

## Article

# Spatiotemporal Evolution of Land Use, Coupled Ecological Responses, and Multi-Scenario Trade-Off Simulation: A Case Study of the Danjiangkou Reservoir Area

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## Abstract

As the core water source area of the Middle Route of the South-to-North Water Diversion Project, the Danjiangkou Reservoir Area plays a critical role in regional ecological security and water resource security. Its land use transitions and associated ecosystem service dynamics are examined. Based on land use, ecological sensitivity, and ecosystem service value data from 2000 to 2020, this study employed the FLUS model to simulate four scenarios—natural development, cropland protection, ecological protection, and ecological–cropland synergy—for 2050, systematically revealing the characteristics of land use transition, the coupled evolution of ecological sensitivity and ecosystem service value, and the trade-off mechanisms between ecological security and food security under multiple scenarios. The results show that: (1) From 2000 to 2020, land use in the reservoir area exhibited an ecological transition characterized by “two expansions and three contractions”: forestland and water bodies increased by 764.16 km<sup>2</sup> and 324.36 km<sup>2</sup>, respectively, while cropland and grassland decreased by 664.33 km<sup>2</sup> and 547.08 km<sup>2</sup>, the comprehensive index of land use degree declined by approximately 1.0%, indicating continuously weakening development intensity. (2) The overall hierarchical structure of ecological sensitivity improved, with the area of highly sensitive zones decreasing from 5201.60 km<sup>2</sup> to 3729.91 km<sup>2</sup>; however, the concentration risk of highly sensitive forestland and the unexpected increase in extremely sensitive cropland persisted. (3) Total ecosystem service value increased from CNY 51.92 billion to CNY 58.35 billion (+12.38%), with hydrological regulation contributing 79.83% of the total increment; regulating services remained the core functional type. Sensitivity analysis indicated that the coefficient of sensitivity (CS) values were below 1, confirming the robustness of the findings. (4) Multi-scenario simulations revealed a rigid ecological–food security trade-off: under natural development, ESV increased by 15.44% but cropland loss reached 1033.29 km<sup>2</sup>; under cropland protection, ESV decreased by 1.50%, the only scenario with negative ecological outcomes; under ecological protection, ESV increased by 16.59% but with the most severe cropland loss (−1072.98 km<sup>2</sup>); under ecological–cropland synergy, water bodies expanded the most substantially (+562.75 km<sup>2</sup>) while cropland loss was the most severe (−1118.19 km<sup>2</sup>), indicating that the synergy goal was not achieved, as gains in regulating services came at the cost of further provisioning services losses. The study confirms the positive effects of ecological land use transition in the reservoir area, while also highlighting the intensifying conflict between ecological protection and food security against the backdrop of ecological improvement.



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**Keywords:** Danjiangkou Reservoir Area; land use/cover change (LUCC); ecological sensitivity; ecosystem service value (ESV); future land use simulation (FLUS) model; multi-scenario simulation

## 1. Introduction

As a major national strategic infrastructure, the Middle Route of the South-to-North Water Diversion Project relies critically on the ecological environmental quality and the stability of land use patterns in its water source area, which are directly linked to the operational safety and long-term comprehensive benefits of the project. As the core water source area of the Middle Route Project, the Danjiangkou Reservoir Area plays a crucial role in regional and basin-wide sustainable development, owing to the rational allocation of its land resources and the security of its ecological environment [1]. Under the dual pressures of global climate change and intensive human activities, land use in the reservoir area is undergoing a significant and complex restructuring process, reflecting the combined effects of multiple policies and engineering initiatives, including the Grain-for-Green program, ecological resettlement, reservoir construction, and urban expansion [2].

Land serves as the fundamental material foundation for the survival and development of human society, and also constitutes the direct medium through which human activities interact with the natural environment [3]. Land use and land cover change (LUCC) not only reflects the allocation patterns of various land resource elements within a region, but is also deeply coupled with the sustainable processes of socioeconomic development and natural environmental evolution [4]. As the most fundamental practical activity of human society, land use is closely and intrinsically linked to the structure and functioning of terrestrial ecosystems [5]. Moreover, the transformation of land use types serves as a critical driving factor that triggers ecological sensitivity issues—a process that not only reflects the qualitative and quantitative characteristics of land resources, but also objectively reveals the dynamic evolution patterns of the spatial configuration of land use [6].

Considerable progress has been made in research on watershed land use dynamics, ecological sensitivity, and ecosystem service values. First, studies on spatiotemporal land use evolution have predominantly focused on the analysis of land use patterns during a single period, confirming that hydraulic engineering projects and ecological policies serve as the core drivers of land use transformation in reservoir areas [7–9]. Second, existing research on ecological sensitivity has largely concentrated on qualitative descriptions of macroscopic spatial differentiation patterns, whereas quantitative and fine-scale analyses remain insufficient, and the clustering characteristics of highly sensitive areas have yet to be effectively identified [10–12]. Third, assessments of ecosystem service value (ESV) have largely emphasized static evaluations of the current status. Although previous studies generally acknowledge the enhancing effect of ecological land expansion—such as forestland and grassland—on water conservation functions, insufficient attention has been paid to the dynamic evolution and gain-loss predictions of ESV under alternative future development scenarios. A few studies have begun to incorporate models such as PLUS and FLUS for multi-scenario simulations; however, a systematic predictive assessment paradigm has not yet been established [13–16].

In this context, recent years have witnessed the increasingly widespread application of next-generation land use simulation models—such as FLUS (Future Land Use Simulation) and PLUS (Patch-Generating Land Use Simulation)—in watershed-scale studies. The FLUS model, by coupling system dynamics with a cellular automaton module, can integrate multiple driving factors including historical land use, socioeconomic changes,

and climate change to project land use areas and spatial distributions under multiple scenarios. The PLUS model, on the other hand, introduces a multi-random seed-based cellular automaton and a land expansion analysis strategy, achieving higher simulation accuracy at the patch scale. In terms of watershed applications, previous studies have employed the FLUS model to simulate the multi-scenario evolution of production-living-ecological spaces in the Fenhe River Basin [17]; constructed a FLUS–Markov model to analyze the eco-environmental effects of the “production-living-ecological” spaces under multiple scenarios in the Yangtze River Basin [18]; established a PLUS-InVEST coupling framework in the Hanjiang River Basin to analyze the dynamic changes of the water-carbon-land system under multiple scenarios [19]; and applied the PLUS model in the Xiangjiang River Basin to simulate changes in ecosystem service value in 2035 under five development scenarios [20]. For the Danjiangkou Reservoir Area specifically, existing studies have used the PLUS model to predict the land use patterns and eco-environmental effects in 2030 under natural development, cropland protection, and ecological protection scenarios [21], while other scholars have applied the PLUS model to simulate the future evolution of ecosystem service value under four scenarios [22]. Internationally, the FLUS and PLUS models have also received widespread attention. Researchers have employed the FLUS model to analyze urban expansion and its encroachment on natural areas in Diyarbakır, Turkey, from 1984 to 2020 [23]; utilized the FLUS model to conduct multi-scenario simulations of agricultural land use change in the coastal Alanya region [24]; applied the PLUS model to perform multi-scenario simulations of land use change in Syracuse, Italy, for 2030 [25]; and assessed the impacts of land use change on hydrological ecosystem services under different scenarios in the Ullia River Basin, Spain [26]. These studies demonstrate that the FLUS and PLUS models have developed into highly influential tools in international land use change research, showing strong applicability across multiple domains including urban expansion simulation, agricultural change prediction, and ecosystem service assessment.

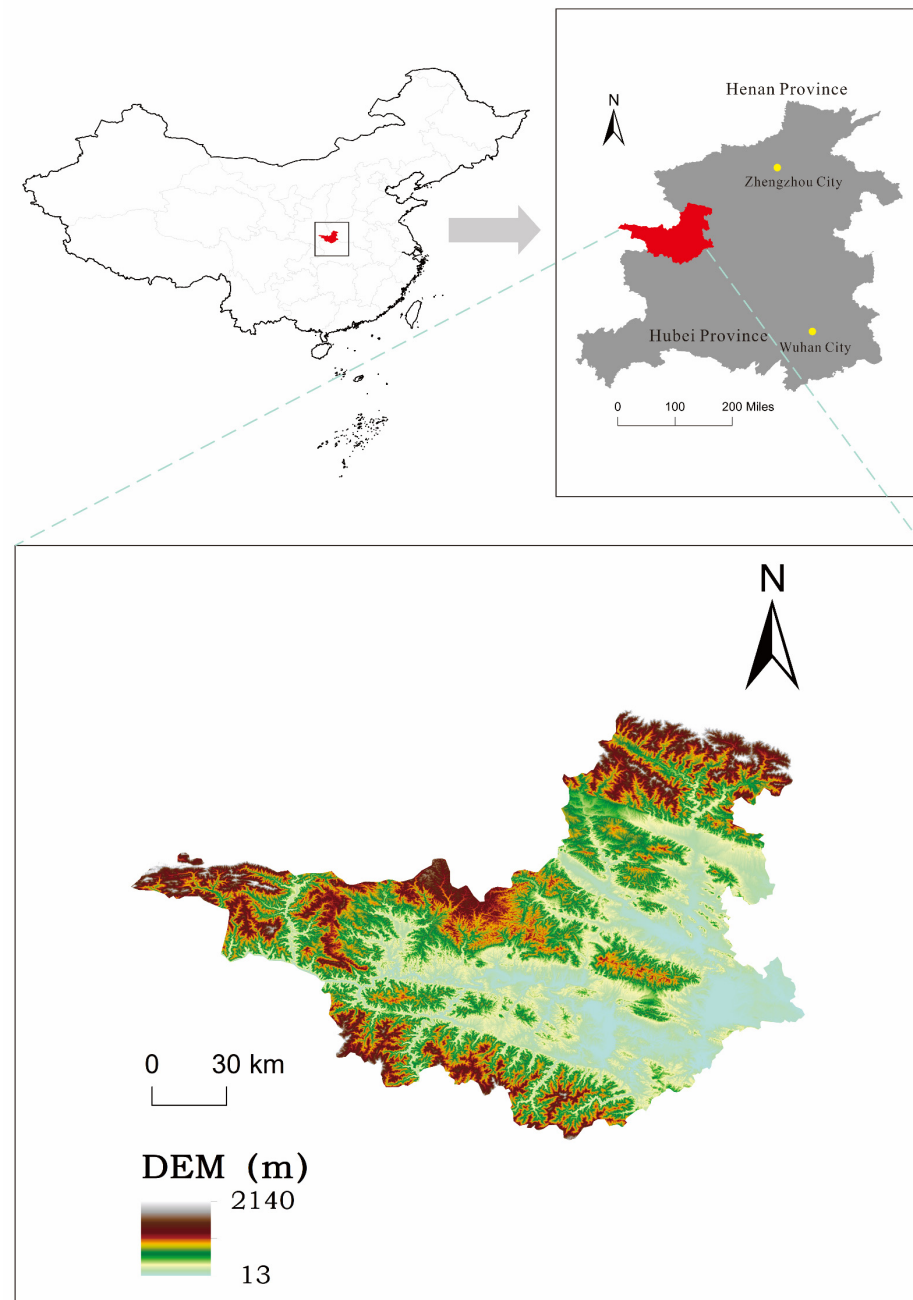
However, the aforementioned studies still exhibit three notable deficiencies, which constitute the impetus for this study. First, there is a fragmentation of analytical frameworks. Existing studies have generally treated land use change analysis, ecological sensitivity evaluation, and ecosystem service value assessment as independent research threads, lacking systematic attempts to integrate them into a unified analytical framework. Although a few studies have begun to explore the coupling relationships between land use and individual ecological elements—such as carbon storage or water conservation—they have yet to construct a complete causal chain linking “land use evolution–ecological sensitivity response–ecosystem service value feedback,” thereby failing to fully characterize the comprehensive ecological effects of land use transition. Second, there is a narrowness in scenario design and a limitation in the dimensionality of trade-off analysis. Most existing multi-scenario simulation studies in the Danjiangkou Reservoir Area have adopted only three scenarios—natural development, cropland protection, and ecological protection—without examining the potential for synergy among multiple policy objectives. Furthermore, trade-off analyses have largely been confined to two-dimensional relationships such as “ecology–economy” or “ecology–food,” while the water resource guarantee function—a critical responsibility of the Danjiangkou Reservoir Area as the core water source of the Middle Route of the South-to-North Water Diversion Project—has not been incorporated into the trade-off analytical framework. Third, the strategic value of the hydrological regulation function has not been adequately highlighted. The core ecological orientation of the Danjiangkou Reservoir Area lies in water conservation and runoff regulation. However, in existing studies, hydrological regulation has been merely mentioned as a sub-category of regulating services without sufficient quantification or emphasis on its strategic value as the fundamental guarantee

of water security for the Middle Route of the South-to-North Water Diversion Project. This under-recognition weakens the guiding significance of research conclusions for water resource management decisions in the reservoir area.

In response to the above deficiencies, this study takes the Danjiangkou Reservoir Area from 2000 to 2020 as the research object and integrates multi-source driving data to conduct systematic investigations from three aspects: (1) revealing the spatiotemporal evolution characteristics of land use in the reservoir area from 2000 to 2020, constructing a systematic analytical framework of “land use evolution-ecological sensitivity response-ecosystem service value feedback,” and elucidating the coupled evolution patterns among the three; (2) based on the calibrated FLUS model, developing four scenarios—natural development, cropland protection, ecological protection, and ecological–cropland synergy—to simulate the spatial pattern of land use in the reservoir area in 2050; and (3) embedding the water resource guarantee function into the trade-off analysis framework, establishing a three-dimensional trade-off framework of “ecological protection–food security–water resource guarantee,” quantifying the differentiation of ecosystem service value under multiple scenarios, and revealing the underlying mechanism of synergy scenario failure—the “ecological priority bias” induced by overly strong water body expansion drivers. This study clarifies the unique land use trade-off mechanisms characteristic of large-scale reservoir areas, providing quantitative support for territorial spatial planning in the water source area of the South-to-North Water Diversion Project.

## 2. Study Area

The Danjiangkou Reservoir is situated in the middle and upper reaches of the Han River, spanning Hubei and Henan provinces. It is the largest artificial freshwater lake in Asia and serves as both the water source and a national first-class water source protection area for the Middle Route of the South-to-North Water Diversion Project. The study area, as defined in this research, is located between 109°27' E and 111°52' E and between 32°14' N and 33°48' N, encompassing Xichuan and Xixia counties in Henan Province, as well as Danjiangkou City, Yunyang District, Maojian District, Zhangwan District, and Yunxi County in Hubei Province (Figure 1). The topography of the Danjiangkou Reservoir Area is higher in the northwest and lower in the southeast, with diverse landforms predominantly consisting of hills and low-to-moderate mountains. The region has a temperate monsoon climate with four distinct seasons, an average annual temperature of approximately 16 °C, and annual precipitation ranging from 600 to 1000 mm. The industrial structure of the reservoir area is predominantly oriented toward green and ecological development. In recent years, notable progress has been made in sectors such as efficient eco-agriculture, industrial restructuring, and tourism-led service industries [21]. However, with the construction and operation of the South-to-North Water Diversion Project, large-scale resettlement, urban expansion, and infrastructure development have substantially intensified anthropogenic activities, thereby exerting profound impacts on regional land use patterns and ecosystem structure [27].



**Figure 1.** Location of the Danjiangkou Reservoir Area.

### 3. Data and Methodology

#### 3.1. Data Sources and Processing

The data used in this study primarily comprise land use data and the driving factors associated with land use change. Land use data for the Danjiangkou Reservoir Area in 2000, 2010, and 2020 were obtained from the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (<https://www.resdc.cn>), with a spatial resolution of 30 m. These data were classified into six categories: cropland, forestland, grassland, water bodies, barren land, and construction land. Considering the ecological conservation orientation, population distribution characteristics, and data availability of the Danjiangkou Reservoir Area, this study selected driving factors from three main aspects: natural conditions, location, and economic factors. The natural factors include elevation, slope, mean annual precipitation, and mean annual temperature; the location

factors include distances to highways, roads, and railways; and the economic factors include population, GDP, and nighttime light data. The 30 m Digital Elevation Model (DEM) used in this study was obtained from the Geospatial Data Cloud platform (<https://www.gscloud.cn>). Based on this DEM, topographic factors including elevation, slope, and aspect were extracted using the spatial analysis tools of ArcGIS. Data on mean annual precipitation, mean annual temperature, population, GDP, and nighttime lights were also sourced from the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences. Data on water bodies, roads, and railways were obtained from Open Street Map (OSM), and the required spatial distances were calculated using the Euclidean distance tool in ArcMap 10.8.2. All the aforementioned driving factors were preprocessed using ArcGIS 10.8.2, and their spatial resolutions were resampled to 30 m. In addition, the administrative boundary of the study area was derived from the National Geographic Information Public Service Platform (Tianditu).

### 3.2. Methods

#### 3.2.1. Land Use Change Analysis

The land use dynamic degree ( $K$ ) is a commonly employed method for quantitatively analyzing changes in land use area and quantity. It can elucidate the outcomes and evolutionary trends of land use change, and quantitatively characterize the net change and quantitative variation of a specific land use type within a given time period [28–31].

$$K = \frac{U_b - U_a}{U_a} \times \frac{1}{T} \times 100\% \quad (1)$$

where  $U_a$  and  $U_b$  represent the areas of a given land use type at the beginning and end of the study period, respectively, and  $T$  denotes the study interval (in years).

The land use transfer matrix is a widely employed method for quantitatively depicting the magnitudes and directions of conversions among different land use types, and is commonly used to describe the transitions of land use categories over a specified time interval. It not only accurately reflects the compositional characteristics of land use across different periods, but also effectively characterizes the trajectories, sources, and spatial distribution patterns of each land use type in the study area over time [32].

$$S = \begin{bmatrix} S_{11} & \dots & S_{1j} & \dots & S_{1n} \\ \dots & \dots & \dots & \dots & \dots \\ S_{i1} & \dots & S_{ij} & \dots & S_{in} \\ \dots & \dots & \dots & \dots & \dots \\ S_{n1} & \dots & S_{nj} & \dots & S_{nn} \end{bmatrix} \quad (2)$$

where  $S_{ij}$  denotes the area converted from land use type  $i$  to land use type  $j$  over the study period;  $i$  represents the land use type at the beginning of the interval, and  $j$  represents the land use type at the end of the interval;  $n$  is the total number of land use categories.

To quantitatively assess the intensity of anthropogenic disturbance on the regional land system, this study introduced a comprehensive index of land use degree ( $L$ ) to reflect the levels of land development and utilization at different stages.

$$L = 100 \times \left( \sum_{i=1}^n A_i \times C_i \right) \quad (3)$$

where  $A_i$  denotes the graded assignment index for land use type  $i$ , and  $C_i$  represents the areal proportion of that type. The grading assignment criteria, adopted from previous studies [33,34], are presented in Table 1.

**Table 1.** Grading assignment values for land use types.

| Graded Assignment Index ( $A_i$ ) | Land Use Type                     |
|-----------------------------------|-----------------------------------|
| 1                                 | Barren land                       |
| 2                                 | Forestland, Grassland, Water body |
| 3                                 | Cropland                          |
| 4                                 | Construction land                 |

### 3.2.2. Comprehensive Ecological Status Assessment

Ecological sensitivity is a comprehensive indicator reflecting the degree to which a regional ecosystem responds to both natural and anthropogenic disturbances, with its spatial differentiation being synergistically regulated by multiple factors including topography, vegetation cover, and land use [35]. To systematically reveal the ecological risk patterns of the study area, this study constructed an ecological sensitivity evaluation system comprising five core indicators, selected from two dimensions: the natural geographical base and human activity disturbances. Specifically, slope, aspect, and elevation were chosen to represent topographical conditions; the Normalized Difference Vegetation Index (NDVI) was adopted to reflect vegetation cover and productivity; and land use type was utilized to indicate land surface cover structure and the intensity of anthropogenic utilization. For weight determination, this study employed the Analytic Hierarchy Process (AHP) combined with expert scoring. To ensure the scientific validity of the weighting results and to mitigate the potential biases inherent in a single subjective method, the expert panel was composed of 15 researchers and practitioners specializing in ecological protection of the South-to-North Water Diversion water source area, land use planning, and geographic information system applications. Each expert independently judged the pairwise importance of the indicators using the 1–9 scaling method, and factor weights were calculated after consistency testing ( $CR < 0.1$ ). Meanwhile, to validate the robustness of the AHP-derived weights and to address the inherent uncertainty of subjective weighting methods, this study concurrently introduced the Entropy Weight Method (EWM) for objective weight calculation, determining objective weights based on the degree of information entropy dispersion of each evaluation indicator. On this basis, the Spearman rank correlation coefficient and the Index of Agreement (IOA) were employed to test the consistency of the comprehensive ecological sensitivity scores derived from the two weighting schemes, in order to assess whether expert subjective judgments introduced significant systematic biases into the evaluation results. Previous studies have demonstrated that this approach can effectively test the spatial robustness of ecological evaluation results under different weighting schemes. If the two sets of results are highly consistent ( $IOA > 0.80$  and the correlation coefficient passes the significance test), the AHP weighting system is considered to possess satisfactory objectivity and robustness. If significant discrepancies are detected, the multiplicative normalization method is applied to compute combined weights that incorporate both subjective and objective information. On this basis, and with reference to the Interim Regulation on Ecological Function Zoning [20] and relevant studies in the reservoir area, we defined ecological sensitivity as the degree of vulnerability of ecosystems in response to natural and anthropogenic disturbances. We emphasized its attribute as a “sensitivity to disturbance” rather than an “ecological value” property, so as to ensure consistency between the indicator classification and the conceptual connotation. Five levels of ecological sensitivity were established: non-sensitive, slightly sensitive, moderately sensitive, highly sensitive, and extremely sensitive (Table 2). The threshold for each level was determined using the Natural Breaks (Jenks) method. Finally, a weighted spatial overlay analysis of the factor raster layers was conducted in the ArcGIS platform to gener-

ate a comprehensive distribution map of ecological sensitivity in the study area, thereby providing a data foundation for subsequent coupling analysis with land-use change.

**Table 2.** Ecological sensitivity evaluation index system and factor weights for the Danjiangkou Reservoir Area.

| Indicator     | Weight | Non-Sensitive (1)    | Slightly Sensitive (2)       | Moderately Sensitive (3)     | Highly Sensitive (4)         | Extremely Sensitive (5)    |
|---------------|--------|----------------------|------------------------------|------------------------------|------------------------------|----------------------------|
| Slope (°)     | 0.159  | 0–5                  | 5–10                         | 10–15                        | 15–20                        | >20                        |
| Aspect        | 0.195  | Flat, South          | Southeast, Southwest         | East, West                   | Northeast, Northwest         | North                      |
| Elevation (m) | 0.194  | <100                 | 100–200                      | 200–300                      | 300–400                      | >400                       |
| NDVI          | 0.240  | NDVI > 0.8           | $0.6 < \text{NDVI} \leq 0.8$ | $0.4 < \text{NDVI} \leq 0.6$ | $0.2 < \text{NDVI} \leq 0.4$ | $0 < \text{NDVI} \leq 0.2$ |
| Land use type | 0.212  | Forest, water bodies | Grassland                    | Cropland                     | Construction land            | Barren land                |

### 3.2.3. Land Use Change Simulation

Land use and land cover change in the study area is driven by multiple factors, including natural geographical conditions, major water conservancy projects, and relevant ecological policies, with its structural adjustments typically exhibiting pronounced characteristics of phasing, accumulation, and time lag. To effectively characterize the patterns of land use evolution in the Danjiangkou Reservoir Area and its upstream regions under the disturbance of engineering activities, this study adopted a 10-year interval as the time step for land use transition analysis. This temporal scale was chosen because it not only adequately covers the transmission cycle of land use adjustments during the construction and initial operation phases of the Danjiangkou Project, thereby comprehensively reflecting the overall response process of the land system under engineering disturbance, but also helps to mitigate the interference caused by classification errors and short-term fluctuations in annual land cover data. Consequently, it facilitates a more accurate identification of the dominant directions and stage-specific differences in regional land use pattern evolution over the long term [36].

This study employed the GeoSOS-FLUS software (FLUS v2.4) to simulate the spatiotemporal evolution of land use in the Danjiangkou Reservoir Area, integrating multiple driving factors to project future land use patterns and to further quantitatively assess the regional ecological restoration capacity. The FLUS model is a novel land use spatiotemporal simulation model that couples an artificial neural network with an improved cellular automaton. It effectively integrates multiple driving mechanisms—including physical geography, socioeconomic conditions, and policy constraints—to achieve a co-evolutionary simulation of both the quantitative structure and spatial configuration of land use, making it suitable for long-term, multi-scenario land use change simulations in complex regions. In light of the diverse development needs and objectives of the Danjiangkou Reservoir Area, four scenarios—natural development, cropland protection, ecological protection, and ecological–cropland synergy—were established to project the spatial pattern of land use in the reservoir area for 2050.

First, suitability probabilities were generated using an ANN, and the simulation was validated against historical land use data. To avoid the subjectivity inherent in traditional weighting methods, the model first employed a three-layer back-propagation artificial neural network (ANN) algorithm to extract the nonlinear mapping relationships between driving factors and land use types. The input layer included topographic factors (e.g., elevation and slope), location factors (e.g., distances to roads and water bodies), and

economic factors (e.g., population and GDP). Through automatic iterative training, the model generated, for each cell, the suitability probabilities for the spatial distribution of each land use type. In this study, the ANN module embedded in GeoSOS-FLUS V2.4 was used for suitability probability calculation. This module is built upon the open-source machine learning library Shark 3.1.0 and adopts a three-layer BP neural network architecture, with hyperparameters—including the number of hidden layer neurons, learning rate, training epochs, and activation function—set to the software defaults (12, 0.01, 500, and Sigmoid function, respectively), the Adam optimization algorithm, and a sampling rate of 10%. On this basis, using the 2000 and 2010 land use data as the initial baselines, respectively, the suitability probabilities obtained from the ANN were applied, in conjunction with the natural background of the study area, to simulate the land use patterns for 2010 and 2020. The simulated results were then compared with the actual remote-sensing interpreted data for the corresponding years on a cell-by-cell basis, and the overall accuracy (OA), Kappa coefficient, and Figure of Merit (FOM) were calculated to evaluate the simulation accuracy of the model in the study area.

Second, scenario-specific land demand was projected using a Markov Chain model. To ensure consistency between the macro-level total land areas and the micro-level spatial evolution, this study employed a Markov Chain model to project the quantitative structure of land use in 2050 under different scenarios (Table 3). For the natural development scenario, taking into account the completed construction and operational status of the reservoir, the transition probabilities of all land use types to water bodies were reduced by 60% based on the 2000–2020 land use transfer probabilities. For the cropland protection scenario, on the basis of the natural development scenario, careful consideration was given to various cropland protection policies in the reservoir area to prevent excessive exploitation and misuse of cropland, and the probabilities of conversion from cropland to other land use types were reduced by 50%. For the ecological protection scenario, in light of the reservoir area's ecological protection policies and relevant ecological construction requirements—including the Plan for Water Pollution Prevention and Soil and Water Conservation in the Danjiangkou Reservoir Area and Its Upstream Regions—the transition probabilities from cropland, forestland, grassland, and water bodies to construction land were reduced by 40%; the transition probability from cropland to construction land was reduced by 20%; and the probabilities of conversion from cropland and grassland to forestland were increased by 20%. For the ecological–cropland synergy scenario, following the ecological protection scenario, the transition probabilities from forestland, grassland, and water bodies to construction land were reduced by 40%; meanwhile, following the cropland protection scenario, the transition probability from cropland to non-agricultural land was reduced by 30%, aiming to achieve “dual-protection synergy” in spatial configuration. Through these differentiated adjustments to the transfer matrices, the area demands for each land use type in 2050 under the four scenarios were estimated separately, providing a macro-level quantitative constraint boundary for the cellular automaton (CA) module of the FLUS model.

Finally, with the 2020 land use pattern as the baseline, the projected land demands for 2050 obtained from the Markov Chain model were used as the total quantity control. Combined with the trained ANN-derived suitability probabilities and the conversion rules, these were input into the CA spatial evolution module to perform iterative computations, thereby simulating the spatial distribution patterns of land use in 2050 under each of the four scenarios.

**Table 3.** Cost matrix for land use transitions under multiple scenarios (2020–2050).

| Natural Development Scenario (S1) |                |                |                |                |                |                | Cropland Protection Scenario (S2) |                |                |                |                |                |
|-----------------------------------|----------------|----------------|----------------|----------------|----------------|----------------|-----------------------------------|----------------|----------------|----------------|----------------|----------------|
|                                   | L <sub>1</sub> | L <sub>2</sub> | L <sub>3</sub> | L <sub>4</sub> | L <sub>5</sub> | L <sub>6</sub> | L <sub>1</sub>                    | L <sub>2</sub> | L <sub>3</sub> | L <sub>4</sub> | L <sub>5</sub> | L <sub>6</sub> |
| L <sub>1</sub>                    | 1              | 1              | 1              | 1              | 1              | 1              | 1                                 | 0              | 0              | 0              | 0              | 0              |
| L <sub>2</sub>                    | 1              | 1              | 1              | 1              | 1              | 1              | 1                                 | 1              | 1              | 0              | 1              | 1              |
| L <sub>3</sub>                    | 1              | 1              | 1              | 1              | 1              | 1              | 1                                 | 1              | 1              | 1              | 1              | 1              |
| L <sub>4</sub>                    | 1              | 1              | 1              | 1              | 1              | 1              | 1                                 | 0              | 1              | 1              | 1              | 1              |
| L <sub>5</sub>                    | 1              | 1              | 1              | 1              | 1              | 1              | 1                                 | 1              | 1              | 1              | 1              | 1              |
| L <sub>6</sub>                    | 0              | 0              | 0              | 0              | 0              | 1              | 0                                 | 0              | 0              | 0              | 0              | 1              |

| Ecological Protection Scenario (S3) |                |                |                |                |                |                | Ecological–Cropland Synergy Scenario (S4) |                |                |                |                |                |
|-------------------------------------|----------------|----------------|----------------|----------------|----------------|----------------|-------------------------------------------|----------------|----------------|----------------|----------------|----------------|
|                                     | L <sub>1</sub> | L <sub>2</sub> | L <sub>3</sub> | L <sub>4</sub> | L <sub>5</sub> | L <sub>6</sub> | L <sub>1</sub>                            | L <sub>2</sub> | L <sub>3</sub> | L <sub>4</sub> | L <sub>5</sub> | L <sub>6</sub> |
| L <sub>1</sub>                      | 1              | 1              | 1              | 1              | 1              | 1              | 1                                         | 1              | 1              | 1              | 0              | 1              |
| L <sub>2</sub>                      | 0              | 1              | 0              | 0              | 0              | 0              | 1                                         | 1              | 1              | 1              | 0              | 1              |
| L <sub>3</sub>                      | 0              | 1              | 1              | 1              | 0              | 0              | 1                                         | 1              | 1              | 1              | 1              | 1              |
| L <sub>4</sub>                      | 0              | 0              | 0              | 1              | 0              | 0              | 1                                         | 1              | 1              | 1              | 0              | 1              |
| L <sub>5</sub>                      | 1              | 1              | 1              | 1              | 1              | 1              | 1                                         | 1              | 1              | 1              | 1              | 1              |
| L <sub>6</sub>                      | 0              | 0              | 0              | 0              | 0              | 1              | 1                                         | 1              | 1              | 1              | 1              | 1              |

Notes: 0 indicates that conversion is prohibited, and 1 indicates that conversion is permitted. L<sub>1</sub>, L<sub>2</sub>, L<sub>3</sub>, L<sub>4</sub>, L<sub>5</sub>, and L<sub>6</sub> denote cropland, forestland, grassland, water bodies, barren land, and construction land, respectively. In the matrix, rows represent the outgoing (from) land use types, and columns represent the incoming (to) land use types.

### 3.2.4. Ecological Benefit Assessment

Following the ecosystem service value (ESV) calculation formula proposed by Costanza et al. [37] and incorporating the equivalent factor table for terrestrial ecosystems in China developed by Xie et al. [38], this study adopted a modified equivalent factor method to construct an ecosystem service value assessment model for the Danjiangkou Reservoir Area, based on the empirical monetary valuation standard.

By consulting the Henan Statistical Yearbook and the data published by the National Bureau of Statistics of China, the grain yields of three major crops—wheat, rice, and maize—as well as grain prices in Henan Province for 2010, were compiled (Table 4). Following the established empirical approach that the value of one standard ESV equivalent factor is equal to 1/7 of the food production service value per unit area of cropland [39], the economic value of one standard ecosystem service value equivalent factor for the Danjiangkou Reservoir Area was calculated as 1426.15192 CNY/ha using Equation (4). On this basis, the ecosystem service value coefficients per unit area for each ecosystem type in the Danjiangkou Reservoir Area were derived.

$$E_a = \frac{1}{7} \sum_{s=1}^t \frac{m_s p_s q_s}{M} \quad (4)$$

where  $E_a$  denotes the economic value of one standard ESV equivalent factor for the Danjiangkou Reservoir Area;  $m_s$  is the sown area of the  $s$ -th grain crop;  $p_s$  is the average price of the  $s$ -th grain crop;  $q_s$  is the yield of the  $s$ -th grain crop; and  $M$  is the total sown area of all grain crops in the region.

**Table 4.** Grain yields and prices of major crops in the Danjiangkou Reservoir Area.

| Crop Type | Grain Yield per Unit Area (kg/ha) | Grain Price (CNY/kg) | Sown Area (ha) |
|-----------|-----------------------------------|----------------------|----------------|
| Wheat     | 3862.87                           | 1.96                 | 33,560         |
| Rice      | 5665.59                           | 2.75                 | 3400           |
| Maize     | 4834.02                           | 1.84                 | 16,050         |

Based on the standard equivalent unit value, combined with the equivalent coefficients for the 11 ecosystem services corresponding to each land use type, the per-unit-area value of each individual ecological function for each land use type was calculated (Table 5).

$$VC_{k,s} = E_a \times e_{k,s} \quad (5)$$

where  $VC_{k,s}$  is the per-unit-area value of the  $s$ -th ecosystem service for the  $k$ -th land use type (CNY/(ha·yr));  $e_{k,s}$  is the dimensionless ecosystem service equivalent coefficient;  $k$  is the index of land use type; and  $s$  is the index of ecosystem service subcategory.

**Table 5.** Ecosystem service value coefficients per unit area for each ecosystem type in the Danjiangkou Reservoir Area (CNY/ha).

| Ecosystem Classification |                              | Cropland | Forestland | Grassland | Water Body | Barren Land | Construction Land |
|--------------------------|------------------------------|----------|------------|-----------|------------|-------------|-------------------|
| Provisioning services    | Food production              | 1212.23  | 442.11     | 541.94    | 1140.92    | 0.00        | 14.26             |
|                          | Raw material production      | 570.46   | 1012.57    | 798.65    | 328.01     | 0.00        | 42.78             |
|                          | Water provision              | 28.52    | 527.68     | 422.11    | 11,822.80  | 0.00        | 28.52             |
| Regulating services      | Gas regulation               | 955.52   | 3351.46    | 2809.52   | 1098.14    | 28.52       | 156.88            |
|                          | Climate regulation           | 513.41   | 10,025.85  | 7430.25   | 3265.89    | 0.00        | 142.62            |
|                          | Waste treatment              | 142.62   | 2838.04    | 2452.98   | 7915.14    | 142.62      | 422.11            |
|                          | Hydrological regulation      | 385.06   | 5005.79    | 5447.90   | 145,809.77 | 42.78       | 199.49            |
| Supporting services      | Soil conservation            | 1468.94  | 4078.79    | 3422.76   | 1326.32    | 28.52       | 185.40            |
|                          | Nutrient cycling maintenance | 171.14   | 313.75     | 256.71    | 99.83      | 0.00        | 14.26             |
|                          | Biodiversity maintenance     | 185.40   | 3707.99    | 3109.69   | 3636.69    | 28.52       | 171.14            |
| Cultural services        | Aesthetic landscape          | 85.57    | 1625.81    | 1369.11   | 2695.43    | 14.26       | 71.31             |

The total per-unit-area value of all 11 ecosystem services for each individual land use type was first aggregated, and then the regional total ecosystem service value was obtained by summing the products of the per-unit-area total value and the corresponding area of each land use type, thereby quantifying the regional ecological benefits under different land use configurations.

$$ESV = \sum_{k=1}^n A_k \times \sum_{s=1}^{11} VC_{k,s} \quad (6)$$

where  $ESV$  is the total ecosystem service value of the region (CNY);  $A_k$  is the area of the  $k$ -th land use type (ha); and  $n$  is the total number of land use types in the study area.

This study employed a one-factor-at-a-time sensitivity analysis approach to evaluate the impact of uncertainty in equivalent factor values on the  $ESV$  estimation results. Following previous studies [40,41], the land use type with the largest contribution to the total  $ESV$  was selected as the analytical target. Its per-unit-area value coefficients were adjusted by  $\pm 10\%$  and  $\pm 20\%$ , respectively, and the corresponding  $ESV$  change rates and sensitivity index ( $CS$ ) were calculated under each adjustment scenario to assess the robustness of the estimation results.

$$CS = \frac{(ESV_j - ESV_i) / ESV_i}{(VC_{jk} - VC_{ik}) / VC_{ik}} \quad (7)$$

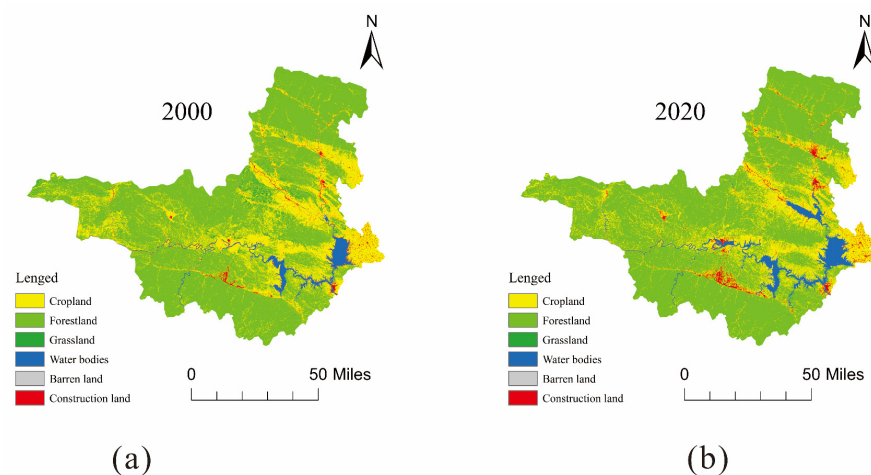
where  $ESV_i$  and  $ESV_j$  represent the total  $ESV$  before and after coefficient adjustment, respectively, and  $VC_{ik}$  and  $VC_{jk}$  denote the value coefficients before and after adjustment,

respectively. If  $|CS| < 1$ , the ESV is considered insensitive to the equivalent factor values, indicating robust results; if  $|CS| > 1$ , the ESV is sensitive to the equivalent factor values, suggesting relatively high uncertainty in the results.

## 4. Results

### 4.1. Spatiotemporal Characteristics of Land Use Change

The land use changes in the Danjiangkou Reservoir Area from 2000 to 2020 were analyzed. Spatially (Figure 2), forestland was the dominant land use type, accounting for over 65% of the total area, followed by cropland, which occupied more than 22%. In terms of temporal trends (Table 6), the area changes of various land use types exhibited pronounced differentiation. Forestland experienced the largest net increase, with a net gain of 764.16 km<sup>2</sup> over the two decades, an annual change rate of 0.33%, and an increment accounting for 4.27% of the total reservoir area. Water bodies showed the second largest expansion, with a net increase of 324.36 km<sup>2</sup> and an annual change rate of 3.33%, representing the most significant growth rate among all types. Conversely, cropland underwent the largest net decrease, with a net loss of 664.33 km<sup>2</sup>, an annual change rate of −3.72%, and a reduction equivalent to 4.27% of the total area. Grassland followed with a net loss of 547.08 km<sup>2</sup> and an annual change rate of −3.06%.



**Figure 2.** Land use maps of the Danjiangkou Reservoir Area in (a) 2000 and (b) 2020.

**Table 6.** Areas and dynamic degrees of each land use type in the study area from 2000 to 2020.

| Land Use Type     | Area in 2000 (km <sup>2</sup> ) | Area in 2020 (km <sup>2</sup> ) | Land Use Dynamic Degree (K/%) |
|-------------------|---------------------------------|---------------------------------|-------------------------------|
| Cropland          | 4715.46                         | 4051.13                         | −0.70                         |
| Forestland        | 11,728.99                       | 12,493.15                       | 0.33                          |
| Grassland         | 654.66                          | 107.58                          | −4.18                         |
| Water bodies      | 486.93                          | 811.29                          | 3.33                          |
| Barren land *     | 0.02                            | 0.16                            | 35.00                         |
| Construction land | 296.03                          | 418.78                          | 2.07                          |

Note: \* Barren land occupies a very small proportion of the total area; its dynamic degree is influenced by the area base effect and should therefore be interpreted with caution.

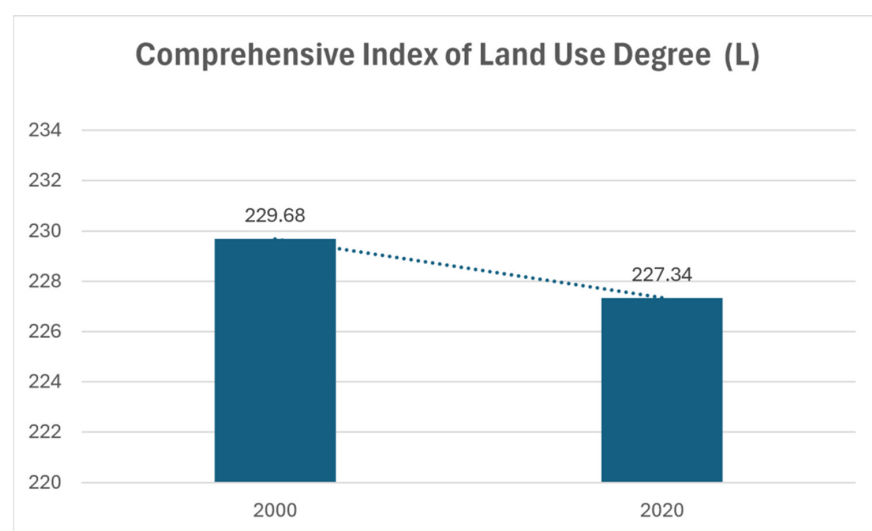
In terms of land use transfers (Table 7), during 2000–2020, the most substantial conversions from cropland were to forestland (1130.88 km<sup>2</sup>), water bodies (256.52 km<sup>2</sup>), and construction land (204 km<sup>2</sup>), accounting for 37.51%, 8.51%, and 6.77% of the total transferred area from cropland, respectively. Forestland was mainly converted to cropland (612.02 km<sup>2</sup>), accounting for 23.30% of its total transferred area. Grassland conversions were predominantly to cropland (268.59 km<sup>2</sup>) and forestland (306.33 km<sup>2</sup>), representing

8.91% and 10.16% of its total transferred area, respectively. Construction land was primarily transferred to cropland (56.43 km<sup>2</sup>) and water bodies (66.61 km<sup>2</sup>), accounting for 1.87% and 2.21% of its total transferred area, respectively. Transfers from water bodies and barren land to other land use types were relatively limited. The significant expansion of water bodies was directly associated with the Danjiangkou Dam heightening project. Following the implementation of the Middle Route of the South-to-North Water Diversion Project, the dam was constructed in phases on the basis of the initially completed scale in accordance with the original plan, with the crest elevation raised from 162 m to 176.6 m, the water storage level elevated from 157 m to 170 m, and the reservoir capacity increased to 29.05 billion m<sup>3</sup>. The majority of the net increase in water body area can be attributed to the elevated water level resulting from the dam heightening, with the remainder originating from policy-driven water body expansion through ecological cropland retirement and wetland restoration. This transition exemplifies the direct reshaping effect of major water conservancy projects on the land use pattern of the reservoir area.

**Table 7.** Land use transfer matrix of the Danjiangkou Reservoir Area from 2000 to 2020 (km<sup>2</sup>).

| Land Use Type     | Cropland | Forestland | Grassland | Water Bodies | Barren Land | Construction Land | Total in 2000 |
|-------------------|----------|------------|-----------|--------------|-------------|-------------------|---------------|
| Cropland          | 3109.40  | 1130.88    | 14.60     | 256.52       | 0.06        | 204.00            | 4715.46       |
| Forestland        | 612.02   | 11,046.79  | 23.31     | 8.48         | 0.04        | 38.35             | 11,728.99     |
| Grassland         | 268.59   | 306.33     | 69.28     | 5.46         | 0.06        | 4.94              | 654.66        |
| Water body        | 4.69     | 4.16       | 0.10      | 474.21       | 0.00        | 3.77              | 486.93        |
| Barren land       | 0.00     | 0.00       | 0.00      | 0.01         | 0.00        | 0.01              | 0.02          |
| Construction land | 56.43    | 4.99       | 0.29      | 66.61        | 0.00        | 167.71            | 296.03        |
| Total in 2020     | 4051.13  | 12,493.15  | 107.58    | 811.29       | 0.16        | 418.78            | 17,882.09     |

From 2000 to 2020, the comprehensive index of land use degree in the Danjiangkou Reservoir Area (Figure 3) decreased slightly from 229.68 to 227.34, representing a reduction of approximately 1.0%. Overall, the land use degree exhibited a modest declining trend, indicating a moderate alleviation of land use intensity and a slight attenuation of anthropogenic disturbance to the land system over the two decades. This trend is consistent with the observed land use transition pattern, characterized by the expansion of ecological land (e.g., forestland and water bodies) and the contraction of agricultural land (e.g., cropland and grassland), suggesting that the implementation of ecological protection and restoration policies has yielded preliminary positive effects.



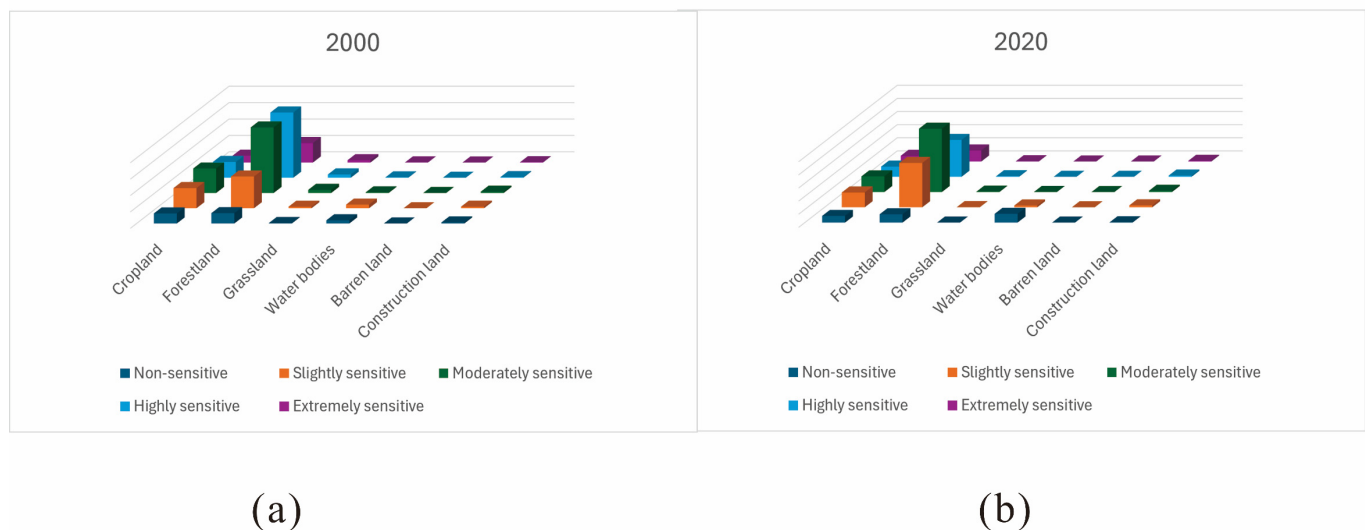
**Figure 3.** Changes in the comprehensive index of land use degree in the Danjiangkou Reservoir Area from 2000 to 2020.

#### 4.2. Coupling Relationship Between Land Use and Ecological Sensitivity

Based on the areal statistics of ecological sensitivity by land use type in the Danjiangkou Reservoir Area from 2000 to 2020 (Table 8) and the three-dimensional coupling distribution map (Figure 4), a systematic analysis of the coupling relationship between land use and ecological sensitivity was conducted from three perspectives: overall hierarchical changes, land use type composition, and area changes of each land use type across sensitivity levels.

**Table 8.** Areal statistics of ecological sensitivity by land use type in the Danjiangkou Reservoir Area for 2000 and 2020.

| Year | Type              | Non-Sensitive | Slightly Sensitive | Moderately Sensitive | Highly Sensitive | Extremely Sensitive |
|------|-------------------|---------------|--------------------|----------------------|------------------|---------------------|
| 2000 | Cropland          | 613.72        | 1231.28            | 1492.59              | 963.53           | 414.33              |
|      | Forestland        | 631.94        | 1935.24            | 3998.81              | 3976.24          | 1186.76             |
|      | Grassland         | 28.97         | 94.79              | 191.68               | 200.46           | 138.76              |
|      | Water body        | 196.93        | 221.05             | 40.24                | 22.61            | 6.09                |
|      | Barren land       | 0.00          | 0.00               | 0.01                 | 0.01             | 0.00                |
| 2000 | Construction land | 64.53         | 96.76              | 78.65                | 38.75            | 17.33               |
|      | Total             | 1536.09       | 3579.13            | 5801.99              | 5201.60          | 1763.28             |
| 2020 | Cropland          | 505.60        | 1131.12            | 1195.83              | 777.00           | 441.58              |
|      | Forestland        | 630.54        | 3380.45            | 4828.50              | 2812.79          | 840.86              |
|      | Grassland         | 1.67          | 12.62              | 30.63                | 45.30            | 17.36               |
|      | Water body        | 663.85        | 137.71             | 8.75                 | 0.90             | 0.08                |
|      | Barren land       | 0.00          | 0.00               | 0.02                 | 0.03             | 0.11                |
|      | Construction land | 19.40         | 149.83             | 99.74                | 93.88            | 55.92               |
|      | Total             | 1821.05       | 4811.73            | 6163.48              | 3729.91          | 1355.92             |



**Figure 4.** Three-dimensional coupling distribution of ecological sensitivity in the Danjiangkou Reservoir Area in (a) 2000 and (b) 2020.

In terms of overall hierarchical changes, the ecological sensitivity structure of the study area exhibited a general trend of “high-sensitivity contraction and low-to-moderate sensitivity expansion” from 2000 to 2020. The highly sensitive area decreased from 5201.60 km<sup>2</sup> to 3729.91 km<sup>2</sup>, a reduction of 1471.69 km<sup>2</sup>, while the extremely sensitive area declined from 1763.28 km<sup>2</sup> to 1355.92 km<sup>2</sup>, a decrease of 407.36 km<sup>2</sup>. Over the same period, the slightly sensitive area increased from 3579.13 km<sup>2</sup> to 4811.73 km<sup>2</sup> (+1232.60 km<sup>2</sup>), the moderately

sensitive area grew from 5801.99 km<sup>2</sup> to 6163.48 km<sup>2</sup> (+361.49 km<sup>2</sup>), and the non-sensitive area expanded from 1536.09 km<sup>2</sup> to 1821.05 km<sup>2</sup> (+284.96 km<sup>2</sup>). Overall, the sensitivity hierarchy shifted toward lower sensitivity levels.

In terms of land use type composition, for highly sensitive areas, forestland consistently dominated, contributing 3976.24 km<sup>2</sup> (76.44%) in 2000 and 2812.79 km<sup>2</sup> (75.41%) in 2020, with a slight decline in proportion, while cropland contribution increased from 963.53 km<sup>2</sup> (18.52%) to 777.00 km<sup>2</sup> (20.83%). For extremely sensitive areas, forestland proportion decreased from 67.30% (1186.76 km<sup>2</sup>) to 62.01% (840.86 km<sup>2</sup>), whereas cropland proportion increased from 23.50% (414.33 km<sup>2</sup>) to 32.57% (441.58 km<sup>2</sup>), indicating enhanced cropland contribution. For moderately sensitive areas, forestland proportion increased substantially from 68.92% (3998.81 km<sup>2</sup>) to 78.34% (4828.50 km<sup>2</sup>), while cropland proportion decreased from 25.73% (1492.59 km<sup>2</sup>) to 19.40% (1195.83 km<sup>2</sup>). For slightly sensitive areas, forestland rose from 54.07% (1935.24 km<sup>2</sup>) to 70.25% (3380.45 km<sup>2</sup>), cropland decreased from 34.40% (1231.28 km<sup>2</sup>) to 23.51% (1131.12 km<sup>2</sup>), while water bodies and construction land maintained proportions of approximately 4–6% and 2–3%, respectively. For non-sensitive areas, the composition changed markedly: in 2000, it was dominated by forestland (41.14%, 631.94 km<sup>2</sup>) and cropland (39.95%, 613.72 km<sup>2</sup>); by 2020, it had transformed into a mix of water bodies (36.45%, 663.85 km<sup>2</sup>), forestland (34.62%, 630.54 km<sup>2</sup>), and cropland (27.77%, 505.60 km<sup>2</sup>).

In terms of area changes of each land use type across sensitivity levels, for forestland, slightly sensitive area increased by 1445.21 km<sup>2</sup>, moderately sensitive by 829.69 km<sup>2</sup>, while highly sensitive decreased by 1163.45 km<sup>2</sup> and extremely sensitive by 345.90 km<sup>2</sup>, indicating a significant optimization of forestland sensitivity structure, with high-sensitivity attributes not intensifying alongside area expansion. For cropland, except for an increase of 27.25 km<sup>2</sup> in extremely sensitive areas, non-sensitive, slightly sensitive, moderately sensitive, and highly sensitive areas decreased by 108.12, 100.16, 296.76, and 186.53 km<sup>2</sup>, respectively, indicating that cropland reduction was concentrated in moderate and above sensitivity levels, but the increase in extremely sensitive areas meant it was not a “comprehensive improvement.” For water bodies, non-sensitive area increased substantially by 466.92 km<sup>2</sup>, while slightly, moderately, highly, and extremely sensitive areas decreased by 83.34, 31.49, 21.71, and 6.01 km<sup>2</sup>, respectively, resulting in a marked overall reduction in sensitivity. For grassland, all sensitivity levels decreased, directly linked to the substantial overall reduction in grassland area. For construction land, slightly, moderately, highly, and extremely sensitive areas increased, with only non-sensitive areas decreasing, indicating that construction land expansion was accompanied by rising ecological sensitivity. Barren land occupies a very small area and exerts no substantial influence on the regional sensitivity pattern.

#### 4.3. Dynamic Responses of Ecosystem Service Value

Analysis of spatiotemporal changes (Table 9) reveals that the spatiotemporal dynamics of ecosystem service value (ESV) were driven by regional land use transitions. From 2000 to 2020, the total ESV of the study area increased from CNY 51.92 billion to CNY 58.35 billion, indicating an overall upward trend in ecological provisioning capacity. Spatially, forestland served as the core ESV carrier across the region, with values of CNY 38.62 billion and CNY 41.14 billion in 2000 and 2020, respectively, accounting for more than 70% of the total regional ESV. Water bodies constituted the second largest source of ESV, with a substantial increase from CNY 8.72 billion to CNY 14.533 billion. In contrast, the ESV of cropland and grassland continued to decline, with cropland decreasing from CNY 2.70 billion to CNY 2.32 billion, and grassland dropping sharply from CNY 1.84 billion to CNY 0.30 billion. Construction land exhibited only a marginal positive service value, increasing from CNY 0.04 billion to CNY 0.06 billion over the two decades,

while barren land provided no ecosystem service output. The temporal comparison indicates that the ecological value gains from the expansion of forestland and water bodies fully offset the value losses caused by the decline of cropland and grassland, resulting in a steady increase in the overall regional ecosystem service stock.

**Table 9.** Ecosystem service value in the Danjiangkou Reservoir Area from 2000 to 2020.

| Land Use Type     | Year 2000         |                       | Year 2020         |                       |
|-------------------|-------------------|-----------------------|-------------------|-----------------------|
|                   | ESV (CNY Billion) | Contribution Rate (%) | ESV (CNY Billion) | Contribution Rate (%) |
| Cropland          | 2.70              | 5.20                  | 2.32              | 3.98                  |
| Forestland        | 38.62             | 74.38                 | 41.14             | 70.51                 |
| Grassland         | 1.84              | 3.54                  | 0.30              | 0.51                  |
| Water bodies      | 8.72              | 16.80                 | 14.53             | 24.90                 |
| Barren land       | 0.00              | 0.00                  | 0.00              | 0.00                  |
| Construction land | 0.04              | 0.08                  | 0.06              | 0.10                  |
| Total             | 51.92             | 100.00                | 58.35             | 100                   |

In terms of service function types (Table 10), regulating services constituted the dominant component of the regional ESV, representing the most critical ecological function of the Danjiangkou Reservoir Area. Among all ecosystem service types, hydrological regulation is the most strategically valuable core service function of the Danjiangkou Reservoir Area. From 2000 to 2020, the hydrological regulation value increased from CNY 13.52 billion to CNY 18.31 billion, a net increase of CNY 4.79 billion, accounting for 79.83% of the total increment across all service types—far exceeding the increases in climate regulation (+CNY 0.43 billion) and waste treatment (+CNY 0.34 billion). The leap in hydrological regulation function directly benefited from the substantial expansion of water bodies in the reservoir area—each 1 km<sup>2</sup> increase in water body area generated approximately CNY 0.015 billion in hydrological regulation value increment. This growth trajectory is highly consistent with the period of enhanced reservoir regulation capacity following the official water delivery of the Middle Route of the South-to-North Water Diversion Project, reflecting the irreplaceable role of the Danjiangkou Reservoir in the spatiotemporal redistribution of water resources at the basin scale. From the perspective of water resource management, the continued strengthening of hydrological regulation implies further enhancement of the reservoir area’s capacity to support downstream water supply reliability, serving as the fundamental guarantee of water security for the Middle Route of the South-to-North Water Diversion Project.

**Table 10.** Changes in ecosystem service values by function type in the Danjiangkou Reservoir Area from 2000 to 2020 (CNY billion).

| Ecosystem Classification |                              | ESV in 2000 | ESV in 2020 | Change |
|--------------------------|------------------------------|-------------|-------------|--------|
| Provisioning services    | Food production              | 1.18        | 1.14        | −0.04  |
|                          | Raw material production      | 1.53        | 1.53        | 0.00   |
|                          | Water provision              | 1.24        | 1.64        | 0.40   |
| Regulating services      | Gas regulation               | 4.62        | 4.70        | 0.08   |
|                          | Climate regulation           | 12.65       | 13.08       | 0.43   |
| Regulating services      | Waste treatment              | 3.95        | 4.29        | 0.34   |
|                          | Hydrological regulation      | 13.52       | 18.31       | 4.79   |
| Supporting services      | Soil conservation            | 5.77        | 5.84        | 0.07   |
|                          | Nutrient cycling maintenance | 0.47        | 0.47        | 0.00   |
|                          | Biodiversity maintenance     | 4.82        | 5.043       | 0.22   |
| Cultural services        | Aesthetic landscape          | 2.17        | 2.30        | 0.13   |

Water conservation is another core ecosystem service of reservoir-type water source areas, directly related to runoff recharge capacity and dry-season flow stability in the reservoir area. During the study period, forestland area increased by 764.16 km<sup>2</sup>, forest cover continued to rise, and vegetation interception and soil infiltration capacity were further enhanced. The expansion of forestland and water bodies formed a synergistic “conservation-regulation” effect: interception and infiltration of precipitation by upstream forests strengthened water supply, while water storage and regulation by downstream reservoir water bodies optimized runoff processes. Together, they supported the overall improvement of water conservation functions in the reservoir area, providing an ecological foundation for ensuring stable water supply to the Middle Route of the South-to-North Water Diversion Project.

Climate regulation, gas regulation, and waste treatment values also increased steadily, with forestland expansion serving as the primary driver of these regulating service gains. Supporting services ranked second in total value after regulating services, with soil conservation and biodiversity maintenance functions being enhanced alongside the expansion of forest cover. Within provisioning services, a pattern of internal differentiation was observed: food production value declined due to the reduction of cropland area, whereas raw material production value increased slightly. The increment in water provision resulting from water body expansion partially offset the loss in total provisioning service value caused by the decline in food production. Cultural services accounted for the smallest proportion of the total ESV, with aesthetic landscape value increasing modestly in association with forestland and water body expansion. Over the study period, the overall structure of regional ecosystem service functions did not undergo a fundamental shift. The functional pattern centered on regulating services became further accentuated, which is highly consistent with the core ecological orientation of the Danjiangkou Reservoir Area—namely, water conservation and soil and water retention.

To examine the dependence of ESV estimation results on equivalent factor values, this study employed a one-factor-at-a-time sensitivity analysis approach, perturbing the equivalent value coefficients of forestland and water bodies by  $\pm 10\%$  and  $\pm 20\%$ , and calculating the ESV change rate and sensitivity index (CS) under each scenario. Forestland and water bodies, which together contributed over 90% of the total ESV (91.19% in 2000 and 95.41% in 2020), were selected as the analytical targets, sufficiently representing the dominant structure of regional ESV. Given the low contribution rates of grassland and cropland, even extreme perturbations of  $\pm 20\%$  in their equivalent coefficients would affect total ESV by less than  $\pm 1\%$ , with no substantive impact on overall conclusions; thus, they were not included in the primary perturbation analysis.

The results (Table 11) indicate that under all perturbation scenarios, the sensitivity index (CS) remained below 1, suggesting that the ESV estimates are insensitive to variations in equivalent factor values and that the study conclusions are robust. From the temporal perspective, for forestland under  $\pm 20\%$  perturbation in 2000, total ESV changed by approximately  $\pm 14.88\%$  in the same direction, with a CS value of 0.74; whereas in 2020, under the same perturbation, the total ESV change was only  $\pm 3.36\%$ , with the CS value declining to 0.17—a reduction of 77%. This reflects a significant decrease in the sensitivity of forestland ESV to equivalent coefficient variations over time. From the land use type perspective, in 2020, under  $\pm 20\%$  perturbation, total ESV changes for forestland and water bodies were approximately  $\pm 14.10\%$  and  $\pm 4.98\%$ , respectively, with corresponding CS values of 0.71 and 0.25—the sensitivity of water bodies being less than one-third that of forestland. Although the CS value for water bodies (0.25) is substantially lower than that for forestland (0.71), and its perturbation effect on total regional ESV is relatively limited, the Danjiangkou Reservoir Area—as a strategically important water source region with water

conservation as its core function—warrants attention to the potential impacts of water body area changes on hydrological regulation services. Future research should prioritize water bodies as a key direction for monitoring and assessment.

**Table 11.** Sensitivity analysis of ecosystem service value to equivalent coefficients in the Danjiangkou Reservoir Area.

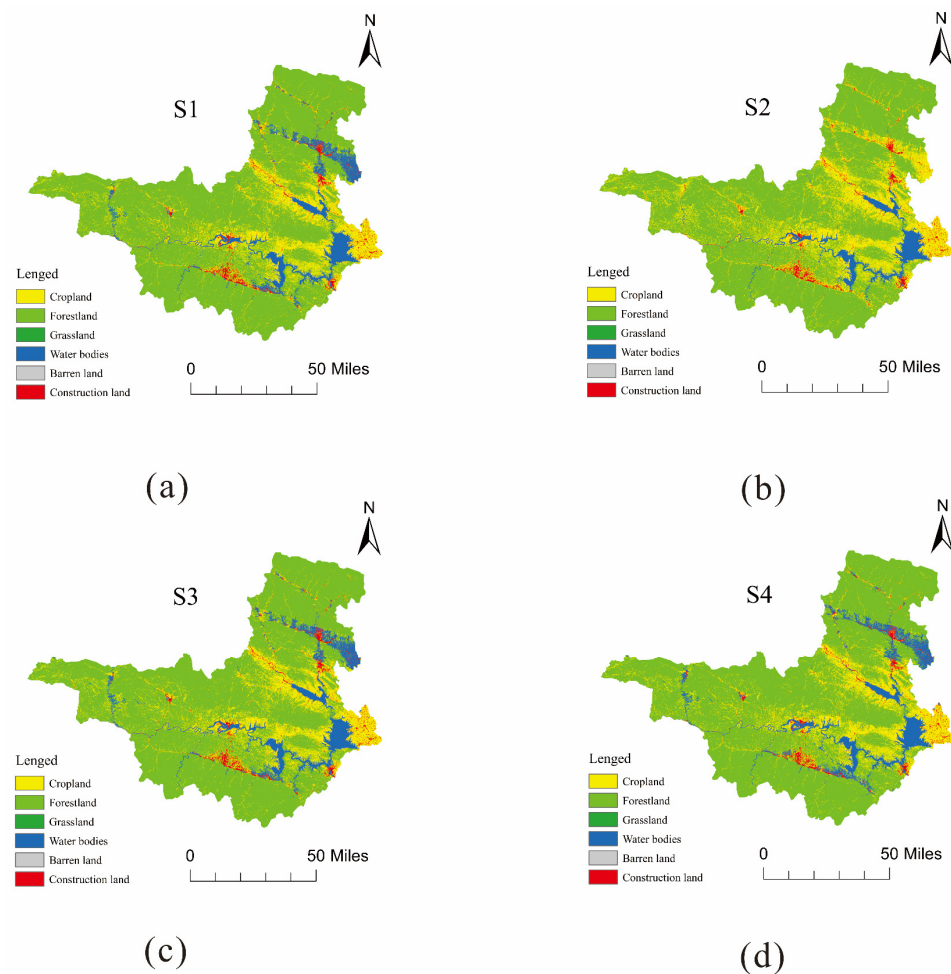
| Year | Land Use Type | Perturbation Range | Adjusted Total ESV<br>(CNY Billion) | ESV Change Rate (%) | Sensitivity Index (CS) |
|------|---------------|--------------------|-------------------------------------|---------------------|------------------------|
| 2000 | Forestland    | +10%               | 55.79                               | 7.44                | 0.74                   |
|      |               | +20%               | 59.65                               | 14.88               | 0.74                   |
|      |               | −10%               | 48.06                               | −7.44               | 0.74                   |
|      |               | −20%               | 44.20                               | −14.88              | 0.74                   |
|      | Water bodies  | +10%               | 52.80                               | 1.68                | 0.17                   |
|      |               | +20%               | 53.67                               | 3.36                | 0.17                   |
|      |               | −10%               | 51.05                               | −1.68               | 0.17                   |
|      |               | −20%               | 50.18                               | −3.36               | 0.17                   |
| 2020 | Forestland    | +10%               | 62.47                               | 7.05                | 0.71                   |
|      |               | +20%               | 66.58                               | 14.10               | 0.71                   |
|      |               | −10%               | 54.24                               | −7.05               | 0.71                   |
|      |               | −20%               | 50.13                               | −14.10              | 0.71                   |
|      | Water bodies  | +10%               | 59.81                               | 2.49                | 0.25                   |
|      |               | +20%               | 61.26                               | 4.98                | 0.25                   |
|      |               | −10%               | 56.90                               | −2.49               | 0.25                   |
|      |               | −20%               | 55.45                               | −4.98               | 0.25                   |

#### 4.4. Prediction of Future Land Use and Ecological Effects

##### 4.4.1. Spatial Patterns of Land Use Under Multiple Scenarios

To validate the model performance, the FLUS model was applied to simulate the land use pattern in the reservoir area for 2020, using the land use data of 2000 and various driving factors, and the simulated results were compared with the actual land use data of 2020. The validation results showed that the overall accuracy (OA) of the FLUS simulation was 0.9201, the Kappa coefficient was 0.8211, and the FoM (Figures of Merit) value was 0.5804, all exceeding the acceptable thresholds and confirming the model's applicability for simulating future land use patterns in the reservoir area. Using the 2020 land use data as the initial baseline, and considering the different development needs and objectives of the Danjiangkou Reservoir Area, the spatial patterns of land use in 2050 were simulated under four scenarios—natural development, cropland protection, ecological protection, and ecological–cropland synergy (Figure 5). Under the natural development scenario (S1), cropland and grassland decreased by 1033.29 km<sup>2</sup> and 55.64 km<sup>2</sup>, respectively, while forestland, water bodies, and construction land increased by 575.79 km<sup>2</sup>, 437.70 km<sup>2</sup>, and 15.50 km<sup>2</sup>, respectively. Barren land showed negligible changes, indicating that, without policy intervention, forestland and water bodies would expand significantly, leading to substantial encroachment on cropland resources. Under the cropland protection scenario (S2), cropland and construction land increased by 115.31 km<sup>2</sup> and 17.06 km<sup>2</sup>, respectively, while forestland, grassland, and water bodies decreased by 49.27 km<sup>2</sup>, 55.46 km<sup>2</sup>, and 23.72 km<sup>2</sup>, respectively, with little change in barren land. This reflects that the achievement of cropland protection objectives would come at the cost of certain ecological land losses. Under the ecological protection scenario (S3), forestland, water bodies, and construction land increased by 622.62 km<sup>2</sup>, 479.50 km<sup>2</sup>, and 17.06 km<sup>2</sup>, respectively, while cropland and grassland decreased by 1072.98 km<sup>2</sup> and 42.28 km<sup>2</sup>, respectively. Barren land showed little variation, indicating that ecological land would be restored and protected to the

greatest extent under this scenario. Under the ecological–cropland synergy scenario (S4), cropland and grassland decreased by 1118.19 km<sup>2</sup> and 55.46 km<sup>2</sup>, respectively, while forestland, water bodies, and construction land increased by 622.62 km<sup>2</sup>, 562.75 km<sup>2</sup>, and 7.79 km<sup>2</sup>, respectively, with negligible changes in barren land. Compared with the ecological protection scenario (S3), S4 exhibited even greater expansion of water bodies (+562.75 km<sup>2</sup>), which resulted in more severe cropland loss (−1118.19 km<sup>2</sup>). This indicates that, under the current simulation settings, the encroachment effect of ecological land protection on cropland resources remains pronounced, and effective synergy between the two objectives has not been achieved.



**Figure 5.** Simulated spatial distribution of land use under multiple scenarios in 2050: (a) natural development scenario (S1); (b) cropland protection scenario (S2); (c) ecological protection scenario (S3); (d) ecological–cropland synergy scenario (S4).

#### 4.4.2. Differentiated Responses of Ecosystem Service Value Under Multiple Scenarios

Based on the land use simulation results under each scenario, the ecosystem service value (ESV) of the study area in 2050 was estimated using the ESV equivalent factor method for the four scenarios (Table 12).

At the aggregate level, the total ESV under scenarios S1, S2, S3, and S4 was CNY 67.35 billion, 57.47 billion, 68.02 billion, and 57.71 billion, respectively, representing changes of +15.44%, −1.50%, +16.59%, and −1.08% relative to the baseline year (2020: CNY 58.35 billion). Among the four scenarios, S3 yielded the highest total ESV, with a 16.59% increase over the baseline, indicating that the positive ecological benefits of conservation policies were most pronounced. S1 ranked second (+15.44%), reflecting that unconstrained natural expansion of forestland and water bodies can also generate substantial ESV gains; however,

the associated encroachment on cropland resources was not accounted for in this scenario. S2 yielded the lowest total ESV (−1.50%), reflecting the ecological value losses caused by ecological land displacement under the cropland protection orientation. S4 (−1.08%) had a total ESV slightly higher than S2, but incurred the most severe cropland loss (−1118.19 km<sup>2</sup>), indicating that effective synergy between ESV enhancement and cropland preservation was not achieved—the marginal ecological gains came at the cost of substantial cropland resources. Examining the ESV composition by land use type in 2020, forestland (CNY 41.14 billion, contribution rate 70.50%) and water bodies (CNY 14.53 billion, contribution rate 24.91%) were the dominant contributors to total ESV, together accounting for 95.41% of the total. This explains why the expansion of forestland and water bodies under S1 and S3 significantly boosted total ESV, and conversely, why the reduction of these land use types under S2 led to a notable decline in total ESV.

**Table 12.** Comparison of total ecosystem service value in the Danjiangkou Reservoir Area in 2050 under different scenarios (CNY billion).

| Land Use Type     | Natural Development Scenario (S1) | Cropland Protection Scenario (S2) | Ecological Protection Scenario (S3) | Ecological–Cropland Synergy Scenario (S4) |
|-------------------|-----------------------------------|-----------------------------------|-------------------------------------|-------------------------------------------|
| Cropland          | 1.73                              | 2.37                              | 1.70                                | 1.67                                      |
| Forestland        | 43.04                             | 40.83                             | 43.04                               | 41.14                                     |
| Grassland         | 0.15                              | 0.15                              | 0.18                                | 0.30                                      |
| Water bodies      | 22.37                             | 14.06                             | 23.04                               | 14.53                                     |
| Barren land       | 0.00                              | 0.00                              | 0.00                                | 0.00                                      |
| Construction land | 0.06                              | 0.06                              | 0.06                                | 0.06                                      |
| Total             | 67.35                             | 57.47                             | 68.02                               | 57.71                                     |

At the individual service function level (Table 13), the primary contributors to ESV increases under S1 and S3 were hydrological regulation and climate regulation, which together accounted for over 80% of the total increments, directly corresponding to the substantial expansion of forestland and water bodies under these two scenarios. Under S2, hydrological regulation exhibited the largest decline due to the reduction in water body area, making it the main factor dragging down total ESV. S4 exhibited pronounced inter-service trade-offs: although its total ESV (CNY 57.71 billion) was slightly higher than that of S2 (CNY 57.47 billion), marked differentiation was observed at the individual service level—regulating services such as hydrological regulation (CNY 18.26 billion) and climate regulation (CNY 13.03 billion) outperformed those in S2, but food production (CNY 1.01 billion) was the lowest among all four scenarios, and provisioning services including raw material production (CNY 1.47 billion) and water provision (CNY 1.63 billion) also reached their lowest levels. This indicates that the regulating service gains from water body expansion under S4 came at the cost of further losses in provisioning services—ecological and cropland protection remained unsynergized in S4, manifesting instead as inter-service trade-offs.

**Table 13.** Individual ecosystem service values in the Danjiangkou Reservoir Area in 2050 under different scenarios (CNY billion).

| Ecosystem Classification |                         | Natural Development Scenario (S1) | Cropland Protection Scenario (S2) | Ecological Protection Scenario (S3) | Ecological–Cropland Synergy Scenario (S4) |
|--------------------------|-------------------------|-----------------------------------|-----------------------------------|-------------------------------------|-------------------------------------------|
| Provisioning services    | Food production         | 1.09                              | 1.14                              | 1.09                                | 1.01                                      |
|                          | Raw material production | 1.54                              | 1.52                              | 1.54                                | 1.47                                      |
|                          | Water provision         | 2.18                              | 1.60                              | 2.22                                | 1.63                                      |

Table 13. *Cont.*

| Ecosystem Classification |                              | Natural Development Scenario (S1) | Cropland Protection Scenario (S2) | Ecological Protection Scenario (S3) | Ecological–Cropland Synergy Scenario (S4) |
|--------------------------|------------------------------|-----------------------------------|-----------------------------------|-------------------------------------|-------------------------------------------|
| Regulating services      | Gas regulation               | 4.83                              | 4.66                              | 4.83                                | 4.59                                      |
|                          | Climate regulation           | 13.71                             | 12.95                             | 13.73                               | 13.03                                     |
|                          | Waste treatment              | 4.77                              | 4.23                              | 4.80                                | 4.27                                      |
|                          | Hydrological regulation      | 24.91                             | 17.85                             | 25.45                               | 18.26                                     |
| Supporting services      | Soil conservation            | 5.97                              | 5.80                              | 5.97                                | 5.68                                      |
|                          | Nutrient cycling maintenance | 0.48                              | 0.47                              | 0.48                                | 0.45                                      |
|                          | Biodiversity maintenance     | 5.38                              | 4.98                              | 5.40                                | 5.02                                      |
| Cultural services        | Aesthetic landscape          | 2.50                              | 2.27                              | 2.51                                | 2.29                                      |

A comprehensive comparison shows that S3 performed best in terms of ecological outcomes; however, its substantial reduction in cropland area may impose pressure on regional food supply. S2 safeguarded cropland security but at the expense of key ecological functions such as hydrological regulation and climate regulation. S4 attempted to balance ecological protection and cropland preservation, yet the simulated results showed limited ecological gains and the most severe cropland loss, with the most pronounced inter-service trade-offs.

#### 4.4.3. Land Use Spatial Conflicts and Ecological–Food Security Trade-Off Mechanisms Under Multiple Scenarios

Combining the results presented in Sections 4.4.1 and 4.4.2, a significant trade-off relationship between food security and ecological security is evident in the Danjiangkou Reservoir Area. Different land use control scenarios exhibit distinct development advantages and disadvantages, and a single development objective tends to induce resource depletion and functional degradation in the other dimension.

The natural development scenario (S1) is characterized by “ecological improvement at the cost of cropland loss.” Under this scenario, forestland and water bodies expanded substantially, increasing the regional ESV by 15.44% relative to the 2020 baseline, with significant enhancements in core ecological functions such as hydrological regulation and climate regulation. However, unconstrained natural evolution led to a drastic reduction of 1,033.29 km<sup>2</sup> in cropland—one of the largest cropland losses among the four scenarios. The inundation caused by reservoir impoundment and the rigid encroachment of ecological land expansion on cropland considerably weakened the regional food supply capacity, failing to achieve synergistic development of food security and ecological security.

The cropland protection scenario (S2) effectively safeguards regional food security, yet entails notable ecological costs. By strictly controlling the conversion of cropland to non-agricultural uses, this scenario achieved a net increase of 115.31 km<sup>2</sup> in cropland, thereby stabilizing the regional food production base. However, the maintenance of cropland area came at the expense of ecological spaces occupied by forestland, grassland, and water bodies, resulting in a 1.50% decline in ESV relative to the baseline—the only scenario with negative ecological benefits among the four. Notably, the reduction in water bodies directly weakened the core hydrological regulation function of the reservoir area, highlighting the ecological shortcomings inherent in a single-minded cropland protection approach.

The ecological protection scenario (S3) yields the highest ecological benefits, but also presents the most acute pressure on food security. Under this scenario, forestland and water bodies increased by 622.62 km<sup>2</sup> and 479.50 km<sup>2</sup>, respectively, continuously optimizing the ecological land configuration, with an ESV increase of 16.59%—the highest among all scenarios—that significantly enhanced core ecological functions such as water conservation

and soil retention. However, intensive ecological restoration caused a sharp reduction of 1,072.98 km<sup>2</sup> in cropland—an even greater loss than under the natural development scenario—severely constraining regional grain production capacity. The ecological priority model thus exhibits a notable deficiency in food security guarantee.

The ecological–cropland synergy scenario (S4) attempted to balance both ecological protection and cropland preservation, yet the simulated results failed to achieve effective synergy. Under this scenario, water body area increased by 562.75 km<sup>2</sup>—the largest expansion among the four scenarios—with ESV declining by a modest 1.08% relative to the baseline, slightly outperforming S2. However, cropland loss reached 1118.19 km<sup>2</sup>, the most severe among all scenarios, and provisioning services including food production (CNY 1.01 billion) dropped to their lowest levels. This conflicting outcome indicates that the rigid encroachment of water body expansion on cropland space far exceeded expectations, and the ecological gains were insufficient to offset the losses of cropland resources. The synergy goal between ecological protection and cropland preservation was not achieved under the current simulation settings.

The above results indicate that the core challenge facing the land use system of the Danjiangkou Reservoir Area is not a simple two-dimensional “ecology–food” trade-off, but rather a three-dimensional synergy dilemma involving “ecological protection–food security–water resource guarantee.” From the water resource guarantee perspective, the expansion of water bodies under S3 and S4 substantially enhanced hydrological regulation and water conservation functions, contributing to the water supply security of the Middle Route of the South-to-North Water Diversion Project. However, overemphasizing water body expansion—particularly under S4 (+562.75 km<sup>2</sup>)—inevitably comes at the cost of scarce cropland resources, thereby undermining regional food self-sufficiency. Conversely, S2 stabilized food production through cropland protection, but the reduction in water body area (−23.72 km<sup>2</sup>) led to a decrease of CNY 7.61 billion in hydrological regulation value compared with S3, potentially weakening the reservoir area’s water storage and regulation capacity, which could affect water supply reliability during extreme dry years. This three-dimensional trade-off framework reveals a fundamental constraint: cropland space and water body expansion space in the Danjiangkou Reservoir Area heavily overlap in low-altitude, flat terrain zones, resulting in rigid competition among the three development objectives—where gains in one dimension necessarily entail losses in another. Future land use policies for the reservoir area must seek a multi-dimensional optimal solution that balances water conservation function, food production capacity, and ecological value enhancement, rather than prioritizing any single objective at the expense of others.

A comprehensive comparison confirms a pronounced trade-off characterized by mutual exclusivity between food security and ecological security in the land use system of the Danjiangkou Reservoir Area. Although S3 yields the highest ecological benefits, it incurs the most severe cropland losses. S2 maintains the cropland red line but leads to notable ecological function degradation. S4 attempts to balance the two, yet the simulated outcomes tend toward a “water-priority” ecological intensification pathway, with the synergy goal remaining unachieved. None of the single-oriented models—natural development, cropland prioritization, or ecological prioritization—can independently support regional sustainable development. Future efforts should introduce more rigid cropland–ecological space control thresholds in scenario design and explore multi-objective optimization approaches that reconcile the bottom line of food security with the pattern of ecological security.

## 5. Discussion

### 5.1. Coupled Evolution Patterns of Historical Land Use, Ecological Sensitivity, and Ecosystem Service Value

By integrating land use, ecological sensitivity, and ecosystem service value data for the Danjiangkou Reservoir Area from 2000 to 2020, combined with multi-scenario simulations using the FLUS model, this study systematically revealed the ecological coupling responses of land use transition and the ecological-food security trade-off mechanisms in the reservoir area. Previous studies have largely focused on single spatial pattern analyses or individual ecological function evaluations [42,43], lacking a systematic chain analysis linking “pattern-sensitivity-service-future scenarios.” This study bridges current evolution, ecological responses, and future projections, refines the differentiated ecological effects of various land use types, and quantifies the trade-offs between ecological security and food security under multiple scenarios, thereby addressing the research gap concerning long-term synergistic development mechanisms in the reservoir area.

During the study period, land use in the Danjiangkou Reservoir Area exhibited a clear ecological transition, with continuously weakening human disturbance and significant ecological governance outcomes. The land use structure of the reservoir area has long been dominated by forestland and cropland, together accounting for over 90% of the total area, consistent with previous findings and reflecting a stable forest-agriculture dominated landscape [44,45]. Over time, the changes among different land use types showed marked differentiation: forestland and water bodies continued to expand, while cropland and grassland contracted substantially. Among these, water bodies exhibited the fastest expansion rate (3.33%/a), followed by grassland with the most rapid contraction rate (−4.18%/a). Cropland was the primary transferring-out type, with 1130.88 km<sup>2</sup>, 256.52 km<sup>2</sup>, and 204.00 km<sup>2</sup> converted to forestland, water bodies, and construction land, respectively, during 2000–2020—resulting from the combined effects of ecological cropland retirement, reservoir expansion, and urbanization, consistent with the overall trend of ecological restoration in water source areas [21]. Among all land-use conversions, the transfer from cropland to forestland was the largest, accounting for 37.51% of the total converted area. The driving mechanisms underlying this transition can be decomposed into three aspects. First, policy-driven artificial afforestation under the Grain-for-Green Program (conversion of cropland to forest). Second, ecological migration and population relocation driving natural succession. Third, agricultural structure adjustment driving voluntary cropland abandonment/conversion. These three driving factors overlap and interact across different spatial units, collectively revealing the intertwined effects of policy intervention, population migration, and market economy forces on land-use change in the reservoir area. The comprehensive index of land use degree declined modestly from 229.68 to 227.34, a reduction of approximately 1.0%, indicating a sustained reduction in regional development intensity and weakening anthropogenic disturbance, confirming the positive role of ecological regulation in optimizing land use patterns.

Land use type was identified as the dominant factor driving the restructuring of ecological sensitivity patterns in the reservoir area, with distinct sensitivity differences among land use types. Forestland dominated the spatial pattern of highly sensitive areas across the entire region [46]. Notably, from 2000 to 2020, the area of highly sensitive zones decreased from 5201.60 km<sup>2</sup> to 3729.91 km<sup>2</sup>, and the extremely sensitive area declined from 1763.28 km<sup>2</sup> to 1355.92 km<sup>2</sup>, indicating an overall optimization trend in the sensitivity hierarchy characterized by “high-sensitivity contraction and low-to-moderate sensitivity expansion.” However, the proportion of highly sensitive forestland consistently remained above 75%, reinforcing the ecological barrier while simultaneously exacerbating the risk of spatial concentration of highly sensitive ecological spaces. Cropland exhibited divergent

trends across sensitivity levels: areas from non-sensitive to highly sensitive all decreased, but extremely sensitive cropland increased by 27.25 km<sup>2</sup>, indicating that cropland reduction did not constitute a “comprehensive improvement” but rather involved localized sensitivity intensification. The non-sensitive area of water bodies increased substantially by 466.92 km<sup>2</sup>, reflecting a marked overall reduction in sensitivity. Grassland experienced decreases across all sensitivity levels, directly linked to the substantial overall reduction in grassland area. Construction land expansion was accompanied by increases in slightly to extremely sensitive areas, reflecting the positive stress effect of artificial surface expansion on ecological sensitivity. Overall, changes in ecological sensitivity in the reservoir area were highly dependent on land use transitions. The expansion of ecological land effectively reduced regional ecological vulnerability; however, the concentration of highly sensitive forestland and the rising sensitivity associated with construction land expansion require targeted management and control.

The ecological transition of land use effectively promoted the enhancement of ecosystem service values, establishing a stable ecological system centered on regulating services [47]. From 2000 to 2020, the total ESV of the reservoir area increased from CNY 51.92 billion to CNY 58.35 billion, with the contribution rates of forestland and cropland changing from 74.38% and 5.20% to 70.51% and 3.98%, respectively, while the contribution rate of water bodies jumped substantially from 16.80% to 24.90%. The gains from forestland and water bodies fully offset the value losses caused by cropland and grassland degradation. Forestland consistently served as the core ecological carrier, while the contribution of water bodies increased substantially, becoming the primary driver of ESV growth and highlighting the supportive role of water body expansion in water conservation functions. In terms of functional structure, regulating services dominated, with hydrological regulation showing the most prominent increase—growing by CNY 4.79 billion from 2000 to 2020, accounting for 79.83% of the total increment across all service types—directly linked to water body expansion and enhanced water conservation capacity, aligning closely with the region’s core ecological orientation. Climate regulation and gas regulation also increased steadily, by CNY 0.43 billion and CNY 0.08 billion, respectively, mainly benefiting from forest vegetation restoration. Among provisioning services, only food production declined slightly by CNY 0.04 billion in response to cropland contraction, while other functions remained stable or increased; water provision increased significantly by CNY 0.40 billion alongside water body expansion. The overall ecological functional structure remained stable with continuously improving service capacity, demonstrating that ecologically oriented land use transitions can effectively enhance regional ecosystem service levels [28].

## 5.2. Trade-Off Mechanisms Between Ecological Security and Food Security Under Multi-Scenario Projections

The multi-scenario simulation results indicate that under the natural development scenario (S1), forestland and water bodies increased by 575.79 km<sup>2</sup> and 437.70 km<sup>2</sup>, respectively, driving a 15.44% increase (CNY +9.01 billion) in ecosystem service value relative to the baseline year (CNY 58.35 billion), with continuous optimization of ecological functions. However, substantial cropland loss (−1033.29 km<sup>2</sup>) led to a marked decline in food supply capacity, posing food security risks. Under the cropland protection scenario (S2), through strict control of cropland conversion to non-agricultural uses, cropland area increased by 115.31 km<sup>2</sup> (+2.85%), effectively stabilizing the regional food production base. However, this came at the cost of encroaching on ecological spaces of forestland (−49.27 km<sup>2</sup>), water bodies (−23.72 km<sup>2</sup>), and grassland (−55.46 km<sup>2</sup>), resulting in a 1.50% decline (CNY −0.87 billion) in regional ESV relative to the baseline—the only scenario with negative ESV growth among the four—highlighting the ecological limitations of a single-minded cropland protection approach. The reduction in water body area resulted in a decrease

of CNY 7.61 billion in hydrological regulation value compared with scenario S3. Based on the average annual water transfer volume of the Middle Route of the South-to-North Water Diversion Project (approximately 9.50 billion m<sup>3</sup>), this reduction may affect approximately 450 million m<sup>3</sup> of regulated storage capacity, which could put pressure on water supply reliability during extreme dry years. Under the ecological protection scenario (S3), forestland and water bodies increased by 622.62 km<sup>2</sup> and 479.50 km<sup>2</sup>, respectively, yielding the highest ecological benefits with an ESV increase of 16.59% (CNY +9.68 billion) and significant enhancements in water conservation and soil retention functions. However, cropland loss was the most severe (−1072.98 km<sup>2</sup>, accounting for 26.48% of the 2020 cropland area). Based on the average grain yield in the Danjiangkou Reservoir area (approximately 4800 kg/hm<sup>2</sup>), the reduction in cropland area corresponds to an estimated annual grain production loss of about  $5.15 \times 10^8$  kg. Calculated against the national per capita grain consumption (approximately 130 kg/year), this loss is equivalent to the annual food demand of approximately 3.96 million people, presenting prominent food security pressures. The ecological–cropland synergy scenario (S4), although designed to balance both ecological protection and cropland preservation, resulted in the largest expansion of water bodies (+562.75 km<sup>2</sup>) and the most severe cropland loss (−1118.19 km<sup>2</sup>, accounting for 27.60% of the 2020 cropland area) in actual simulations. Provisioning services, including food production (CNY 1.01 billion), dropped to their lowest levels among the four scenarios, and although regulating services showed gains, they were insufficient to offset the losses of cropland resources. The synergy goal was not achieved under the current model settings.

From the perspective of land use spatial conflicts, the encroachment of forestland and water body expansion on cropland under S1 and S3 primarily manifested as a unidirectional substitution of “ecological land encroaching on cropland.” S2 exhibited the reverse substitution of “cropland preservation encroaching on water bodies and forestland.” S4, as the theoretically most balanced scheme, resulted in greater cropland loss than S3, reflecting that the driving force for water body expansion in the current model settings was overly strong, causing ecological protection objectives to override cropland preservation constraints at the scenario implementation level. However, model parameter settings are merely the proximate technical driver of the S4 synergy failure; the root cause lies in the high spatial overlap between water area expansion and high-quality cropland retention in the low-elevation gentle terrain of the Danjiangkou Reservoir area. High-quality cropland in the reservoir area is concentrated along the Danjiang River and in river valley flat areas (elevation < 200 m, slope < 6°), while the spatial orientation of reservoir impoundment and water area expansion also points to the same topographical zone. Under this spatial constraint, every incremental expansion of water area inevitably encroaches upon the rigid boundaries of high-quality cropland, rendering the “dual conservation” goals a zero-sum game in terms of spatial implementation. In the S4 scenario, the magnitude of water area expansion was set as the largest among the four scenarios (+562.75 km<sup>2</sup>), and consequently, the marginal cropland loss from spatial expansion was naturally the most severe (−1118.19 km<sup>2</sup>). Therefore, the synergy failure in S4 cannot be attributed to model parameter specifications alone; rather, it is an inevitable reflection of the inherent spatial competition for land resources within the reservoir area, as manifested in scenario simulations. Without introducing rigid spatial control thresholds at the spatial planning level in the future, merely adjusting model parameters cannot fundamentally resolve this conflict.

Overall, a pronounced ecological–food security trade-off characterized by mutual exclusivity exists in the land use system of the reservoir area. Although S3 yields the highest ecological benefits, it incurs the most severe cropland losses. S2 maintains the cropland red line but leads to notable ecological function degradation. S4 attempts to balance the two, yet the simulated outcomes tend toward a “water-priority” ecological intensification pathway,

with the synergy goal remaining unachieved. These results are generally consistent with the scenario simulations conducted by Li et al. [48], who employed the CLUE-S model for the Danjiangkou Reservoir Area and designed three scenarios—ecological security, economic development, and integrated development—further confirming the inherent difficulty of achieving synergistic development between ecological security and food security in the reservoir area.

In summary, the ecological transition of land use in the Danjiangkou Reservoir Area from 2000 to 2020 has yielded notable achievements, with continuous optimization of ecological patterns and steady improvement in ecosystem service capacity, demonstrating the effectiveness of ecological management policies. This study further confirms that, against the backdrop of ecological improvement in the reservoir area, the trade-off between ecological protection and food security has become increasingly prominent, constituting a core constraint on regional coordinated development. Of particular concern is that the S4 simulation results show that even under the presupposed goal of “synergistic protection,” the rigid encroachment effect of water body expansion on cropland space still resulted in a pronounced “ecological priority” bias in the actual outcomes, reflecting that the priority setting of ecological objectives in the current land system simulation may override cropland protection objectives—an important model mechanism underlying the synergy failure. Looking ahead, the reservoir area must optimize cropland layout and improve utilization efficiency while safeguarding the core ecological function of water conservation. Rigid cropland-ecological space control thresholds should be introduced in scenario design, and multi-objective optimization approaches that reconcile the bottom line of food security with the pattern of ecological security should be explored. Additionally, attention should be paid to scale differences and spatial location choices in multi-scenario policy implementation. Zoning-based management should be adopted to reduce the concentrated encroachment of ecological land expansion on prime cropland, thereby promoting sustainable and coordinated development of ecological, agricultural, and urban spaces in the reservoir area.

### *5.3. Uncertainties, Limitations, and Future Research Directions*

This study has certain limitations that warrant further investigation.

First, the ecosystem service value assessment method itself entails inherent uncertainties. The equivalent factor method employed in this study, based on nationally derived per-unit-area value equivalents with regional adjustments, has been widely applied in previous studies [38]; however, it does not fully capture the localized ecological processes and geographical heterogeneity of the Danjiangkou Reservoir Area. The effects of intra-class variations in vegetation type, stand structure, and soil texture on ecosystem service supply capacity are not adequately represented in the equivalent factor framework. Furthermore, the valuation focused solely on positive service provision, without incorporating ecological costs such as carbon emissions and habitat fragmentation associated with land use change into the comprehensive accounting, which may lead to an overestimation of net ecological benefits. Second, model simulation accuracy is constrained by data resolution and the selection of driving factors. The training of the FLUS model relies on historical land use data and natural and socioeconomic driving factors. Moreover, the future scenario settings did not fully account for the potential impacts of climate change on hydrological regimes and vegetation growth, nor did they incorporate policy perturbation variables such as the operation of major water conservancy projects, which may introduce deviations from the actual development trajectory of the reservoir area. Third, the spatial mechanism underlying the synergy failure in the S4 scenario warrants further in-depth analysis. This study finds that the rigid spatial encroachment of water onto cropland under the ecological–cropland

synergy scenario is substantially greater than anticipated. From a modeling perspective, this phenomenon may be related to the neighborhood weight assignment for water area suitability in the FLUS model. However, the deeper cause lies in the high spatial overlap between cropland and water area expansion in the low-elevation gentle terrain of the reservoir area, while the current model framework has not yet effectively embedded rigid spatial control constraints. Future work should conduct parameter sensitivity experiments and scenario-based comparative simulations to identify the critical parameter ranges that lead to synergy failure, and explore technical pathways for embedding spatial control thresholds into the model, thereby offering a methodological pathway for achieving the “dual conservation” synergy goal.

In response to the above limitations, future research directions may include the following:

First, advancing the development of a localized ESV accounting system. By incorporating field observation data from the Danjiangkou Reservoir Area—such as evapotranspiration, runoff coefficients, and soil organic carbon content—the value coefficients for individual services of different land use types can be revised to establish a more regionally tailored parameter system for ecosystem service valuation. Where conditions permit, process-based models such as InVEST and SWAT could be introduced to spatially refine the characterization of supply capacity and spatial distribution of key services such as water conservation and soil retention. Second, coupling multi-source data within an integrated multi-model framework. The FLUS model could be coupled with climate change scenarios (e.g., CMIP6) and reservoir operation models to simulate long-term evolutionary trajectories of land use and ecosystem services under different climate-policy combination scenarios, thereby enhancing the policy guidance value of multi-scenario projections. Third, deepening the spatial mechanism analysis of ecological-food security trade-offs. Rigid ecological-cropland spatial control thresholds could be introduced into scenario design, and the assignment of neighborhood factors and conversion costs could be optimized through multiple sets of parameter sensitivity experiments to identify the critical parameter ranges leading to S4 synergy failure, providing model-based support for “parametric regulation” of future land use policies in the reservoir area. Furthermore, multi-objective optimization algorithms could be incorporated into the simulation framework to directly solve for the Pareto frontier between maximizing ecological value and minimizing cropland loss, offering quantitative decision support for spatial management policy formulation. Fourth, attending to the socioeconomic drivers and equity implications of land use transition. Land use change not only reflects the implementation effects of ecological policies but is also closely intertwined with socioeconomic processes such as population migration, industrial transformation, and adjustments in household livelihood strategies. Future research could incorporate farmer behavioral decision-making, land transfer policies, and ecological compensation mechanisms into the analytical framework to evaluate policy implementation costs and social equity under different scenarios, thereby providing more actionable policy recommendations for integrated management of the reservoir area.

## 6. Conclusions

(1) From 2000 to 2020, land use in the Danjiangkou Reservoir Area exhibited a pronounced ecological transition. Forestland and water bodies continued to expand, with net increases of 764.16 km<sup>2</sup> and 324.36 km<sup>2</sup>, respectively, while cropland and grassland contracted substantially, with net decreases of 664.33 km<sup>2</sup> and 547.08 km<sup>2</sup>, respectively. Cropland was mainly transferred to forestland (1130.88 km<sup>2</sup>), water bodies (256.52 km<sup>2</sup>), and construction land (204.00 km<sup>2</sup>). The comprehensive index of land use degree decreased from 229.68 to 227.34, indicating a sustained reduction in regional development intensity and initial positive effects of ecological management.

(2) The hierarchical structure of ecological sensitivity was optimized, yet localized risks persisted, while ecosystem service value (ESV) steadily increased and was dominated by regulating services. The highly sensitive area decreased from 5201.60 km<sup>2</sup> to 3729.91 km<sup>2</sup>, reflecting a trend of “high-sensitivity contraction and low-to-moderate sensitivity expansion”; however, highly sensitive forestland consistently accounted for over 75%, and extremely sensitive cropland increased by 27.25 km<sup>2</sup>. Total ESV increased from CNY 51.92 billion to CNY 58.35 billion (+12.38%), with hydrological regulation contributing 79.83% of the total increment. Sensitivity analysis indicated CS values of 0.71 for forestland and 0.25 for water bodies, both below 1, confirming the robustness and reliability of the conclusions.

(3) Multi-scenario simulations revealed a rigid ecological-food security trade-off, indicating that single-objective or unbalanced pathways are unsustainable. Under the natural development scenario (S1), ESV increased by 15.44% at the cost of 1033.29 km<sup>2</sup> of cropland loss. Under the cropland protection scenario (S2), ESV decreased by 1.51%, the only scenario with negative ecological growth. Under the ecological protection scenario (S3), ESV increased by 16.59%, but cropland loss reached 1072.98 km<sup>2</sup>, exerting the greatest pressure on food security. Notably, the ecological–cropland synergy scenario (S4) not only fails to achieve a “dual conservation” synergy but also exposes deeper structural imbalances. First, in terms of total ecological value, S4 exhibits the largest water area expansion among the four scenarios (+562.75 km<sup>2</sup>) yet suffers the most severe cropland loss (−1118.19 km<sup>2</sup>). Its total ESV (CNY 57.71 billion) is only marginally higher than that of S2 (CNY 57.47 billion) and far below those of S1 (CNY 67.35 billion) and S3 (CNY 68.02 billion), indicating that large-scale water expansion yields disproportionately low ecological returns. Second, in terms of functional trade-offs, although S4 outperforms S2 in hydrological regulation (CNY 18.26 billion) and climate regulation (CNY 13.03 billion), its provisioning services—food production (CNY 1.01 billion) and raw material production (CNY 1.47 billion)—are the lowest among all scenarios. This implies that the ecological gains in S4 are not “incremental win-wins” but rather “substitutive gains” achieved by entirely displacing cropland’s provisioning function. Third, with respect to underlying mechanisms, the synergy failure originates from the high spatial overlap between water area expansion and high-quality cropland retention in the low-elevation gentle terrain of the Danjiangkou Reservoir area, combined with the absence of rigid spatial control thresholds in the simulation. This results in a unidirectional and potentially irreversible encroachment of water upon cropland. In essence, S4 degenerates into an unbalanced “water-area-first” pathway; its so-called “synergy” remains confined to the target-setting stage and fails in both spatial implementation and functional trade-off coordination. These results highlight that a “dual conservation” strategy relying solely on quantitative indicator regulation while neglecting spatial compatibility control is unlikely to achieve its intended goals in this region.

(4) Based on the above results, we propose the following management recommendations. First, clarify the core objective orientation—taking “ensuring the core function of water conservation” as the primary goal, and treating the maintenance and enhancement of hydrological regulation functions as an insurmountable ecological bottom line. Any development model oriented towards a single objective cannot independently support regional sustainable development. Second, implement zoned differentiated management—steep slope areas (>25°) should prioritize the conversion of cropland to forest (Grain-for-Green), gentle slope areas (<6°) should prioritize the preservation of high-quality cropland, and low-to-medium mountain and hilly areas (6–25°) should adopt a staggered layout of forest and cropland. Third, introduce rigid spatial control thresholds—clearly delineate rigid boundaries for cropland protection and ecological conservation redlines in territorial spatial

planning, and set allowable intervals for changes in the area of each land-use type, so as to avoid intensifying conflicts between the dual goals of cropland and ecological protection due to spatial overlap. Fourth, establish a collaborative monitoring and early-warning mechanism—conduct regular assessments and early warnings of key indicators related to land-use change, food security, and water resource security. Fifth, explore multi-objective optimization pathways—introduce multi-objective optimization methods to identify optimal trade-off solutions between enhancing ecological value and minimizing cropland loss.

This study confirms the positive effects of the ecological transition of land use in the Danjiangkou Reservoir Area on water body expansion, hydrological regulation enhancement, and water conservation capacity improvement, providing ecological evidence for water quantity security assurance in the water source area of the Middle Route of the South-to-North Water Diversion Project. Future land use management in the reservoir area should prioritize “ensuring the core function of water conservation” as the primary objective, while maintaining the baseline of food security and ensuring both water quality stability and water quantity security in the reservoir area.

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