition to yielding added social and environmental benefits.

Integrating ecosystem service assessment into policy and planning frameworks may enable the development of more holistic and sustainable outcomes. For instance, considering carbon sequestration and climate regulation alongside traditional objectives like flood control and water supply can achieve co-benefits and more integrated waterfront area management [36,52,53]. Spatial heterogeneity in service distribution points to the need for area-specific interventions that maximize benefits. Targeting geographical expanses with high sequestration potential for afforestation, for example, can enhance carbon storage whilst improving water quality and regulating runoff.

Incorporating nature-based solutions as mainstream practices may avoid costly technological interventions and yield more sustainable results at larger scales [54–56]. For example, employing paddy fields, marshes, and forests for water purification can curb pollution at lower economic and environmental costs compared to wastewater treatment facilities alone [57]. Harnessing the climate regulation potential of forests can achieve more sustainable cooling compared to energy-intensive air conditioning [58]. Transitioning to integrated policy and planning frameworks that recognize and give due consideration to nature's contributions in providing essential services on which societies rely may cultivate resilience and long-term security [59,60].

4.3. Contributions, Limitations and Future Research

This study contributes to our understanding of ecosystem services in land use management. Firstly, by conducting a case study in the demonstration zone, the study expands our knowledge of managing waterfront areas in urbanized regions. Previous research often focused solely on water conservation and utilization, neglecting the importance of safeguarding hydrological source ecosystems and ensuring sustainable water supply. This study integrates ecosystem services assessment into waterfront area management, providing a comprehensive perspective to balance development and environmental considerations.

Secondly, the study assesses and maps the quantities, spatial distributions, and economic values of four key ecosystem services (carbon sequestration, water purification, stormwater runoff regulation, and climate regulation) in the demonstration zone. These results provide valuable insights for policymakers to make informed decisions. Quantifying and valuing ecosystem services helps decision makers better understand their significance, allocate resources effectively, and promote sustainable development.

Moreover, the methods and models employed in this study can serve as a reference for ecosystem services assessment in other regions and contexts. Given the representative nature of the study area, replicating and adapting the research methods can guide ecosystem services assessment in similar areas. This facilitates a deeper understanding of the capacity and value of ecosystem services in different regions, providing lessons and inspiration for global ecosystem services management.

This study contributes to our knowledge of ecosystem services in land use management by integrating them into the management of waterfront areas in the demonstration zone. The assessment of key ecosystem services' quantities, spatial distributions, and economic values is of vital importance for both theoretical and practical aspects of ecosystem services management. The methods and results of this study provide valuable insights and serve as a reference for similar research in other regions and contexts.

While contributing saliently to assimilating ecosystem service perspectives into policy and management spheres, limitations persist in this inquiry, including the static assessment of service provisions over a discrete year and focus on a select suite. Interrogating additional services such as cultural, supporting and provisioning categories may furnish comprehension of aggregate values and benefits engendered. Future undertakings should examine service distribution across prolonged timescales utilizing methods such as time series modeling to glean insight into interactions with wider socioeconomic and environmental vicissitudes.

Juxtaposing additional landscapes and administrative units may capacitate the determining of geographical expanses most proficient in furnishing targeted ecosystem services and accordingly prioritizing conservation resources. For instance, comparing water purification services between the demonstration zone, Shanghai City and other circumjacent areas may facilitate the allocation of fiscal and technical resources to address critical lacunae.

Employing integrated modeling and forecasting techniques can generate projections of ecosystem service values under variant policy, climate and land use scenarios, assessing trade-offs between options and crafting adaptive strategies maximizing services even as demands intensify and environments transform. For example, projecting the impacts of urban expansion and agricultural intensification on water purification and climate regulation may guide zoning and evade costs from services divested.

In synopsis, this inquiry has demonstrated the substantial benefits accorded by ecological infrastructures within the demonstration zone across select services. By highlighting economic valuations, spatial heterogeneity and comparative advantages in service provisions, this research presents a compelling argument for transitioning towards integrated policy, planning and management frameworks due to the recognition and consideration of nature's contributions buttressing sustainable regional development. Future works building on these findings may continue generating scientific knowledge and support essential for balanced decision making and governance. Safeguarding and harnessing ecosystem service potentials may prove pivotal to cultivating long-term resilience in an era of intensifying anthropic pressures and climate change.

5. Conclusions

The outcomes reinforce factoring nature and its considerable benefits into policy spheres as imperative for cultivating sustainability. Transitioning towards integrated frameworks recognizing ecological infrastructures as assets underwriting security may prove sine qua non.

The demonstration zone harbored potential for generating and sustaining pivotal services, attenuating threats, diminishing risks, and enabling resilience. The carbon sequestration, water purification, stormwater regulation and climate regulation services furnished by ecological infrastructures modulated, extracted, retained and removed substantial resources and pollutants, securing society and the economy.

However, service capacities and intensities varied spatially, necessitating area-specific strategies to maximize benefits. Wujiang District constituted the majority capacities overall due to its larger expanse, though Jiashan County showed superior per unit intensities. Future works should examine service provisions across time and space to glean interactions with change, determining regions most proficient in targeted services and allocating resources accordingly.

Overall, this inquiry contributes to recognizing and harnessing nature's contributions to supporting sustainable regional development. Safeguarding ecosystem service potentials may prove essential for cultivating long-term security in an era of intensifying pressures and change. Averting existential crises and harmonizing progress with integrity necessitates understanding, protecting and wisely managing the life support systems on which the economy, society and human well-being ultimately depend. By arguing for the integration of ecological infrastructures as natural assets into policy and decision making, this work aims to buttress balanced progress and prosperity.

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