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Evaluation framework for multi-scale ecological infrastructure construction benefits based on nature-based solutions: A case study of Guangdong-Hong Kong-Macao Greater Bay Area

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ABSTRACT

Spatially, ecological infrastructure (EI) is a multi-scale and cross-level ecological network promoting sustainable urban development. Due to the distinct features of different scales, researchers have emphasized the importance of the multi-scale EI construction, which calls for support from a framework for scientific evaluation. Thus, based on the nature-based solutions (NbS) criteria, this study proposes a multi-scale EI construction benefits (MECBs-NbS) evaluation framework with scale differences and chooses the Guangdong-Hong Kong-Macao Greater Bay Area (GBA) as a case study. The results show that: (1) the MECBs-NbS evaluation framework is fairly applicable; (2) in 2020, the ecological benefits of EI construction for building ecological security patterns at the macro-scale (GBA urban agglomeration) by around 203.63 billion RMB; for improving human-nature harmony, the ecological, physical, and social benefits of EI construction at the *meso*-scale (Huizhou city) were about 358.50 billion RMB; while the EI construction benefit of completing engineering tasks at micro-scale (site) was about 34.85 million RMB; (3) overall, with the built-up area as the center, as scale decreased, the EI construction benefits gradually changed from being dominated by ecological benefits to being dominated by social benefits; (4) by supporting the status quo analysis before construction and the benefit assessment following construction, this evaluation framework may not only support the planning, design and management of EI, but also serve as a crucial tool to encourage public participation and evaluate the performance of government work. This study aims to provide a new perspective on the multi-scale evaluation of EI construction that will support and improve urban resilience.

1. Introduction

Urbanization is one of the important manifestations of human activities, the most significant global trend of the 21st century (UN-Habitat, 2016). However, the conventional unsustainable development paradigm exacerbates the conflict between population, resources, and the environment (Mcphearson et al., 2021). Water pollution (Cao et al., 2020), drinking water safety risk (Davison et al., 2005), biodiversity loss (Ctcab et al., 2021; Su et al., 2015), declining ecosystem stability (Schmeller et al., 2017), extreme weather (McPhillips et al., 2018), and urban heat island (Grimmond, 2007), etc. have seriously threatened urban health and the survival and development of human society. Given this context, the United Nations (UN) explicitly included sustainable urban development (SDG 11) in the list of global sustainable development goals (SDGs) in 2015, calling for making cities and human settlements inclusive, safe, resilient, and sustainable(UNEP, 2018). Meanwhile, the International Union for Conservation of Nature (IUCN) has emphasized nature is essential for human existence and good quality of life and proposes the use of nature-based solutions (NbS), which are the measures taken to safeguard, sustainably manage, and restore both natural and modified ecosystems in ways that effectively and adaptively solve societal challenges, thereby prompting both human well-being and biodiversity benefits (IUCN, 2020a).

Ecological infrastructure (EI) construction is one sort of NbS that uses ecological engineering (preserving, restoring, or creating natural and semi-natural ecological landscapes or systems) to combat the

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ecological and social challenges that threaten sustainable development worldwide. In line with NbS, EI emphasizes the sustainable support capacity of natural landscapes and hinterlands for sustainable development (Liu et al., 2005) with a broader concept and connotation than the open green space in green infrastructure (GI) (Childers et al., 2019; Liu et al., 2023). From the perspective of composition elements, EI is the natural and semi-natural landscape that eases the pressure of traditional gray infrastructure, including natural forests, rivers, farmlands, wetlands, and even parks, roof gardens, three-dimensional greening, and other low-impact development (LID) facilities (Han et al., 2019a; Li et al., 2014; Yu et al., 2004). Regarding functions, EI can work in tandem with all-natural elements (including water, soil, air, sound, and wind) (Romero-Duque et al., 2020; Tao, 2015) to maintain, improve and increase regional ecosystem services and prevent environmental problems. Spatially, EI is a multi-scale(Li et al., 2014; Romero-Duque et al., 2020; Tao, 2015; Yu et al., 2007) and cross-level blue-green-turquoise-brown spatial network (Liu et al., 2023; Tao, 2015) that affects ecological security patterns. Practices have proven that EI construction is conducive to maintaining and improving the urban ecological environment(Jayakaran et al., 2020), enhancing regional ecosystem services (Li et al., 2017; Romero-Duque et al., 2020), improving the urban environment (Radhakrishnan et al., 2019), and the human health(Li et al., 2017; Radhakrishnan et al., 2019). This is of great importance in promoting harmony, stability, security, and sustainable development between humans and nature (Cheshmehzangi and Griffiths, 2014; Cumming et al., 2017; Kumar et al., 2019).

Meanwhile, to comprehend and guide landscape planning and management, scholars have developed a number of classical ecosystem valuation methods during the past 20 years. It includes such as the evaluation method of ecosystem service functions proposed by Daily (Daily, 1997) and Costanza(Costanza et al., 1997), the evaluation of ecosystem service value based on per unit area(Xie et al., 2015), the Gross Ecosystem Product (GEP) accounting (Ouyang et al., 2020), and the benefits assessment of LID construction (Nordman et al., 2018; Randall et al., 2019; Rong et al., 2021; Yang et al., 2022). These methods all provide technical help for quantifying benefits of EI construction. However, it is important to note that EI is inherently spatial(Liu et al., 2023). Scientific multi-scale EI construction benefit evaluation is essential for optimizing the design and planning of the EI network and implementing or setting related policies. However, the current spatial ecosystem services evaluation method overlooks the discrepancy of ecosystem services caused by variations of different scales(Jing et al., 2018; Luan et al., 2017; Romero-Duque et al., 2020). Even some scholars have pointed out the great value of multi-scale system planning, design and co-management for transboundary environmental resource management(Cohen-Shacham et al., 2016) and ecological protection, yet we still lack multi-scale framework to evaluate and manage the EI construction. How to scientifically evaluate the multi-scale EI construction benefit remains largely unexplored needing breakthroughs.

Fortunately, a global standard for NbS has been produced by the International Union for Conservation of Nature (IUCN), which proposes eight criterions for NbS construction. It emphasizes the significance of addressing societal challenges, spatial design, result in environmentally sustainable, socially equitable and economically viable, and short and long-term benefits trade-offs, adaptive management, and embedding the concept and actions into policy or regulatory framework in NbS design and implementation(IUCN, 2020b). From the criterion, we can learn how crucial it is to have a systematic understanding of the difference in ecological advantages and characteristics at different scales and to balance trade-offs between the primary construction goals and the continued provision of multiple benefits during benefits assessment, which provides a new perspective in our study.

Accordingly, based on the NbS criterion, this study constructed an evaluation methodology known as the MECBs-NbS framework. It highlights the ecological advantages and characteristics of different scales and suggests that prioritized eco-benefits at macro-scale, carefully considered ecological, physical, and social (Eco-Physical-Social) benefits at *meso*-scale, and depended on construction objectives at micro-scale to improve the current single-scale ecosystem service assessment model. Meanwhile, based on the established evaluation framework and classical ecosystem valuation method, three geographical scales, the Guangdong-Hong Kong-Macao Greater Bay Area (GBA), the Huizhou City, and an EI construction site, are being employed simultaneously for a case study to examine the multi-scale difference while measuring the EI construction benefits in the scenario in 2020. This study aims to answer the following problems: *1) What difference in EI construction benefit at different scales? 2) How can we apply the benefit evaluation framework based on NbS criteria to support the process of EI construction?* The findings of this study can provide a foundation for multi-scale quantitative evaluation of EI construction projects as well as for planning and managing ecological landscapes in urban.

2. MECBs-NbS: A multi-scale evaluation framework of EI construction benefits

2.1. Enlightens from NbS global criterion

IUCN released the NbS global standard (IUCN, 2020b) and guidance (IUCN, 2020a) in 2020. The proposed criteria emphasize the significance of NbS addressing social challenges (criterion 1); should direct design in terms of key spatial considerations (criterion 2); correspond to the environment sustainability, social equity, and economic viability (criterion 3, 4, 5); navigate and balance the trade-offs of short- and long-term natural resource management needs (criterion 6); promote an adaptive management method (criterion 7); and encourage mainstreaming of NbS within national policy (criterion 8)(Liu et al., 2022b). The NbS Standard Criteria, as depicted in Fig. 1, not only reflects the necessity of multi-scale quantitative evaluation but also requires that the NbS benefit evaluation framework thoroughly and methodically assess the ecological advantage and goals at various scales by trade-offs; in addition, the evaluation system should be integrated with current standards, policies, or methods to ensure the application and management of NbS adaptively. EI construction is a nature-based ecological engineering solution(Liu et al., 2023). Thereby, the EI construction benefit evaluation framework should be multi-scale, systematic, trade-off, quantifiable, and adaptive.

2.2. Multi-scale difference analysis of EI construction

EI is multi-scale in nature and can provide various ecosystem services; many scholars have underlined the importance of conducting scale-difference studies in management(Han et al., 2019b; Xu et al., 2016), as well as in planning and design(Greer, 2019; Yang et al., 2020), in order to meet the objectively needs. Macro, meso and micro scales are typically used in these researches. Based on the evaluation principles 1, 2, and 3, multi-scale, systematic, and trade-off evaluation requirements (Fig. 1), the difference in EI construction at each scale, as shown in Table 1.

(1) Macro-scale, which can take the form of nation, province, large river basin, or urban agglomeration (Liu et al., 2022a; Luan et al., 2017). At this scale, EI refers to the ecological network and barrier of a region, and the mainly components include the ecological core areas, patches, and corridors(Luan et al., 2017; Yu et al., 2009). Spatially, it displays a complex and networked form to sustain the stability and integrity of large-scale ecological processes (Ma et al., 2004; Yang et al., 2020; Yu et al., 2009). The construction objective is to form an ecological security pattern and protective barrier through ecological restoration, protection, and management.
(2) The Meso-scale is typically a city or built-up area(Ding et al., 2023; Luan et al., 2017; Yang et al., 2020), which facing serious

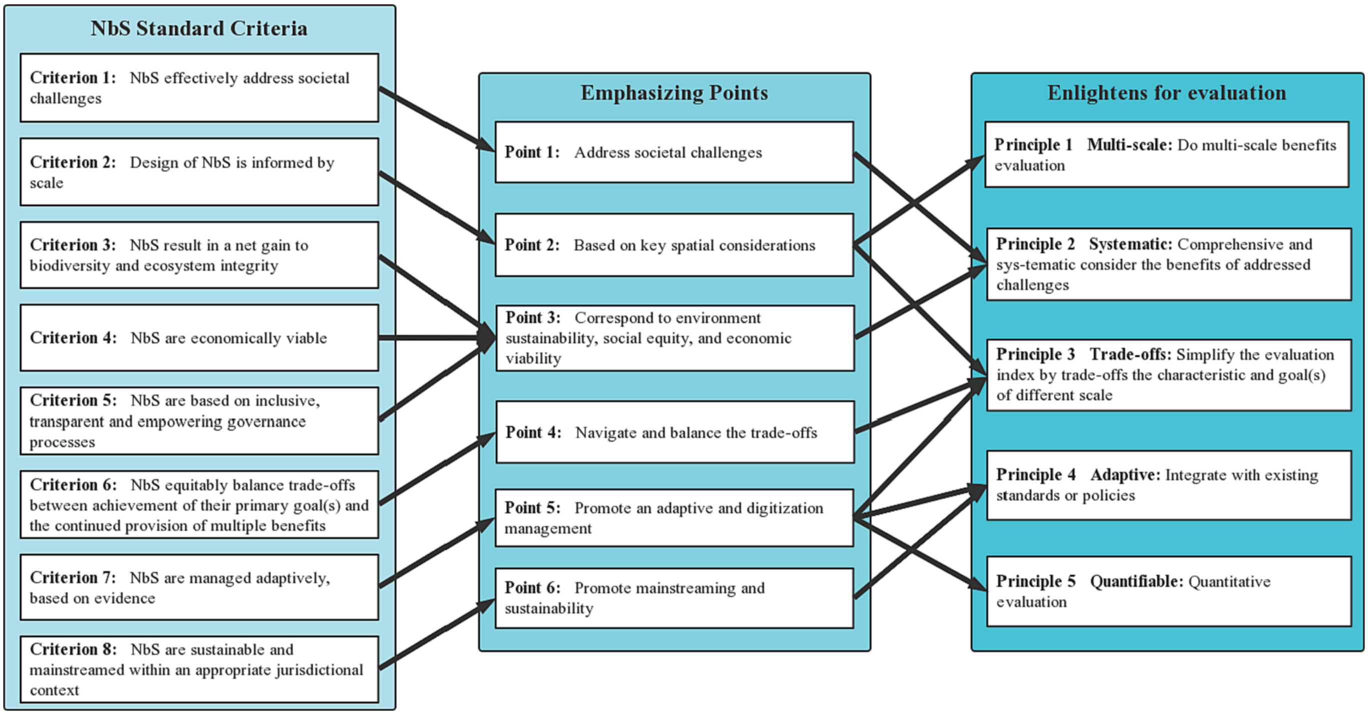

Fig. 1. Links and enlightens from the Nb Standard Criteria.

Table 1
EI multi-scale division and difference analysis.

Scale class	Spatial scale	Spatial characteristic	Construction objectives	Construction approaches	Component elements
Macro-scale	Country and region (e.g., province, large river basin, or urban agglomeration, etc.)	Complex and networked spatial form	Maintain ecological security pattern of the country or region	Protection, restoration and construction of the ecological core area, corridor, and patch	National natural life support system, including ecological core area, river & green corridor, and patch, etc.
Meso-scale	City, district, block, etc.	High population density, high artificial, high ecological fragmentation	Restore urban and rural landscapes and ecological safety networks, improve living environments, and promote harmonious coexistence between humans and nature	Restoration and reconstruction of natural and artificial ecological systems	The landscapes consist of a regional ecological network, including mountains, rivers, wetlands, urban agriculture, forest, grassland, sand, greenway, etc.
Micro-scale	Facility construction site	Simple spatial structure, single or multiple EI facilities	Stormwater runoff control, water purification, air purification, building energy saving, improve human health, leisure and entertainment, and prevent soil erosion, etc.	Sustainable design, planning, and green technology (e.g., LID)	Ecological site: single or multiple EI facilities (e.g., rain garden, green roof, greening wall, bioretention, etc.)

contradiction between urban expansion and ecological environment(Hu et al., 2023), due to the high population density, level of artificialization, and ecological fragmentation(Meng and Wu, 2023). At this scale, mountains, water, forests, farmland, sand, and the artificial green–blue open space are all EI component elements(Li et al., 2017). Its main construction objectives include maintaining and improving the urban and rural landscape and ecological safety network(Luan et al., 2017; Yang et al., 2020) by ensuring the integrity and connectivity of the EI structure(Fang et al., 2020; Yu et al., 2016), alleviating urban problems through scientific technologies(Andersson et al., 2019), and even meeting the needs of residents' ecological activities through land ecological transformation.

(3) Micro-scale mainly refers to single or multiple facilities sites(Ding et al., 2023; Luan et al., 2017), such as parks, green roofs, constructed wetlands, rain gardens, greening wall, and the other LID facilities(Luan et al., 2017). Typically, the EI construction objective is to restore, improve, and enhance the ecosystem service capacity of the site and optimize and upgrade the human settlements by using scientific planning and design technique.

2.3. Establishment of evaluation framework

This study established an evaluation framework for multi-scale EI construction benefit based on the NbS criterion (MECBs-NbS), which contains the following design. First, this study refers to the contributions produced by preventing and controlling ecological disasters (maintaining an ecological security pattern) as ecological benefits (Eco-benefit), the improvement of the human settlement's spatial physical environment refers as physical benefits (Physical-benefit), and the benefits of contributing to humanistic society as social benefits (Social-benefit). Secondly, ensure the evaluation indicators are multi-scale, systematic, and trade-offs (Principles 1, 2, 3). Based on the findings from the difference analysis in Section 2.2, macro-scale EI construction devotes to maintaining ecological security that mainly provides Eco-benefits; *meso*-scale EI construction focus on the harmony between human and nature in urban and rural areas, the benefits evaluation indicators therefore should systematically consider the ecological, physical and social benefits aspects; the micro-scale EI construction relates to a specific engineering project (e. g. LID facilities construction in Sponge Cities), therefore the benefit in this scale depends on the engineering objectives, mainly from the physical and social benefits and some ecological benefits. Thirdly, coordinating with current regulations, standards, and technological documents ensures the evaluation framework is adaptive and quantifiable (Principles 4 and 5). China is carrying out GEP accounting and sponge city construction; a series of guidelines, standards, and technical reports have been promulgated(Fang et al., 2021; Song and Ouyang, 2020; Wu et al., 2022). Therefore, this study's chosen indicators and calculation methods referenced the GEP accounting and Sponge Cities assessment.

In detail, in the MECBs-NbS evaluation framework, the macro-scale evaluation indicators include soil retention, water retention, sandstorm prevention, flood mitigation, and carbon sequestration, which are closely related to ecological security, highlighting the maintenance of natural ecological stability by EI construction. According to principle 5 (quantifiable), in the *meso*-scale, in addition to the Eco-benefit evaluation index that is consistent with the macro-scale, the Physical-benefit evaluation index chooses climate regulation and air purification related to urban heat islands and air pollution, respectively; and the Social-benefit evaluation selects the ecotourism service most related to resident recreation. And based on the construction goals of LID facilities, the benefits evaluation indicators of micro-scale EI construction include stormwater runoff control, water purification, air purification, soil retention, ecotourism, human health, and building energy saving. The MECBs-NbS evaluation framework is shown in Fig. 2, characterized by Eco-benefit priority on the macro-scale, Eco-Physical-Social benefit systematic evaluated on the *meso*-scale, and completing of engineering objectives on the micro-scale.

3. Methods and materials

3.1. Study area

GBA is located in the south of China, which consists of two special administrative regions of Hong Kong and Macao, and the nine municipalities of Guangzhou, Shenzhen, Zhuhai, Huizhou, Foshan, Dongguan, Zhongshan, Jiangmen, and Zhaoqing in Guangdong Province, with a total area of 56,000 km^2(Gao et al., 2022; Wen et al., 2020). As one of China's most dynamic economic zones, the pressure on resources and the environment is increasing with rapid urbanization. To release the conflict between population, resources, and environment and promote the goal of building high-quality areas that are sustainable for living, working, and traveling(Liu et al., 2022a), a series of policies have been introduced to comprehensively promoting urban ecological transformation. This study selects the GBA, Huizhou city, and one EI construction site in Huizhou as the macro-scale, *meso*-scale, and micro-scale research objects, respectively. The detailed geographical location is

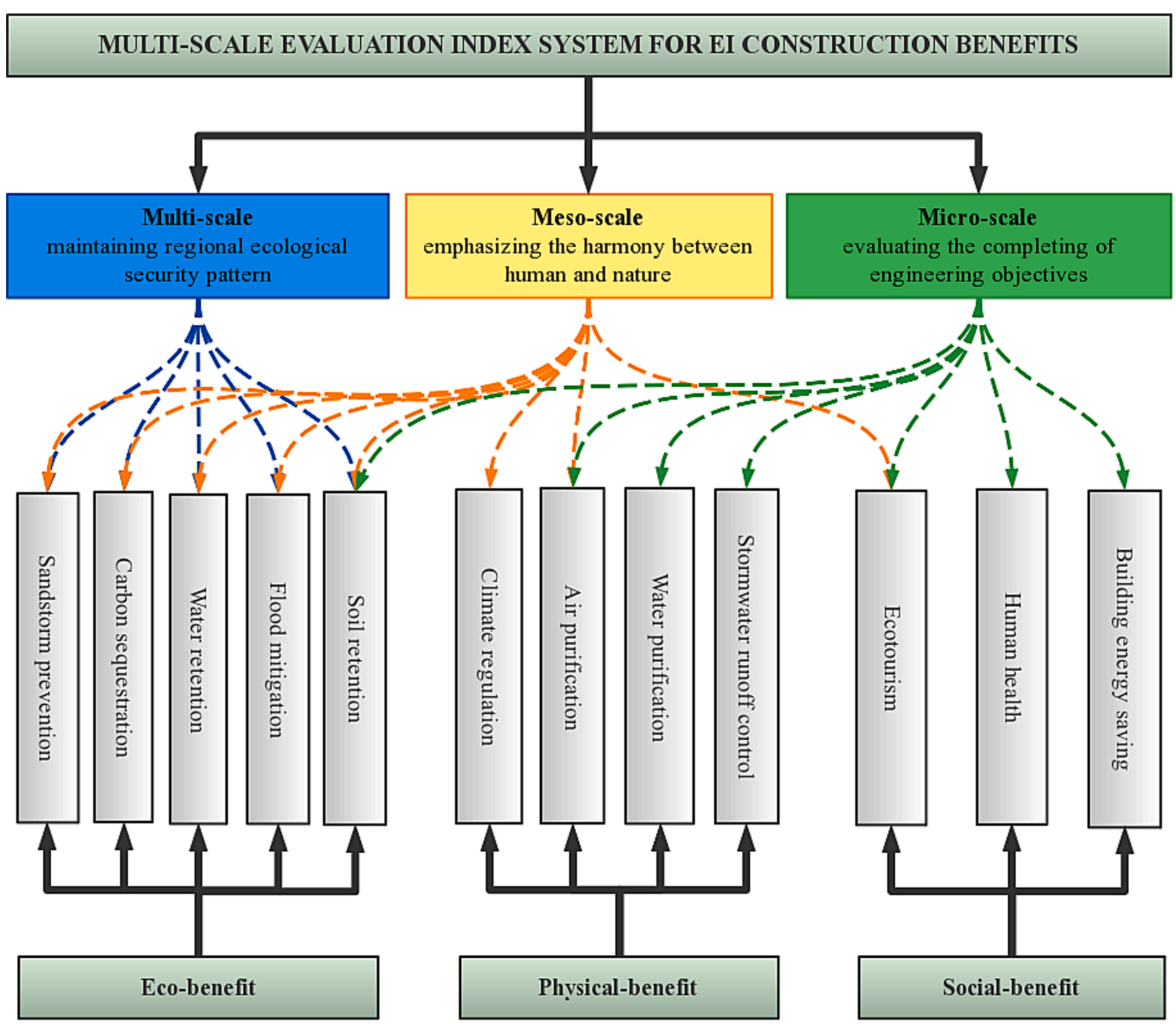

Fig. 2. Framework of multi-scale EI construction benefits evaluation.

shown in Fig. 3. Among them, although Huizhou city is second only to Zhaoqing city in the GBA in terms of greening rate, there are significant issues with the water ecological environment. The environmental and ecological issues that are typical of Huizhou can be seen at the construction site for EI, with poor water body quality and a straight, hardened river flow. It is imperative to restore the natural appearance and control the non-point source pollution. Therefore, the EI construction site relates to an ecological restoration project, with a total construction area of about 896 m^2.

3.2. Data

In this study, multi-sources and heterogeneous data are integrated and utilized for spatial and statistical analysis. The dataset includes land-use data, normalized difference vegetation index (NDVI) data, digital orthophoto map (DOM) data, potential evapotranspiration data, digital elevation model (DEM) data, net ecosystem productivity (NEP) data, soil data, cooling degree days data, ecotourism income data, coefficient of surface runoff data, air purification parameter data, rainfall data (daily and real-time), water surface evaporation data, water quality data, and questionnaire data. A detailed introduction is shown in Table 2. Except micro-scale, these related data are spatialized into uniform grid units to ensure data compatibility; each unit is 1 hm^2.

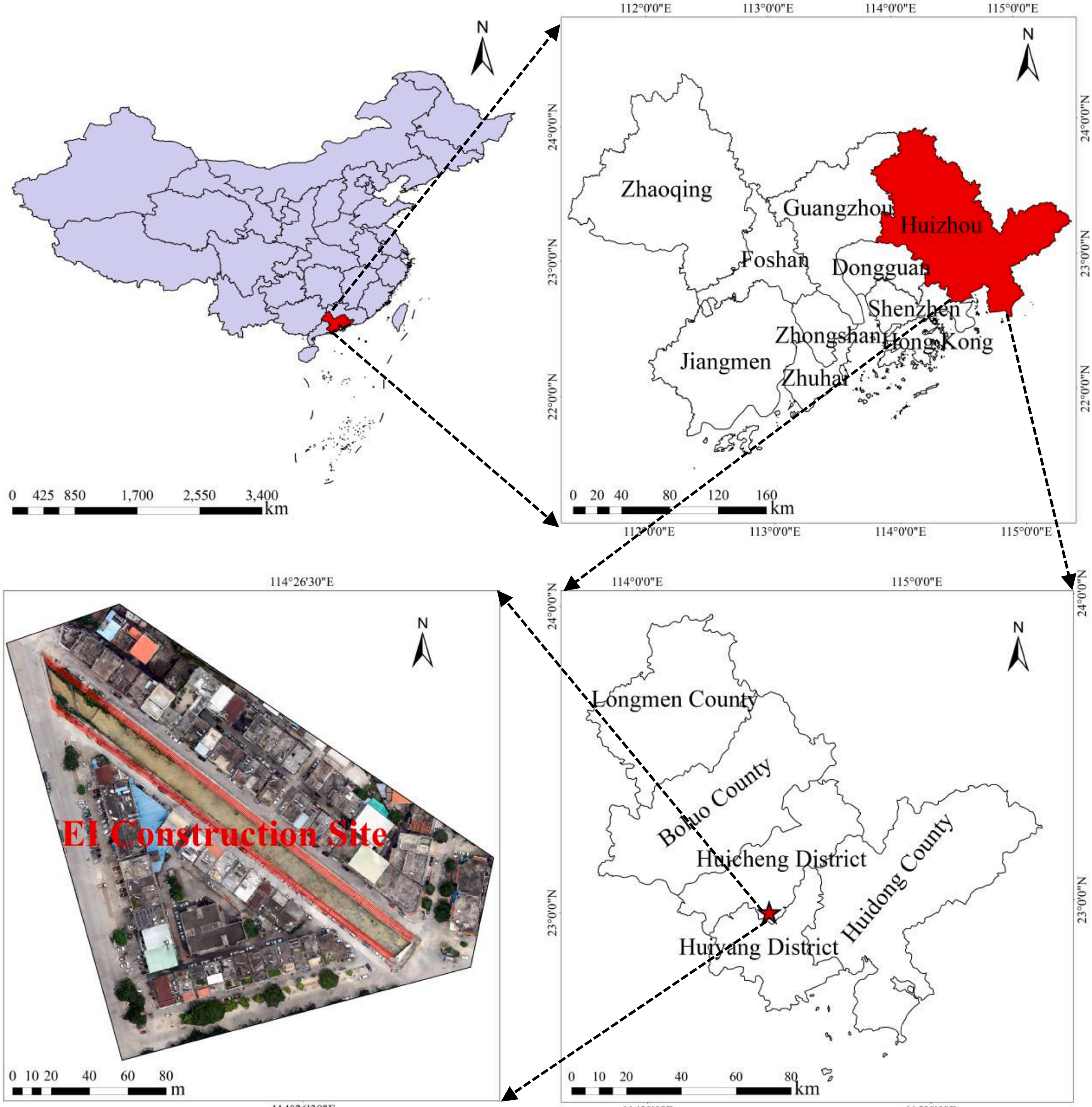

Fig. 3. Location of study areas.

Table 2
Overview and explanation of the multi-type of dataset.

Dataset	Year/format	Descriptions	Sources
Land-use	2020/raster (30 m)	A primary data about land-use in 2020, support for identifying EI type and area during water retention, air purification, flood mitigation calculation	GLOBELAND 30 http://globeland30.org/
DOM	2020/raster (1.4 m)	A drone orthophoto, used to evaluate the micro-scale EI construction benefits	Drone aerial photography
Potential evapotranspiration	2020/raster (1 km)	Data used to represent the evapotranspiration while measuring the water retention	Loess Plateau SubCenter National Earth System Science Data Center, National Science & Technology Infrastructure of China (http://loess_geodata.cn)
DEM	Raster (30 m)	Digital elevation model data, used to generate the LS factor while measuring soil retention service	Geospatial Data Cloud
NEP	2019/raster (0.072727°×0.072727°)	Data about net ecosystem productivity, used to calculate the carbon sequestration service in 2020	https://doi.org/10.12199/nesdc.ecodb.2016YFA0600200.02.003.
NDVI	2020/raster (30 m)	Annual NDVI in 2020, used to generate the C factor during soil retention calculation	https://doi.org/10.12199/nesdc.ecodb.rs.2021.012
Soil	2008/raster (1 km)	Topsoil clay, sand, silt, and organic carbon fraction, used to generate the K factor in soil retention service	Harmonized World Soil Database (HWSD, v1.2)
	2013/raster (30 × 30 arc-second)	Data about Bulk Density, TK, TN, TP, applied to calculate the benefits of reducing sediment deposition, soil fertility protection, and preventing non-point pollution in soil retention services	A China dataset of soil properties for land surface modeling(Shangguan and Dai, 2014)
Cooling degree days	2020/numerical value (day-by-day)	Days for using air conditioner, applied to measure the service of climate regulation	China Meteorological Data Service Center
Ecotourism Income	2020/numerical value	Statistical data in Huizhou, which reflects the service of EI in Ecotourism benefit	2020 Huizhou Economic and Social Development Statistical Communique
Rainfall (>50 mm is rainstorm)	2020/numerical value (day-by-day)	Statistic rainfall data, used to generate raster data of annual rainfall, cumulative rainstorm, storm runoff, and R factor for counting soil retention, flood mitigation, and water retention	China Meteorological Data Service Center
Water surface evaporation	2020/numerical value	Annual water surface evaporation in 2020, used to measure climate regulation benefit by water	China Hydrological Annual Report 2021
Rainfall	2020/numerical value (mm, minute-by-minute)	Real-time rainfall data, used to calculate the stormwater runoff control and water purification benefit in EI construction site	Field monitoring by IoT
Water quality	2020/numerical value	Water quality before and after EI purification, used to calculate the benefit of water purification	Sample analysis
Questionnaire	2021 Spring/questionnaire (as *Appendix* A2)	Residents' satisfaction questionnaire data, applied to count the number of people who receive services from EI site construction and value their willingness to pay	Questionnaire surveys (323 valid questionnaires)
Coefficient of surface runoff	Coefficients from literatures	Applied for generating surface runoff raster data to calculate water retention and flood mitigation	(Gong et al., 2017; Lu et al., 2012; Yu et al., 2020)
Air purification parameter	Parameters from literatures	Used to calculate the air purification service	(Han and Zhou, 2015; Ma et al., 2002; Qian, 2010; Zhang, 2017)

3.3. Benefits accounting methods

EI is an essential component of our complex urban systems, which directly and indirectly delivers ecosystem services needed for human production and life through ecosystem service functions(Romero-Duque et al., 2020; Xie et al., 2001) that results in benefits(Potschin and Haines-Young, 2011). This study used ArcGIS and IUEMS (a GEP accounting platform Ouyang and his team developed) to calculate the biophysical quantity and monetary value of EI construction benefits in GBA, Huizhou City, and the EI site in 2020. Besides, because of no sandstorm risk in the history of the study area and the EI site relates to riparian restoration, the indicator of sandstorm prevention and building energy saving are not counted in the case study. The benefits assessment method related to the case is shown in *Appendix* Table A1.

3.4. Classification of comprehensive benefits

Based on the important assessment of ecosystem services, the normalized index method is used to process the benefit assessment results to get the benefit index EB_i of each evaluation indicator. Meanwhile, this study believes that the importance weight of each indicator is the same, value 1. Therefore, the comprehensive benefit index is calculated as follows:

$$EBI = \frac{\sum_{i=1}^{n} EB_i}{n}$$

Where EBI represents the comprehensive benefit index, n reflects the number of benefits involved.

Finally, based on the natural break method in ArcGIS, the comprehensive benefit of EI construction is classified into five grades: good, relatively good, moderate, relatively poor, and poor.

4. Results

4.1. Eco-benefits of EI construction in GBA (Macro-scale analysis)

The benefits of EI construction in GBA in 2020 are depicted in Fig. 4. Affected by the spatial distribution of rainfall in the current year, water retention and flood mitigation benefits are higher in the northeast and southwest but less in the northwest region. On the contrary, the carbon sequestration and soil retention benefits are highly consistent with the EI spatial distribution, mainly concentrated in the northwest and northeast forest areas. Table 3 shows the quality and value of ecosystem services for each benefit. In detail, based on water retention, carbon sequestration, soil retention, and flood mitigation indicators, the Eco-benefits of EI construction in 2020 in GBA were about 203.63 billion RMB. Among them, the carbon sequestration benefit was about 3.35 billion tCO_2, and the monetary value was 73.65 billion RMB, accounting for 36.17 % of total Eco-benefits. Water retention benefit comes in second, with a biophysical quantity benefit of 11.29 billion m^3 and a monetary value of 68.96 billion RMB, accounting for 33.86 % of the total Eco-benefits. The quantity of flood mitigation was about 6.93 billion m^3, and the value

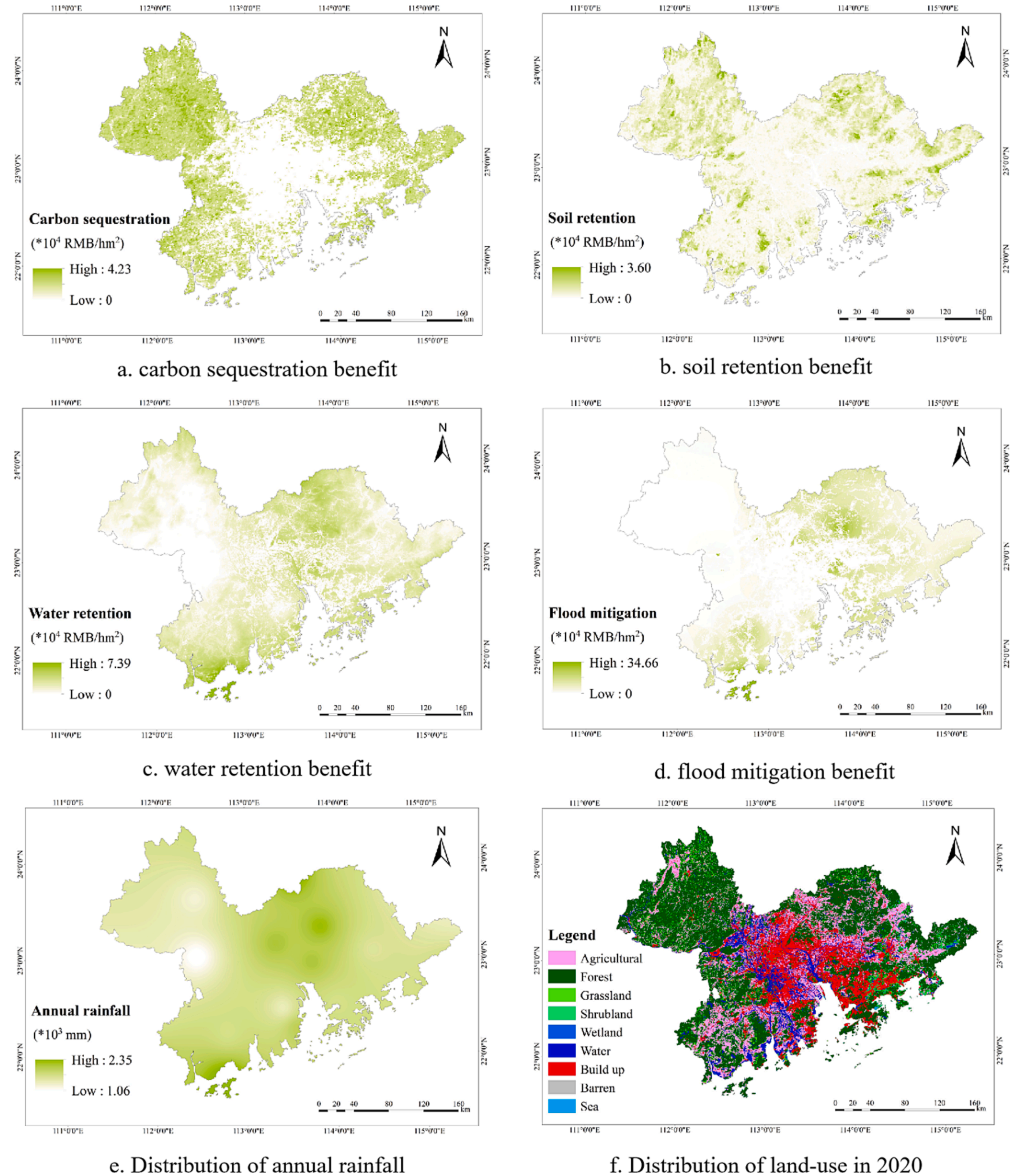

Fig. 4. Distribution of EI construction Eco-benefits in GBA in 2020.

was 42.37 billion RMB, accounting for 20.81 % of the total Eco-benefits. Among the Eco-benefits of GBA's EI construction in 2020, the soil retention function generates a minor benefit, preserving about 3.64 billion t of soil, preventing 0.73 billion m^3 of sediment deposition, and reducing the loss of N, P, K nutrients and non-point source pollution caused by soil erosion. Therefore, the soil retention benefit was 18.65 billion RMB, accounting for 9.16 % of the total Eco-benefits. In other words, based on the dataset collected in this study, the EI construction benefits of GBA in 2020 were ranked as carbon sequestration, water retention, flood mitigation, and soil retention.

Table 3
Eco-benefits of EI construction in GBA.

Functions	Benefit indicators		Biophysical quantity	Monetary value（billion RMB）		Percentage (%)
Water retention	Water retention (billion t/a)		11.29	68.96		33.86
Soil retention	Soil retention (billion t/a)		3.64	18.65		9.16
	Reduce sediment deposition (billion m^3/a)		0.70	9.19		4.13
	Soil fertility maintenance	N (million t/a)	1.63	0.52	3.04	1.37
		P (ten thousand t/a)	6.28	0.15		
		K (million t/a)	1.08	2.37		
	Nonpoint pollutants prevention	N (million t/a)	1.63	5.72	6.42	2.89
		P (ten thousand t/a)	6.28	0.70		
Carbon sequestration	Carbon sequestration (billion t CO_2)		3.35	73.65		36.17
Flood mitigation	Flood mitigation (billion m^3/a)		6.93	42.37		20.81
Total eco-benefits				203.63		100

By EBI classification, the result of the Eco-benefits grade more clearly shows the spatial distribution of EI construction benefits in GBA. As shown in Fig. 5, the areas with high EI construction benefits in 2020 are mainly distributed in GBA's northwest, northeast, southwest, and southeast coastal areas. The distribution pattern overlaps with the regional ecological core areas, including the northeast Jiulian Mountains, the southwest Jiangjun Mountains, the southeast Lianhua Mountains, and the northwest Qixin and Huashi Mountains(Liu et al., 2022a). So, mountains are essential for maintaining ecological security in GBA. Meanwhile, in the EI construction and planning process, the local governments should strengthen the ecological environment protection of the regional mountains to ensure the ecological security pattern. Meanwhile, during the urbanization process, the destruction of the integrity and connectivity of the mountain should be avoided.

4.2. *Comprehensive benefits of EI construction in Huizhou (Meso-scale analysis)*

Table 4 shows Huizhou's EI construction benefit in 2020 was about 358.50 billion RMB. Regarding Eco-benefits, the biophysical quantity of water retention was about 2.39 billion t, with a value of 14.63 billion RMB, accounting for 4.08 % of the total Eco-Physical-Social benefits. Soil retention capacity was about 0.94 billion t. Considering the benefits of reducing sediment deposition, preventing non-point source pollution, and reducing soil nutrient loss brought by this service, the soil retention of Huizhou EI construction in 2020 was about 4.47 billion RMB, accounting for 1.25 % of the total Eco-Physical-Social benefits. At the same time, the Huizhou EI fixed 0.81 billion tCO_2 and mitigated flood 2.09 billion m^3, with the monetary value of about 17.71 billion RMB and

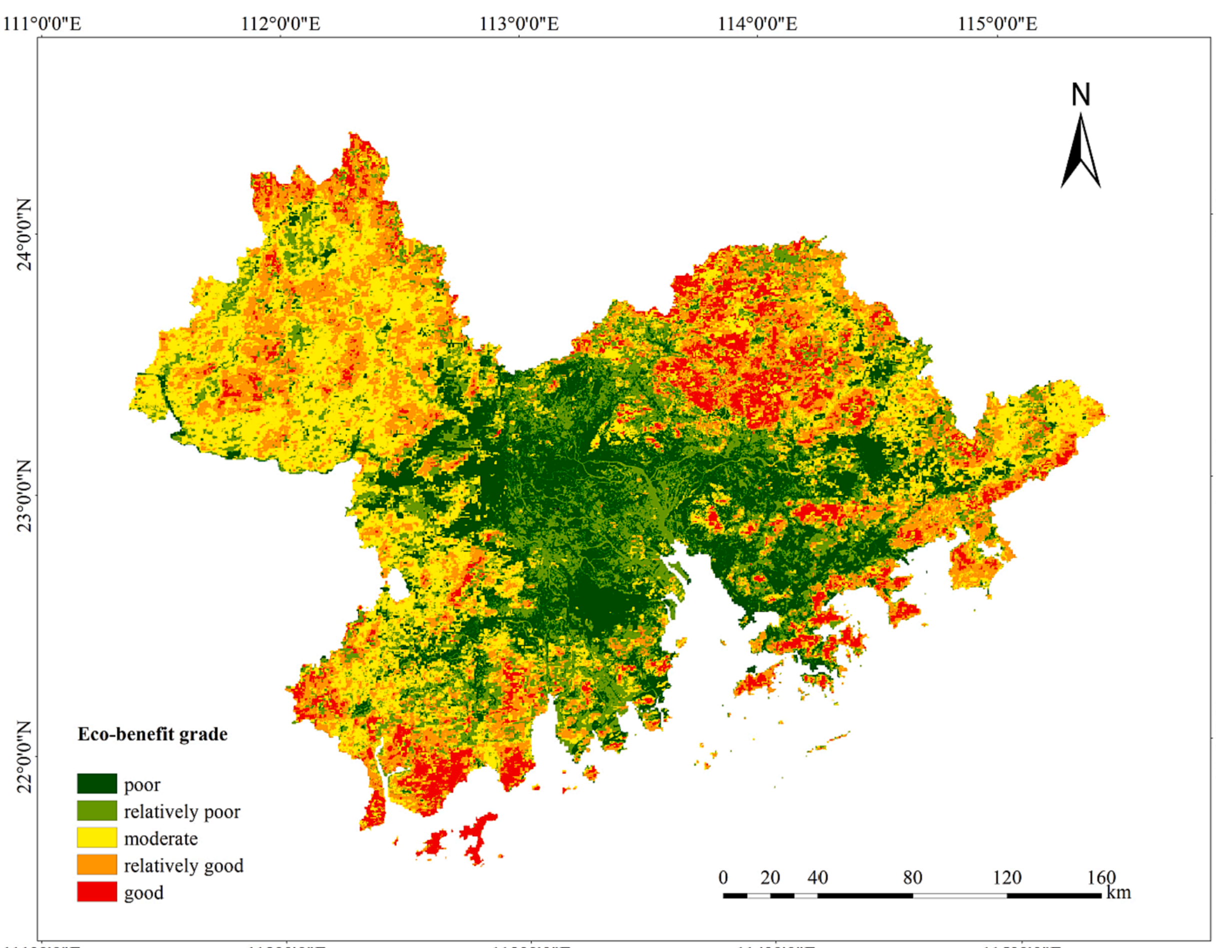

Fig. 5. Eco-benefits grade distribution of EI construction in GBA in 2020.

Table 4
The results of Eco-Physical-Social benefits in Huizhou in 2020.

Types	Functions	Benefit indicators		Biophysical quantity	Monetary value （billion RMB）		Percentage (%)
Eco-benefits	Water retention	Water retention (billion t/a)		2.39	14.63		4.08
	Soil retention	Soil retention（billion t/a）		0.94	4.47		1.25
		Reduce sediment deposition (billion m^3/a)		0.17	2.17		0.61
		Soil fertility maintenance	N (million t/a)	0.40	0.13	0.74	0.21
			P (ten thousand t/a)	1.46	0.035		
			K (million t/a)	0.26	0.58		
		Nonpoint pollutants prevention	N (million t/a)	0.40	1.39	1.55	0.43
			P (ten thousand t/a)	1.46	0.16		
	Carbon sequestration	Carbon sequestration（billion t CO_2/a）		0.81	17.71		4.94
	Flood mitigation	Flood mitigation (billion m^3/a)		2.09	12.76		3.56
Physical-benefits	Air purification	Air purification		—	6.90		1.92
		SO_2（ten thousand t/a）		6.25	0.12		0.033
		NO_x（ten thousand t/a）		1.31	0.025		0.0070
		PM_{10}（million t/a）		15.02	6.76		1.89
	Climate regulation	Climate regulation（billion kWh /a）		386.27	276.95		77.25
Social-benefits	Ecotourism	Service population（million man-time/a）		—	25.08		7.00
Total benefits					358.50		100

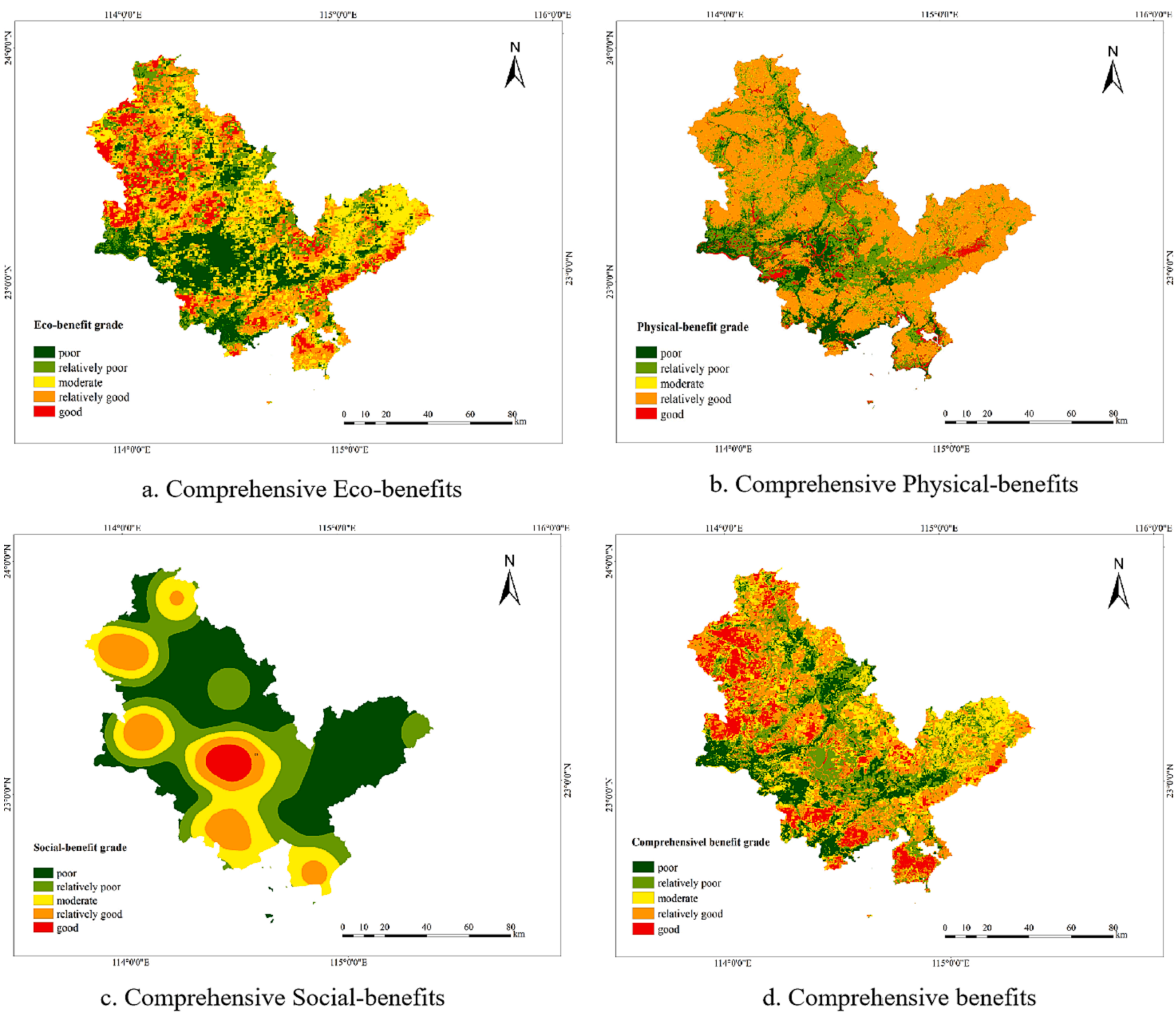

Fig. 6. Grade distribution of Huizhou EI benefits in 2020 (a) grade distribution of Eco-benefits, (b) grade distribution of Physical-benefits, (c) grade distribution of Social-benefits, (d) grade distribution of comprehensive benefits.

12.76 billion RMB, respectively, accounting for 4.94 % and 3.56 % of the total Eco-Physical-Social benefits. Among the Physical-benefits, air purification reached 6.90 billion RMB, accounting for 1.93 % of the total Eco-Physical-Social benefits, in which the annual SO_2 removal amount was about 6.25×10^4 t, the total amount of NO_X removal was 1.31×10^4 t, and the removal amount of atmospheric suspended particulate matter was 15.02×10^9 t. Therefore, the air purification benefit of EI construction mainly comes from vegetation's retention and adsorption of suspended particles in the atmosphere. The climate regulation benefit calculated by the principle of transpiration was about 386.27 billion kWh. Based on the relevant provision in value, the monetary value of climate regulation was about 276.95 billion RMB, accounting for 77.25 % of the total Eco-Physical-Social benefits of EI construction in Huizhou. The value of ecotourism brought by leisure and entertainment services was evaluated at Social-benefits. Based on relevant documents and data statistics, its value was about 25.08 billion RMB, accounting for 7.00 % of the Eco-Physical-Social benefits of EI construction in the same year. To sum up, among the comprehensive benefits of EI construction in Huizhou in 2020, the Physical-benefits is the largest about 79.18 %, followed by the Eco-benefits and Social-benefits, about 13.83 and 7.00 %, respectively. The specific benefits are listed in the following order: climate regulation, ecotourism, carbon sequestration, flood mitigation, water retention, air purification, and soil retention.

The ecological, physical, and social benefits evaluation results have been graded by EBI classification method. As shown in Fig. 6, there are apparent noticeable spatial differences among the three types of benefits. The high Eco-benefits regions are mainly distributed in the study area's northwest and southeast mountains and nature reserves (Fig. 6 (a)). Meanwhile, the areas with high Physical-benefits are distributed in the region's river and lake zones, as shown in Fig. 6 (b). The reason includes the high contribution of climate regulation in Physical-benefits and the water's high specific heat capacity. Besides, unlike the spatial distribution of the benefits discussed before, the social benefits brought by ecotourism are mainly concentrated along the northwest to southwest of the study area, where, the central region presents the highest ecotourism benefit (Fig. 6(c)). Overall, the result of the comprehensive benefits classification of Huizhou City in 2020 (Fig. 6 (d)) shows that the spatial distribution of the high comprehensive benefits zone is consistent with the regional primary and secondary ecological core areas and corridors, including Jiulian Mountains, Lianhua Mountains, Mangrove Nature Reserve, Pingfeng Nature Reserve, Xiangtou Mountain Nature Reserve, and Honghua Lake Scenic area(Liu et al., 2022a).

4.3. Benefit of EI construction in site (Micro-scale analysis)

In this study, the EI construction at the micro-site research area aims to restore the regional water ecological environment and meet the recreational needs of residents. It is worth emphasizing that the site survey indicates no soil erosion phenomenon before EI engineering in history. In other words, the EI construction has only modest and insignificant benefits from soil retention.

Therefore, except for soil retention benefit, according to the MECBs-NbS evaluation framework, Table 5 shows that the value of EI construction benefits in the micro-study area in 2020 was about 34.85 million RMB. Among them, regarding Physical-benefits, the total surface runoff collected and purified by EI construction in 2020 was about 898.03 m^3. Combined with the unit price of drinking water in the region, the value of water purification benefits was about 6.49 thousand RMB, accounting for 0.019 % of the total Eco-Physical-Social benefits in the same year. In terms of runoff control benefits, based on the annual rainstorm monitoring data and the catchment area of the study area, the biophysical quantity was about 1370.00 m^3, and the monetary value was around 4.58×10^4 RMB, accounting for 0.13 % of the total Eco-Physical-Social benefits. Moreover, the on-site EI construction air purification benefit was about 1.42×10^5 RMB, accounting for 0.41 % of the total Eco-Physical-Social benefit in 2020. Besides, the Social-benefits have been evaluated, including ecotourism and human health services. Questionnaire survey data shows that in 2020, the service number of the EI site was about 0.28 million man-time, and its monetary value was about 23.52 million RMB, based on 84.00 RMB per person's willingness to pay, accounting for 67.49 % of the total Eco-Physical-Social benefits. Meanwhile, the human health benefit was about 11.13 million RMB, accounting for 31.95 % of the total Eco-Physical-Social benefits. Therefore, the Social-benefits of EI construction on the site in 2020 accounted for 99.44 % of total Eco-Physocal-Social benefits. In other words, the production of EI site benefits mainly comes from the social and cultural services provided to regional residents.

5. Discussion

5.1. Difference of EI construction benefits at different scale

Based on the ecosystem services cascade model proposed by Postchin and Haines-Young(Potschin and Haines-Young, 2011), ecosystem services originate from a series of biophysical structures and functional processes, while the benefits come from the use of these services by human beneficiaries (Romero-Duque et al., 2020). Namely, benefits are seen as gains in welfare generated by ecosystems, leading to the supply–demand flow of ecosystem services within the complex urban system(Potschin and Haines-Young, 2011). Meanwhile, the benefits are influenced not only by time but also by spatial places with different ecological structures, component elements, and functions(Fisher et al., 2009). Therefore, there are differences in EI construction benefits with different spatial scales.

As shown in Fig. 7, with the built-up area as the center, as the spatial scale shrank, EI construction benefits gradually changed from being dominated by Eco-benefits to being dominated by Social-benefits, in which ecotourism service becomes the leading benefit source in the micro-scale. The intrinsic reason is that factors such as ecological network connectivity and integrity, the size of the ecological core area, and the accessibility of ecosystem services all influence the benefits of ecosystem services(Bai et al., 2018). As we know, biophysical services are generated from the ecological process and structure(Childers et al., 2019; Potschin and Haines-Young, 2011). As a result, the fragmentary ecological core area and the destruction of the connectivity within the ecological network caused by urbanization will become more

Table 5
The results of Eco-Physical-Social benefits in EI site in 2020.

Types	Functions	Benefit indicators	Biophysical quantity	Monetary value (RMB)	Percentage (%)
Physical-benefits	Water purification	Water purification (m^3)	898.03	6.49×10^3	0.019
	Storm water runoff control	Storm water runoff (m^3)	1370.00	4.58×10^4	0.13
	Air purification	Air purification	—	1.42×10^5	0.41
		SO_2 (t/a)	1.10	2.08×10^3	0.0060
		NO_x (t/a)	0.12	232.07	0.00067
		PM_{10} (t/a)	311.27	14.01×10^4	0.40
Social-benefits	Ecotourism	Service population (Man-time/a)	0.28×10^6	23.52×10^6	67.49
	Human health	Residents' satisfaction	—	11.13×10^6	31.95
Total benefits				34.85×10^6	100

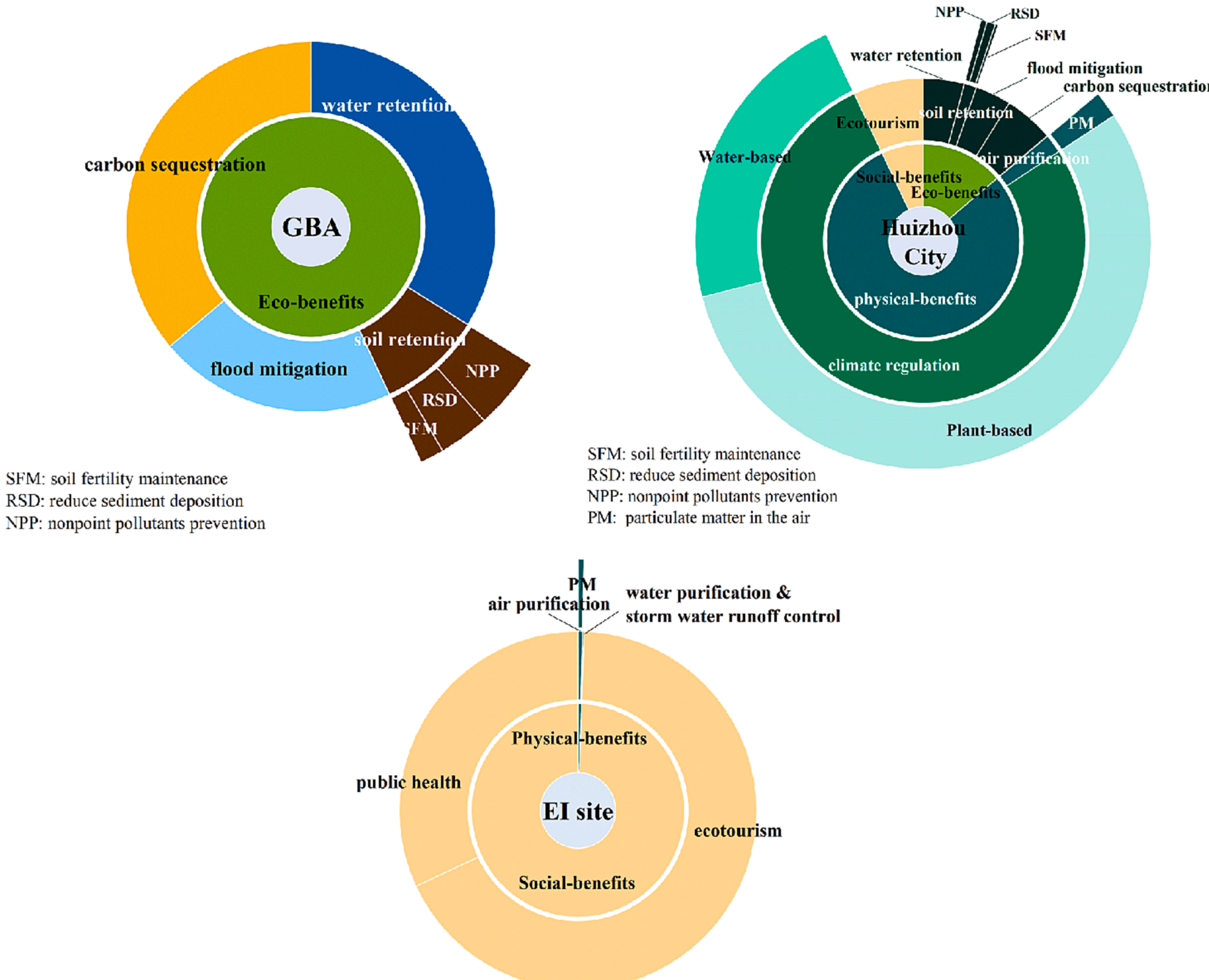

Fig. 7. Changes of ecosystem benefits in multi-scale EI construction.

pronounced with a reduction in spatial scale, breaking ecosystem security patterns, limiting the production of ecosystem services, and eventually leading to a sharp decline in the Eco-benefits (DEFRA, 2011; Wang et al., 2021). Considering the spatial relationship between service-providing and benefiting areas, the accessibility of ecosystem services is the main reason for the Eco-benefits' decline and the Social-benefits' gradual dominance with scale decline(Ala-Hulkko et al., 2016). Fig. 8 presents the central location of Huizhou's good ecological, physical, and social benefits grade region by ArcGIS median center tool and the distance from the built-up center. The result shows that the distance between the center of high Social-benefits and the built-up center is the shortest, followed by the distance of Physical-benefits, and the distance between the center of high Eco-benefits and the center of built-up is the farthest. It reflects the importance of the accessibility of ecosystem services. In summary, we think this law of benefit change exists, even though the choice evaluation indicators impact it.

Therefore, it is essential to ensure the regional ecological security pattern by constructing ecological corridors and protecting ecological core areas at the macro-scale(Jongman, 1995). Simultaneously, to enhance the quality of human settlement and address urban problems, more investigation must be done on the potential and actual ecosystem service demand of regional residents during the construction process of the smallest structure unit (Han et al., 2020). A more intricate process, the *meso*-scale EI construction must balance the interaction between humans and nature while considering ecosystem services that directly or indirectly benefit humans(Lovell and Taylor 2013). In other words, *meso*-scale EI construction should ensure the connection with the macro-ecological network(Liu et al., 2023) and pay attention to the rationality of regional ecological spatial distribution(Metzger et al., 2021).

5.2. How MECBs-NbS framework supports process of EI construction

Realistic ecological problems and needs at the small-scale cannot be well represented by large-scale ecological networks (Tao et al., 2022). To develop and execute strategies for adaptive management, we need to identify what people value at different scales in order to recognize or problematize the significant biophysical processes(Potschin and Haines-Young, 2011). According to the EI construction flow(Liu et al., 2023), sustainable assessment, multi-scale scheme formulation, and adaptive management are the three critical aspects of EI construction. By identifying the typical environmental problems and major societal challenges, supporting multi-scale system planning and design, and even the adaptive co-participation and management for transboundary environmental stakeholders, the proposed MECBs-NbS framework is expected to facilitate the implementation of NbS action, as depicted in Fig. 9.

Specifically, before engineering, it is imperative to identify the specific problems and needs of EI construction at each scale during state quo analysis(Liu et al., 2023; Potschin and Haines-Young, 2011). By

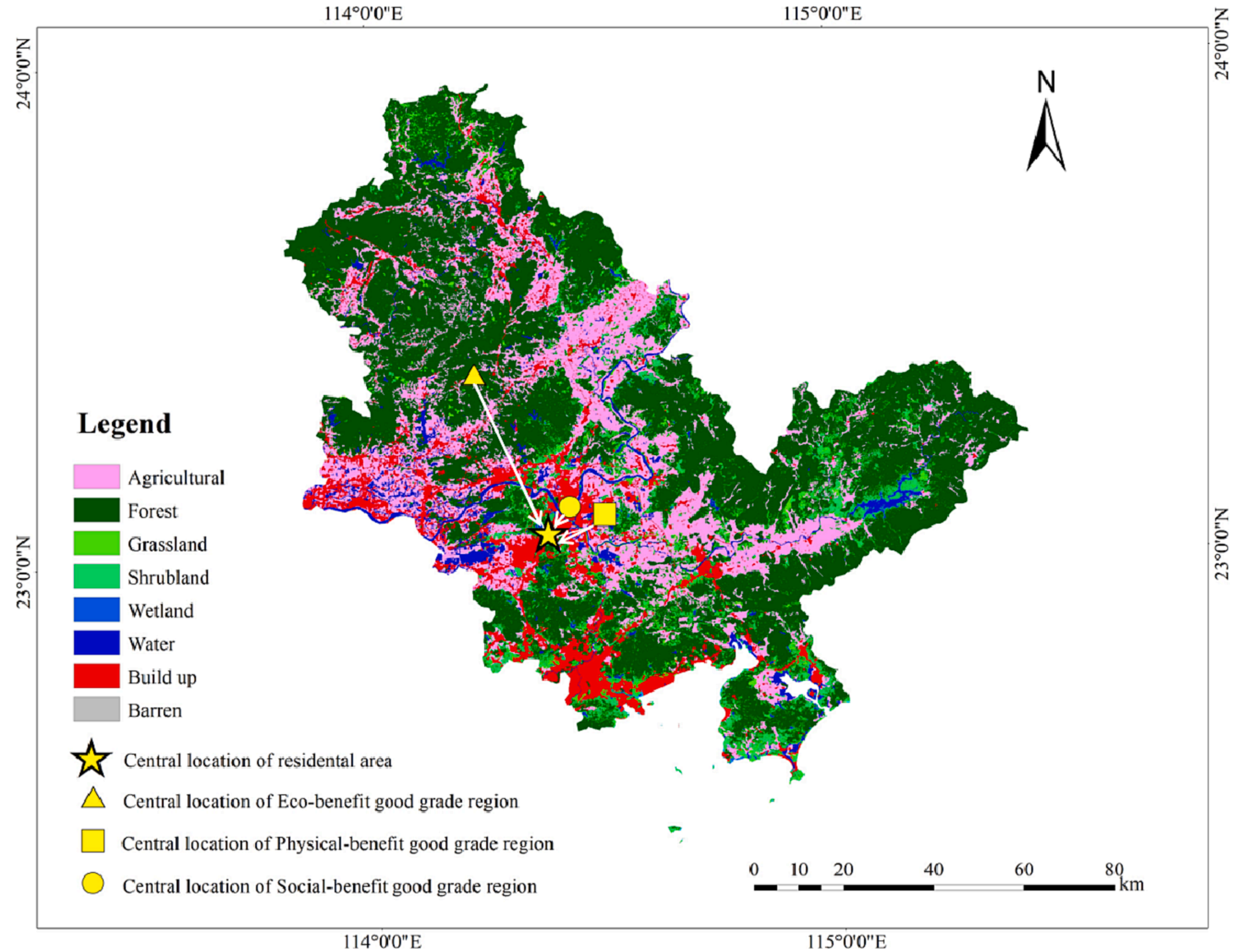

Fig. 8. Central location of good grade region of Ecological, Physical and Social benefit in Huizhou in 2020.

evaluating environmental carrying capacity and confirming the critical social challenge (path one), the MECBs-NbS evaluation framework serves as a fundamental tool for the sustainability assessment; the outcomes then directly support the multi-scale scheme formulation to meet the specific requirements at spatial scales accurately. Besides, after EI construction, the MECBs-NbS framework is a quantitative evaluation method (path two). It supports the phased benefit assessment for the acceptance and management of engineering projects, as well as stage improvement(Liu et al., 2023). Meanwhile, the results can be used as a money transfer or points basis to encourage individuals, groups, and companies to participate in the ecological construction activities of a city in nature(Zou et al., 2020). Besides, integrating with existing standards and policies, the MECBs-NbS evaluation framework may facilitate regional ecological compensation or trading and serve as a guide for evaluating the efficacy of policies and managers' performance (path three).

5.3. Research prospect

The evaluation of EI construction benefits is a systematic engineering project that relies not only on the scientific design of evaluation indicators but also on the quality of primary data, the development and updating of calculation models and software. By comparing results from various literatures (Lin et al., 2021; Wang et al., 2020; Wen et al., 2020; Xu et al., 2020; Zhang et al., 2023), we were able to determine that variations in data or model led to distinct evaluation results. Consequently, even though researchers have studied ecosystem services extensively, more research on comparison and systematic comprehension of evaluation model error, as well as technical data standardization must be done. Second, only data that is currently accessible is used in this study. There is still room for improvement in this evaluation framework, which we continue refining. The purpose of this study is to provide a new perspective on multi-scale EI construction evaluation.

6. Conclusion

Regarding the multi-layer characteristics of EI, the benefits of EI construction should be assessed at different scales, with each assessment providing a specific reference to EI planning and management from its own viewpoint. Therefore, based on the NbS criteria, this study proposes a MECBs-NbS evaluation framework for multi-scale EI construction benefit assessment, in which macro-scale prioritized Eco-benefits, *meso*-scale comprehensively consider the Eco-Physical-Social benefits, and the micro-scale is dependent on the construction objectives. By reflecting the disparities in human and natural well-being (resolved problems, demands, and requirements) at various scales that EI meets, the design of this evaluation framework seeks to provide a perspective on how to evaluate the multi-scale EI construction benefits. This framework has been followed in the case study. The obtained conclusions are as follows.

Firstly, the case study proves the feasibility of the multi-scale EI

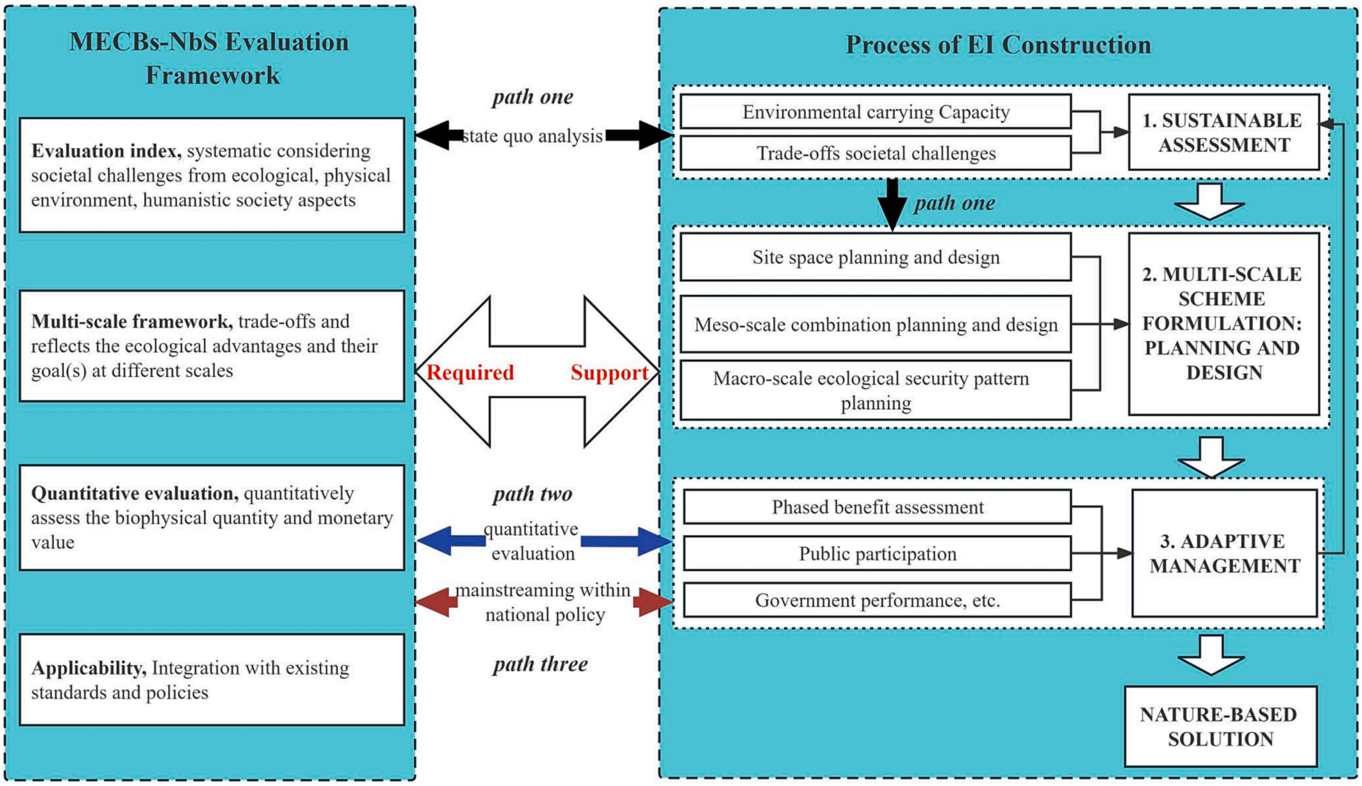

Fig. 9. Relationship between MECBs-NbS evaluation framework and process of EI construction.

construction evaluation framework. Moreover, compared with meso and micro-scale, the macro-scale EI construction emphasizes the protection of the overall regional ecological security pattern. The Eco-benefits of EI construction in GBA in 2020 reached 203.63 billion RMB, among which carbon sequestration presents a significant dominance over water retention, flood mitigation, and soil retention. At the meso-scale, to improve the harmony between humans and nature, the total benefit value of EI construction in Huizhou in 2020 was about 358.50 billion RMB. The ecological, physical, and social benefits account for 13.83 %, 79.18 %, and 7.00 % of the total benefits, respectively. At the micro-scale, to restore the regional water ecological environment and meet the recreational needs of residents, the total benefit in 2020 was 34.85 million RMB, of which the Physical-benefits account for 0.56 %, and the Social-benefits account for 99.44 %. With the built-up area as the center, as the spatial scale shrank, EI construction benefits gradually changed from being dominated by Eco-benefits to being dominated by Social-benefits, in which ecotourism service became the leading benefit source on the micro-scale. This is due to the influence of the accessibility of ecosystem services, the connectivity and integrity of the ecological network, and the size of the ecological core area at different scales. Besides, the MECBs-NbS framework could aid the whole EI construction process by performing a state quo analysis, quantitative evaluation, and integrating existing policies and standards to ensure EI follows multi-scale design, trade-offs, and addresses social challenges, as well as standardized management.

CRediT authorship contribution statement

Lingyu Liu: Conceptualization, Supervision, Investigation, Formal analysis, Data curation, Writing – review & editing. **Longyu Shi:** Conceptualization, Supervision. **Meng Yang:** Investigation, Writing – review & editing. **Fengmei Yang:** Investigation, Writing – review & editing. **Ting Lan:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2024.111609.

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