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Integrating Ecosystem Services Supply–Demand and Spatial Relationships for Intercity Cooperation: A Case Study of the Yangtze River Delta

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Abstract: Transboundary environmental problems caused by urban expansion and economic growth cannot be solved by individual cities. Successful intercity environmental cooperation relies on the clear identification and definition of the rights and obligations of each city. An Ecosystem services (ES) approach not only budgets the ES supply and demand of a city, but also defines the spatial relationships between Services Provisioning Areas (SPA) and Services Benefiting Areas (SBA). However, to date, quantitative studies integrating ES budgets and spatial relations have been scarce. This study integrates ecosystem services supply-demand budgeting with flow direction analysis to identify intercity environmental cooperation in the highly urbanized Yangtze River Delta (YRD) region of China for water-related ecosystem services (flood protection, erosion regulation and water purification). The results demonstrated that there were significant spatial mismatches in the supply and demand of three water-related ES among 16 core cities in the YRD region: five to six cities in the southern part of the region had significant service surpluses, while ten to 11 cities in the north-central part had significant service deficits. We then went on to offer definitions for Ecosystem Services Surplus City, Ecosystem Services Deficit City and Ecosystem Services Balance City, as well as Service Provisioning City, Service Benefiting City and Service Connecting City in which to categorize cities in the YRD Region. Furthermore, we identified two intercity cooperation types and two non-cooperation types. This framework can be used to promote ecological integration in highly urbanized regions to advance sustainable development.

Keywords: ecosystem services; supply and demand; spatial relationship; Yangtze River Delta; transboundary cooperation

1. Introduction

Urban expansion and economic growth have caused serious transboundary environmental problems which have deeply undermined regional sustainable development [1–3]. Such problems, such as flooding and water pollution, cannot be solved by individual cities in an urbanizing region [4,5]. Neighboring administrative units, e.g., countries and cities, usually have mutual interests in environmental conservation since they often share ecosystems [4]. In situations where mutual interests do not align, innovative approaches, such as creative transboundary collaborations, may be used to find common ground [4]. The ultimate objective in such a transboundary collaboration is improving



human livelihoods while safeguarding ecosystems [6,7]. Ecosystem services (ES) can be defined as intermediate and connecting links between an ecosystem's biophysical structures and processes on the one hand, and human benefits and values on the other [8]. Previous studies balanced natural science and ecological economics with social aspects in ES production by recognizing that ES flows are an integrated result of coupled social–ecological systems and natural and human capital [9–11]. Frameworks for global ecosystem service assessments by Millennium Ecosystem Assessment [12] and the Intergovernmental Platform on Biodiversity and Ecosystem Services [13] identified previously

unrecognized ways through which environmental governance indirectly affects human well-being by (re)organizing interactions between ecosystems, ecosystem services and people [14]. However, frameworks guiding intercity environmental cooperation were still rare because of the complexity of the categories and scales of different ecosystem services.

Successful intercity environmental cooperation relies on the clear identification and definition of the rights and obligations of each city within the region. An ES approach not only budgets the ES supply and demand of a city, but also defines the spatial relations of Ecosystem Services Provisioning Areas (SPA) and Ecosystem Services Benefiting Areas (SBA), thereby providing an effective tool to identify the quantity of the ES supply–demand and spatial relations of a city for intercity cooperation. There have been several recent ES-based applications for transboundary cooperation in China and other countries [15–18]. However, to date, quantitative studies integrating ES budgets and spatial relations have been scarce. To develop a framework for intercity environmental cooperation using an ES approach, two aspects need to be considered: (1) Which cities have an ES surplus or ES deficit based on the ES supply–demand budget? (2) Does a city benefit from another city, as understood by ES flow direction analysis?

An Ecosystem Services Surplus City is a city where ES supply is greater than ES demand, while an Ecosystem Services Deficit City is a city where ES demand is greater than supply; both reflect the city's ES match or mismatch. ES Surplus and ES Deficit Cities can be identified by using an ES supply-demand budget. In recent years, the use of ES supply-demand budgets have been on the rise [19–22] and can be conducted by participatory methods [23,24], modelling methods [25,26] and mapping methods [17,27]. Modelling methods have found their applications in data-rich regions for quantitative assessments [28]. Participatory methods have been used in some successful cases in ES supply-demand budget studies in data-scarce regions and have often been combined with mapping. For example, Burkhard et al. [29] proposed an ES supply-demand matrix based on expert knowledge and mapping. Additionally, ES supply and demand can be made spatially explicit by linking these factors to land cover [20,29,30], an approach adopted in a study of recreational service supply and demand for the Basque Country in Spain at the regional scale [31], and the study of ES matrixes and supply-demand ratios for the spatial-temporal analysis of the Taihu Lake Basin in China [32]. Both ES supply and demand can be easily assessed and visualized by an ES supply-demand matrix, especially for data-scarce regions [33,34].

Whether a city can benefit from another city in terms of ES depends on ES flow directions and scales. ES flow analysis has attracted growing academic and policy attention in recent years [35,36]. An ES flow is defined as a general service provision [20], a pathway of delivery from provisioning to benefiting areas [37], and also as spatial movement of ecosystem-derived material, energy and information between a sending and a receiving socio-ecological system [38]. ES types can be classified by their flows [17,20–22]. Besides flow directions, scales should also be clearly identified to design targeted cooperation models, otherwise successful intercity environmental cooperation would be unfeasible. Unlike tourism and recreation services, which usually benefit local sites or cover entire regions [39], water-related services are usually restricted by watersheds [40] (e.g., flooding protection [41,42]). Carbon sequestration usually has global-scale or regional-scale effects [43], while the effects of air-related services are often local or regional in scale [44–46] (e.g., air quality regulation [44]). The scale of ES related to species migration depends on the boundary of biological activities [35].

The Yangtze River Delta (YRD) region is one of the largest and most highly urbanized regions in China. It has experienced remarkable population growth and urbanization over the past several decades [43,47]. This growth has dramatically changed regional land use/land cover (LULC) patterns, causing transboundary environmental problems such as water pollution and flooding which result in ES supply–demand mismatches [30,32]. Preliminary attempts at intercity environmental cooperation have been carried out in the YRD region, such as a water purification prefecture-level eco-compensation program in Jiangsu Province [48]. This program required the identification and definition of the rights and obligations of a city in the cooperation framework. In this paper, we present a general ES framework integrating an ES supply–demand budget with flow direction analysis, identifying ES city types and spatial relations for intercity environmental cooperation in a highly urbanized region.

2. Framework

We defined several key concepts which are summarized in Table 1. A general framework integrating ES supply–demand budget with flow direction analysis was developed and several intercity environmental cooperation models of water-related ES for highly urbanized regions were proposed. The details are presented in Section 2.2, Figure 1.

Concept	Definition	References		
Ecosystems Services (ES) Supply of a City	ES supply means the provision of a service by a particular ecosystem. We define the ES supply of a city as the provision of a service by all of the ecosystems in that city.	Defined following [20,29]		
ES Demand of a City	ES demand refers to the need for specific ES by a society, particularly stakeholder groups or individuals. We define the ES demand of a city as the corresponding need of that city.	Defined following [20,29]		
ES Supply–Demand Budget of a City	Each field in the budget matrix can be calculated based on the corresponding field in the supply and the demand matrix. We define the ES supply–demand budget of a city as the sum of differences between ES supply and demand of a city.	Defined following [20,29]		
ES Surplus City	A city in which ES supply is greater than demand in an ES supply–demand budget.	Defined in this study		
ES Deficit City	A city in which ES demand is greater than supply in an ES supply–demand budget.	Defined in this study		
ES Balance City	A city in which ES supply is equal to ES demand.	Defined in this study		
Service Provisioning City (SPC)	Service provisioning area refers to an area that is the source of an ES or multiple ES. We define SPC as a city that is the source of an ES or multiple ES.	Defined following [17,20–22,29]		
Service Benefiting City (SBC)	Service benefiting area means an area benefiting from an ES or multiple ES. We define SBC as a city benefitting from an ES or multiple ES.	Defined following [17,20–22,29]		
Service Connecting City (SCC)	Service connecting area refers to the intervening space between providing and benefiting areas, if the latter two are not contiguous. We define an intervening city as SCC between SPC and SBC if SPC and SBC do not border each other. An SCC can be an ES Deficit City or ES Balance City.	Defined following [17,20-22,29]		
Intercity ES flow	Ecosystem service flows refer to the spatial and temporal connections between provisioning and benefiting areas. We define Intercity ES flow as the spatial and temporal connections between SPC and SBC.	Defined following [17,20–22,29]		

Table 1. Definitions of key concepts.

2.1. Identifying Transboundary Environmental Problems and Objectives

Identify transboundary environmental problems: The main transboundary environmental problems for the entire region were identified through a review of administrative documents and academic reports at different levels (e.g., national, regional, municipal). In the meantime, local expert consultation and field work helped to identify transboundary environmental problems in specific areas.

Set intercity environmental cooperation objectives: Intercity cooperation objectives should be relevant to specific transboundary environmental problems in the study area, such as enhancing water purification in upstream cities. Moreover, objective-setting should be made on the basis of stakeholders' requirements, as laid out in regional or local ecological/ environmental and development plans, with respect to environmental criteria such as water quality [48].

2.2. Analyzing Relationships Among These Problems and Their Relevant ES

Identify causal relationships: First, local ecosystem types were identified by combining local expert knowledge with land cover systems, linking with relevant ecosystem services. Next, natural drivers (e.g., precipitation, landform, vegetation) and human activities related to transboundary environmental problems were identified through a literature review, including academic reports and government documents, or through expert elicitation. Finally, the impacts of natural drivers and human activities on ecosystem degradation and loss of ecosystem services were identified through similar means.

Choose Relevant ES: Based on identification of environmental problems and their causal relationship to ES, ES categories targeted to transboundary environmental problems were identified. Next, ES with definite flow direction were selected so that they were suitable for defining intercity environmental cooperation. In the case study of the YRD region, examples of the directional and in situ ES types were chosen (e.g., water-related ES). Omni-directional types had ES flows between cities, but it was difficult to identify their flow directions (e.g., air-related ES) [49–51].

Relationships among transboundary environmental problems and objectives are showcased in Figure 1.



Figure 1. The general framework of ES intercity environmental cooperation.

2.3. Defining ES Surplus, Deficit and Balance City

Set up a city's ES supply-demand matrix: It is fundamental to carry out the relevant ES supply-demand assessments of a city [52]. We used the ES supply-demand matrix method [29] for intercity cooperation in a highly urbanized region, since it has spatial explicitly advantages and provides quick decision support for data-poor regions [32]. Other methods have better results for quantitative ES supply-demand assessments in data-rich regions, such as modeling [25,26]. The selection and application of these methods depends on data availability, research and decision-making objectives.

Construct a city's ES supply–demand budget: Based on the matrix, calculated the ES supply, demand and budget of a city in order to unify the dimensions of ES assessment. An ES supply–demand budget may be converted into monetary values or relevant scores [20,29].

Identify ES Surplus, Deficit and Balance City: Based on an ES supply–demand budget, a city was defined as ES Surplus City, ES Deficit City or ES Balance City (Table 1).

2.4. Defining Service Provisioning, Benefiting and Connecting Cities

(i) Identifying ES flow carrier:

ES flows can usually be classified into three types. (1) Water-related ES flows (e.g., water supply, flood protection service, water purification service and erosion regulation service). Water is the carrier of these ES flows. These ES flows can only be delivered by water in a river network in a drainage basin [53]. The flow path of these ES flows is naturally hydrological, where the capacity to produce a service upstream (ES source) affects the flow of benefits downstream (benefit zone) [41,54]. (2) Air-related ES flows include air quality regulation service, and air is the carrier of these ES flows [55]. It is difficult to delineate the boundaries of air-related ES flows because of the variability of wind direction, strength and influencing area. (3) People-related ES flows include the delivery of cultural services [56]. Here, service benefiters such as tourists move directly to the SPAs, where they gain the benefit of scenic spots [57]. Our study selected water-related ES as a case for intercity environmental cooperation.

(ii) Analyzing ES flow directions:

ES flow directions can be analyzed by modelling. Currently, the most widely-adopted ES model is the InVEST model. However, this does not focus on ES flow quantification analysis [17,37,58]. Other process-models include hydrological models for directional water-related ES [59] and the ARIES (Artificial Intelligence for Ecosystem Services) for complex ES flow simulation [17,37,58], which can be useful tools for simulating ES flows directions.

(iii) Identify Service Provisioning City (SPC), Service Benefiting City (SBC) and Service Connecting City (SCC):

If an ES Surplus City is upstream and an ES Deficit City is downstream in the same basin, and their boundaries are directly connected, there is ES flow from the ES Surplus City to the ES Deficit City. We defined the ES Surplus City as SPC and the ES Deficit City as SBC. For example, in the Basin B of our model, City D is an SPC and City E is an SBC (Figure 2).

If an ES Surplus City is upstream and an ES Deficit City is downstream in the same basin, but they are separately located, ES flow can be delivered through a carrier (e.g., river) in a connecting city. For example, in Basin A of our model, City A is the SPC, City C the SBC and City B is the SCC. There are no SPC, SBC or SCCs in the Basin C and City F can neither be an SPC nor an SBC because there is no direct ES flow between City F and other cities (Figure 2).

2.5. Developing Intercity Environmental Cooperation

Finally, based on our model (Figure 2), we outlined two ES intercity cooperation types and three non-cooperation types for water-related ES. The two cooperation types are:

- (i) SPC–SBC cooperation: For example, City D and City E could establish SPC–SBC cooperation in Basin B (Figure 2).
- SPC-SCC-SBC cooperation: For example, City A, City C and City B could build SPC-SCC-SBC cooperation in Basin A (Figure 2).

The three non-cooperation types are

- (i) Non-cooperation among the same type of cities: e.g., ES Surplus or Deficit or Balance City in the same basin, as the same type of cities require no cooperation, even if there are ES flow deliveries among them. For example, between City F and City G (Figure 2).
- (ii) Non-cooperation between an ES Balance City and an ES Deficit City in the same basin since the former has no excess ES to provide to the latter.
- (iii) Non-cooperation between an ES Surplus City and an ES Deficit City located in the different basins since there is no SPC–SBC relation or the former cannot deliver ES flow to the latter due to natural obstacles such as a sea or a landform. For example, between City A in Basin A and City E in Basin B or City F in Basin C (Figure 2).



Figure 2. A conceptual diagram for ES intercity cooperation in a given region.

3. Case Study

3.1. Study Area

The YRD Region is located in the eastern coastal region of China (Figure 3), which has a subtropical monsoon climate. It has an area of about 116,171 km² and a population of over 102 million people in 2010. There is significant spatial heterogeneity in terms of landforms and ecosystems in this region: urban areas and cultivated land are mainly distributed in the northeast plain, whereas forests and grasslands are mainly located in the southwest mountainous region. The YRD region included Shanghai Municipality, eight prefecture-level cities in Jiangsu Province (Wuxi, Suzhou, Changzhou, Nanjing, Taizhou, Zhenjiang, Nantong and Yangzhou) and seven prefecture-level cities in Zhejiang Province (Hangzhou, Jiaxing, Ningbo, Zhoushan, Taizhou, Shaoxing and Huzhou) (Figure 3).

Taihu Lake Basin, approximately 3.69×10^4 km² in size [60], is located in the Yangtze River Delta, crossing the administrative boundaries of Jiangsu Province, Zhejiang Province and Shanghai

Municipality. Taihu Lake Basin is one the most developed economic regions in China, with a population of more than 52 million in 2010 [32]. In 2010, urbanization caused spatial mismatches in ES supply and demand among cities, resulting in serious ecological and environmental problems, and decision-makers recognized that comprehensive ES assessments and decision-support approaches were urgently required [32,61].

3.2. Data Sources

LULC data of the YRD region in 2010 with 30 m spatial resolution and an overall classification accuracy of 85.58% were obtained from the National Geomatics Center of China. Year 2010 is a typical year in the stage of urbanization for the YRD region [43,61]. The Digital Elevation Model (DEM) with 30 m spatial resolution was provided by the Geospatial Data Cloud (http://www.gscloud.cn/). Based on the DEM, the elevations, catchment and stream order were simulated and mapped using the terrain and hydrology modules of ArcGIS 10.0. In addition, we leveraged local environmental reports such as the Taihu Lake Basin and the Southeast Rivers Water Resources Bulletin (http://www.tba.gov.cn/tba/content/TBA/lygb/index.html) to score ES supply and demand and identify ES flow directions.



Figure 3. Location of the Yangtze River Delta region, China.

3.3. Identifying Transboundary Environmental Problems and Objectives

Identify transboundary environmental problems: The main transboundary environmental problems were identified for the YRD region through government documents and a review of the academic literature (Table 2). These were one national environmental planning report the Regional Plan for the Yangtze River Delta Region (2009–2020) [62], one environmental report related to natural disasters in the YRD region (Comprehensive Ecological Risk Prevention: Natural Disaster Factors and Risk Assessment in the Yangtze River Delta Region [63]), six watershed-level environmental reports related to flooding problems (Annual Report of Flood Control and Typhoon Prevention in Taihu Lake Basin (2013–2018) [64]), a watershed-level environmental report related to water pollution problems

(The Health Status Report of Taihu Lake (2008–2017) [60]), one municipal environmental report related to natural resource endowments and environmental conditions (Annual Report on the Resources and Environment of Shanghai (2012)) and a literature review (e.g., [65–67]).

The identified water quality problems were as following [60,68]. In recent decades, the overall quality of the Taihu Lake Basin's surface water rapidly deteriorated. From June 2005 to May 2009, the standard exceeding ratios (exceeding Category III) were over 75% according to the Chinese Government standard for water quality issued in 1988 (GB 3838–88) [69]. In 35 water quality monitoring position records at the provincial boundaries from May 2010, only 10 reached the basic requirement of Category III, while the other 25 were all below Category III (4 were IV, 9 were V and 12 were worse than V).

Level	Name	Year	Number	Reference
National	Regional Plan for the Yangtze River Delta Region (2009–2020)	2010	1	[62]
Regional	Comprehensive Ecological Risk Prevention: Natural Disaster Factors and Risk Assessment in the Yangtze River Delta Region	2014	1	[63]
Regional	The Health Status Report of Taihu Lake	2008-2017	10	[60]
Regional	Annual Report of Flood Control and Typhoon Prevention in Taihu Lake Basin	2013–2018	6	[64]
Municipal	Annual Report on the Resources and Environment of Shanghai	/	1	[68]

Table 2. The main government documents and academic reports review.

Flooding was also a severe problem over the study period [63,64]. From 1980 to 2010, floods occurred 130 times in the YRD region, with a gradually increasing trend. In 1981–1990, the average annual occurrence was 3.2 times, while the number increased to 4.3 in 2001–2010. In 1949–2010, the official deaths from flooding was reached 8269 in the YRD region and were mainly in Jiangsu Province. In 1981–2010, direct economic losses from flooding totaled ¥ 172.6 billion.

Compared with water-related transboundary problems that have definite flow directions and boundaries (i.e., catchments), air-related problems usually do not have the clear boundaries necessary for constructing a spatially definite intercity cooperation framework. Therefore, this case study focused on problems from three water-related problems—transboundary water pollution, erosion and flooding—in order to identify the spatial relations among cities.

Set intercity cooperation objectives: The "Ecological construction and environmental protection" section in the authoritative Regional Plan for the Yangtze River Delta Region (2009–2020) stated [62] that efforts should be focused on protecting the water quality of source sites for a centralized drinking water supply. Mechanisms for protecting the sources of drinking water should be established and optimized, securing a win-win for all rivers as well as for downstream and upstream regions. Improved water quality and sufficient water supply should be guaranteed at water source sites with serious pollution and insufficient quantities, and their water quality should be made to qualify official standards.

For prefecture city-level objectives, Jiangsu's Departments of Finance and Environmental Protection jointly issued the Administrative Measures on the Use of Regional Payment-for-Ecosystem-Service Funds for Environmental Resources in the Taihu Lake Basin, Jiangsu Province, and put forward a bidirectional compensation management mechanism in 2010. The bidirectional compensation model is meant to be implemented at cross sections along river segments separating two cities: when the water quality at the cross section exceeds the standard, the upstream city compensates the downstream city; when the water quality meets the standard, the downstream city compensates the upstream city. Lastly, in the case of stagnant flow, no compensation was made by either city. Water quality was classified according to the Chinese Government Standard for Water Quality issued in 1988 (GB 3838–88) [69].

3.4. Analyzing Relationships Among These Problems and Their Relevant ES

Identifying causal relationships: First, the land cover and ecosystem types of this case study were identified by combining local expert knowledge in the Yangtze River Delta region with the CORINE

(Co-ordinated Information on the Environment) land cover system [61] (Table 3): (1) Urban land, (2) Rural residential land, (3) Arable land, (4) Forests, (5) Shrublands, (6) Grasslands, (7) Barelands, (8) Inland marshes, (9) Salt marshes, (10) Streams and lakes, (11) Estuaries, and (12) Shallow sea wetlands. Then, we identified the causal relationships of transboundary environmental problems through a literature review and local expert consultation in the YRD region: urbanization and economic growth, LULC change, ecosystem degradation [61,70], ecosystem services decline [15,67,71], water pollution [32,67,69,72–75], and flooding and soil loss [63,76,77].

In terms of water pollution problems, the YRD experienced rapid economic growth and concomitant water resources exploitation, but the prevention and control of water pollution was insufficient, causing imbalances of resource use and environmental conservation, generating deteriorating water quality [32,67,69,72–75]. In the meantime, population growth and urban expansion made the YRD, especially the Taihu Lake Basin, a site of escalating tension between the supply of ecosystem services and social demand in China [32]. In terms of flooding problems, flood disasters were mainly influenced by natural causes (e.g., precipitation, topography) and human activities (e.g., land cover change) [63,64]. First, with respect to precipitation: in 1951–2005, the average rainstorm was above 260 mm based on 25 primary weather stations in the region; 1951–1962 and 1987–2005 were two peak periods for rainstorms, with rainstorms averaging 305 mm and 295 mm. At the same time, the number of annual average rainstorms also reached peak numbers in 1951–1962 and 1987–2005, with the highest number being five in 1954 and 1989 [63,64]. With respect to topography: the north of the YRD has mainly been covered by plains, the northern area being alluvial and the center being the drainage area of Taihu Lake, with the Qiantang River alluvial plain located along the Hangzhou Bay to the east. The plain areas were below 20 meters, therefore making the YRD vulnerable to flooding. Finally, flooding was influenced by land cover change [63]. Forests shrublands and wetlands in the region were converted into urban land with the expansion of impervious surfaces exacerbating flood risks.

Choosing relevant ES: three water-related ecosystem services relevant to intercity environmental cooperation mechanisms were identified in the YRD region: flood protection, erosion regulation and water purification. Flood protection refers to the flow of natural run-off, which dampens extreme flood events. Erosion regulation refers to the role that vegetation coverage plays in soil retention and the prevention of landslides. Water purification refers to the service performed by ecosystems to purify water.

3.5. Defining ES Surplus, Deficit and Balance Cities

Establishing a city's ES supply–demand matrix: We created the ES supply–demand matrix by relating the 12 land cover classes with the ten ecosystem services for the YRD region (Table 2). The score in the matrix indicates the amount of an individual ecosystem service supplied or required per unit area of a specific land cover class. The scores were determined following a three-step assessment procedure.

In the first step, we assigned a score for each matrix sheet by applying the original matrix presented by Burkhard et al. [29].

In the second step, we interviewed and asked 15 experts, five from government bodies (one from Shanghai, two from Jiangsu Province, two from Zhejiang Province), four from East China Normal University, one from Nanjing University, one from the Nanjing Institution of the Chinese Academy of Sciences, one from Jiangsu University, and two from an environmental institution employed by the government of Zhejiang Province) to score each regional ecosystem services supply and demand for the Yangtze River Delta metropolitan region.

In the third step, we divided the 15 experts into three groups depending on their location, with five experts in each: a Shanghai group, Zhejiang group and Jiangsu group. The "median" score of an expert in each group was collected first for every ES-to-land cover category. Then, the median score for each group was considered the final score.

During the scoring process, each expert adjusted the original score for each ES based on their own expertise. For the scoring process of erosion regulation supply (Table 3), local experts considered

shrubland as providing "high relevant supply" based on vegetation coverage, with an indicator suggested by Burkhard et al. [29] and Burkhard et al. [20].

The areas with high supply (score 3–5) were mainly distributed in the southwest of the region and accounted for over 30% of the total area, while the areas with low supply (score 0–2) were mainly located in the northeast of the region. In particular, the areas with a score of 2 for Flood Protection and Water Purification were distributed in the eastern estuary areas. The areas with scores of 5 or 4 for Flood Protection were dispersed across the whole region and occupied a relatively small proportion of the total area (Figure 4).



Figure 4. Example of expert scoring process.

The spatial patterns of the demand for the three ES were different from those of the supply. The areas with high demand (score 4–5) for Erosion Regulation were scattered across the coastal plain, while the areas with high demand for Flood Protection were densely concentrated in the urban areas and the cultivated lands, and areas with high demand for Water Purification were densely clustered in the urban areas in the northeast of the region (Figure 5).

Table 3. The supply-demand matrix of three water-related ES (Flood Protection, Erosion Regulation, Water Purification) in the YRD Region.

Land Cover	Flood Protection			Erosion Regulation			Water Purification		
Luna cover	S	D	В	S	D	В	S	D	В
Urban Land	0	4	-4	0	1	-1	0	1	-1
Rural Residential Land	0	5	-5	0	1	-1	0	2	-2
Arable Land	1	2	-1	0	2	-2	0	5	-5
Forest	3	0	3	5	0	5	5	0	5
Shrublands	0	0	0	4	0	4	4	0	4
Grasslands	1	0	1	5	0	5	4	0	4
Barelands	4	0	4	0	0	0	0	0	0
Inland Marshes	5	0	5	0	0	0	0	0	0
Salt Marshes	1	0	1	0	0	0	0	0	0

Table 3. Cont.	
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Land Cover	Flood Protection			Erosion Regulation			Water Purification		
Luita Cover	S	D	В	S	D	В	S	D	В
Streams and Lakes	1	0	1	0	0	0	1	0	1
Estuaries	3	0	3	0	0	0	2	0	2
Shallow Sea Wetlands	0	0	0	0	0	0	0	0	0

Note: S–Supply, D–Demand, B–Budget. Scale from 0/1/2/3/4/5/ = no/low/relatively low/high/very high/relevant supply or demand [20,29]. 1 = low relevant supply, 2 = relevant supply, 3 = medium relevant supply, 4 = high relevant supply, and 5 = very high relevant supply. 0 = no relevant demand, 1 = low relevant demand, 2 = relevant demand, 3 = medium relevant demand, 4 = high relevant demand, and 5 = very high relevant demand. The values indicate budgets from <math>-5 = demand exceeds supply significantly = undersupply, via 0 = demand = supply = neutral balance, to 5 = supply exceeds the demand significantly = oversupply.



Figure 5. Spatial patterns of ES supply, demand and budget of Flood Protection, Erosion Regulation, and Water Purification in the YRD Region. Scale from 0/1/2/3/4/5/ = no/low/ relatively low/high/very high/relevant supply or demand [20,29]; -5/brown red = demand exceeds supply significantly = undersupply, via 0/grey = demand = supply = neutral balance, to 5/dark green = supply exceeds the demand significantly = oversupply.

Based on the results of the supply-demand budgets, the areas with high positive scores for the three ES were centered in the southwest of the region, while the areas with high negative scores were mainly scattered or concentrated in the northeast of the region (Figure 5). These patterns implied that there were serious spatial mismatches in the supply and demand of the three ES within the region, especially for Water Purification services.

Calculating a city's ES supply–demand budget: We calculated and compared the amount of ES supply, demand and budget for cities based on the score and area of each LULC. The scale was 0 = no relevant flow, 1 = low relevant flow, 2 = relevant flow, 3 = carrier relevant flow, 4 = high relevant flow, and 5 = very high (maximum) relevant flow [20]. The unit of the amount of ES was score $\times km^2$.

$$S = \sum S_i \times A_i \tag{1}$$

where S (supply) is the total amount of flow of different land cover classes in providing ES, S_i (score) represents the quantity or importance score of flows of land cover class i to provide ES, and A_i (km²) indicates the area of land cover class i.

$$S = \sum D_i \times A_i \tag{2}$$

where D (demand) stands for the amount of relevant demand for ES from people living within the different land cover classes, D_i (score) means the score of the relevant demand for ES from people living within land cover class i, and A_i (km²) denotes the area of land cover class i.

$$B = S - D \tag{3}$$

where B (budget) is the amount of the supply-demand budget of the targeted ES.

The ES supply–demand score matrix table revised by local experts was applied in calculating the ES supply, demand and budget. Using the erosion regulation service of Hangzhou as an example, the supply (Se) = the "expert score of ES capacity of forest" × the "area of forest" + the "expert score of ES capacity of shrublands" × the "area of shrublands" + the "expert score of ES capacity of grasslands" × the "area of grasslands" = $5 \times 10492.04 + 4 \times 13.04 + 5 \times 657.48 = 55799.76$ score*km², when the expert score of the capacities of other land covers are zero. The demand (De) = the "expert score of ES demand of urban land" × the "area of urban land" + the "expert score of ES demand of arable land" × the "area of rural residential land" + the "expert score of ES demand of arable land" × the "area of rural residential land" + the "expert score of ES demand of arable land" (Se) = 1 \times 496.27 + 1 \times 424.95 + 2 \times 4235.11 = 9391.44 score* km², when the expert score of the capacities of other land covers are zero. The budget (Be) = the amount of supply (Se) - the amount of demand (De) = 46408.32 score* km².

Table 4 shows that there were significant differences in the supply, demand and budget for the three ES among the 16 cities. The differences between the highest and the lowest supply amount was extremely large for the 16 cities, except for Flood Protection. The differences between the highest and the lowest demand amount was relatively small for the 16 cities. Shanghai was the top city in terms of the demand for Erosion Regulation and Water Purification, and Nantong was the top city in terms of the demand for Flood Protection. Zhoushan was the city with the lowest demand for Erosion Regulation and Huzhou was the city with the lowest demand for Water Purification. The results indicated significant mismatches in supply and demand for the three ES in the 16 cities of the YRD Region.

Defining ES Surplus, Deficit and Balance City: Based on the above budget, ES Surplus, Deficit and Balance Cities in our case study area were identified (Table 4 and Figure 6). Hangzhou, Taizhou-Z, Shaoxing, Ningbo and Zhoushan were ES Surplus Cities for Flood Protection, Erosion Regulation and Water Purification, while Huzhou was an ES Surplus City for Flood Protection and Erosion Regulation.

Defining Service Provisioning, Benefiting City and Connecting City

Defining ES flow carrier: Water is the carrier of the three selected ES and water flow is realized in the river networks of the YRD region. Hydrological models in the ArcHydro tools of ArcGIS were used to identify the ES flow relevant to the catchment, such as Flood Protection, Erosion Regulation and Water Purification. Based on the DEM, the catchments (Catchment A–H) in the YRD Region were delineated and the flow directions of the rivers were analyzed by stream order analysis in the ArcHydro module of ArcGIS 10.0. The terrain-influenced directions were stimulated by river orders from higher to lower (1–5) (Figure 7).

Analyzing ES flow directions: Both the Water Purification and Flood Protection services were directional–slope dependent, while Erosion Regulation was in situ. The flow directions of the three water-related services were influenced by the natural river networks dominated by terrain (slope) and artificial river networks (e.g., canals) (Figure 7). According to the stream order, three main streams flowed from the southwest hilly and mountainous areas to the: (1) northeast plain area and then directly into the Yangtze River; (2) eastern plain area and then directly into the Yangtze River; and (3) southern plain area and then into the Qiantang River. The gravitational flow directions were obstructed by the Great Canal and Taihu Lake. The Great Canal changed the flow directions and made the water flow from the north to south into Taihu Lake. The natural rivers, mainly comprised of the Eastern and Western Tiao Rivers and the Southern River, flowed from west to east into Taihu Lake. (Figure 7).

Identifying Service Provisioning City (SPC), Service Connecting City (SCC) and Service Benefiting City (SBC): Based on the integration of ES supply–demand budget and flow direction analysis, SPC, SBC, SCC and their spatial relationships were identified for the YRD.

(1) SPC–SBC relationships for Erosion Regulation: Huzhou (SPC)–Jiaxing (SBC), Huzhou (SPC)–Suzhou (SBC), Hangzhou (SPC)–Jiaxing (SBC) and Hangzhou (SPC)–Suzhou (SBC) were.

(2) (i) SPC–SBC relationships for Flood Protection: Huzhou (SPC)–Jiaxing (SBC), Huzhou (SPC)–Suzhou (SBC), Hangzhou (SPC)–Jiaxing (SBC), and Hangzhou (SPC)–Suzhou (SBC);

(ii) SPC–SCC–SBC relationships for Flood Protection: Huzhou (SPC)–Jiaxing (SCC)–Shanghai (SBC), Huzhou (SPC)–Jiaxing (SCC)–Shanghai (SCC), Hangzhou (SPC)–Jiaxing (SCC)–Shanghai (SBC) and Hangzhou (SPC)–Jiaxing (SCC)–Shanghai (SBC).

(3) (i) SPC–SBC relationships for Water Purification: Hangzhou (SPC)–Jiaxing (SBC) and Hangzhou (SPC)–Suzhou (SBC);

(ii) SPC–SCC–SBC relationships for Water Purification: Hangzhou (SPC)–Jiaxing (SCC)–Shanghai (SBC) and Hangzhou (SPC)–Jiaxing (SCC)–Shanghai (SBC).

3.6. Developing Intercity Environmental Cooperation Models

Based on the above analysis, two types of cooperation and two types of non-cooperation framework were identified in the case study area. In terms of cooperation types, the two were:

(1) SPC–SBC cooperation: In Taihu Lake Basin, there were SPC–SBC relations between Hangzhou (SPC) upstream and Jiaxing or Suzhou (SBC) downstream for the three water-related ES, while there were SPC–SBC relations between Huzhou (SPC) upstream and Jiaxing or Suzhou (SBC) downstream for Erosion Regulation and Flood Protection.

(2) SPC–SCC–SBC cooperation: In Taihu Lake Basin, there was an SPC–SCC–SBC relation among Hangzhou (SPC) upstream-Jiaxing or Suzhou (SCC)–Shanghai (SBC) downstream for Water Purification and Flood Protection, while there was an SPC–SCC–SBC relation among Huzhou (SPC) upstream-Suzhou (SCC)–Shanghai (SBC) downstream for Flood Protection.

The two non-cooperation types were:

(1) Non-cooperation required among cities of the same type (ES Surplus City or ES Deficit City) in the same basin: For example, both Suzhou and Wuxi in the Taihu Lake Basin were ES Deficit Cities that had no ES surplus to deliver to each other. Another example was Hangzhou and Shaoxing in the Qiantang River Basin (E). Both were ES Surplus Cities that had no need to cooperate with each other.

(2) Non-cooperation between an ES Surplus City and an ES Deficit City in the different basins: Most of the 16 core cities belonged to several basins (e.g., Taihu Lake Basin, Qiantang River Basin). For example, Taizhou-Z had an ES surplus in the three ES, but it could not deliver its ES surplus to all of the ES Deficit Cities in Jiangsu Province since they had no SPC–SBC relations.

4. Discussion

4.1. Implications for Intercity Environmental Cooperation

At present, the YRD region is vigorously promoting the integration of environmental protection and governance and is strengthening all-round cooperation among cities in the region [78,79]. However, based on the results, whether or not cities can cooperate is conditional. The ES surplus and deficit of a given city, different service types and service flow directions may all influence ES flow deliveries among cities, affecting intercity cooperation in a region. Different ES cooperation mechanisms should be established for different ES intercity relationships. For the SPC–SBC cooperation type, we suggest that the relevant cities should carry out payment of ecosystem services (PESs) mechanisms or eco-compensation mechanisms which are currently being tested in some cities such as Suzhou [80].

For the SPC–SCC–SBC cooperation type, in addition to the cooperation between SPC and SBC, SCCs should actively join the cooperation. Therefore, mechanisms for basin or regional coordination of SPC, SBC and SCC cooperation need to be established. For example, Administrative Measures on the Use of Regional Payment-for-Ecosystem-Service Funds for Environmental Resources in the Taihu Lake Basin was issued by Jiangsu's Department of Finance and the Department of Environmental Protection, as well as by Shanghai Municipality [71,81]. This policy aims to specify the rules on the use and allocation of the funds of both Category A (payment to upstream areas from downstream areas) and Category B (local payment to provincial financial agencies).

There are two situations for ES non-cooperation. One is that there is no possibility of cooperation among cities located in different basins due to obstacles of ES flow delivery, despite the presence of an ES Surplus City and an ES Deficit City in the region. For example, Huzhou (ES Surplus City) in Taihu Lake Basin and Yangzhou (ES Deficit City) in another basin did not have SPC–SBC relations in the three water-related services, and there was thus no possibility of cooperation between them.

But some artificial networks such as "South-to-North Water Transfer" may be used to remove the obstacle of ES flow delivery to achieve intercity cooperation [82].

The other is that there is no requirement for ES intercity cooperation among the same types of cities, e.g., ES Deficit City or ES Surplus City. For example, there is no need for cooperation in these three water-related services between Jiaxing (ES Deficit City) and Suzhou (ES Deficit City) in Taihu Lake Basin. However, to ensure sustainable land use management in these cities through ecological restoration [15,83], the ES Deficit City upstream could be transformed into an ES Surplus City and then SPC–SBC cooperation could be established.

Additionally, ES supply–demand budgets can be used to distinguish cities' rights and obligations in intercity cooperation since the score of an ES supply–demand budget can be transferred into monetary value [20,29]. At present, there are still arguments over this value conversion method [20,84]. However, through validation by interviews of local experts and officers in the Taihu Basin Authority, the ES supply–demand budget of a city could be improved to become a best practice for catchment-level intercity environmental cooperation.

	City	Flood Protection			Ere	osion Regulati	on	Water Purification			
riovince		S	D	В	S	D	В	S	D	В	
Zhejiang	Hangzhou	37,192.95	12,580.05	24,612.90	55,799.76	9391.44	46,408.32	55,957.51	22,521.72	33,435.79	
	Taizhou-Z	18,362.32	9325.78	9036.54	26,752.79	6980.61	19,772.18	26,446.62	16,834.84	9611.78	
	Shaoxing	14,605.68	9538.62	5067.06	20,025.34	7837.11	12,188.23	19,921.69	18,463.31	1458.38	
	Ningbo	14,858.42	11,445.92	3412.50	19,632.80	7557.60	12,075.20	19,586.43	18,407.13	1179.30	
	Zhoushan	2077.04	1321.10	755.94	3371.65	904.39	2467.26	12,845.27	14,903.94	1030.80	
	Huzhou	10,325.05	7494.54	2830.51	12,942.15	6077.47	6864.68	3216.32	2185.52	-2058.67	
	Jiaxing	3480.89	9370.37	-5889.48	127.35	7023.49	-6896.14	305.90	16,916.21	-16,610.31	
Jiangsu	Zhenjiang	3803.69	7120.00	-3316.31	2046.60	5407.04	-3360.44	3028.50	12,615.93	-9587.43	
	Changzhou	4400.34	8398.65	-3998.31	1306.05	5780.17	-4474.12	1588.60	14,191.99	-12,603.39	
	Nanjing	4367.53	8502.00	-4134.47	1523.20	6359.68	-4836.48	2121.72	15,301.62	-13,179.90	
	Wuxi	7518.65	12,715.24	-5196.59	3857.05	9797.13	-5940.08	3871.93	20,291.54	-16,419.61	
	Yangzhou	6364.86	12,617.43	-6252.57	1062.08	8663.64	-7601.56	4592.32	23,686.96	-19,094.64	
	Taizhou-J	7011.37	13,383.05	-6371.68	2750.85	12,762.03	-10,011.18	1532.09	21,984.08	-20,451.99	
	Suzhou	8116.22	18,625.45	-10,509.23	151.95	10,186.31	-10,034.36	3984.11	27,163.26	-23,179.15	
	Nantong	8983.04	22,245.66	-13,262.62	295.10	10,879.19	-10,584.09	1286.16	26,810.37	-25,524.21	
Shanghai	Shanghai	5488.08	19,036.37	-13,548.29	10.44	15,915.92	-15,905.48	325.21	39,122.35	-38,797.14	
Total	-	156,956.13	183,720.23	-18,951.35	151,655.16	131,523.22	20,131.94	160,610.38	311,400.77	-150,790.39	

Table 4. The amount of supply (S), demand (D) and the budget (B) of three water-related ES in 16 cities of the YRD region. The amounts in this table were calculated by formula (1)–(3) with score Table 2 with unit of score × km². The red color of the negative value in budget (B) means ES demand is greater than supply for that city, which has a deficit in the budget. The positive value in budget (B) means ES supply is greater than demand and that city has a surplus in the budget.



Figure 6. The spatial pattern of the supply-demand budget of three water-related ES (Flood Protection, Erosion Regulation, Water Purification) for core cities in the YRD Region: The "A1–H" were Natural Catchment Numbers in Terrain and Catchment Map. Blue Column: Amount of Supply; Purple Column: Amount of Demand; Yellow Column: Amount of Budget.

4.2. Contributions and Limitations

Previous ES frameworks have connected ES approaches with environmental policy decision support [83,85,86]. Some of these studies have applied ES supply-demand budget analysis to the preliminary stage of environmental management [42]. Others have applied ES flow direction analysis to identify SPA and SPA for decision support (e.g., biodiversity conservation management) [35] and PES and eco-compensation [87]. Despite the potential usefulness of ES supply-demand budget and flow direction analysis for environmental management, there have been few studies taking both cities' ES supply-demand or mismatch and spatial relations as a scientific basis for intercity environmental cooperation [88]. This study presented a general framework integrating ES supply and demand budget with ES flow direction analysis with the aim of calculating the ES surplus or deficit of a city, defining SPC, SBC and SCC and identifying intercity ES cooperation models. We have applied this framework to one particular case study region, but it is applicable to similar regions as well.

In this study, Burkhard's matrix method was used to score each ecosystem type of land use/cover in the YRD region. Although there are some debates on the expert knowledge-based method, it is still considered to be both convenient and analytically effective [23,84], especially in data-poor regions [24], and is best used in the exploratory phase of science-based projects [89]. Relative valuations of expert ratings on the relative 5 to –5 scale offers a way of evaluating alternatives to monetary accounting or value-transfer methods [29]. Unlike the valuation of provisioning services with direct market values, the valuation of regulating services should consider more aspects of non-market values, which is one of the advantages of local expert knowledge [90]. Naturally, there is a high dependence on the observer's experience, knowledge and objectivity [91]. In addition, the relative valuations of the landscape matrix can be substituted by suitable units [20] (e.g., energy [92]). In this study, we evaluated the uncertainty in the matrix scores by standard deviation and the results were consistent with that of Tao, Wang, Ou and Guo [30].

Although the findings in this case study show that cooperation was restricted to upstream-downstream situations, the extent that geographic limits place on cooperation depends on the principles and carriers of delivery for different categories of ES. Whether in China or other parts of the world, the delivery of the three water-related services were mainly restricted by geographic principles in watershed and topography, although artificial river networks may be helpful in building cross-basin ES markets for these services. For provisioning services (e.g., food provision) and cultural services (e.g., tourism) with tele-coupling relationships [38], the regional "market" in ES credits and debits will surely help serve to increase the potential for needed enhancements of ES.

Currently, the Chinese government has been attempting to clarify the rules on the evaluation of ecological values to promote eco-compensation, enforce property rights for ecological values, and establish mature market mechanisms that provide convenience for the transaction of ecological goods and services [80,93,94].

In this paper, we focused on regional-scale cooperation, not the local scale within a city. This study used a single city as the ES budget unit to discuss intercity environmental relations. However, a city is composed of different landscapes and is also likely to have its own different SPA, SBA and SCA at smaller scales [45,95]. For future research, we will explore spatial relations of multiple landscapes within a city, such as in Hangzhou, which has both ES Surplus Areas that could be potential ES SPAs and ES Deficit Areas that could be potential ES SBAs.



Figure 7. Terrain, Catchment, Stream Net and Flow Directions in the YRD Region. The "A1–H" are Natural Catchment Numbers in Terrain and Catchment Map (Left), the "1–5" are numbers of stimulation stream order numbers in Stimulation of Stream Net and Catchment Map (Middle). The dashed arrows in the Stimulation of Stream Net and Catchment Map (Middle) indicate the flow directions only due to the terrain. The solid arrows in the Real Stream Net and Catchment Map (Right) indicate the actual flow directions influenced by human activities.

5. Conclusions

An ES approach makes it possible to not only budget the ES supply and demand of a city, but also define to the spatial relations of SPCs and SBCs in order to develop an effective tool for intercity cooperation. In this study, we presented a general framework integrating ES supply-demand budget with flow direction analysis for intercity environmental cooperation and revealed spatial mismatches of supply, demand and budgets for three water-related ES in 16 cities of the YRD region. This study proposed a framework for improving the management and decision-making processes for intercity environmental cooperation and ecosystem management in the following ways. Our framework helps to define which city has an ES surplus, deficit or balance and then to identify SPC, SBC and SCC by spatial relation analysis. In the case study of the YRD region, we found that five to six cities in the southern part of the region had significant surpluses in services while ten to 11 cities in the north-central part had significant deficits in services. We further identified two intercity cooperation types and two non-cooperation types in the YRD region. For SPC-SBC cooperation and SPC-SCC-SBC cooperation, our research identified cooperation opportunities and designed ES cooperation models based on the cities' respective ES supply-demand budgets. For cities that do not have direct ES spatial relations, ecosystem restoration for self-provisioning of ES supply could be a means to improve local conditions. Some geographic barriers could be overcome by artificial infrastructure, to some extent, such as artificial river networks for water-related services. To further advance the utility of this proposed model in PES mechanisms, higher spatial resolution and a greater variety of data could be incorporated in future studies.

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