

Article

Assessing the Impact of Rural Multifunctionality on Non-Point Source Pollution: A Case Study of Typical Hilly Watershed, China

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Abstract: In the context of rural development and transformation, it is crucial to identify the impact of rural multifunctionality on non-point source (NPS) pollution. This study applies the Soil and Water Assessment Tool (SWAT), geographical detector, and principal component analysis in Liyang, a typical hilly subbasin in China, in order to assess the rural multifunctional development that influences the spatial differentiation of NPS pollution and detect the interactive effects of rural multifunctionality. The R^2 and NSE demonstrated that the calibrated SWAT model successfully simulated NPS pollution in Liyang. The village scale was identified as the optimal research scale for examining the rural multifunctional development on NPS pollution distribution. The rural multifunctional indicators, such as the proportion of vegetable farming, sowing area, and grain farming, would influence NPS distribution. The number of family farming cooperatives, the area of pond farming, and the nature reserves area were also significant. The rural multifunctionality in Liyang could be classified into five categories: grain production, mixed agriculture, ecological conservation, leisure tourism, and industry and business function. The superposition of rural multifunctionality has a strengthening effect on NPS pollution, especially when the ecological conservation function is combined with the grain production or modern agriculture function. The study could provide NPS pollution control strategies for policymaking in rural multifunctional development.



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Keywords: rural multifunctionality; non-point source pollution; interaction effect; SWAT model; spatial differentiation; modifiable areal unit problem

1. Introduction

With ongoing socioeconomic development in rural China, the primary function of rural area has changed from solely agricultural production to diversification, leading to corresponding alterations in the rural landscape and environmental responses [1,2]. Non-point source (NPS) pollution is the main source of eutrophication, which refers to diffuse pollution from agriculture, street runoff, and atmospheric deposition [3]. The reasons for NPS pollution in China include excess fertilizer, policy factors, and social and environmental changes [4].

As China's rural development enters a new phase of transformation and upgrading, rural areas have been significantly reconfigured in the spatial pattern [5]. The rural multifunctionality has also been constantly strengthened [6]. A rural territory system is composed of economic, social, and environmental sub-systems, which possesses complicated characteristics [7]. From the traditional productionist perspective, the rural territory just has a single function that provides food and natural resources. With the development of urbanization and industrialization, the interactions between urban and rural territorial systems are gradually increasing. The flow of socioeconomic factors, such as population and capital, has driven the emergence of rural industries, business, and tourism. The

ecological function of rural space has been paid more attention. The connotation of multifunctional development in rural areas is gradually enriched [7]. In Europe, the potential rural functions were identified as four types: intensive farming, off-farm employment, countryside tourism and biodiversity preservation [8]. In China, Liu et al. [9] suggested that the diverse needs of society and the different environments make the rural space have various functions, which can be summarized into four types: economic development, food production, social security and ecological conservation. However, environmental problems, especially NPS pollution, have gradually emerged during the process of rural multifunctional development [10]. Agricultural NPS pollution accounted for more than half of the total nitrogen (TN) and total phosphorus (TP) pollutants [11,12].

NPS pollution is characterized by spatial extensiveness, timing indeterminacy, and hysteresis, resulting in the difficulty in estimation [13,14]. The common methods of estimating NPS pollution load generally include cross-sectional measurement [15], empirical statistical models such as output coefficient, inventory analysis [16], and physically based models [17]. Among them, the cross-sectional measurement method is often limited by the discontinuity of monitoring periods, monitoring errors, and other factors. The empirical statistical model is used to multiply the unit pollution production coefficient of different land types to obtain the pollutant output. This method does not take into account the migration and transformation mechanism of NPS pollutants in soil and rivers. The mechanism model generalizes the actual NPS pollution formation process such as regional rainfall runoff, soil erosion, surface solute leaching and soil solute seepage with the large number of mathematical equations, and then it determines the key parameters to estimate the load [18]. The Soil and Water Assessment Tool (SWAT), one of the physically based models, was selected due to its advantages in working with spatial data, which is also suitable for urban–rural transitional areas with mixed land use [19]. Previous research has proved that the calibrated SWAT models could well simulate the transport processes and intensity of NPS pollution loads [20]. Several scholars have conducted SWAT simulations on national and local scales [21,22]. Relevant scholars also have conducted some applicability simulation in Liyang, confirming the model's effectiveness [23,24]. As the process of generation and transport could be influenced by different landscapes, management practices and other natural conditions and socio-economic activities, NPS pollution loads have represented significant spatial heterogeneity [25].

The impact factors of environmental change can be classified into direct and indirect factors. The former refers to processes directly affecting the ecosystem, including physical, chemical, and biological elements. The latter emphasizes socioeconomic factors, such as demographics, economics, management practices, technology and culture, which have important implications for environmental protection [26]. The research on the effect of land use, farming practices and landscape changes on NPS pollution has yielded profound and substantial results [27,28]. Most studies concentrated on NPS pollution with the consideration of direct factors, thus neglecting the socioeconomic changes of rural multifunctional development and NPS pollution. They ignored the comprehensive effects of rural multifunctionality in the transforming phase [29]. Existing hydrological models focus more on natural boundaries, such as subbasins or hydrological response units (HRUs). However, the socioeconomic survey, policymaking and local planning are often conducted based on administrative boundaries. This results in a discrepancy between model simulations and policy implementation. The relationship between NPS and rural transformation was investigated through the inventory analysis method in the plain river network [30]. Although plenty of research has been conducted in plain areas, the research on the relationship between rural development and NPS in the hilly area is still inadequate because of the complicated hydrological and nutrient processes.

To fill the gap in the literature, this study focuses on the spatial association between rural multifunction and NPS pollution in Liyang, which is a typical hilly watershed in China. This study aimed to explore the relationship between rural multifunctionality and NPS pollution followed by the process. This study aims to address the following three

questions: (1) What is the optimal research scale for identifying the relationship between rural multifunctional development and NPS pollution? (2) What are the primary rural multifunctional indicators influencing the spatial heterogeneity of NPS pollution? (3) In rural multifunctional development, how does the interaction between different functions impact NPS pollution? This research aims to propose effective NPS control strategies in the context of rural multifunctional development in China.

2. Material and Methods

2.1. Study Area

Liyang is a typically hilly area in China. It is situated in the alluvial plain of the Taihu Lake watershed in the lower reaches of the Yangtze River, which is characterized by low mountains and hills, plains and polders, and rivers, lakes, ponds, and reservoirs, resulting in a diverse ecosystem (Figure 1). The watershed is named after Liyang City, which comprises a main proportion of the watershed. The southern part of Liyang benefits from suitable precipitation and heat conditions, making it ideal for agricultural production, particularly wheat, oil, tea, aquatic products, and bamboo. Agriculture plays an essential role in Liyang city. In addition, Liyang also has strengths in its rural industries and business services, which have become the primary driving force for rural development. The rural service industry, especially rural tourism, has developed rapidly. The rural industry and tourism sectors have seen rapid growth and development in this region.

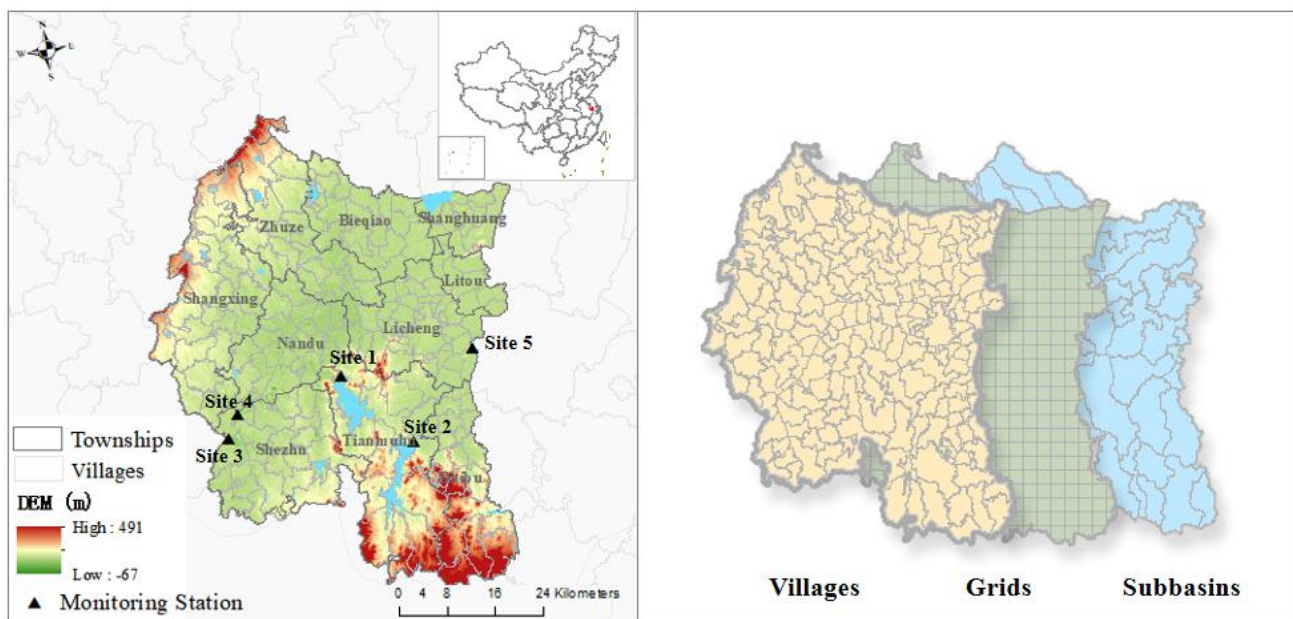


Figure 1. The location of the study area and the spatial units at different scales.

2.2. Data Sources

This study used the following data to evaluate the impact of rural multifunctional development and simulate NPS pollution in Liyang, including land use data, geospatial data, and statistical data. All data are described in the table below (Table 1).

Table 1. Data sources.

Name	Sources	Resolution	Application
Land-use data	RESDC [31]	30 m × 30 m	For the distribution of land-use type(Farmland/ water /forest/grassland/bare land/built-up land)
DEM	USGS [32]	90 m × 90 m	For sub-watershed division, river network digitization, and slope division
Soil	HWSD [33]	1 km × 1 km	For soil database in SWAT
Meteorological data	Liyang National meteorological Station	2010~2020	For weather database in SWAT
Flow and water quality data	Monthly Water Quality Report	2010–2014	For calibration and validation
Rural multifunctional indicator	Liyang Statistical Yearbook	2018	For the development analysis in the study area

2.3. The Simulation of NPS Pollution

The simulation of NPS pollution was assessed with the SWAT model, a continuous-time, long-term, distributed-parameter model, which is usually used to simulate flows, sediments and nutrients in a watershed system [34,35]. The water cycle processes in this model include rainfall, snowmelt, infiltration, evaporation, plant uptake, lateral flow, percolation, and baseflow. The SWAT model in the Liyang watershed was calibrated with SWAT-CUP. The SWAT model was used to obtain the estimates of TN and TP pollutant at the sub-watershed level for the watershed for 10 years. Before the analysis, the parameters of the model were calibrated and verified. Using SWAT-CUP, combined with the monthly data of the monitoring stations from 2010 to 2014, the multi-station calibration test was adopted. The R^2 and NSE were used for the model's accuracy [36–38]. The SWAT model was adapted to typical conditions in the hilly area [21]. The database was built with DEM, meteorological station data, land use, soil type and river network data. Hydrological monitoring data were used for calibration and validation.

$$R^2 = \left\{ \frac{\sum_{i=1}^n (Q_{o,i} - Q_{avg}) (Q_{p,i} - Q_{pavg})}{\left[\sum_{i=1}^n (Q_{o,i} - Q_{avg})^2 \sum_{i=1}^n (Q_{p,i} - Q_{pavg})^2 \right]^{0.5}} \right\}^2 \quad (1)$$

$$NSE = 1 - \frac{\sum_{i=1}^n (Q_{o,i} - Q_{p,i})^2}{\sum_{i=1}^n (Q_{o,i} - Q_{avg})^2} \quad (2)$$

where $Q_{o,i}$ is the observed value of runoff/TN/TP, $Q_{p,i}$ is the simulation, Q_{avg} is the mean value of the observation, Q_{pavg} is the average value of simulation.

2.4. The Identification of Rural Multifunctionality

The rural multifunctionality is supported by local resources, environment and the social economy. In order to identify the multifunctionality of villages, it is essential to fully understand their socioeconomic characteristics. This paper proposed using the socioeconomic data to explore the potential influencing factors of NPS pollution, and corresponding factors were selected based on the availability, comparability and accessibility of the relevant data (Table 2). The rural multifunctional indicators, collected at the village scale, encompass various metrics such as agricultural production and other industries, reflecting the farming structure, diversified development, and environment protection. It provides a comprehensive reflection of the multifaceted development in rural areas. This study examines the spatial differentiation of rural multifunctional development in Liyang in 2018 due to data availability.

Table 2. The description the rural multifunctional indicator at a village scale.

No.	Factors	Calculation	Unit
X1	Actual sown rate	The ratio of actual sown area and total farmland at the end of the year	%
X2	Grain farming rate	The ratio of grain farming area and sown area	%
X3	Vegetable farming rate	The ratio of vegetable farming area and sown area	%
X4	Pond density	The density of pond farming	%
X5	Family farming cooperatives	The number of family farm and agricultural cooperatives per unit area	/km ²
X6	Rural industrial enterprises	The number of rural industrial enterprises per unit area	/km ²
X7	Individual business	The number of individual business per unit area	/km ²
X8	Market	The number of markets over 50 square meters per unit area	/km ²
X9	Tourist arrivals	The number of tourist arrivals per unit area	/km ²
X10	Households engaged in leisure agriculture	The number of households engaged in leisure agriculture per unit area	/km ²
X11	Ecotourism area	The proportion of the ecotourism area	%
X12	Nature reserves	The proportion of nature reserves	%

Therefore, the rural multifunctionality is represented from two levels: the indicator level and function level. The indicator level was represented by socioeconomic factors. To ensure comparability, absolute values have been transformed into proportions or densities. On the other hand, rural multifunctionality is a complex system formed by social, economic and other factors, and it is difficult to fully summarize the development situation with a single indicator. Therefore, the multifunction level was encapsulated as different functions, expressing the relative development intensity of the village. Principal component analysis (PCA) is a common statistical tool for examining and diagnosing a set of variables with internal relationships [39]. This method also could reduce the dimension of factors, which is conducive for subsequent interactive analysis [40].

2.5. Geographical Detector

The spatial representation of the complicated coupling process of natural and social forces is spatial differentiation [41]. The geographical detector model was employed to assess the impact of rural socioeconomic factors on NPS pollution through spatial variation analysis of the geographical strata. This method enables the comparison of the relative importance of different functions in driving the spatial differentiation of NPS pollution.

The socioeconomic indicators and NPS pollution load were imported into the geographic detector model to calculate the influence value. A higher q -value indicates a greater effect on NPS pollution, while a lower q -value indicates a lesser effect. The p -value was also calculated. Factors with a p -value less than 0.1 were selected.

The factor detector was utilized to determine the degree of influence of the socioeconomic factor on the NPS load. The following equation is used:

$$q = 1 - \frac{\sum_{i=1}^h N_i \sigma_i^2}{N \sigma^2} \quad (3)$$

where q indicates the impact of the determinant. The q -value is referred to as $q(X)$, where X represents the values of factors and their interannual variations.

The interaction detector examines if two components work independently or not or if their effects are diminished or enhanced when they coexist in space. In this case, interaction detectors are employed to detect whether rural multifunctions have interactive effects on the spatial distribution of NPS.

The $q(x_i \cap x_j)$ denotes the interaction between components, which is used to identify whether co-actions between drivers increased or decreased the explanatory power of the analyzed variables. The interaction detector describes the interaction as follows:

- (1) Nonlinear-weaken: $q(x_i \cap x_j) < \min(q(x_i), q(x_j))$
- (2) Uni-enhance/weaken: $\min(q(x_i), q(x_j)) < q(x_i \cap x_j) < \max(q(x_i), q(x_j))$

(3) Bi-enhance:

$$q(x_i \cap x_j) > \max(q(x_i), q(x_j)) \tag{4}$$

(4) Nonlinear-enhance: $q(x_i \cap x_j) > q(x_i) + q(x_j)$

(5) Independent: $q(x_i \cap x_j) = q(x_i) + q(x_j)$

According to Equation (4), the three types of enhancement are distinct. The interactions labeled as “nonlinear-enhance” exhibit the highest strength, while the interactions termed as “uni-enhancement” are the weakest.

The research procedure is graphically represented in Figure 2. Firstly, this study encompassed a comprehensive data collection process, incorporating rural statistical data, land use data, a Digital Elevation Model (DEM), soil type information, and meteorological data. Then, the analysis could be divided into two parts: rural multifunctionality and NPS pollution. The rural multifunctionality considered both single indicators and rural functions at the village scale. The socioeconomic data selected as single indicators represented rural multifunctional development. Then, PCA was applied to reduce dimensionality to extract the predominant rural functions. The NPS pollution utilized the SWAT model to simulate the spatial variation of NPS at the subbasin scale, with TN and TP as the main pollutant. Since rural socioeconomic data were collected at the village scale, but NPS pollution was simulated at the subbasin scale, scale conversion is required. Referring to Min’s work, this study first converts the rural multifunctional development factor and NPS using unit area intensity to the grid scale (1 km × 1 km) with the Zonal Statistical tool in ArcGIS. Through this gridding process, this study facilitated the conversion of NPS data and rural multifunctional data across three scales. Subsequently, the geographical detector was employed to explore the Modifiable Areal Unit Problem (MAUP), influencing the factor detection and interactions between functions. Finally, corresponding policy recommendations were proposed.

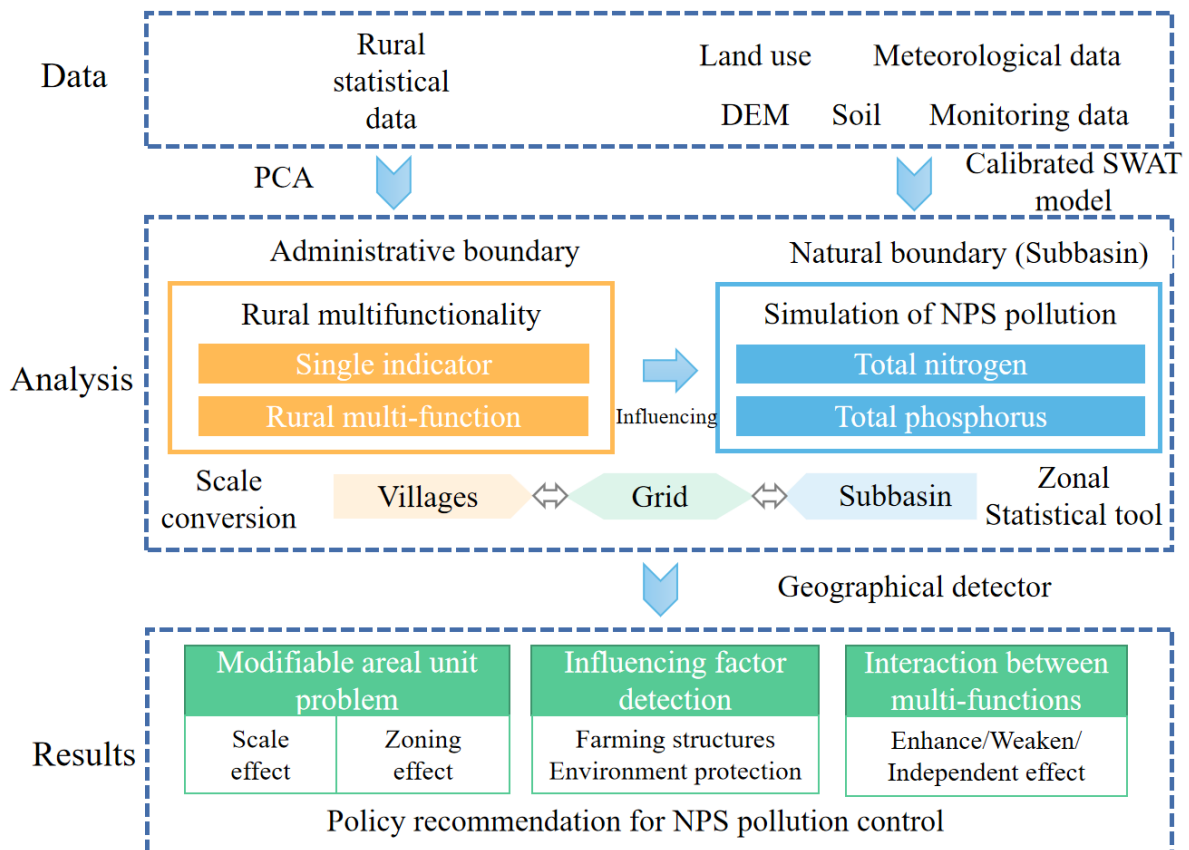


Figure 2. The research procedure of assessing the impact of rural multifunctionality on NPS pollution.

3. Results

3.1. The NPS Pollution Estimation in Liyang

The SWAT model estimated the NPS pollution, delineating the Liyang watershed into 61 sub-watersheds. As indicated in Table S1 (see the supplementary document), the initial sensitivity analysis determined the final calibrated parameters. According to the sensitivity results, the parameters chosen in this model were suitable to estimate stream flow and nutrient loads.

The model calibrated the runoff through historical data in monitoring site 2 and calibrated nutrition (TN and TP) using all monitoring site data from January 2010 to December 2015. The values of simulations and observations were plotted on a scatter plot, along with a regression line, as depicted in Figure 3. The R^2 for the comparison between simulated and estimated runoff was 0.76 and 0.74, respectively. The NSE was determined to be 0.68 and 0.66, respectively, demonstrating a satisfactory agreement.

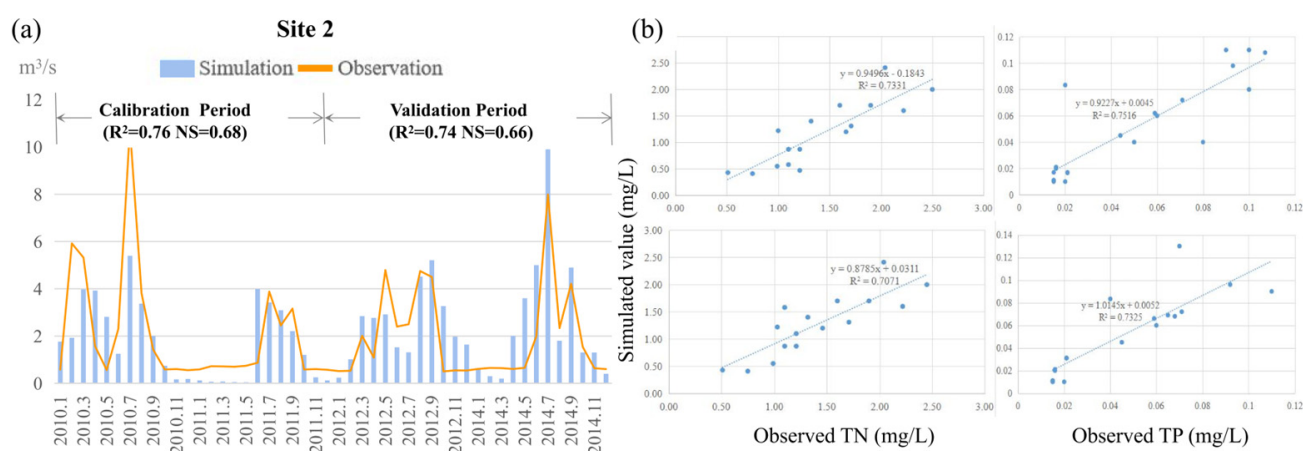


Figure 3. Calibration and validation results ((a) results for the runoff in monitoring site 2; (b) results for the TN and TP in all monitoring sites).

The spatial distributions of the NPS unit load at the village scale are shown in Figure 4. For TN load, approximately 39% of the villages are in low and relatively low classes and 18% of the villages are in high and relatively high classes. The distribution pattern exhibited higher values in the northeast and lower values in the south. Approximately 31% of the villages have low and relatively low TP loads, while the proportion of villages with high and moderately high TP loads is 20%. Whether TN or TP, the high values were concentrated around the urban area, while the low values were concentrated in the villages around the reservoir. At the temporal scale, the spatial distribution of TN and TP load remained consistent, but the average loading experienced a slight increase. The average annual load for TN in 2010 and 2020 was recorded as 6.9 and 6.2 kg/ha/year, respectively. This trend can be directly attributed to the shrink of agricultural lands. Consequently, the NPS loading initially showed an increase and later a slight decrease (Figure S1). By examining the temporal–spatial distribution of NPS pollution and its interactions with changes in land use types, valuable insights could be gained to aid in reducing pollution.

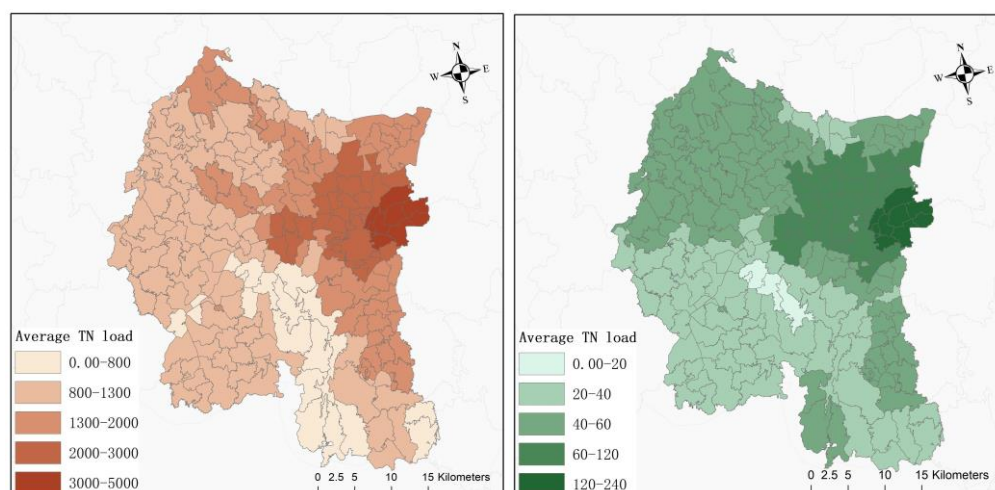


Figure 4. The distribution of average TN and TP load at the village scale in Liyang (kg/km^2).

3.2. The Modifiable Areal Unit Problem (MAUP)

The MAUP is a widespread issue in geographical and spatial analysis. It arises due to the fact that there are modifiable study units for geographical objects, leading to different results based on various aggregated sizes or spatial arrangements [42]. The MAUP has two related issues: the scale effect and the zoning effect. The former one refers to the variation in results obtained when data for one set of areal units are progressively aggregated into fewer and larger units for analysis. The latter one pertains to any variation in results due to the alternative classes of analysis while keeping the number of units constant.

This study analyzes both the scale and zoning effects. The scale effect is firstly examined to determine an optimal scale for analysis. The q -values represent the relative importance, which is crucial for subsequent analysis. The optimal spatial scale was selected when q -values were the highest for most variables [43]. Then, the zoning effect was tested using selected factors of different types at the optimal scale. The optimal scale for each factor was calculated using the optidisc function in R. Both the scale effect and zoning effect tests depend on the determination of the number of classes, which is crucial for accurate analysis [44]. Fewer classes might not adequately capture spatial heterogeneity, whereas more classes scatter the data over space. Therefore, it is crucial to investigate both scale and zoning effects before the research.

To determine the best scale for the geographical detector model, the scale effect is examined. The relative relevance of factors was represented by the q -value. There are 61 sub-watersheds, 184 villages, and 410 grids involved in this research area. The results of the influencing factor showed that the village scale had more statistically significant q -values. The q -value at the subbasin level was moderate, but more factors were statistically insignificant than at the village scale (Figure 5). The q -value at the grid scale was the lowest, suggesting that it has the least power of determination. Therefore, the village scale was the most appropriate for subsequent analysis.

The zoning effect refers to the pattern in which the analysis results vary with the difference of the classes and statistical method [42]. By applying five methods, we can observe the variation in the spatial distribution of NPS pollution based on different zoning schemes (Figure S2). The results showed that the q -values were various with five classification methods. The best results were extracted for subsequent analysis.

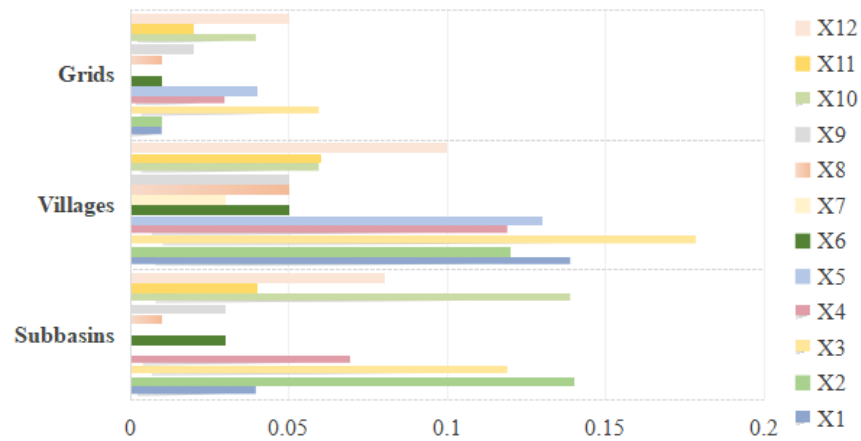


Figure 5. The scale effects on q -value of the significant factors (p).

3.3. Factor Detector of NPS Pollution and Rural Multifunctionality

The results indicated that the spatial distribution of NPS pollution in Liyang was affected by various indicators (Figure 6). The q -value was used to assess the importance of different factors, and the factor detector identified nine factors that significantly impacted the distribution of TN and TP loads. The significant factors were ranked according to the size of the q -value as $X3 > X1 > X5 > X2 = X4 > X12 > X10 > X11 > X6$ (Table 3).

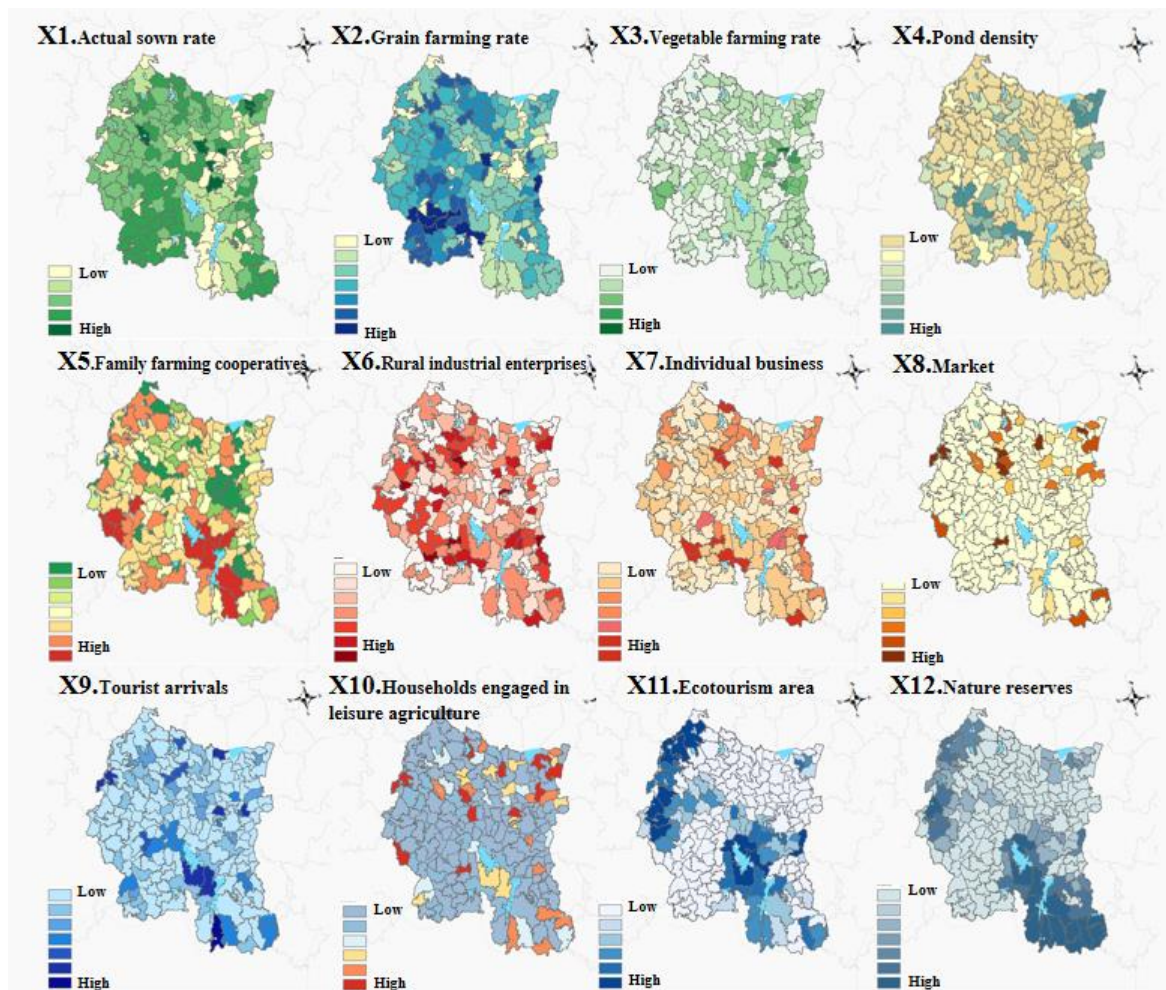


Figure 6. The distribution of rural multifunctional indicators in Liyang.

Table 3. Detection results of driving factors for spatial differentiation of TN load.

Indicators	TN		TP	
	<i>q</i> -Value	Rank	<i>q</i> -Value	Rank
X1	0.14	2	0.13	2
X2	0.12	4	0.12	4
X3	0.18	1	0.17	1
X4	0.12	4	0.13	2
X5	0.13	3	0.10	5
X6	0.05	9	0.04	9
X7	0.03	12	0.01	12
X8	0.05	9	0.06	7
X9	0.05	9	0.02	11
X10	0.06	7	0.05	8
X11	0.06	7	0.03	10
X12	0.10	6	0.09	6

Regarding the TN pollution, the explanatory power of the proportion of vegetables was more than 0.18, which is the most important, and this was followed by the proportion of actual sowing area, which accounted for approximately 0.14. The explanatory power of the proportion of grain farming and the number of family farming cooperatives was similar: approximately 0.13. The explanatory power of pond density was 0.12. The area of nature reserves accounted for 0.10. These are essential factors affecting the spatial differentiation of NPS. In addition, the *q*-values of other factors were all over 0.03. Their influences on the spatial differentiation of TN loading were limited. The research showed that the rural multifunctional indicators explained the influence mechanism of NPS pollutant spatial differentiation to varying degrees. Based on the ranking of *q*-value, agricultural structure factors were dominant factors in explaining the spatial differentiation of NPS pollution, such as the proportions of grain, vegetable and pond farming. Followed by environmental protective factors, the areas of nature reserves and ecotourism also influenced NPS distribution. The agricultural operation factors were important, including the actual sown area and the number of family farming cooperatives.

Overall, the total impacts of rural multifunctional indicators on the distribution of TN and TP loads were similar, but TN was affected with a higher *q*-value. The mechanism of rural multifunctional indicators impact on NPS is complicated; the single indicator was not strongly affecting the distribution of NPS pollution in this study. Therefore, the synergic relationship was considered in the subsequent analysis.

3.4. The Identification of the Rural Multifunctions

Due to the potential cooperation of rural multifunctional indicators, PCA was used to reduce the dimension for the subsequent interactive analysis. The standard deviation standardization method was used to standardize the 11 social and economic indicators of the rural development of Liyang, and then the software SPSS17.0 was employed to conduct PCA. It was found that the KMO test value was 0.6, and the *p*-value of the Bartlett was equal to 0.000, indicating that PCA can be performed in this study. According to Kaiser [45], the main principles were extracted according to an eigenvalue greater than 1 (Figure 7). The accumulative contribution rate of the five principal components was 77.41%. They comprehensively reflected that the rural multifunctional indicators could be generated as rural multifunctions, which can represent the trend of rural diversified development in Liyang (Table S3). The first principal component F1 was highly correlated with the proportion of nature reserves and ecotourism areas. F2 was highly correlated with the number of tourist arrivals and households engaged in leisure agriculture. F3 was related to the number of individual businesses, rural industrial enterprises, and markets. F4 was about the proportion of actual sown area and the area of grain production. F5 was related to the proportion of pond farming as well as the number of family farms and agricultural

cooperatives. Therefore, the rural functions of Liyang could be classified into five categories, representing ecological conservation (EC), leisure agriculture (LA), industry and business (IB), grain production (GP) and modern agriculture (MA) functions, respectively.

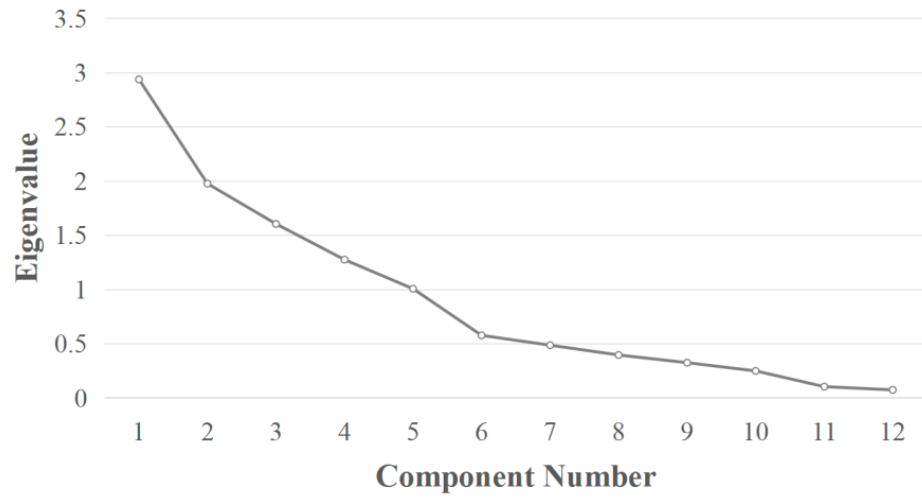


Figure 7. Scree plot of PCA result analyzing the indicators of rural multifunctions.

3.5. The Interaction Detector of Rural Multifunctions

The results showed that the spatial distribution of NPS pollution in Liyang was affected by rural multifunctions (Figure 8). The factor detector measured the *q*-value to represent the relative importance of each function first. There are five rural functions that had greater impacts on the distribution of TN and TP loads, while all of them were statistically significant. The functions were ranked according to the size of *q*-value as GP (0.2134) > MA (0.1595) > LA (0.1287) > EC (0.0914) > IB (0.0556). The GP function of townships accounts for approximately 21.34% of the spatial variation in NPS and stands as one of the most influential rural functions, followed by MA. The IB functions in rural areas have a relatively minor impact on NPS, indicating that commercial trade has limited relevance to the spatial variation of NPS.

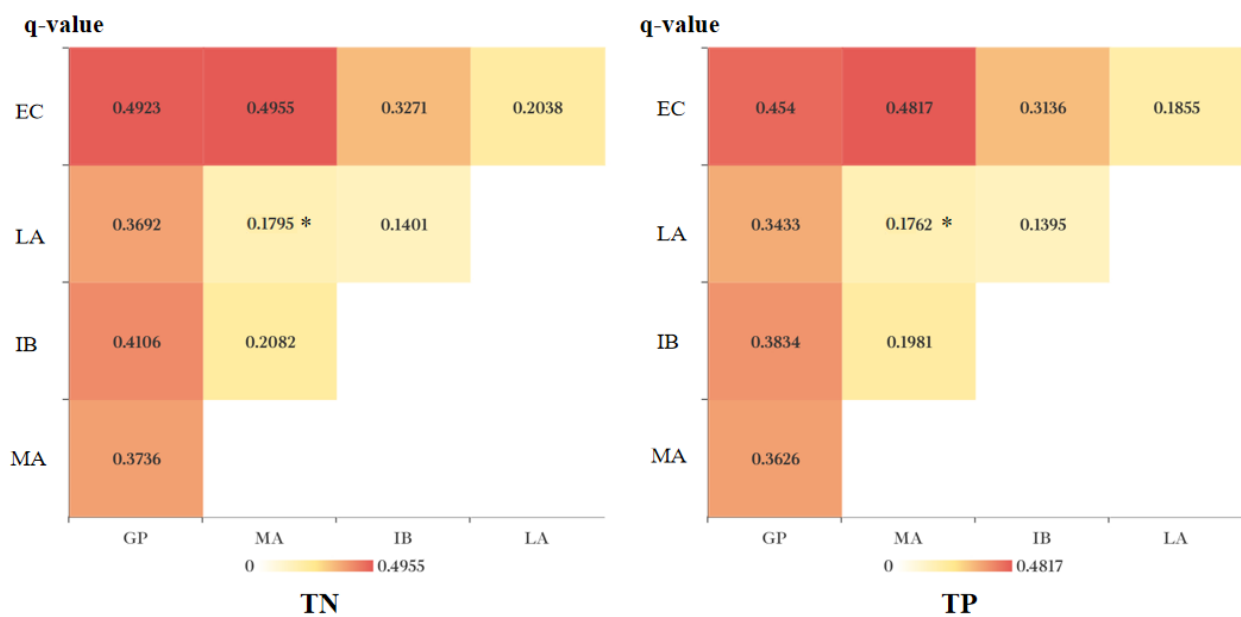


Figure 8. Interaction effect between rural multifunctions on NPS pollution (* means bi-enhanced while the others are nonlinear-enhanced).

The results showed that the interaction between any two rural functions is more significant than a single function. The types of interaction were mainly bi-enhance and nonlinear-enhance, indicating that the result of spatial differentiation of NPS would be affected by the joint action of different rural functions. Specifically, MA and EC functions had the strongest effect on TN spatial differentiation, and the interaction detection q -value was the highest at 0.4955, which was followed by $EC \cap GP$ (0.4923), $IB \cap EC$ (0.4106), $MA \cap GP$ (0.3736), $LA \cap GP$ (0.3692) and $EC \cap IB$ (0.3271). Although the q -values of the other interactions were below 0.30, they also showed that the two functions have a higher influence on the spatial differentiation of NPS than the single function. In addition, $LA \cap MA$ (0.1795) is an interaction enhancement. The interactive detector had similar results between TN and TP loads.

4. Discussion

4.1. The Impact of Rural Multifunctionality on NPS Pollution

This research provides an important foundation for understanding the impact of rural multifunctionality on NPS pollution. First, the result reveals the influence of rural multifunctional indicators on NPS pollution. Specifically, rural multifunctional indicators, including the proportion of vegetable farming, sowing area, and grain farming would influence NPS distribution. The number of family farming cooperatives, the area of pond farming, and the nature reserves area also demonstrate influence. The variation of topography, soil, land cover, fertilization, and other factors are accumulated with precipitation, resulting in the creation, output, migration, and transformation of NPS pollution [46,47]. The high intensity of NPS is mainly distributed in the north of Liyang, and the southern hilly areas are low, which is consistent with previous studies [24,48]. The agricultural indicators have the most significant effect on the NPS loads. Long-term and intense agricultural activities produce environmental stresses through land-use variation and the discharge of NPS nutrients into streams [49]. The effects of rural multifunctional development on NPS pollution were consistent with previous assumptions. These findings substantiate the applicability of rural multifunctionality in the analysis and prognostication of the spatial distribution of NPS.

Second, the MAUP is an essential question from a geographical perspective [50]. It is necessary to explore the scale effect in multi-scale research. In the analysis of natural processes and rural multifunctional development, the spatial granularity of the two variables, Y and X , is often varied [41]. In this paper, the dependent variable Y (NPS pollution intensity) is an environmental variable that is generally formed based on natural boundaries such as hydrological watersheds or terrain units. The independent variable X is from the socioeconomic data, which are generally investigated in administrative units. The inappropriate selection of study units would lead to the inconsistent results [51]. Therefore, it is necessary to consider the balance between accuracy and efficiency in the research [44]. This paper discussed the MAUP through quantitative analysis and demonstrated that the village scale was optimal for evaluating the correlation between NPS pollution and rural multifunctionality. Duan and Li [52] found that the spatial scale would not influence NPS loads, which is inconsistent with this study. This difference may be due to the socioeconomic factors used in previous MAUP analysis, which are demographics and GDP rather than agricultural production factors. A village is the smallest regional unit that can reflect the characteristics of rural production and lifestyle, and it is also the geographical scope that reflects the multiple rural functions of the countryside [2]. The average area of a village in Liyang is approximately 8.32 km². Liyang has both plains and hills, and the division of sub-watersheds is complicated because of the topography. A sub-watershed usually contains several villages, and it is difficult to describe the differentiation of villages. Subsequently, the village scale is an appropriate choice for exploring the spatial differentiation caused by natural and administrative boundaries in the study area.

Third, the impact of rural multifunctionality on TN and TP exhibits a comparable similarity albeit with varying degrees of impact. Upon comparative analysis of TN and TP,

it was discerned that pond density exerts a greater influence on TN, while its effect on TP is relatively minor. A previous study has indicated that the primary pollutants discharged from rice and shrimp cultivation are TN followed by TP [53]. TN emerges as the pivotal pollutant for pollution prevention and control. In the case of Liyang, aquaculture predominantly centers around shrimp farming, with the concentrated discharge of shrimp culture effluents potentially heightening the risk of eutrophication in surrounding water bodies.

Finally, the differentiation of NPS pollution is the result of the combined effect of multiple functions in rural areas. While the geographical detector identified single factors, the power of socioeconomic data was not as high as the physical factor [54]. The potential reason is that the single indicator does not influence NPS pollution directly. They usually affect NPS pollution through the synergistic effect. PCA grouped these factors into different principal components to understand them in aggregation as the same rural function. The grain production function of villages is represented by agricultural indicators, such as actual sowing rate, grain farming rate, and the number of agricultural cooperatives that reflect the agricultural planting structure and production capacity. The agricultural factors demonstrated a circle distribution, and NPS pollution has a similar pattern. Higher NPS output usually occurs in areas with frequent agricultural production activities [48]. Farmers tend to pursue higher economic output in these areas, and they will apply more agricultural chemical fertilizers, further increasing the risk of NPS pollution [55]. The interaction types of the five main factors are all enhanced, and the interaction between GP and EC is the most significant, fully explaining the conflict between rural ecological functions and grain production functions, which indicates the profound effect of rural multifunctionality on the distribution of NPS pollution.

4.2. The Mechanism of Impacts of Rural Multifunctionality on the Spatial Differentiation of NPS Pollution and Policy Implication

The rural multifunctionality significantly affects NPS pollution through the generation and transport. The traditional pattern of rural development, which relies mainly on grain production, has changed. The specialization, regionalization and intensification of agriculture have broken the original energy cycle in traditional agricultural department [30,56]. In the context of rural vitalization, the coordinated development of the rural economy and environment is crucial to enhance rural resilience. Previous studies mostly analyzed NPS pollution risk areas from the direct driving force, such as soil and topography, so as to design the placement of NPS control measures. However, an NPS control strategy without the consideration of rural socioeconomic development would be inefficient [56]. Consequently, identifying rural multifunction can clarify the complicated and diverse driving mechanism between rural socioeconomic development and NPS pollution generation.

The main source of NPS pollution and the transition process are highly correlated with the NPS control strategy. The NPS control strategy encompassing “reduction, retention, reuse, and restoration” (4R) were suggested in south China [57]. A localized control strategy could be proposed with the consideration of rural multifunctionality and the NPS pollution control strategy (Figure 9). The corresponding control strategies can be emphasized based on different rural functions. Based on the results and literature, the increase in NPS pollution in GP and MA villages is primarily attributed to the generation of pollution from the source such the fertilizers and livestock. Therefore, effective strategies would involve source reduction and nutritional reuse. In LA and IB villages, tourism leads to an increase in rural residential pollution. The strategies could be directed toward source reduction to diminish the total amount of pollution. In EC’s villages, the higher ecosystem service would mitigate NPS pollution through the transport path. The expansion of ecological space can be further pursued through ecological restoration.

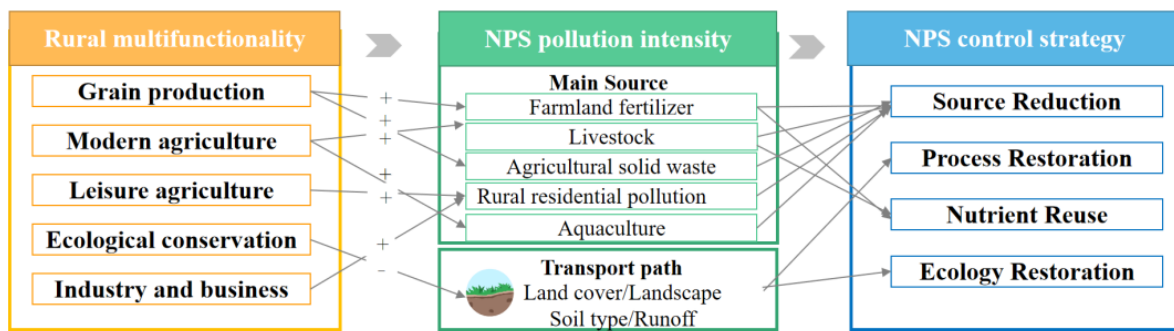


Figure 9. The mechanism of impacts of rural multifunctionality on NPS pollution and control strategy (“+” represent a strengthening effect on NPS pollution loads; “-” represents a weakening effect on NPS pollution loads).

Environmental regulations have positive impacts on NPS pollution control. Establishing water conservation areas and nature reserves could reduce the NPS pollution loads through ecological restoration [53]. The ecological conservation function of a village is represented by environmental protective indicators, such as the proportion of nature reserves, which reflect the ecological importance of the village. There are two reservoirs in the study area, both of which are drinking water sources, as well as the surrounding wetland and forest protection areas, so they have high ecological service value. In this type of villages, due to the limitation of protected areas, agricultural production and industrial activities are often protected by stricter regulations. For instance, the upper limit of the application extent and number of fertilizers is under control according to Tianmu Lake Protection Regulations. In addition, there are some protective projects, such as ecological restoration between the ridgelines of the two reservoirs. A series of comprehensive measures have been implemented to maintain ecological function, which also reduces the NPS intensity.

The critical points of NPS pollution control and environmental policy in the future are as follows. First, the local NPS control strategy should be guided by rural multifunctionality. For instance, promoting green technologies and clean production in ecological function villages could drive the transformation of agricultural production to achieve sustainable agriculture. The most cost-effective NPS management involves prioritizing the implementation of comprehensive NPS management in GA or MA villages, combining policy tools such as incentive measures and Best Management Practices (BMPs). Second, the rural development should take into consideration the NPS control. This, in turn, facilitates the formulation of guiding policies. For instance, in areas with a higher ecological functionality, it is advisable to focus on eco-tourism or commerce for minimum NPS pollution. Finally, it may be considered to designate the village as NPS control units, such as incorporating pollution discharge limits for NPS control into rural planning.

5. Conclusions

Currently, rural policy is closely linked to two concepts: diversity (multifunctionality) and sustainability [58]. This study assessed the impact of rural multifunctional development on NPS pollution. Firstly, the distribution of non-point source pollution in Liyang City was simulated based on sub-watershed analysis, and it was found that the distribution of NPS pollution in Liyang City showed spatial heterogeneity. Secondly, the optimal research scale for examining the rural multifunctional development that affects the NPS pollution was the village scale, which is capable of both reflecting the spatial heterogeneity of NPS pollution and integrating well with socioeconomic data. Subsequently, factor detection results revealed that rural multifunctional indicators, particularly agricultural indicators, have a high influence on the differentiation of NPS loads. Finally, by reducing the dimensions of indicators, this study identified the rural functions of Liyang. The study found that the superposition of rural multifunctionality has a strengthening effect on NPS pollution, particularly when the ecological conservation function is combined with grain production

or mixed agriculture function. This finding is conducive to clarifying the mechanism of socioeconomic factors influencing NPS pollution, and it provides a reference for the effective reduction in NPS pollutants and precise environmental governance policies.

The estimation and modeling of NPS is the foundation of exploring the environmental response of rural multifunctionality. The NPS pollution control may be unsuccessful if there is inadequate research on the influencing factors that generate and contribute to it at the administrative scale. Therefore, a combination of natural-process NPS estimation and rural multifunctional development is essential in informing policy making. In this study, the geographical detector has the advantage of capturing the interrelationships between the natural process and socioeconomic factors without making assumptions or imposing any limitation on the explanatory and response variables. However, it still has some limitations. First, because of the availability of data, it is difficult to obtain official data for every important indicator at the village scale (rural economic data, planting structure), which affects the integrity of the rural multifunctional development. The continuous analysis of rural multifunctional development impacts on NPS pollution is inadequate due to the lack of historical socioeconomic data. Second, the identification of rural multifunctions in the current study only considers the function of a village unit without detailed information about farmers' behavior. Therefore, we suggest that future studies could focus on the process of rural multifunctionality and NPS variation with historical data. Additionally, as farmers are important agents in rural multifunctionality and NPS pollution, future research could consider the trade-off between the economic benefit and environmental effect from farmers' perspectives.

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