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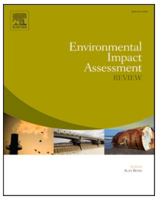

Assessing inter-industrial ecosystem service flows and economic benefits of sponge city: A comprehensive input-output analysis

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ABSTRACT

Sponge cities, crucial components of urban eco-infrastructure, play a vital role in mitigating urban waterlogging, enhancing water resource management, and improving ecosystem resilience. However, the economic and ecosystem services benefits of low-impact development (LID) facilities in cities remain unclear. This study classified sponge city facilities as distinct subsectors within an input-output framework and develops a partial closure model to assess their economic and ecological impacts during construction and operation phases. Additionally, an ecological satellite account for carbon sinks, SS removal and water conservation is compiled to quantify the economic value of ecosystem services. Using Xining City's sponge city project as a case study, the findings reveal that the primary sector benefits most from water conservation (34.58 %), while government consumption (58.9 %) is the largest indirect beneficiary of suspended substance (SS) removal and carbon sequestration, reflecting the public good nature of environmental benefits. Sponge city construction stimulates economic activity, with total inputs exceeding four times the direct investment, driving growth in hidden sectors such as food processing, finance, and energy distribution. Additionally, the carbon sequestration from sponge city facilities offsets construction-related emissions within 4.07 years, though only 41.78 % of maintenance-phase emissions are balanced by carbon sinks, emphasizing the need for long-term sustainability measures. These results highlight sponge cities' unique role in economic restructuring, distinguishing them from traditional infrastructure. The study provides a framework for integrating ecological and economic indicators, supporting evidence-based urban planning and the transition toward a sustainable, eco-economic development model.

1. Introduction

With the acceleration of global urbanization, the expansion and renewal of urban infrastructure has emerged as a pivotal driver in promoting economic growth and social development. However, conventional urban development models, characterized by excessive land consumption, impermeable surfaces, and inefficient water management systems, have often led to severe environmental degradation. Studies show that between 1992 and 2015, urban land expansion caused significant losses of global natural vegetation (van Vliet, 2019), while over 60 % of urban areas worldwide suffer from water stress due to poor water cycle management (United Nations, 2022). These unsustainable practices have exacerbated a range of environmental challenges, including water scarcity, frequent urban flooding, declining water quality, and the intensification of the urban heat island (UHI) effect, which has led to urban temperatures rising by 3–5 °C compared to surrounding rural areas (Oke et al., 2017). These environmental threats not only undermine urban ecological security but also hinder sustainable economic development. For instance, extreme urban flooding events have caused global economic losses exceeding $77 billion annually over the past two decades (CRED, UNDRR, 2020). Consequently, there is an urgent need for a paradigm shift in urban infrastructure planning—one that integrates ecological sustainability with economic resilience. As integral components of urban ecosystems, well-

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designed infrastructures can mitigate environmental risks while enhancing human well-being and biodiversity (Pandit et al., 2017).

Among various innovative urban infrastructure approaches, the "sponge city" concept has gained widespread recognition for its ability to enhance urban resilience by optimizing ecosystem services. By integrating nature-based solutions (NbS) such as low-impact development (LID) facilities, sponge cities have demonstrated their effectiveness in reducing flood risks and improving water resource efficiency (Islam et al., 2021; Ma et al., 2024; Ma and Jiang, 2023; Vineyard et al., 2015). These ecological strategies not only enhance urban livability but also provide long-term economic benefits by reducing disaster recovery costs and enhancing land value (Xu et al., 2019). Recent research has highlighted their critical contribution to both environmental sustainability and economic productivity. This paradigm shift has led to a growing emphasis on quantifying, managing, and even commercializing ecosystem services, transforming them from freely available public goods into marketable assets.

1.1. Ecosystem services: From natural benefits to marketable products

The study of the processes and mechanisms shaping urban ecosystems, ranging from monetized measures of service provision at the static level (Vineyard et al., 2015; Xu et al., 2019) to dynamic assessments incorporating multilevel stakeholder perspectives (de Groot et al., 2002; Li et al., 2019; Ma et al., 2024; Mao et al., 2023; Wang et al., 2022; Xu et al., 2017), especially the regional variability, dynamic changes and spatial-temporal coupling of ecosystem service flows (Ma and Jiang, 2023; Vačkářová et al., 2023; Wolff et al., 2015; Zhu et al., 2019). This transition from cross-sectional analyses to process studies has led to an enhancement in the systematic understanding of the mechanisms that shape urban ecosystem services. The spatial disjunction and industrial correlation between the supply and consumption of ecosystem services drive the flow of service products across spatial, temporal, and industrial sectors (You et al., 2024), The research is also gradually extending from the locational theory of ecosystem service flow studies, utilizing tools such as GISs (Wolff et al., 2015) to industry linkage analysis. It is important to note that ecosystem services are undergoing a transformation from unpaid public goods to marketed commodities. The rise of emerging businesses, such as carbon trading (Du et al., 2025; Gao et al., 2023; Jiang et al., 2025; Rosa and Sánchez, 2015). indicates that ecosystem protection has entered a new phase of exploration. The concept of the "fourth industry" of ecosystem products (Wang et al., 2021) signifies an elevation of ecological resources to an economic factor characterized by independent industrial attributes. The transformation shifts ecosystem services from physical "assets" to virtual "capital", enabling their intrinsic value to be converted into a tradable state, generating cash flow, and reflecting the value of ecosystems from an economic perspective. The conversion of ecosystem services from physical assets to virtual capital can be achieved through input-output analysis (Zhang et al., 2024).

Existing studies have clarified the spatial supply–demand relationships among ecosystem services, indicating the distribution and quantity of ecosystem services (Chen et al., 2024; Sun et al., 2022; Zeng et al., 2023). However, significant knowledge gaps remain. First, while previous research has mapped ecosystem service distributions, it has largely failed to resolve the delivery mechanisms governing ecosystem service flows. This includes an incomplete understanding of flow processes, service pathways, and the identification of beneficiary groups. Second, although ecosystem service flows provide an empirical reflection of the actual benefits ecosystems deliver (Bagstad et al., 2013), the majority of existing analyses remain confined to natural systems, failing to integrate socio-economic linkages. Third, a fundamental incompatibility exists between conventional industrial classification systems and ecological-economic frameworks, restricting the institutional design necessary for the marketization of ecosystem services. This disconnect is particularly pronounced in applied contexts. For example, while ecological infrastructure projects such as sponge cities demonstrably enhance ecosystem service provision, the quantitative characterization of their cross-sectoral value flows lacks effective methodological support.

1.2. Sponge city ecosystem services and economic analysis

Sponge city infrastructure provides a range of ecosystem services that contribute to urban resilience and sustainable development. From an economic perspective, these services can be viewed as part of the "fourth industry" — a sector that transforms ecological benefits into economic assets. The core objective of this transformation is to establish a supply–demand management strategy that connects service providers with consumers, enabling a more precise valuation of both the ecological losses caused by production and consumption activities and the economic gains generated by ecosystem restoration. In this framework, the flow of ecosystem services functions as an ecological satellite account within an economic input–output model, offering a scientific foundation for intersectoral compensation policies (Forssell and Polenske, 1998; Minx et al., 2009; Suh and Kagawa, 2005).

The construction and implementation of sponge cities, grounded in the principles of green and sustainable development, have drawn considerable scholarly attention (Huang et al., 2024; Liu and Jensen, 2018; Vymazal, 2022). Particularly, research on LID facilities—such as vegetative roofs (El Bachawati et al., 2016; Mihalakakou et al., 2023), rain gardens (Vineyard et al., 2015) and permeable pavements (Wei et al., 2024) — has evolved from isolated facility-based evaluations to comprehensive life cycle assessments (LCA) of integrated LID systems (Chui et al., 2016; Jia et al., 2015; Li et al., 2019). This shift in focus reflects an increasing recognition of the synergistic benefits of LID infrastructure, not only in terms of engineering performance but also in areas such as carbon footprint reduction (Moore and Hunt, 2013) and overall cost-benefit analysis (Li et al., 2019).

Although LID facilities may require higher initial investments, life cycle cost analysis (LCCA) has demonstrated that they generally incur lower long-term operational costs compared to conventional urban infrastructure, particularly in stormwater management (Chan et al., 2018; Nguyen et al., 2019). By reducing the need for large-scale drainage network expansion and lowering maintenance costs, LID solutions significantly alleviate the financial burden of urban water management (Abdeljaber et al., 2022; Wang et al., 2023). Moreover, LID facilities offer notable climate benefits. A life cycle assessment of a sponge city project in Shenzhen found that green infrastructure reduced environmental impacts by 24 % compared to traditional urban drainage systems, particularly in terms of mitigating eutrophication and climate change effects (Tang et al., 2023). Similarly, research by Kavehei et al. (2018) found that rain gardens completely offset their carbon footprint, while bioretention basins and green roofs achieved 70 % and 68 % carbon offset, respectively.

Despite the increasing application of LCA in sponge city research, several limitations persist. First, most LCA studies focus predominantly on the construction phase of LID facilities, with limited assessments of their long-term operational performance (Tighnavard Balasbaneh et al., 2024). Second, many existing evaluations treat ecosystem services as static entities, failing to capture the dynamic transmission mechanisms of ecosystem services across different economic sectors. Third, prevailing studies often consider sponge cities as homogeneous systems, overlooking the differentiated economic linkages between specific LID facilities and industrial sectors. For example, while rain gardens are closely associated with the primary sector, traditional construction activities are more aligned with industries such as metal smelting, mineral product manufacturing, and energy production. Recognizing these sector-specific interdependencies is essential for designing effective policies that enhance the economic viability of sponge cities.

1.3. Integrating ecological and economic system dynamics

To address these gaps, this study develops an integrated ecological-economic framework that combines hybrid input–output life cycle assessment (IO-LCA) with ecosystem service flow analysis. This framework evaluates both the construction and operational phases of sponge cities, offering a more comprehensive understanding of their economic and environmental impacts. By incorporating sponge city ecosystem services into national economic accounting systems, this study aims to: (1) Identify key economic sectors that benefit from sponge city construction and maintenance, thereby improving sectoral compensation mechanisms for ecosystem services. (2) Analyze the value transfer pathways of ecological products, such as rainwater management and carbon sink services, across industrial sectors. (3) Examine the industrial stimulation effects of sponge city development, distinguishing its input structure and economic pull effects from those of traditional construction and urban utility sectors.

By accurately quantifying the intersectoral value flows of ecosystem services, this study provides cross-scale decision support for ecosystem service compensation policies and market-based mechanisms. Ultimately, it contributes to shifting sustainable urban development from an engineering-driven approach to a system-level governance framework that integrates economic and ecological priorities.

2. Methods

2.1. Methodological framework for establishing ecological satellite accounts in the urban IO model

The construction of sponge cities is widely recognized for generating positive economic and ecological benefits. However, these impacts have not been comprehensively quantified. LCA is a well-established method for evaluating resource consumption, energy use, and environmental burdens across the entire life cycle of a product or system (Rebitzer et al., 2004; Zhang et al., 2010). From a life cycle perspective, incorporating both the construction and operational phases into an accounting framework enables a more holistic assessment of the ecosystem services provided by sponge cities. Within the economic system, industrial sectors are highly interdependent, and ecosystem services are exchanged across sectors through intersectoral flows. The input–output (IO) model, which represents the structure of the entire national economy, provides a systematic approach to analyzing the economic and ecological interactions among sectors during the construction and operation phases of sponge cities.

To address the limitations of existing quantification methods, this study develops a hybrid life cycle assessment (LCA) integrated with input–output (IO) analysis to evaluate the economic and ecological impacts of sponge city development. The proposed methodological framework, illustrated in Fig. 1, facilitates the assessment of economic benefits and the flow of ecosystem services across industrial sectors during both the construction and operation phases of sponge cities. This framework consists of two key components: (1) Development of an input–output model that captures the sectoral interactions in the construction and operational phases of sponge cities. (2) Quantification of economic and ecological benefits, including industrial stimulation effects and environmental gains such as carbon sequestration and water resource recovery.

The first step in the framework involves constructing a non-competitive input–output (IO) table, which separates the economic data of sponge city construction and operation into distinct sectors. This disaggregation includes subsectors, final demand, and value-added components for each phase. Since labor plays a critical role in both the construction and operational phases, this study introduces an input–output partial closure model that incorporates labor compensation and household consumption. This refinement improves upon traditional IO models by explicitly accounting for labor-driven economic feedback loops. By distinguishing sponge cities as an emerging industry from traditional sectors, this approach highlights their unique structural and operational characteristics, thereby laying the foundation for a more precise assessment of both economic and ecological benefits.

Second, building upon the input–output model, this study develops methods to analyze the industrial influence and stimulation effect. The influence coefficient measures how changes in final demand for sponge city-related sectors affect other industries relative to the average impact across the entire economy. This enables an evaluation of how ecosystem services contribute to other sectors. The industrial stimulation effect assesses the broader economic ripple effects generated by sponge city development across the entire national economy. This approach identifies sectors that are indirectly stimulated by sponge city investments and reveals interconnections between these sectors and key industries involved in sponge city construction and operation. Besides, using pollutant impact assessment methods, the ecological benefits of sponge city construction—particularly in reducing carbon emissions, removing suspended substance (SS) and enhancing water management efficiency—are systematically evaluated.

2.2. Construction of an input-output model of sponge city based on its life cycle

2.2.1. Development of a noncompetitive input-output table

The input–output (IO) table is a fundamental economic accounting tool that represents the interdependencies between different sectors within the national economy. It provides a systematic balance of product sources and uses, capturing both sectoral interactions and economic flows. A key characteristic of the IO table is that the sum of each row equals the sum of its corresponding column, ensuring consistency in economic transactions. Depending on the treatment of imports, IO tables can be classified into competitive and non-competitive formats.

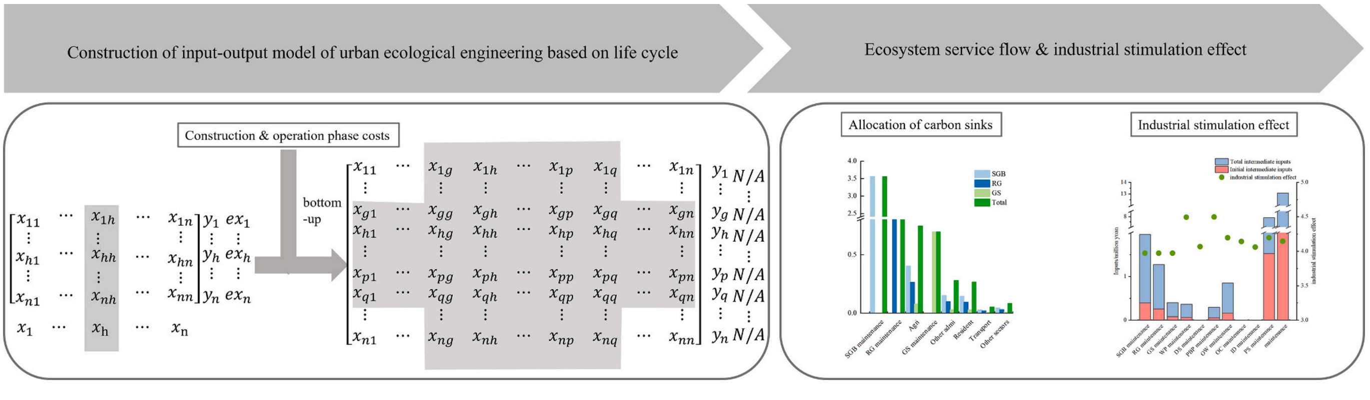


Fig. 1. The methodological framework.

A competitive IO table includes both domestic production and imported products in the same sector, potentially leading to overestimated economic linkages (Su and Ang, 2013). To improve accuracy, this study converts the competitive IO table into a non-competitive format, which separates domestic production, international imports, and interprovincial imports (Shen and Wu, 2003; Wu et al., 2015). This transformation ensures a more precise representation of regional economic structures and prevents distortions caused by the aggregation of different sources of supply.

Mathematically, the general structure of an IO system can be expressed as:

$$X = Y$$

$$\sum_{i=1}^{n} x_{ij} + v_i = \sum_{j=1}^{n} x_{ij} + y_i - m_i - z_i \tag{1}$$

$$a_{ij} = \frac{x_{ij}}{x_j} \tag{2}$$

where X represents the total input matrix; Y is the total output matrix; v_i denotes the added value, and x_{ij} is the intermediate matrix, reflecting the input-output relationship between product sectors. From a column perspective, it represents the consumption of products from sector i in the production of sector j; from a row perspective, it shows the allocation and utilization of the products from sector i to the products of sector j. m_i is the value of products or services purchased from abroad; z_i is the value of products or services purchased from the rest of the country; and a_{ij} is the direct consumption coefficient, representing the consumption of product i by the production unit product j.

To transform a competitive IO table into a non-competitive IO table, the assumption is made that the distribution of imported goods mirrors that of domestic products. Under this assumption, the treatment of international imports follows:

$$m_i = \sum_{j=1}^{n} x_{ij}^m + y_i^m \tag{3}$$

$$x_{ij}^m = m_i \frac{x_{ij}}{\sum_{j=1}^{n} x_{ij} + \sum_{j=1}^{k} y_i}$$

$$y_i^m = m_i \frac{y_i}{\sum_{j=1}^{n} x_{ij} + \sum_{j=1}^{k} y_i} \tag{4}$$

Similarly, for interprovincial imports:

$$z_i = \sum_{j=1}^{n} x_{ij}^z + y_i^z \tag{5}$$

$$x_{ij}^z = z_i \frac{x_{ij}}{\sum_{j=1}^{n} x_{ij} + \sum_{j=1}^{k} y_i}$$

$$y_i^z = z_i \frac{y_i}{\sum_{j=1}^{n} x_{ij} + \sum_{j=1}^{k} y_i} \tag{6}$$

After transformation, the relationship between the non-competitive and competitive IO tables is expressed as:

$$x_{ij}^d + x_{ij}^m + x_{ij}^z = x_{ij}$$

$$y_i^d + y_i^m + y_i^z = y_i \tag{7}$$

$$a_{ij}^d = \frac{x_{ij}^d}{x_j}, a_{ij}^m = \frac{x_{ij}^m}{x_j}, a_{ij}^z = \frac{x_{ij}^d}{x_j} \; a_{ij}^d + a_{ij}^m + a_{ij}^z = a_{ij} \tag{8}$$

where, x_{ij}^d, x_{ij}^m, and x_{ij}^z are the elements of the intermediate flow matrix of regional products, international imports and interprovincial imports in the noncompetitive input-output table, respectively. x_{ij} is the element of the intermediate matrix of the original competitive input-output table. y_i^d, y_i^m, and y_i^z are the elements of the regional product final use matrix, international imported product final use matrix, and interprovincial import final use matrix in the noncompetitive input-output table, respectively. y_i is the element of the original competitive input-output table final use matrix. a_{ij}^d, a_{ij}^m, and a_{ij}^z are the direct consumption coefficients of regional products, international imported products and interprovincial imported products in the noncompetitive input-output table, respectively. a_{ij} represents the direct consumption coefficient in the original competitive input-output table.

Following this transformation, the final equilibrium relationship in the non-competitive IO table is given by the Leontief equation:

$$X = (I - A)^{-1} Y = LY \tag{9}$$

where, X is the total input matrix; Y is the total output matrix; $L = (I - A)^{-1}$ is the Leontief inverse matrix; I is the identity matrix and A is the direct consumption coefficient matrix.

2.2.2. Division of the input-output table based on the life cycle

In the Chinese input–output (IO) system, economic activities are typically classified into 42, 149 or 153 sectors. However, even the most detailed 153-sector IO table fails to distinguish between the construction and operation phases of sponge cities. This omission poses a significant challenge to accurately capturing the sectoral linkages and interdependencies involved in sponge city development. In existing economic assessments, sponge city construction is often categorized under broad sectors, such as construction (42-sector classification), civil engineering construction (149-sector classification), or other civil engineering construction (153-sector classification). However, this generalized classification does not reflect the unique economic characteristics of sponge city infrastructure, particularly in terms of its upstream and downstream sectoral relationships during different life cycle phases.

One key limitation of standard IO tables is that they group multiple economically distinct activities into a single sector, even when these activities exhibit differentiated linkages with other industries in the production process. Using the existing sectoral classification for sponge city analysis leads to traditional sector-level insights, overlooking the economic and environmental distinctions between emerging and conventional sectors. Given that sponge city construction represents a new industry with unique value chains, distinguishing it from traditional civil engineering is essential for designing targeted policies that support sustainable infrastructure development.

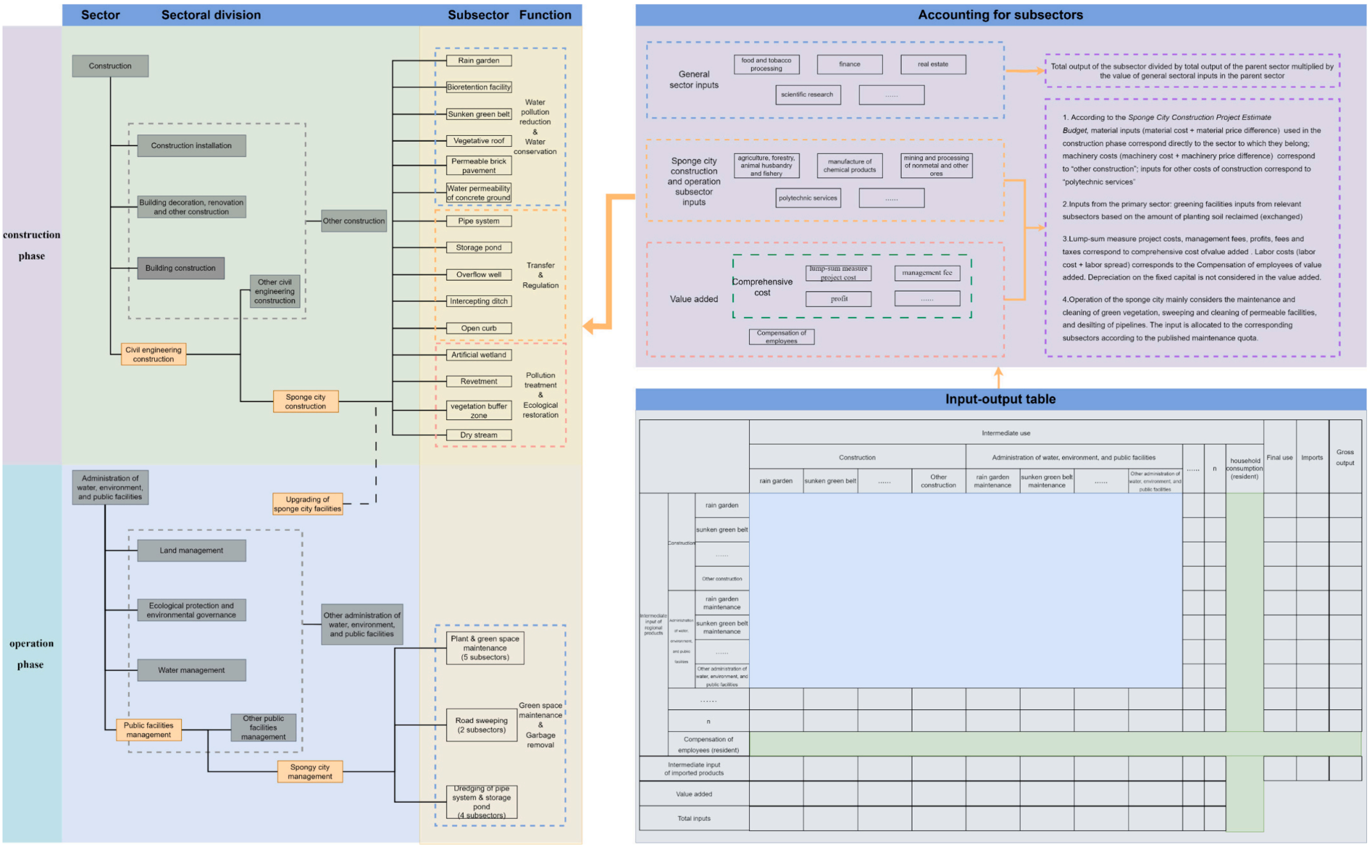
To address this gap, this study modifies the input–output framework by explicitly incorporating the construction and operation phases of sponge cities. This is achieved by dividing the intermediate flow matrix, value-added matrix, and final demand matrix into separate subcategories that better reflect the economic structure of sponge city investments. Due to limited data availability on the end-of-life phase of municipal infrastructure (Xu et al., 2019), this study does not consider the abandonment phase. Instead, the focus remains on the construction phase, which involves the installation of sponge city components, and the operation phase, which encompasses maintenance and periodic renewal. According to the *Sponge City Construction Technical Guide*, *Sponge City Construction Project Estimate Budget*, public construction data, and other standards, the boundary of the sponge city system and the construction scale of its subprojects are determined. Common facilities in a sponge city include rain gardens, sunken green belts, roof greening, permeable brick pavement, pipe systems, storage ponds, and vegetation buffer zones. These facilities have different responsibilities within the sponge city system and work together to collect and transmit rainwater, achieving comprehensive control from the source to the process endpoint. Although gray infrastructure such as pipelines is typically categorized separately, it plays an essential role in stormwater transmission and is therefore included in the sponge city sectoral classification. The classification framework for the construction and maintenance phases is shown in Fig. 2.

In alignment with the *Industrial Classification for National Economic Activities*, this study reclassifies sponge city-related economic activities within the IO system. For the construction phase, sponge city infrastructure primarily involves municipal projects, such as pipeline systems, permeable pavements, and rain gardens. These activities align with “civil engineering construction” in the 149-sector IO classification and fall under “construction” in the 42-sector classification. For the operation phase, the primary activities include green space maintenance, cleaning of permeable pavements, and desilting of stormwater infrastructure. These functions are categorized under “municipal facility management” and, in the 42-sector IO classification, correspond to “administration of water, environment, and public facilities”.

For the construction phase, this study first identifies the subsectors associated with sponge city development and then categorizes the input requirements for materials, labor, and other costs. Material inputs are classified into: (1) Specialized sectors: Manufacturing of non-metallic mineral products, polytechnic services, and other construction-related industries. (2) General sectors: Financial services, real estate, and administrative costs. Each input is assigned to its corresponding sector, ensuring that material, labor, and service costs are properly accounted for: Machinery costs → “Other construction”; Supervision, surveys, and bidding services → “Polytechnic services”; Labor costs, project management fees, and taxes → “Value-added components”.

In the 2017 China Input-Output Table, civil engineering construction demonstrates a high reliance on intermediate inputs, with approximately 77.8 % of total inputs originating from other industries. Moreover, in final demand accounting, fixed capital formation constitutes 99.6 % of total end-use, indicating that this sector primarily absorbs inputs from other industries rather than contributing to subsequent production cycles. Based on this economic pattern, it is assumed that the sponge city construction phase does not generate additional input demand for general economic sectors, except for those directly involved in infrastructure development. Depreciation costs are also minimal in this sector. In civil engineering construction, the share of fixed capital depreciation is only 0.95 % and is therefore excluded from this analysis. Furthermore, machinery rental and construction services, which are critical to sponge city projects, are classified under “other construction” and linked to the parent sector via service-based transactions.

For the operation phase, sponge city maintenance activities are categorized under “administration of water, environment, and public facilities”. This sector is further divided into: (1) sponge city-specific maintenance (covering vegetation management, cleaning of permeable pavements, and pipeline desilting) and (2) general municipal facility administration, which includes other non-sponge city-related urban services. The calculation of maintenance and operational costs is based on the resource requirements for each maintenance activity, which are then allocated to their respective sectors. Given that municipal infrastructure has an expected lifespan of 30–50 years, this study assumes a facility renewal rate of 1 % per decade, translating to 0.1 % annual replacement. To ensure analytical clarity, sponge city maintenance is modeled as an independent sector, operating without interdependencies among subsectors. The input structure of the operation phase is estimated using the sector-specific ratio of intermediate inputs to total construction inputs, ensuring consistency with the broader IO



Total output of the subsector divided by total output of the parent sector multiplied by the value of general sectoral inputs in the parent sector

1. According to the *Sponge City Construction Project Estimate Budget*, material inputs (material cost + material price difference) used in the construction phase correspond directly to the sector to which they belong; machinery costs (machinery cost + machinery price difference) correspond to “other construction”; inputs for other costs of construction correspond to “polytechnic services”

2.Inputs from the primary sector: greening facilities inputs from relevant subsectors based on the amount of planting soil reclaimed (exchanged)

3.Lump-sum measure project costs, management fees, profits, fees and taxes correspond to comprehensive cost ofvalue added . Labor costs (labor cost + labor spread) corresponds to the Compensation of employees of value added. Depreciation on the fixed capital is not considered in the value added.

4.Operation of the sponge city mainly considers the maintenance and cleaning of green vegetation, sweeping and cleaning of permeable facilities, and desilting of pipelines. The input is allocated to the corresponding subsectors according to the published maintenance quota.

Fig. 2. The subsectors of the sponge city construction phase and operation phase.

framework.

2.2.3. Construction of the input-output partial closure model

Under the framework of national economic circulation, the residents participate in economic operations through dual identities. As suppliers of production factors, residents obtain labor remuneration that constitutes initial inputs, while as end consumers, they form final demand. Specifically, in the production process, laborers obtain remuneration through labor input; in the consumption process, they sustain labor force reproduction through commodity purchases. It forms a closed-loop transmission mechanism of "labor supply — income acquisition — consumption expenditure — production stimulation". The traditional input-output model can only describe the driving effect of consumption demand on industrial production when analyzing industrial correlation, and cannot reflect the feedback effect of industrial expansion on residents.

Sponge cities require significant human labor input during both construction and operation. Employee compensation constitutes a non-negligible part of the investment. Maintenance activities, such as green space upkeep and pipeline desilting, require significant labor input, which is crucial during the sponge city operation phase.

Establishing endogenous correlation between the residents and the industrial sectors effectively reveals how construction industry expansion promotes consumption growth and drives related industries. The input-output partial closure model overcomes the unidirectional transmission assumption in traditional input-output analysis and creates a feedback mechanism between industrial sectors and residents. This model also facilitates assessment of multi-industry ripple effects in sponge city construction.

The labor input of residents is expressed as employee compensation, while household consumption is expressed as household expenditure. Employee compensation is considered value added, and household consumption is considered final use. Therefore, household consumption and employee compensation are incorporated into the intermediate flow matrix, referred to as the residential sector in the input-output table. Household consumption is classified as intermediate use, and employee compensation is classified as intermediate inputs, with the intersection between them set to zero. This expands the intermediate flow matrix from $n \times n$ to an $(n+1) \times (n+1)$ flow matrix that includes the residential sector, and the expanded input-output table is shown in Fig. 2. Household consumption is represented toas F ($F = (F_1, F_2, \dots, F_n)^T$), where F_i indicates the use of products allocated to resident consumption in sector i.

$$f_i = \frac{F_i}{\sum_{i=1}^{n} F_i}, i = 1, 2, 3, \dots, n \tag{10}$$

where f_i is the share of the products of sector i in the household consumption, i.e. the direct consumption coefficient of household consumption. Vector $f = (f_1, f_2, \cdots, f_n)^T$ is the vector of the direct consumption coefficients of residents. Satisfy: $\sum_{i=1}^{n} f_i = 1, i = 1, 2, 3, \dots, n$.

The compensation of employees is set as W ($W = (W_1, W_2, \dots, W_n)$), and W_i represents the consumption of the product of sector i by the residents.

$$w_i = \frac{W_i}{x_j} \tag{11}$$

where w_i is the employee compensation coefficient and w ($w = (w_1, w_2, w_3, \cdots, w_n)$) is the vector of employee compensation coefficients. The vector of employee compensation coefficients w is increased to $n+1$ rows of the matrix of direct consumption coefficients, and the vector of direct consumption coefficients of residents f is increased to $n+1$ columns of the matrix of direct consumption coefficients. A new direct consumption coefficient matrix A^* is obtained.

$$A^* = \begin{pmatrix} A & f \\ w & 0 \end{pmatrix} = \begin{pmatrix} a_{11} & \cdots & a_{1n} & f_1 \\ \vdots & \ddots & \vdots & \vdots \\ a_{1n} & \dots & a_{nn} & f_n \\ w_1 & \cdots & w_n & 0 \end{pmatrix} \tag{12}$$

2.3. Ecosystem service flow analysis for sponge city construction

2.3.1. Water conservation

Sponge cities employ LID infrastructure, such as green spaces, permeable pavements, and bioswales, to enhance rainwater capture and infiltration. The rainwater storage capacity of these facilities can be mathematically expressed as:

$$V = 10H\varphi F \tag{13}$$

where, V represents the rainwater harvesting volume, m^3; H represents the design rainfall depth, mm; φ represents the rainfall runoff coefficient; and F represents the catchment area, hm^2.

2.3.2. Suspended substance removal

One of the key ecosystem services provided by sponge cities is the removal of SS from stormwater. The SS removal efficiency of each LID facility is determined based on the *Sponge City Construction Technical Guidelines* and existing studies. The treatment cost of SS is assessed by calculating the reduction in SS concentration achieved through different sponge city interventions.

2.3.3. Carbon sink

Green infrastructure in sponge cities contributes to carbon sequestration, primarily through the absorption and storage of atmospheric CO_2 by vegetation. The carbon sink potential of sponge city greenery is estimated using the following model:

$$C = n \times C' \text{ or } C = S \times C' \tag{14}$$

where: C represents the carbon sink of greening vegetation; n represents the number of vegetation units (e.g., trees, shrubs); S represents the area of green vegetation (e.g., shrubs, flowers, grasses); and C' represents the average annual carbon sink per unit (number/area) of plants.

The input–output table highlights the complex interconnections between production and consumption across industries (Chong et al., 2023; Gao et al., 2024a). To ensure fair and efficient ecosystem service distribution, this study adopts an allocation mechanism based on the principles of shared benefits and incentive-compatible design. Following the "shared responsibility for emissions" principle, emissions generated throughout the supply chain should be jointly accounted for by direct and indirect participants. Correspondingly, ecosystem services should be allocated across industrial networks, ensuring that environmental benefits flow equitably among stakeholders. This study applies ecosystem services as a flow distribution metric, assigning a proportional share of services to upstream suppliers and downstream recipients (Gallego and Lenzen, 2005). Furthermore, the green innovation efficiency of each industry is introduced as a weighting coefficient, establishing a dynamic link between ecosystem service benefits and emission reduction performance (Gao et al., 2024b). This market-based incentive mechanism not only rewards industries that contribute to carbon reduction and environmental sustainability but also stimulates continuous eco-innovation, accelerating the green transformation of enterprises.

Carbon sinks generated in sector k provide environmental benefits not only to the direct sink sector but also to intermediate-use sectors and final consumers. To analyze the distribution of carbon sink benefits across sectors, it is crucial to distinguish between direct and indirect linkages within the industrial network. These relationships are categorized into two stages. Stage I (Direct Sink Sector): Industries that are directly engaged in carbon sequestration, such as green infrastructure and afforestation projects; Stage II (Downstream Beneficiaries): Industries that interact with carbon sink sectors, either by utilizing ecosystem services or by engaging in activities that benefit from carbon sequestration. Each stage has a corresponding set of final consumers, and the benefits of carbon sinks are allocated to three key groups: the sink sector itself, intermediate-use sectors, and final consumers (Gao et al., 2024b). Upon completion of sponge city projects, primary beneficiaries of carbon sinks include industries that integrate green infrastructure, stormwater management, and urban forestry into their operations.

It is assumed that sector k generates carbon sinks, which are then distributed through the supply chain. A portion of these sinks is retained by sector k for final demand, while another portion is allocated to intermediate outputs and subsequently passed on to downstream industries. The allocation mechanism is defined as follows:

$$x_k = \begin{cases} \delta y_k \rightarrow \text{assigned to final consumers of sector } k \\ (1-\delta)y_k + (1-\gamma)(x_k - y_k) \rightarrow \text{assigned to industry } k \\ \gamma(x_k - y_k) = \gamma \sum_h a_{kh} x_h \rightarrow \text{assigned to sectors h downstream from } k \end{cases} \tag{15}$$

To further refine the model, green innovation efficiency is introduced as an allocation coefficient (γ and δ), ensuring that carbon sink benefits are distributed in a manner that rewards industries based on their emission reduction performance. ω is the environmental factor of carbon sinks. The total carbon sinks transferred from sector k to upstream and downstream sectors are given by:

$$x_k = \begin{cases} \omega_k \delta_k y_k \\ \omega_k [(1-\delta_k) y_k + (1-\gamma_k)(x_k - y_k)] \\ \omega_k \gamma_k \sum_h a_{kh} x_h \end{cases} \tag{16}$$

A similar approach is applied to water conservation and SS removal services, following the same ecosystem service flow allocation framework, though the analysis of final-use water allocation is not included in this study.

2.4. *Life cycle economic impact assessment of sponge city*

The influence coefficient is a measure of the strength of the production wave generated by an increase in final demand in an industry for each industry sector relative to the industry-wide average. The induction coefficient is a measure of the strength of the demand-sensing effect on industry i relative to the industry-wide average.

$$F_j = \frac{\sum_{i=1}^{n} \overline{b}_{ij}}{\frac{1}{n}\sum_{i=1}^{n}\sum_{j=1}^{n} \overline{b}_{ij}} \tag{17}$$

$$E_i = \frac{\sum_{j=1}^{n} \overline{b}_{ij}}{\frac{1}{n}\sum_{i=1}^{n}\sum_{j=1}^{n} \overline{b}_{ij}} \tag{18}$$

$(i = 1, 2, 3, \cdots, n; j = 1, 2, 3, \cdots, n)$

where F_j is the influence coefficient, which is greater than 1, indicating that the industry has a large pull effect and radiation on other industries; E_i is the inductance coefficient, whichis greater than 1, indicating that the industry is generally susceptible to the influence of other industries, and is mostly an intermediate demand-type industry sector; $\sum_{i=1}^{n} \overline{b}_{ij}$ and $\sum_{j=1}^{n} \overline{b}_{ij}$are the sum of the jth column and the sum of the i-th row of the Leontief inverse matrix, respectively; and $\frac{1}{n}\sum_{i=1}^{n}\sum_{j=1}^{n} \overline{b}_{ij}$and $\frac{1}{n}\sum_{i=1}^{n}\sum_{j=1}^{n} \overline{b}_{ij}$ are the average of the column sums and the average of the row sums of the Leontief inverse matrix.

Input sectors can drive industrial activities in various sectors through the correlation between industries, presenting a comprehensive industry pull effect. All the layers of inputs can be analyzed through Taylor expansion of the input-output column balance formula. To analyze the first layer pull effect (direct inputs) and the overall pull effect (the sum of inputs pulled by the first, second, third layers and all industrial chains interrelated) during the construction and operation of the sponge city, this study considers only the value of the final demand for the sponge city construction phase and the operation phase, and the final demand of all other sectors is set to 0 to obtain the final use Y'.

$$X'_1 = A^* \times Y'$$

$$X'_2 = A^* \times A^* \times Y'$$

$$X'_3 = A^* \times A^* \times A^* \times Y'$$

$$\begin{aligned} \overline{X'} &= IY' + X'_1 + X'_2 + X'_3 + \ldots + X'_n \\ &= IY' + A^*Y' + A^*A^*Y' + A^*A^*A^*Y' + \ldots + (A^*)^n Y' = (I - A^*)^{-1} Y' \end{aligned} \tag{19}$$

where $X'_1$is the first layer input (inputs from initial input sectors for sponge city construction and operation), X'_2 is the second layer input, and X'_3 is the third layer input. $\overline{X'}$ represents the total inputs from all sectors of the system for the direct inputs and final demand pull for the construction and operation of the sponge city.

Scale and structural characteristics can be used to analyze the industrial stimulation effect. The pull multiplier $\overline{ST}$ reflects the magnitude of the pull effect, i.e., how much output of all sectors of the national economy can be pulled by each unit of currency spent on the construction or operation of sponge cities (Lu et al., 2023).

$$\overline{ST} = \frac{(I - A^*)^{-1} Y'}{A^* Y'} \tag{20}$$

The main contributing sectors and contributions can reflect structural characteristics. The direct input sector is the sector pulled by the first layer industry. The direct input sectors are those that are pulled by the first layer industries. Sectors are interrelated, and the first layer industry, as the initial driving force, also has a pulling effect on other sectors of the whole input-output table. Structural characteristics can reflect the invisible relationships between sectors. This helps determine the sectors that have outstanding contributions in the construction and operation phases of sponge cities that are pulled by the initial inputs.

2.5. *Case study and data sources*

2.5.1. *Study area*

China introduced economic support policies for sponge city construction in 2015, and over the past decade, the initiative has expanded significantly. Today, sponge city pilot projects cover almost all provinces, providing a comprehensive reference framework for large-scale implementation and evaluation.

For this study, Xining City, Qinghai Province, was selected as a case study to apply the proposed methodological framework. Xining, located in the inland region of Northwest China, experiences an average annual precipitation of approximately 500 mm. Despite its relatively low rainfall, the city frequently suffers from urban waterlogging, a challenge common to many cities in Northwest China (Liu et al., 2022). As one of the second-phase sponge city pilot cities, Xining has played a key role in shaping China's national sponge city strategy. It has been included in *the List of Reproducible Mechanisms for Sponge City Construction*, which provides standardized guidelines for replication and policy implementation across other regions. This makes Xining a strategically significant case, as its sponge city program not only contributes to local resilience but also offers valuable insights for broader national applications.

2.5.2. Data sources

According to the data of *Qinghai Statistical Yearbook 2018* and *Xining Statistical Yearbook 2019*, there are significant differences in the industrial structure of cities in Qinghai Province, with Xining City emerging as the economic core (Table S1). The tertiary industry in Xining City accounts for more than 50 % of GDP (the province-wide proportion is 46.69 %), and the secondary industry occupies an important position, while the primary industry accounts for only 3.28 % (other cities are 5.68 %–43.52 %). In the composition of value added, Xining City contributes more than 40 %, and the compensation of employees accounts for nearly 50 %, a structure of key significance for the assessment of sponge city construction. In terms of total output, Xining City accounts for 51.42 % of the province's total output (over 50 % in all industries except the primary industry), while the province's total output of the primary industry is only 5.51 %, which has little impact. In terms of GDP by expenditure approach (i.e. final use), Xining City accounts for 43.55 % of the province's final use, which is a higher proportion. Overall, Xining's industrial structure, dominated by secondary and tertiary industries, has had a significant impact on the economic structure of Qinghai Province. Therefore, the 2017 input-output table for Qinghai Province (42 sectors) was used for division and calculation. The construction of this sponge project began in 2022, and the 2022 inputs were adjusted to 2017 prices using the Qinghai Province Industrial Producer Price Index (PPI) in the *China Price Statistics Yearbook*.

It is worth noting that Xining City, as the provincial capital of Qinghai Province, has a significantly higher industrialization level than the regional average. Although Xining's economic structure is similar to that of Qinghai province, the use of the input-output table of Qinghai Province still shows insufficient resolution when characterizing Xining's industrial structures. This leads to a certain degree of overestimation or underestimation of benefits across industries during ecological benefit allocation. Sensitivity analysis (Section 3.1.4) shows that even with some fluctuations in numerical values, there is no significant impact on the results.

The maintenance of sponge city operation is divided into facility renewal and facility cleaning and maintenance. Since the *Sponge City Construction Technical Guidelines* do not specify regional variations in green space maintenance standards, this study assumes that green space maintenance costs are similar across different regions. To ensure data reliability and consistency, cost data from Beijing and Shenzhen were incorporated. These values were then adjusted to match the input–output table's pricing system, minimizing potential errors and ensuring comparability across different cities. The data sources are shown in Table 1. The initial inputs in the sponge city are shown in Fig. S1.

Table 1
Data sources.

Data	Source
Input-Output Table of Qinghai Province	Statistical Yearbook of Qinghai Province
Sponge City Construction Scale and Cost	Sponge City Construction Budget
Greening Vegetation Maintenance	Beijing Urban Landscaping and Greening Maintenance Budget Quota
Greening Cleaning & Pervious Facilities Sweeping	Shenzhen Sanitation Engineering Consumption Quota
Pipeline Inspection and Dredging	Outdoor Drainage Pipe Non-excavation Rehabilitation Project Calculation Quota
Producer Price Index	China Price Statistics Yearbook
Carbon Sink Capacity of Green Vegetation	Huo et al. (2023)

3. Results

3.1. Sponge city ecosystem service flow analysis

3.1.1. Water conservation

Xining City receives an average annual precipitation of 500 mm, with the sponge city construction area covering 90 ha. According to the *Sponge City Construction Technical Guidelines*, achieving an 85 % total annual runoff control rate in Xining City requires a design rainfall depth of 12.7 mm. Key rainwater harvesting facilities — include sunken green belt, rain gardens, and grass swale — have a rainwater storage capacity (ϕ) of 0.35 with designed collection volumes of 39.25 m^3, 25.79 m^3, and 7.66 m^3, respectively. Additionally, permeable surfaces such as concrete ground ($\phi = 0.85$) and permeable brick pavements ($\phi = 0.4$) contribute 45.45 m^3 and 17.16 m^3, respectively.

The total green infrastructure and permeable surface area is approximately 23,945 m^2, with an average rainwater runoff coefficient (ϕ) of 0.445. With 90 annual precipitation days, the estimated annual rainfall volume in these areas reaches 11,972.5 m^3, while the total additional rainwater collection capacity of sponge city facilities is 12,178.26 m^3. This capacity enables that all rainwater within the construction area can be fully collected post-construction, significantly reducing urban waterlogging risks.

Following the completion of sponge city construction, an estimated 21,552.3 m^3 of water will be required annually for facility maintenance. The collected rainwater will supply 56.51 % of this demand, reducing reliance on external water sources. According to the *2017 Qinghai Water Resources Bulletin*, 10,000 yuan of GDP production in Qinghai consumes 98 m^3 of water. Based on this benchmark, the construction phase is expected to use approximately 52,357.8 m^3 of water, with full water resource recovery achieved within 5-6 years.

Without downstream allocation, rainwater collected by sponge city facilities is retained within the sector itself. However, when considering downstream distribution, the water is allocated across various industries, reducing the portion retained by the sponge city sector itself. As shown in Table 3, the agriculture, forestry, animal husbandry, and fishery sector is the largest beneficiary, receiving 34.58 % of the total conserved water. The service industry follows, utilizing 52.10 % of the total, primarily for public administration, finance, sponge city maintenance, and transport services.

3.1.2. Suspended substance removal

The SS concentration in road runoff in Xining City ranges from 199 to 2030 mg/L, while green spaces exhibit lower concentrations between 120 and 179 mg/L (Li et al., 2018; Wang et al., 2017; Yuan et al., 2011; Zhang et al., 2011). According to the *Sponge City Construction Technical Guidelines*, different sponge city facilities achieve varying SS removal rates (Table S2). After treatment, the SS concentration in collected rainwater meets domestic sewage discharge standards (Wei et al., 2020). This transition lowers wastewater treatment costs from industrial-grade to residential-grade standards, resulting in an estimated cost savings of 1 yuan/m^3 (Fang and Cao, 2017). This financial efficiency is particularly significant for water resource management in the arid regions of Northwest China, where optimizing urban water reuse is crucial for sustainability.

Table 4 presents the allocation of SS removal benefits across industries, taking into account downstream distribution effects. The government sector receives more than half of the total benefits, highlighting the public service nature of sponge city infrastructure. This reallocation

Table 3
Allocation of water conservation among industries (unit: m^3).

Water conservation sector Water conservation allocation sector	Sunken green belt maintenance	Rain garden maintenance	Grass swale maintenance	Water permeability of concrete ground maintenance	Permeable brick pavement maintenance	Total water conservation
Agriculture, forestry, animal husbandry and fishery	13.58	8.92	2.65	15.72	5.93	46.80
Other public administration, social insurance, and social organizations	5.08	3.33	0.99	5.88	2.22	17.50
Resident	4.85	3.18	0.95	5.61	2.12	16.70
Water permeability of concrete ground maintenance	0.00	0.00	0.00	15.37	0.00	15.37
Sunken green belt maintenance	13.27	0.00	0.00	0.00	0.00	13.27
Rain garden maintenance	0.00	8.72	0.00	0.00	0.00	8.72
Permeable brick pavement maintenance	0.00	0.00	0.00	0.00	5.80	5.80
Transport, storage, and postal services	0.97	0.64	0.19	1.12	0.42	3.34
Grass swale maintenance	0.00	0.00	2.59	0.00	0.00	2.59
Other sectors	1.51	0.99	0.30	1.75	0.66	5.22

Table 4
Allocation of SS removal benefits among industries (unit: yuan).

SS removal sector SS removal allocation sector	Sunken green belt maintenance	Rain garden maintenance	Grass swale maintenance	Water permeability of concrete ground maintenance	Permeable brick pavement maintenance	Total SS removal
Government consumption	2079.59	1366.22	406.00	2407.65	909.10	7168.56
Water permeability of concrete ground maintenance	0.00	0.00	0.00	1383.08	0.00	1383.08
Sunken green belt maintenance	1194.62	0.00	0.00	0.00	0.00	1194.62
Rain garden maintenance	0.00	784.83	0.00	0.00	0.00	784.83
Permeable brick pavement maintenance	0.00	0.00	0.00	0.00	522.24	522.24
Agriculture, forestry, animal husbandry and fishery	135.17	88.80	26.39	156.49	59.09	465.94
Grass swale maintenance	0.00	0.00	233.23	0.00	0.00	233.23
Other public administration, social insurance, and social organizations	50.54	33.20	9.87	58.51	22.09	174.20
Resident	48.25	31.70	9.42	55.86	21.09	166.31
Other sectors	24.73	16.25	4.83	28.64	10.81	85.26

helps reduce government financial burdens on wastewater treatment subsidies, demonstrating the cost-effectiveness of integrating sponge city strategies into urban water management.

Among economic sectors, the benefits from SS removal correlate positively with the volume of rainwater collected by sponge city facilities, providing a basis for optimizing infrastructure scale, efficiency, and spatial distribution. Excluding sponge city-related subsectors, the agriculture, forestry, animal husbandry, and fishery sector emerges as the largest beneficiary (3.83 %), likely due to improved soil and water conservation that enhances agricultural productivity. Other significant beneficiaries include: Other public administration, social insurance, and social organizations, which gain from improved urban environmental quality; Residents, benefiting from increased employment opportunities in green infrastructure maintenance, contributing 1.37 % of total SS removal benefits.

These findings underscore the synergistic relationship between environmental management, economic growth, and social welfare, reinforcing sponge cities as an integral component of sustainable urban development.

3.1.3. Carbon sink

Carbon sinks of different types of greening capacity are shown in Table S3. Following the completion of sponge city construction, the annual carbon sink contribution is estimated at 6.31 tons from trees, 8.39 tons from shrubs, 0.22 tons from flowers, and 4.57 tons from grass, resulting in a total additional carbon sequestration of 19.49 tons per year. Among these, trees and shrubs serve as the primary carbon sinks, while flowers and grasses contribute mainly to landscaping and aesthetic functions. The selection of vegetation types in urban green infrastructure is closely tied to ecosystem service objectives, including carbon sequestration and biomass accumulation.

By sector, carbon sinks are predominantly generated by “green” infrastructure. The sunken green belt contributes 10.52 tons, the rain garden accounts for 6.91 tons, and the grass swale provides 2.05 tons annually. In 2022, Xining City’s urban area covered 397 km^2, with sponge city projects spanning 0.9 km^2, including 0.016 km^2 of newly added green space. Extrapolating from these figures, sponge city construction is projected to add approximately 7.06 km^2 of new green space, which will result in an additional 8597.26 tons of carbon sequestration, supporting Xining City’s efforts to achieve carbon neutrality before 2060.

The carbon emissions of the Sponge city construction and maintenance sub-sector are shown in Table S4. If only construction-phase emissions are considered (excluding maintenance-related emissions), sponge city carbon sinks fully offset emissions within 4.07 years. However, if maintenance-phase emissions are included, only 41.78 % of emissions are offset, indicating that long-term sustainability depends on the lifespan and maintenance efficiency of green infrastructure. A facility-specific analysis reveals that the sunken green belt, rain garden, and grass swale achieve carbon neutrality within 3.4, 3.2, and 3.1 years, respectively, after accounting for both construction and maintenance emissions. Given a 30-year service life, amortizing construction-phase emissions over this period results in net positive carbon benefits, reinforcing the long-term sustainability of sponge city investments.

Without downstream allocation, the carbon sinks generated by sunken green belts, rain gardens, and grass swales remain within the respective sectors. However, when considering downstream distribution, carbon sinks are redistributed across industries and final consumers, reducing the share retained by the carbon sink sector itself. Administration of water, environment, and public facilities is non-competitive, as the services provided by this industry are public goods primarily funded by government fiscal expenditures. Government consumption accounts for 89 % of the total output. The products of this industry rarely enter the production processes of other industries, resulting in an extremely low proportion of intermediate demand. As shown in Table 5, government consumption is the largest beneficiary, receiving 58.86 % of total carbon sinks. This reflects the government's dual role as both a primary investor and a key recipient of ecosystem service benefits, reinforcing its influence over carbon credit allocation. From the investment perspective, the government reduces the proportion of high-carbon industries and accelerates energy structure transformation through financial support, policy guidance, and infrastructure development. As a beneficiary of ecosystem services, the government significantly enhances land carbon sink capacity by implementing ecological conservation and restoration projects. Through carbon trading mechanisms, the government can convert urban ecosystem services into economic assets, facilitating a synergy between ecological conservation and economic development.

Among non-government beneficiaries, the largest recipients of sponge city carbon sinks are green infrastructure maintenance sectors, with sunken green belt maintenance receiving 18.26 %, rain garden maintenance 11.99 %, and grass swale maintenance 3.56 %. Additionally, the agriculture, forestry, animal husbandry, and fishery sector benefits from 3.83 %, while the other administration of water, environment, and public facilities receives 1.43 %. These findings underscore the broad economic and environmental impact of sponge city carbon sequestration, particularly in urban service sectors and environmental management industries, where ecosystem services contribute to both sustainability and economic development.

3.1.4. Sensitivity analysis

Discrepancies in industrial structure and production technology between Xining City and Qinghai Province introduce potential uncertainties when using the provincial input–output table to represent Xining's economy. As Qinghai's economic hub, Xining contributes approximately 50 % of the province's GDP and has a more advanced industrial base compared to other regions. For instance, Yushu Prefecture's economy remains centered on traditional agriculture and animal husbandry, whereas Xining has developed modern industrial clusters in new energy and advanced materials. Directly applying provincial-level production and consumption data may underestimate Xining's technological advancements, leading to potential biases in the analysis.

We assess the sensitivity of the results by calculating the elasticities of environmental factors, the intermediate transaction matrix, and final demand (Lin et al., 2020; Yang et al., 2023). According to the sensitivity analysis results in Tables S5-S9, most parameters exhibit small elasticities, indicating that the findings are insensitive to changes in these parameters. The elasticity value of the carbon sink environmental factor for sunken green belt maintenance reaches 0.54. Specifically, a 10 % change in the carbon sink environmental factor of this sector would result in a 5.4 % change in the carbon sink allocation results. However, the robustness of these findings remains constrained by data completeness in Xining's economic system. Enhancing input–output accuracy through enterprise-level resource consumption monitoring and improved data collection would significantly enhance the precision and reliability of the allocation model.

Table 5
Allocation of carbon sinks among industries and final consumption (unit: ton).

Carbon sink sector Carbon sink allocation sector	Sunken green belt maintenance	Rain garden maintenance	Grass swale maintenance	Total carbon sink
Government consumption	6.19	4.07	1.21	11.47
Sunken green belt maintenance	3.56	0.00	0.00	3.56
Rain garden maintenance	0.00	2.34	0.00	2.34
Agriculture, forestry, animal husbandry and fishery	0.40	0.26	0.08	0.75
Grass swale maintenance	0.00	0.00	0.69	0.69
Other administration of water, environment, and public facilities	0.15	0.10	0.03	0.28
Resident	0.14	0.09	0.03	0.27
Transport, storage, and postal services	0.03	0.02	0.01	0.05
Finance	0.01	0.01	0.00	0.02
Other sectors	0.04	0.02	0.01	0.07

3.2. Economic effects of sponge city

3.2.1. Industrial stimulation effect

Both the construction and operation phases of sponge cities exhibit low induction coefficients, indicating that sponge city investments primarily serve as final demand sectors rather than intermediate inputs. This aligns with the finding that fixed capital formation accounts for 100 % of final use in the construction phase, while government consumption represents 89.94 % of final use in the operation phase. In contrast, the high influence coefficients across both phases highlight the strong economic pull effect of sponge city investments, as they require substantial inputs from multiple industries. Thus, sponge city construction and operation function as final demand sectors, driving broad economic activity (Table 6).

Sponge city construction and operation significantly amplify total industrial inputs beyond their initial investment, as illustrated in Fig. 4. The overall industrial stimulation effect is estimated at 4.2 times, meaning that every yuan invested in sponge city construction in Xining generates 4.2 yuan in total economic output.

In the first-layer input stage, direct investment amounts to 14.91 million yuan, with the pipe system accounting for the largest share (7.88 million yuan, 52.85 %), followed by the sunken green belt (2.15 million yuan, 14.45 %). In contrast, dry streams, open curbs, and intercepting ditches contribute the smallest shares. Facilities with distinctive “green” characteristics, such as sunken green belts, rain gardens, and grass swales, exhibit an industrial stimulation effect of 4.6 times, surpassing that of other infrastructure types (4.1 times). This higher impact is largely due to greater agricultural input requirements, given the strong backward linkages to labor-intensive sectors. Expanding input–output models to include employee compensation and household consumption would further enhance the agricultural sector's influence, boosting the industrial stimulation effect of green infrastructure.

During the operation phase, the industrial stimulation effect remains high at 4.1 times, though it is slightly lower than during construction. Green infrastructure facilities experience a reduced effect of 4.0 times, largely due to a decline in agricultural input intensity once the construction phase is complete. In contrast, permeable concrete and brick pavements exhibit the highest industrial stimulation effect at 4.5 times, as they continue to rely heavily on labor inputs. Since labor-intensive industries drive cross-sector inputs through “income-consumption” cycles, maintaining facilities with strong employment linkages, such as

Table 6
Influence coefficient and induction coefficient for sponge city construction and operation.

Construction phase subsector	Influence coefficient	Induction coefficient	Operation phase subsector	Influence coefficient	Induction coefficient
Sunken green belt	1.35	0.35	sunken green belt maintenance	1.08	0.35
Rain garden	1.36	0.35	rain garden maintenance	1.08	0.35
Grass swale	1.38	0.35	grass swale maintenance	1.08	0.35
Water permeability of concrete ground	1.22	0.35	water permeability of concrete ground maintenance	1.08	0.35
Dry stream	1.16	0.35	dry stream maintenance	1.16	0.35
Permeable brick pavement	1.24	0.35	permeable brick pavement maintenance	1.08	0.35
Overflow well	1.16	0.35	overflow well maintenance	1.11	0.35
Open curb	1.21	0.35	open curb maintenance	1.21	0.35
Intercepting ditch	1.25	0.35	intercepting ditch maintenance	1.25	0.35
Pipe system	1.18	0.35	pipe system maintenance	1.11	0.35
Average	1.25	0.35	average	1.12	0.35

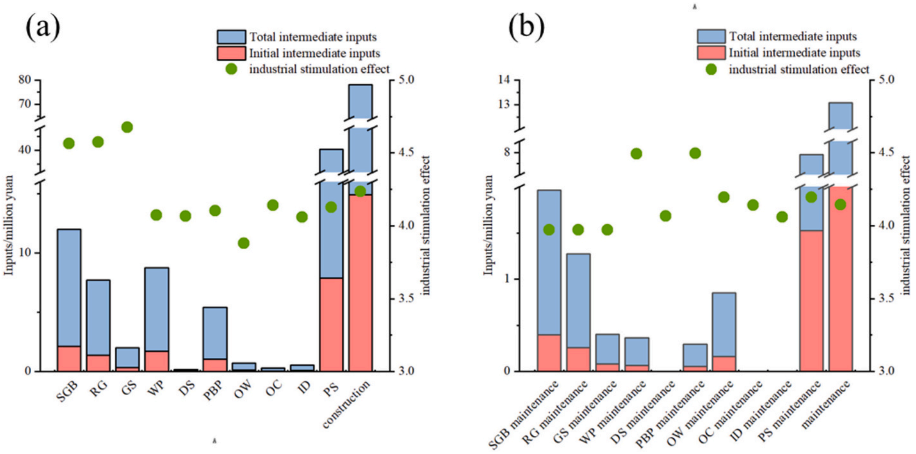


Fig. 4. Industrial stimulation effect in subsectors. (a) is the sponge city construction phase and (b) is the sponge city operation phase. Sunken green belt (SGB), rain garden (RG), grass swale (GS), water permeability of concrete ground (WP), dry stream (DS), permeable brick pavement (PBP), overflow well (OW), open curb (OC), intercepting ditch (ID), and pipe system (PS). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

permeable pavements and water-permeable concrete surfaces, can sustain and enhance economic returns over the long term.

3.2.2. *Invisible sectors in the total inputs of sponge city*

The total sectoral inputs driven by the sponge city construction phase are shown in Fig. 5. While agriculture, forestry, animal husbandry, fishery, chemical manufacturing, and residential inputs—which have high initial investment shares—continue to account for a significant proportion of total inputs, several previously overlooked sectors also emerge as key contributors. Notably, food and tobacco processing (3.5 %–6.1 %), electric power and heat production (4.7 %–7.1 %), and finance (3.3 %–3.7 %) play a larger role in total inputs than initially recognized.

Although these sectors were not originally considered critical, their indirect economic influence surpasses many primary input sectors when assessed through interindustry linkages. These hidden sectors continuously drive inputs from their upstream industries, reinforcing cross-sector economic dependencies. For instance, the production and distribution of electric power and heat power significantly stimulate demand for coal mining, petroleum extraction, and natural gas processing. Similarly, materials and machinery operations in sponge city construction depend on stable energy supplies, further linking invisible sectors to resource extraction. Additionally, many hidden sectors are closely tied to the service industry, which maintains strong forward linkages with both primary and secondary industries. This creates a ripple effect, where sponge city investments indirectly drive service-sector demand, amplifying their overall economic impact.

The total sectoral inputs pulled by sponge city operations, illustrated in Fig. 6, highlight a continued reliance on key sectors such as chemical manufacturing, leasing and commercial services, and tap water production and distribution. However, invisible sectors become even more prominent, with electric power and heat production (4.5 %–7.1 %), food and tobacco processing (3.5 %–7.5 %), finance (3.3 %–4.0 %), and agriculture, forestry, animal husbandry, and fishery (2.9 %–5.9 %) accounting for a larger share of total inputs.

A key observation is that food and tobacco processing plays an increasingly dominant role (7.44 %) in water permeability of concrete ground maintenance and permeable brick pavement maintenance, which have higher labor input requirements. This sector also drives upstream inputs from agriculture, forestry, animal husbandry, and fishery, reinforcing their elevated shares across all subsectors. Furthermore, service-sector contributions grow significantly in the operation phase, particularly for second-category facilities, where residential inputs increase. This highlights the greater economic pull of labor-driven activities, emphasizing the importance of employment-intensive sectors in sponge city operations.

For auxiliary facilities, the top invisible sectors—electric power and heat production, other construction, and non-metallic mineral manufacturing—exhibit a stronger industrial presence compared to the service sector. Unlike other facility types, auxiliary facilities rely heavily on periodic upgrades and infrastructure renewal, mirroring the direct inputs required during initial construction. Consequently, their industrial input shares surpass those of service-sector inputs, reinforcing a highly concentrated industrial linkage network. This distinction underscores

Fig. 5. The total sectoral inputs pulled by the sponge city construction phase(Excluding sponge city construction and maintenance sub-sectors).

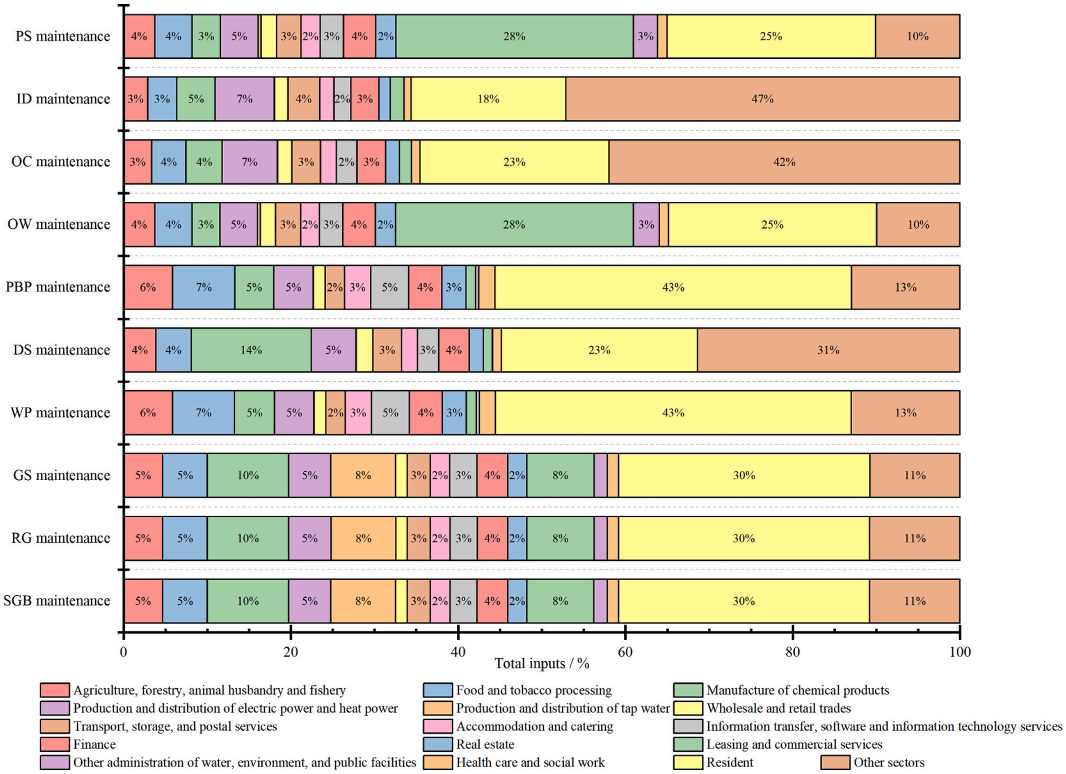


Fig. 6. The total sectoral inputs pulled by the sponge city operation phase (Excluding sponge city construction and maintenance sub-sectors).

the differentiated economic impacts of sponge city facilities, where auxiliary infrastructure maintains stronger ties to the industrial sector, while other facility types show greater integration with service industries and labor-intensive sectors.

4. Discussion

Cities function as complex adaptive systems, integrating urban infrastructure and natural environments, where human and ecological systems continuously interact and co-evolve (Sun et al., 2016). Ecosystems sustain life-supporting processes, including air and water purification, biodiversity conservation, and climate regulation, which are essential for human well-being. However, human needs extend beyond basic survival, varying across regions and populations, leading to diverse expectations for ecosystem services. In response, societies modify and manage natural systems, directing socioeconomic investments to enhance ecosystem service provision.

Low-impact development (LID) facilities constructed within sponge cities play a long-term role in delivering ecosystem services, necessitating integrated planning and management to fully realize the value of ecological products from a comprehensive, multidimensional perspective. Establishing effective policies and guidelines for sponge city development is critical for achieving sustainable urban growth, ensuring both ecological integrity and long-term economic viability.

During sponge city construction, policy interventions should target industries that derive lower benefits from ecosystem services, ensuring a balanced distribution of ecological gains. This study quantifies potential carbon sinks generated by LID facilities, facilitating the development of an ecological satellite account for carbon sequestration. Such an approach enables a granular analysis of carbon sink benefits across different economic sectors. The findings indicate that the service sector is the primary beneficiary, followed by the primary sector, while industrial sectors with lower green innovation coefficients receive fewer ecosystem service benefits. To address this imbalance, the government should adopt a “two-way regulation” strategy. For high-benefit industries, partial compensation for LID facility maintenance could be required, proportional to carbon sink revenues. In contrast, low-benefit industries, such as metal manufacturing and textiles, should be mandated to pay ecological taxes based on annual revenue. These taxes should be allocated toward cleaner production technologies, improving ecological service efficiency to offset emissions. Implementing a “beneficiary pays—polluter repairs” dual-track mechanism (Zheng et al., 2023) would redistribute ecological dividends more equitably, increasing ecosystem service accessibility for less advantaged sectors while supporting regional carbon neutrality goals.

Facilities with distinct green attributes should be prioritized in future urban ecological construction (Herath and Bai, 2024). The ecological transformation of cities extends beyond environmental conservation, playing a pivotal role in regional economic development. A comparison between sponge city construction and other urban eco-infrastructure projects, such as afforestation and wetland restoration, highlights a fundamental distinction in initial sectoral inputs.While afforestation and wetland restoration predominantly involve the primary sector (forestry and agriculture), sponge city construction necessitates a more multifaceted, cross-sectoral implementation strategy. A prime example is the reliance on non-metallic mineral products, such as permeable bricks and cement, which are integral to various LID facilities. The production and supply chains for these materials are deeply interconnected with the manufacturing industry, underscoring the need for interdisciplinary collaboration and strategic input from multiple sectors to fully unlock the potential of sponge city initiatives.

Sponge city construction has a pronounced industrial stimulation effect, with each unit of currency invested generating at least four times its value in productive economic activities. This substantial multiplier effect underscores the economic viability of sponge city development, reinforcing its role as a driver of regional growth. Given their dual ecological and economic benefits, sectors with strong green characteristics, such as rain gardens and sunken green belts, offer the highest returns on investment. Allocating greater financial resources to these facilities can enhance both environmental sustainability and economic efficiency, ensuring that sponge cities contribute holistically to urban resilience, climate adaptation, and economic expansion.

5. Conclusion

The construction of sponge cities marks a significant advancement in urban ecological infrastructure, providing essential ecosystem services such as rainwater recycling and carbon sink. The primary beneficiaries of sponge city carbon sinks include sectors such as agriculture, forestry, animal husbandry, and fishery, while the primary industry, as the largest water consumer, benefits from water conservation efforts that offset resource consumption. Additionally, service industries, which do not directly generate ecosystem services yet benefit from them, could contribute more toward ecological infrastructure development through higher service-based fees.

This study highlights the flow of ecosystem services through the national economy, demonstrating their potential for conversion into economic value. By differentiating sponge city subsectors from traditional construction, the research provides a refined understanding of green infrastructure’s unique contributions to urban environments and economies. The findings reveal complex interindustry relationships and significant industrial stimulation effects driven by the construction and operation of sponge cities. Notably, total investment stimulated by sponge city construction exceeds four times the direct investment, fostering positive economic development and stimulating service-sector growth, thereby shaping a more service-oriented urban industrial structure.

The integration of ecological and economic indicators in this study establishes a comprehensive framework for assessing the impact of urban infrastructure projects, aiding evidence-based policymaking and promoting sustainable urban development. This methodological framework is adaptable to other ecological construction projects, such as river training and land restoration, and can be expanded to incorporate additional ecosystem service indicators in future research. For example, in wetland restoration initiatives, the “water conservation–carbon sink service flows” approach could quantify how hydrological regulation reduces agricultural irrigation costs and how carbon sequestration offsets industrial emissions, helping to identify key beneficiary sectors. Similarly, the industrial stimulation effect methodology could be applied to other infrastructure projects to assess their cascading impacts on material supply chains and knowledge-intensive service industries, offering critical insights for optimizing project financing structures.

The dominance of government consumption in ecological service distribution underscores the need for systematic assessments of inclusive ecological welfare benefits generated by public fiscal investments in carbon sinks. Future research should focus on developing adaptive parameter databases and benefit transmission algorithms tailored to regional resource endowments and project characteristics. Moreover, further studies should explore the integration of livelihoods such as education and healthcare into eco-benefit allocation systems, along with precise measurements of investment return cycles to prioritize eco-investments effectively.

Despite its contributions, this study has certain limitations, including the use of provincial data for city-level analysis and the reliance on averaged carbon sink values, which may affect result accuracy. Future research should focus on utilizing localized data and refining carbon sink calculations to improve precision, ensuring more accurate and region-specific policy recommendations.

Credit author statement

WC Chang contributed to methodology development, conducted validation, and contributed to the writing of early drafts and final draft.

GY Liu is corresponding credit author, and they were responsible for overall project supervision, conceptualization, project management, and final draft writing, review and editing.

Y Chen, ZM Huo, DL Fang, F Agostinho, CMVB Almeida, BF Giannetti contributed to the data curation and revision checking.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2025.107955.

Data availability

Data will be made available on request.

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