Assessing the Potential Impacts of Urban Expansion on Hydrological Ecosystem Services in a Rapidly Urbanizing Lake Basin in China

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1. Introduction

Hydrological ecosystem services (HESs) are important to ecological management and protection within watersheds [1,2] and not only provide key natural resources to human society but also sustain freshwater ecosystem structure and ecological processes [2,3]. HESs include the provisioning of water in sufficient quality and quantity for agricultural, industrial, and residential uses and habitat provisioning for aquatic biota. However, land use change in general and regional urban expansion in particular affects HESs through altering regional hydrological characteristics, such as erosion, infiltration, and ground water recharge. Urban land expansion also leads to an increase in impervious surfaces, which alters runoff, increased water pollution, and even simultaneously threatens the provisioning capacity of HESs. Therefore, researchers are increasingly interested in quantitative evaluations of the effects of urban expansion on these services.

In recent years, demand for quantitative and spatially explicit methods to evaluate the effects of land use change on multiple ecosystem services has increased. Ecological models, which explicitly incorporate key features or processes determining ecosystem services...
provisioning, are well suited for quantitative spatial assessments. InVEST (integrated valuation of environmental services and tradeoffs) models incorporating both on hydrological and ecological processes, have been widely applied since they prevail in special explanatory and analysis scenarios [4,5]. This program consists of a suite of modules that employ land use and land cover patterns to estimate the levels of ecosystem services. The CLUE-S model is a spatial model used to simulate the spatio-temporal dynamics of land use [6] and is widely applied to simulate land use changes including urban expansion [7]. Various land use scenarios with user-defined assumptions can be simulated through the CLUE-S model. By analyzing ecosystem services using InVEST and modeling land use change scenarios with CLUE-S, corresponding changes in ecosystem services provisioning can be predicted. In addition, such a combination can provide information relevant for land-use planning and policy making that minimizes potential negative impacts on HESs and human well-being within target watersheds.

Numerous studies have investigated the impact of urbanization on the provision of ecosystem services. For example, Delphin et al. (2016) modeled the effects of urbanization on regulating and provisioning services using InVEST, and their findings revealed how urbanization drove the spatio-temporal dynamics of ecosystem services and their trade-offs [8]. Urban expansion has led to a continuous loss of most ecosystem services, which have been proven by many previous studies [9–11]. Despite the recent growing literature on the urbanization effects on ecosystem services [12–15], there is still no clear guidance for properly identifying and assessing specific HESs provided by freshwater lake basin. Case specific HESs assessments in rapidly urbanizing freshwater lake basin are still limited [16]. For example, Hoyer and Chang (2014) assessed the potential response of freshwater ecosystem services on increased urbanization using InVEST in two river basins under distinct urbanization scenarios [17]. Yohannes et al.(2021) evaluated the response of HESs to structural landscape changes and found soil and water conservation interventions are vital to minimize and control water-related problems and enhance HESs [18].

Despite these attempts to predict the impacts of urbanization on ecosystem services, integrating methods and case studies of HESs into land management, decision making and urban planning are still lacking in lake basin [19–21]. Freshwater has tremendous eco-economic value and provides diverse HESs contributing to the well-being of humans living in lake basin and adjacent river sub-watersheds. Surface flood, soil erosion, and non-point source pollution are water-related ecological and environmental problems affect human wellbeing [22,23]. Even worse, some urban development planning in the absence of ecological policy do not incorporate multiple water-related environmental issues into strategic development decisions [16,18]. To promote wise decision-making, policymakers need more information from scientists about how different land use and ecological policies decisions may affect the condition of ecosystems and the flow of HESs in rapidly urbanized watersheds. To achieve this, different urbanization scenarios via specific ecological policy pathways for future quantitative and spatial assessment of variations of HESs need to be further clarified in freshwater lake basin.

To balance the trade-offs between agricultural production and urban sprawl, the Chinese government has attempted to develop an explicit Farmland Redline Policy (FRP) in 2009 [24]. After FRP was implemented, China’s farmland is currently increasing area [25,26]. However, the FRP has not yet been very successful due to the declining of farmland quality [27–30]. To reconcile the conflicts between ecological conservation and development, in 2011, the State Council of China proposed the ecological redlines as the national strategy for ecological environmental protection and management [31] and listed it as an important part of ecological civilization in 2013 [32]. In 2014, the Ministry of Environmental Protection of China issued “the National Ecological Protection Red Line-Technical Guidelines for the Delineation of Ecological Functions Red Line (Trial)” [33] and issued the formal version in 2015 [34]. In 2017, China implemented the designation of Ecological Protection Redlines at a national scale [32,35]. By integrating conservation areas into red lines for stricter and unified management, the well-known Ecological Redline Policy (ERP) explains how to
delineate the ecological redline to preserve ecosystem services and to guarantee the national ecological safety [28,36]. Although the ecological civilization characterized by the ERP has been a new long-term national development strategy in China, current institutional management conflicts, spatial mismatches and unanticipated problems exist between ERP and FRP due to the lack of spatial redlining boundary at present in FRP [29].

Recently, scientists have been urging policymakers to develop China’s ERP using ecosystem services-based approach [28,29,36–38]. For example, using ecosystem services assessments for land use planning, Bai et al. (2018) examine ERP effectiveness by comparing land use scenarios to reduce tradeoffs between environmental quality and development [28]. Yang et al. (2020) explored the ecological protection redline demarcation process based on ecosystem services to provide a guideline for the protection and improvement of the geographical ecosystem. These studies attempt to find a solution to effectively manage and protect a targeted zone and to help policy makers formulate the proper measures for the improvement of ecological environment. Therefore, ecosystem services may be used as a tool for solving the conflicts between ERP and FRP.

Scenario analysis can provide effective information for enhancing the quality of arable land and sustainable ecological environmental protection combined with the current ERP and FRP. However, the future spatiotemporal changes in HESs based on the ERP and FRP are not well understood due to lacking of mutual understanding of the priorities for future land-management practices. There are few published examples of a lake basin implementing spatial plans based on HESs assessment [16].

Nansihu Lake basin is an agricultural area where crops currently occupy approximately 70% of the total area but are quickly replaced by urban expansion. This expansion has led to many ecological and environment problems, including the degradation of the lake and related riparian ecosystems, lake eutrophication and deterioration of water quality, and loss of biodiversity, which has caused great damage to the hydrological ecosystem services [39,40]. Assessing the impacts of future urban expansion on HESs remains challenging but modeling such changes could help reduce the uncertainty and thus help strengthen land-use policies within the basin.

In this study, we evaluated the effects of land use change from 1980 to 2030, especially urban expansion, on HESs in Nansihu Lake basin by linking the CLUE-S model and the InVEST freshwater modules, including the water yield, nutrient, and sediment delivery. Our objective was to provide spatially explicit information to government agencies to improve watershed management and decision making under different urbanization scenarios. The CLUE-S model was used to predict future land use changes based on current trends up to 2030. This information was then used to map changes in HESs provisioning from 1980 to 2030 using InVEST model. Second, we analyzed the effects of land use change and urbanization on ecosystem services from 1980 to 2015. Finally, based on four alternative trajectories of land use change in 2030 simulated by the CLUE-S model, we determined potential impacts on the HESs caused by rapid urbanization.

2. Materials and Methods

2.1. Study Area and Data Sources

Nansihu Lake, located downstream from the Huaihe River, is the largest lake in northern China. The total drainage area of Nansihu Lake basin is 31,700 km², covering 34 counties in Shandong Province predominantly (Figure 1) and with 53 streams and rivers draining into the lake. The basin is in the warm temperate zone and has a semi-humid climate. In addition, the average annual temperature of the basin is 14 °C with an average rainfall of 700 mm and a potential evapotranspiration of 1400 mm. The predominant land use in Nansihu Lake basin is agricultural land, which occupies 69.5% of the total area (Figure 2). Nansihu Lake is important to northern China since it serves as a storage reservoir for the east line of China’s South-North Water Transfer Project (SNWTP), which will transfer water to cities in northern China such as Beijing and Tianjin. Furthermore, the lake itself is a natural conservation area that possesses abundant biodiversity. However, recently, the
biodiversity in this lake has declined due to anthropogenic activity and land use changes. Over the past few decades, Nansihu Lake basin has been experiencing dramatic urban expansion, and this trend is expected to continue in the future with ecosystem services in the basin being negatively impacted.

Figure 1. Location of the study area.

The data used for this research included land use maps, meteorological data, soil distribution data, and digital elevation models (DEM). Maps of land use and land cover data for 7 time periods (1980, 1990, 1995, 2000, 2005, 2010 and 2015) were obtained from a land use remote sensing monitoring database (1:100,000 scale). A total of 26 types of land use categories were available for each period (Figure 2). These were combined into six primary classes, including cropland (Land use codes 112, 113, 121, 122, 123, 124), forest (21, 22, 23, 24), grassland (31, 32, 33), water bodies (41, 42, 43, 46), urban land (51, 52, 53) and unused land (61, 63, 64, 65, 66, 67). We used the average annual precipitation and temperature data from approximately 41 meteorological stations. Table 1 listed the types and sources of input data for different models.
Figure 2. Land use change in 1980–2015. 21: Forest land; 22: Shrub land; 23: Open woodland; 24: Other woodland; 31: High coverage grassland; 32: Moderate coverage grassland; 33: Low coverage grassland; 41: Canals; 42: Lakes; 43: The reservoir pond; 46: Beach land; 51: Urban land; 52: Rural residential land; 53: Other urban land; 61: Sand; 63: Alkaline land; 64: Swapland; 66: Bare rocks; 67: Other land; 112: Irrigation land in the hills; 113: Irrigation land on the plains; 121: Mountainous arid land; 122: Arid land in the hills; 123: Arid land on the plains; 124: Arid land with a greater than 25-degree slope. The same legend is also used below.
Table 1. Data sources of the InVEST model and CLUE-S model.

| Data Type              | Model                                                                 | Sources and Descriptions                                                                 |
|------------------------|----------------------------------------------------------------------|------------------------------------------------------------------------------------------|
| Land use               | Water yield, nutrient and sediment delivery ratio model in the InVEST model, CLUE-S model | Downloaded from the Data Center for Resources and Environmental Sciences, Chinese Academy of Science (http://www.resdc.cn) (1980–2015) (accessed on 1 September 2019) |
| Digital elevation model (DEM) | Water yield, nutrient and sediment delivery ratio model in the InVEST model, CLUE model | 30 m Digital elevation model, available on USGS/NASA, SRTM data (http://srtm.csi.cgiar.org) (accessed on 1 September 2019) |
| Climate data           | Water yield, nutrient and sediment delivery ratio model               | The climate data in all meteorological stations, including annual average precipitation and temperature were downloaded from China meteorological data network(http://data.cma.gov.cn) (1980–2015) (accessed on 5 September 2017) |
| Soil properties        | Water yield, nutrient and sediment delivery ratio model               | The geographical soil properties data, including soil depth, clay content, clay content, silt content, sand content, organic carbon content, were derived from the Harmonized World Soil Database)(HSWD) (http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database (accessed on 1 February 2016)) |
| Socio-economic data    | CLUE-S model                                                          | Socio-economic data including population density (1990–2015) and Gross Domestic Product (1995–2015) (raster) downloaded from the Data Center for Resources and Environmental Sciences, Chinese Academy of Science (http://www.resdc.cn) (accessed on 1 September 2019) |

2.2. Setting Urban Expansion Scenarios in 2030

In this study, the CLUE-S model was employed to simulate the trajectories of the urban expansion in the study basin. During the past several decades, this basin has experienced rapid urban expansion resulting in significant changes in agricultural land use and vegetation cover. The farmland redline, put forward for the first time by the Ministry of Land and Resources of China in 2009, is the policy targeting the preservation of farmland to guarantee a baseline area of high-quality farmland [41]. The overall aim of the ERP (ecological redline policy) is to protect the integrity of important ecosystems to secure diverse and coupled ecosystem services delivery to meet different stakeholders’ needs in ecological redline areas [28,36]. To evaluate the effect of these two new land use policies, the following four alternative scenarios of potential land-use change in 2030 simulated by the CLUE-S model were developed:

UEP (urban expansion policy scenario): urban expansion continues at the current trend predicted for 2030 and based on the current urbanization rate (2005–2015) in Nansihu Lake basin.

ERP (ecological redline policy scenario): restore 229.5 km$^2$ of the land area to forest land which was converted from forest land to farms in 1980–2015.

FRP (farmland redline policy scenario): primary farmland was well protected. According to China’s new ecosystem service protection and human development policies, i.e., the
Relocation and Settlement Program [42], the residents in vulnerable villages were relocated to urban settlements; therefore, rural land was reconverted to farmland.

EFRP (ecological and farmland redline policy scenario): the same conditions as FRP but with the addition of increasing forest land converted from the poor farmland.

2.3. The Land Use in 2030 Simulated by CLUE-S Model Based on Different Urbanization Scenarios

The CLUE-S model simulates future urban expansion and has been used in many studies [7,43]. This study used the CLUE-S model to map and predict future land use in 2030 based on trends observed in the recent past (2005–2015) when the study area had come into the era of rapid urbanization. The CLUE-S model considers five components that are described in detail below.

(1) Spatial policies and restrictions such as area restrictions of some land use types. In this research, UEP scenario did not have any area restrictions on land use. Under the ERP scenario, changes in farmland area are usually limited, particularly the primary farmland in protected areas due to the redline policy; under the FRP scenario, forests are usually not allowed to be converted to other land use types in the ecological protection zone; and the EFRP scenario limited changes in the areas of basic farmland and ecological protection zones.

(2) Land use type specific conversion setting: Considering the simulation ability of the model, we chose six types of land use to simulate. For each of the scenarios, land use type specific conversion settings were defined and implemented by the relative elasticity for change (ELAS) of land use type into any other land use type in the model [6]. In the model, we assigned each land use type a dimension factor that represents the relative elasticity to conversion, ranging from 0 (easy conversion) to 1 (irreversible change). In this study, based on previous studies and the specific requirements of each scenario for 2030, the ELAS values of each land use type are shown in Table 2.

(3) Land use requirements (demand): We adjusted related parameters through the linear interpolation methods in this study. The land requirements (demand) for the different land use types are calculated with the trend extrapolation method under the UEP scenario and linear interpolation under the other scenarios.

(4) Location characteristics and suitability: parameters describing the relation between the driving factors of land use in particular locations and scales. The logistic regression model was used to relate the probabilities and the characteristics the study location. Therefore, in this study, we chose logistic regression to investigate the probability of converting each grid cell to another type of land use.

(5) Model calibration. The ROC (receiver operating characteristic) curve was used to measure the fit of the regression results to the model in the study [44]. The accuracy of the model results was assessed by the Kappa coefficient, which can be used to compare a reference map with a simulated map or to compare two reference maps [6]. When $0.75 \leq Kappa$ coefficient $< 1.0$, then the accuracy of the simulation is considered high [6]. In this study, simulated land use in the Nansihu Lake basin in 2015, derived from the CLUE-S model using land use patterns in 2000, was compared with the actual land use patterns observed in 2015. The general equation for the Kappa coefficient is as follows [45]:

Table 2. The ELAS values used in the CLUE-S model for four land use change scenarios in 2030.

| Scenarios | Cropland | Forest Land | Grassland | Water Body | Urban Land | Unused Land |
|-----------|----------|-------------|-----------|------------|------------|-------------|
| UEP       | 0.4      | 0.9         | 0.6       | 0.7        | 1          | 0.3         |
| ERP       | 0.5      | 1           | 0.6       | 1          | 0.9        | 0.6         |
| FRP       | 0.9      | 0.8         | 0.6       | 0.8        | 0.5        | 0.5         |
| EFRP      | 0.8      | 1           | 0.6       | 1          | 0.5        | 0.6         |
where \( p_0 \) is the correct proportion, \( p_c \) is the expected correct proportion for a random case, and \( p_p \) is the correct proportion when the classification is perfect. \( \text{Kappa} \) values closer to 1 suggest better similarity between the two products under comparison.

2.4. HESs Assessment by the InVEST Model

InVEST is a spatially explicit modeling framework tool that assesses the impact of land use change on ecosystem services. In this study, hydrological ecosystem services, including water yield, nutrient export (nitrogen and phosphorous), and sediment export, were evaluated by InVEST specific modules (http://www.naturalcapitalproject.org/invest/) (accessed on 10 September 2019). The InVEST 3.3.1 model suites provide a framework for estimating and rating various ecosystem services through a set of standalone but linkable modules. In this study, the CLUE-S model and InVEST model were linked to examine the impacts of urban expansion on HESs in Nansihu Lake basin from 1980 to 2030 (Figure 3).

![Conceptual framework for integrating CLUE-S and InVEST models.](image)

**Figure 3.** Conceptual framework for integrating CLUE-S and InVEST models.

2.4.1. Water Yield

Water yield in the InVEST model estimates the relative contributions of water from different land use and reflects how changes in land use patterns affect annual water yield [46]. Annual precipitation (P) was derived from China meteorological data network, and reference evapotranspiration (ET\(_o\)) was estimated using modified Hargreaves equation. The root-restricting layer depth was replaced with soil depth. The parameters of soil depth are derived from the Harmonized World Soil Database (v1.2 data) (Table 1) as well as the results of local studies [47,48]. We estimated the parameter of plant available water content (PAWC) following the method of Zhou et al. (2005) [49]. The watershed layers were generated using ArcGIS software by inputting digital elevation model (DEM) data (retrieved from NASA’s online database) (Table 1). The evapotranspiration coefficients (\( K_e \)) were estimated based on the land use and previous literature [5] (Table 3). Seasonality parameter \( Z \) that characterizes the natural climatic-soil properties was derived from the results of local studies [47,48].
Table 3. Coefficients for the InVEST model.

| Land Use       | Kc  | Root_depth | Load_n | Eff_n | Load_p | Eff_p | C Factor | P Factor | Sedret_eff |
|----------------|-----|------------|--------|-------|--------|-------|----------|----------|------------|
| Cropland       | 0.8 | 2100       | 5.8    | 0.25  | 1.1    | 0.25  | 0.25     | 0.3      | 0.25       |
| Forest         | 1.2 | 7000       | 1.4    | 0.8   | 0.01   | 0.8   | 0.003    | 1        | 0.6        |
| Grassland      | 0.75| 2600       | 2.6    | 0.4   | 0.2    | 0.4   | 0.003    | 1        | 0.4        |
| Water body     | 1   | 1000       | 0.001  | 0.05  | 0.001  | 0.05  | 0.001    | 1        | 0.05       |
| Urban land     | 0.001| 1          | 36     | 0.6   | 2      | 0.8   | 0.003    | 0.001    | 0.8        |
| Unused land    | 1   | 1000       | 2      | 0.8   | 0.05   | 0.8   | 0.1      | 0.2      | 0.6        |

2.4.2. Nutrient Delivery Ratio Model

The InVEST nutrient delivery ratio (NDR) model aims to quantify relative nutrient export and retention through space, and to reflect changes in nutrient export/retention under different change scenarios. The required DEM and land use data sources are showed in Table 1. We used the average annual precipitation to define the nutrient runoff proxy. The watersheds were also generated based on the DEM by ArcGIS software. Borsellik was calibration parameter to determine the shape of relationship between hydrological connectivity. The other input parameters including nutrient loads (Load_n, Load_p) and nutrient retention efficiency (Eff_n, Eff_p) were shown in Table 3 followed the previous studies [5,50].

2.4.3. Sediment Delivery Ratio Model

The model first used the revised universal soil loss equation (RUSLE) to estimate the eroded sediment and then computed the sediment export which was the soil loss actually reaching the catchment outlet. The basic input data including DEM, rainfall erosivity index (R), and soil erodibility (K), land use were raster dataset. The watersheds and sub-watersheds were similar to that in the nutrient delivery ratio model. Besides, there needed to input a excel table (CSV format) that assigns factors including cover-management (C) factor, support practice (P) factor and sediment retention efficiency (Sedret_eff) for each land use class. In this module, we modified and determined C, P factors and Sedret_eff from the former literature of this region (Table 3) [47,48]. IC_0 and k_b are calibration parameters were derived from the results of local studies [47,48]. Specially, we use sediment export level to reflect the decrease of sediment retention in the results.

2.5. Model Calibration and Validation

2.5.1. Calibration and Validation of CLUE-S Model

According to the results of the logistic regression analysis, the ROC value of each land use type are as follows: cropland, 0.711; forest land, 0.705; grassland, 0.815; water body, 0.816; urban land, 0.805; unused land, 0.705. In general, the simulation results were accepted if ROC values exceeded 0.6 [44]. The spatial distribution of all land use types could adequately be explained by the selected driving variables, as indicated by the high ROC test statistics (>0.7) [7]. Therefore, the selected driving factors could reflect the conversion of all land use types. Kappa values reached 86.4%, which suggested that simulation results of the CLUE-S model were satisfactory.

2.5.2. Calibration and Validation of the InVEST Model

To obtain precise output variables, z coefficient of water yield, the parameter (Borselli k) of the nutrient delivery ratio module and the calibrated coefficients (k_b and IC_0) of sediment delivery module were calibrated according to previous studies and derived from the results of local studies [47,48].
2.6. Assessing HESs Status and Changes

To assess the temporal change of HESs, the study adopted the Ecosystem Services Change Index (ESCI) to analyze the change of HESs from 1980 to 2015. The ESCI suggests the relative gain or loss of each of the individual ecosystem services [51], which can be calculated as:

\[ ESCI_x = \left( \frac{ES_{\text{CUR}_x} - ES_{\text{HIS}_x}}{ES_{\text{HIS}_x}} \right) \times 100 \]  

(2)

where \( ESCI_x \) represents the degree of change index of ecosystem service \( x \) and \( ES_{\text{CUR}_x} \) and \( ES_{\text{HIS}_x} \) represent the current and historic state (1980) of ecosystem service values of service \( x \) at times \( j \) and \( i \), respectively.

3. Results

3.1. Land Use Changes and Urban Expansion from 1980 to 2015

The changes in six land use categories from 1980 to 2015 in Nansihu Lake basin are shown in Figure 4. The current land use pattern in 2015 suggested that land use is dominated by cropland and urban areas, accounting for 69.53% and 18.31% of the total area of the basin, respectively. According to the trend of land use changes from 1980 to 2015, areas of cropland showed a steady decline, decreasing by 8.2% from 1980 to 2015. In contrast, the urban areas grew significantly, increasing by 40.2% from 1980 to 2015. Also worth noting are the areas of forest land and grassland that declined progressively in the basin over the same time period. Overall, the cropland and urban land changed more dramatically than other land use categories (Table 4).

As shown by Figure 4, the rate of urban expansion in the Nansihu Lake basin during the 1980–2005 periods was slow, but the rate of urban expansion increased rapidly from 2005 to 2015. Most of the cities in the basin were in the initial stage of rapid expansion, and the growth rate of urban land from 2005–2015 was approximately twice as fast as that during the 1980–2005 period. During 1980–2015, the conversion of cropland to urban land is most significant. The area of this conversion is 2158.72 km², accounting for 10.1% of the total area of cropland, which is the main conversion type in the basin. It is also clear that forest land converts to grassland and grassland converts to crop land (Table 4), resulting in the tendency of forest land ecosystems to decline. The area of forest land converted to grassland is 339.50 km², accounting for 7.5% of the total area of transformed land.

![Figure 4. Percent change in land use types from 1980 to 2015.](image-url)
Table 4. Land use transition matrix from 1980 to 2015 in Nansihu Lake basin (km²).

| Land Use Types      | Final Cropland | Final Forest | Final Grassland | Final Water Body | Final Urban Land | Final Unused Land |
|---------------------|----------------|--------------|-----------------|-----------------|-----------------|------------------|
| Initial cropland    | 19,004.3       | 26.5         | 31.7            | 234.1           | 2158.7          | 2.3              |
|                     | 88.57%         | 0.12%        | 0.15%           | 1.09%           | 10.06%          | 0.01%            |
| Initial forest      | 229.5          | 603.3        | 339.5           | 9.2             | 45.1            | 2.2              |
|                     | 18.68%         | 49.10%       | 27.63%          | 0.75%           | 3.67%           | 0.18%            |
| Initial grassland   | 308.0          | 6.01         | 788             | 7.5             | 47.1            | 0.8              |
|                     | 26.61%         | 0.52%        | 68.08%          | 0.65%           | 4.07%           | 0.07%            |
| Initial water body  | 105.6          | 5.6          | 19.0            | 1345.6          | 19.1            | 8.4              |
|                     | 7.02%          | 0.37%        | 1.26%           | 89.51%          | 1.27%           | 0.56%            |
| Initial urban land  | 720.1          | 6.0          | 5.0             | 8.0             | 3102.2          | 1.6              |
|                     | 18.74%         | 0.16%        | 0.13%           | 0.21%           | 80.73%          | 0.04%            |
| Initial unused land | 96.0           | 3.7          | 2.4             | 71.2            | 16.7            | 49.9             |
|                     | 40.02%         | 1.54%        | 1%              | 29.68%          | 6.96%           | 20.80%           |

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3.2. Changes in HESs from 1980 to 2015

The predicted basin-wide annual water yield was $53.45 \times 10^8$ m³, and the annual average depth of runoff was 181.57 mm in 2015 as simulated by the water yield module. As shown by Figure 5a, water yield in the study basin had an increasing trend during the 1980–2015 period. The annual water yield reached a maximum in 2015, which was 1.05 times greater than that in 1980. The simulation results from the nutrient delivery ratio module showed a similar trend. However, the results of the annual sediment yield simulated by the sediment delivery ratio module suggested a decreasing trend overall from 1980 to 2015. On the whole, the water yield and TN and TP export in 2015 increased by 5.5%, 7.38% and 7.02%, respectively. The sediment export has decreased during the same period by 4%.

Changes of ESCI in hydrological ecosystem services were analyzed at the basin scale. As displayed in Figure 5b, the ESCI value of water yield, TN and TP export experienced a net increase over the entire time period in the Nansihu Lake basin (maximum ESCI = 5.49, 7.38, 7.02 respectively in 2015). In particular, the ESCI value of water yield increased at a greater rate (ESCI = 3.52) than TN and TP export services (ESCI = 0.12, 0.38 respectively) in 1990. However, the ESCI value of sediment export services experienced a substantial decrease in the Nansihu Lake basin from 1980 to 2015 (minimum ESCI = 3.95), especially in 2000. Overall, the magnitude of change in ecosystem services in 2010 and 2015 was greater than that in previous years indicating an accelerating rate of change (Figure 5b).
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3.3. Spatial Variations in HESs from 1980 to 2015

As shown in Figure 6, spatial variation in the water yield was observed around the lake areas. However, in the hilly areas east of the lake, the spatial variation in water yield...
presented a decreasing tendency from 1980 to 2015. The water yield of the plains in the western region of the basin presented an increasing tendency. The spatial distribution of TN and TP export suggested an increasing tendency in the hilly area and the plains. However, TN and TP export in the lake areas presented a slightly decreasing tendency. The spatial variation in sediment export showed an increasing tendency in the hilly area and the eastern basin. The spatial distribution of sediment export around the lake suggested a decreasing trend. In the western basin, the spatial variation in sediment export suggested a significantly decreasing trend from 1980 to 2015.

Figure 6. Spatial distributions and variations of HESs in per pixel from 1980 to 2015.

The added value of water yield in urban construction land reached 150–200 mm. The significant increase in urban construction land resulted in an increase in water yield throughout the basin during 1980–2015. Likewise, the variation in TN export showed an overall increasing trend in the construction land, particularly in the expanded urban areas. The increase in TN export reached 388.89–666.67 kg·km\(^{-2}\) in cities. In addition, the change in TP export in the construction land also suggested an increasing tendency. The increase in TP export reached 333.33–500 kg·km\(^{-2}\) in the sprawling cities. However, the sediment export presented a decreasing trend in the eroded arable land. Sediment export decreased as much as 0–44.44 t·km\(^{-2}\) in most urban areas.

3.4. Trade-Offs between Different Ecosystem Services
3.4.1. Correlation between HESs

We performed spatial correlation analysis of pairs of HESs in county scale with normalized values in Nansihu Basin, which yielded a scatterplot matrix, correlation coefficient (r-value) matrix and significant values (p-value). Figure 7 presents the results of the correlation analysis. TN export matched best with TP export. Namely, TN export had a significant (p < 0.001) and positive (r > 0.9) correlation with shown in the Figure 7. This is since both
TP export and TN export are mainly influenced synchronously by urban expansion and fertilization in agricultural activity. Also, water yield showed a high positive correlation with TN exports (0.92), and TP export (0.95). This was due to the fact that nutrients delivery and transport were dramatically controlled by runoff. Likewise, soil export also had strong positive correlations with TN exports and TP exports, with correlation coefficients at 0.47 and 0.56 for TN and TP since the increases in sediment yield in rivers dramatically affected water quality. Similarly, water yield showed a significant ($p < 0.001$) and positive relationship with sediment export since they were principally affected by rain intensity. Therefore, greater precipitation contributed greatly to runoff and further resulted in higher rainfall erosion and more soil loss.

![Figure 7. Relationships between different ecosystem services indicated by Pearson's correlations (Correlation analysis of the pair-wise interactions between ecosystem services). *** significant at the 0.001 level (2-tailed). ** significant at the 0.01 level (2-tailed).]

3.4.2. Trade-Offs of HESs in Main Land Use Types

The results of correlation analysis suggested interdependence among indicator of HESs (water yield, soil export, TN and TP export). Many investigators have proved the relationships of different ecosystem services are often highly complex and non-linear process. Therefore, we employed a polar diagram (Figure 8) to expressly demonstrate the relationships among HESs for the representative land use class (cropland, forest land, grassland and urban land) with the normalized values from 0 to 10. In arable land, nutrient (TN, TP) export was the greatest, followed by water yield, while soil export appeared to be low. TN and TP export declined from 1980 to 2015. For forest land, water yield was very high, while nutrient (TN, TP) export was least, indicating the forest land may effectively reduce the nutrient export and purify water quality. It’s worth noting that sediment export experienced a great decrease significantly in forest from 1980 to 2015. This showed the forest land may effectively control soil erosion. For grassland, sediment export and water yield were dominant. Since both sediment export and water yield were affected by rainfall intensity and complex topography. Whereas TN export seemed to be moderate and TP export appeared to be lowest, further revealing the complex relationship of TN and TP export for grassland. Most obviously, nutrient export and water yield prevailed in urban land due to the increases in impervious area. Nevertheless, the sediment export was the lowest probably due to the effect of check dam construction on hydrological processes.
Figure 8. Polar diagram of ecosystem services in main land uses for 1980 and 2015.
3.5. HESs in 2030 Based on Different Scenarios

Extrapolating from current trends, urban areas dramatically increase while arable land decreases significantly in 2030 as simulated by the CLUE-S model. In the context of rapid urbanization (UEP scenario), annual water yield in 2030 increase by 8.3% compared to that in 2015, and TN export and TP export increase by approximately 13% and 12%, respectively, whereas sediment export decreases by 3.6% (Table 5, Figure 9).

Table 5. Percent changes in HESs in 2030 relative to the current trend in different scenarios (%).

| Scenarios in 2030 | Water Yield | TP Export | TN Export | Sediment Export |
|------------------|-------------|-----------|-----------|-----------------|
| UEP              | 8.3         | 12        | 13        | −3.6            |
| ERP              | −7.72       | −5.30     | −4.46     | −9.97           |
| FRP              | −1.91       | 3.46      | 3.22      | 8.14            |
| EFRP             | −2.76       | −1.12     | −2.27     | −1.14           |

Figure 9. Spatial distribution of HESs in four scenarios.
Under the ERP scenario, water provision and TN and TP export decrease by 7.72%, 5.3% and 4.46%, respectively. In contrast, sediment export services experience a dramatic decrease (9.97%) during the same time period, which suggests the effective prevention of soil losses. The improvement in regulating services (water purification and soil conservation function) contrasts with declines of water provisioning services. The government policy of farmland redline is intended to protect primary cultivated land, since substantial farmland is typically lost to urban construction land during the process of urbanization. As shown by Table 5 and Figure 9, under the FPR scenario, the annual water yield decreased by 1.91% in 2030 compared to 2015, and TN and TP export increased by 3.46% and 3.22%, respectively. However, there was a marked increase (8.14%) of sediment export in 2030 compared to 2015 under the FRP scenario (Table 5). Therefore, water purification and soil conservation function degrade under the FRP scenario. Under the EFRP scenario, results were similar to that observed under the ERP scenario. Water yield, TN, TP and sediment export decreased by 2.76%, 1.12%, 2.27%, and 1.14%, respectively. Water purification and soil conservation function improve to some extent.

4. Discussion
4.1. Comparison of Urbanization Impact on HESs among Urbanizing Basin

The overall observed results show a rapid alteration of land use change and urban expansion from 1980 to 2015 (Figure 2, Table 4). Rapid urbanization has led to a sharp increase in impervious surface areas as well as a sharp decline in farmland (Figure 4). Previous studies on urban expansion have shown a host of land use changes induced by this process, especially cropland which seems particularly vulnerable to transformation in this context [8,52]. This rapid urbanization may be attributed to encouragement by local governments and may be driven by economic interest during this period [53,54]. At the current rate of urban expansion, more farmland and vegetation are expected to be converted to urban construction in the absence of the protection provided by the farmland redline policy. The simultaneous losses of ecosystem services caused by urban expansion is a common phenomenon worldwide [12,55]. Previous studies have shown that urban expansion may result in the simultaneous losses among different ecosystem services at different scales [12,56–58]. For example, the former studies have shown urban expansion will likely lead to the simultaneous losses of habitat quality, water conservation, and food production over the next 15 years at the global and national scale by [59,60]. Numerous studies on ecosystem services response to urbanization exist, but most focus on individual cities, city-regions, metropolitan areas, or in a few cases, countries [12,57,58,61]. In contrast to other studies, we observed the simultaneous HESs losses associated with urban expansion in a lake basin. (e.g., degraded water quality and flood control). Polar diagrams (Figure 8) clarify how HESs varied between land use classes, and results suggested forest land may effectively control soil erosion. However, observed reductions in the sediment export are linked with aforementioned the farmland loss (Table 4). This is different from previous studies on soil control services improvement due to the increases of woodland and vegetation restoration in other river basins [62–64]. Farmland loss has led to an overuse of land resources and poses serious threats to ecological sustainability in lake basin [19,48]. In contrast to other studies, loss of agricultural land resulted in increased surface water flow in another agricultural watershed [65,66]. Our results demonstrated the increase of water yield from 1980 to 2015 (Figure 6) might mainly be attributed to impervious surface reduced evapotranspiration and infiltration of precipitation, which increased surface runoff. This increase in TN and TP export explain more clearly how HESs has been reversed due to water quality degradation influenced by urban expansion. This is consistent with that observed in other river watersheds and lake basins [17,20,65].
4.2. Scenarios of Future Urban Expansion in 2030 and Its Impact on HESs

In this study, we linked the CLUE-S model and the InVEST model to explore the potential future impacts of urbanization on HESs. Different urban expansion scenarios have contrasting effects on HESs. Under the UEP scenario, by 2030 the water yield, TN and TP exports are expected to increase dramatically due to increases impervious surfaces and high nutrient exports from household and industrial waste water. Under the ERP scenario, water purification and soil conservation were improved at the expense of water provisioning services due to an increase in the amount of farmland converted to forest. However, income for local people is decreased since this is largely a function of the area of agricultural land in cultivation. Thus, the ERP scenario may threaten food security and the well-being of local residents if farmland decreases. This outcome was similar to that observed in other contexts (e.g., Gao et al., 2017 [64], Zheng et al., 2016 [5]). Under the FRP scenario, water purification and soil conservation functions were threatened by degradation due to agricultural expansion and an inevitable reduction in forest land (similar to Zheng et al., 2016 [5]). Essentially, the cropland redline policy has not achieved considerable success in China, where the area of farmland is increasing but with declining quality [28]. Under the EFRP scenario, the cropland that is not suitable for farming is converted into woodland. Hence, water purification and soil conservation function have been improved to some extent. Thus, a moderate decrease in water yield not only helped reduce the peak flood risk but also did so without impacting the water provisioning services. With this information, the hybrid scenario can best address the serious conflicts arising from the conflicting demands of resource users and environmental managers. Our results demonstrated that the farmland and ecological redline policy is probably effective in preserving farmland and guaranteeing the continued delivery of ecosystem services in Nansihu Lake basin. However, our findings was also inconsistent with the previous studies such as Bai et al. (2018) [28], Feng et al. (2021) [67] whose research were conducted in metropolitan area in China. Bai et al. (2018) support that ERP would potentially reduce the tradeoff between urbanization and ecosystem protection in Shanghai while minimizing agricultural losses [28]. Feng et al. (2021) revealed that conversion of farmland to the natural ecosystem can be taken as a good way to enhance HESs [67]. However, their findings do not apply at the level of in a rapidly urbanizing lake basin.

4.3. Limitations

This study has some limitations. First, the urban expansion process can affect multiple HESs. However, in this study, we quantified just three kinds of HESs and did not consider several important HESs (e.g., aquatic production provision, habitats for aquatic and terrestrial organisms, and hydrological cultural service due to data availability and the applicability of HESs mapping methods [16,68,69]). Second, the key challenge with regards to rapid urbanization lead the demand for HESs is growing. The use and demand for HESs has received more attention, as have the spatial flows of services from ecosystems to people [70]. Third, the major input data was land use data, it would be a major limitation in this study. On the one hand, the land use data used in this study had a coarse spatial resolution (30 m), which cannot precisely reflect heterogeneity of HESs. Fourth, we adopted a correlation analysis to quantify the interaction relationships between different ecosystem services indicated. This interaction relationships needs to be examined by further analysis. In the future, we will select more indicators that can provide an accurate and spatially explicit quantification of other important HESs. The impact of demands for multiple HESs on rapid urbanization needs to be investigated. We will characterize social demand for HESs based on urban growth in freshwater lake basin. Third, land use data with finer spatial resolution can be used to accurately map HESs within lake basin. Fourth, the relationship between HESs should be examined by other analytical methods, such as the Bayesian belief networks [71], Bagplot and cumulative correlation coefficients method [72], and the ecosystem services bundle approach [73].
5. Conclusions

In our study, we examined the impacts of land use change and urbanization on hydrological system services in Nansihu Lake basin by linking the CLUE-S and InVEST models. Land use change analysis indicated that 10.06% of the cropland in the basin was converted to urban construction land from 1980 to 2015, while 18.68% of forest land and 26.61% of grassland were converted into cropland, respectively. In addition, the basin experienced a rapid expansion of urban construction land, which led to a 40.2% increase in construction land area from 1980 to 2015. The urban expansion influenced the HESs dramatically; for example, compared to those in 1980, the water yield and TN and TP export in 2015 increased by 5.50%, 7.38%, and 7.02%, respectively. The sediment export has decreased overall during the same period by 4%. The change in HESs increased the risk of flooding and water quality degradation. Furthermore, at the current trend of urbanization, the future land use change in 2030 would result in more degradation of HESs. The three redline policy scenarios affect HESs differently. Farmland redline or ecological redline policies alone will not effectively protect natural ecosystem services. The hybrid scenario could significantly alleviate the extent of HESs degradation and resolve the gap between recognizing environmental problems and implementing policies. This information provides a new integrated approach for quantifying the ecological effects of urbanization.

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