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Calculation of Connectivity Between Surface and Underground Three-Dimensional Water Systems in the Luan River Basin

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Abstract

While water conservancy projects continuously enhance flood control and resource allocation capabilities, the adverse impacts on basin systems, particularly the structural disruption of surface water–groundwater continuity, have become increasingly pronounced. Therefore, establishing quantitative assessment of water system connectivity as a critical foundation for optimizing spatial water distribution, maintaining ecohydrological equilibrium, and enhancing flood–drought regulation efficacy is important. Focusing on the regulated reaches of the Panjiakou, Daheiting, and Taolinkou reservoirs in the Luan River Basin, this study established and integrated a three-dimensional assessment framework that synthesizes hydrological processes, hydraulic structural effects, and human activities as three fundamental drivers, and employed the Analytic Hierarchy Process (AHP) to develop a quantitative connectivity evaluation system. Results indicate that water conservancy projects significantly altered basin connectivity: surface water connectivity decreased by 0.40, while groundwater connectivity experienced a minor reduction (0.25) primarily through reservoir seepage. Consequently, the integrated surface–groundwater system declined by 0.39. Critically, project scale governs surface connectivity attenuation intensity, which substantially exceeds impacts on groundwater systems. The comprehensive assessment system developed in this study provides theoretical and methodological support for diagnosing river connectivity, formulating ecological restoration strategies, and protecting basin ecosystems.

Keywords: water system connectivity; three-dimensional water systems; connectivity indicators; Luan River Basin

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1. Introduction

Water system connectivity is a fundamental attribute of watershed systems, playing a vital role in maintaining ecological integrity, enabling material transport, and facilitating energy cycling within riverine environments [1,2]. However, increasing anthropogenic pressures, including infrastructure development and land-use changes, have disrupted these systems, leading to diminished connectivity, increased flood frequency, water scarcity, and reduced environmental carrying capacity. Consequently, quantifying the impacts of human interventions, particularly engineering projects, on water system connectivity has

emerged as a critical scientific imperative for guiding environmental protection, ecosystem restoration, and sustainable water resource management [3,4].

While early conceptualizations of connectivity originated from "landscape connectivity" theory in the 1980s, subsequent extensions to water systems established "river connectivity" as a framework encompassing spatial and functional interrelationships within riverine landscapes. Research has since expanded across hydrological, ecological, and restoration-oriented dimensions.

Kondolf et al. [5] established horizontal floodplain connectivity's ecological role in nutrient–sediment exchange, while Renard et al. [6] advanced vertical connectivity through groundwater–surface runoff studies. Wang et al. [7] elucidated hydrological cycle-driven connectivity mechanisms, and Deng et al. [8] identified implementation challenges for river–lake projects in southern China. Subsequent theoretical developments include Tan et al.'s framework [9] and Yang et al.'s classification system [10]. Recent quantitative advances feature Abdi Dehkordi et al.'s multidimensional indicators [11], Bu et al.'s component-based indices [12], and specialized applications by Xu et al. (urban structural-functional metrics) [13] and Huang et al. (composite structural–hydrodynamic indices) [14], Li et al. (hydro-connectivity eco-environmental assessments) [15], and Tian et al. (wetland connectivity thresholds via water environment responses) [16]. Further innovations encompass Dou et al.'s system dynamics modeling [17], Herzog et al.'s hydrologic connectivity stress-test models [18], Dong et al.'s fractal geometry quantification [19], Zhang et al.'s hydrodynamic water quality scenario assessments [20], and Hu et al.'s isotope–spatial network fusion [21].

Despite these contributions, prevailing methodologies, including graph theory, hydrodynamic modeling, and multi-index evaluations, exhibit persistent limitations: graph theory analysis is restricted to small-scale, structurally simple networks; hydrodynamic approaches require prohibitively precise parameters; and composite methods often remain qualitative. Critically, existing frameworks predominantly address surface water systems while neglecting groundwater connectivity quantification, thereby failing to capture the continuous surface–subsurface interactions that define holistic watershed behavior.

This study methodology significantly advances existing theoretical frameworks and indicator systems. First, by integrating hydrological processes, hydraulic infrastructure effects, and human activities drivers, we achieve multi-process fusion that expands the dimensional scope of connectivity assessments. Second, treating the watershed as an integrated system, we couple quantitative analyses of surface water connectivity and groundwater connectivity to enable comprehensive three-dimensional connectivity quantification. Finally, through spatial division strategies, this study overcomes the spatial constraints of graph theory and parametric limitations of hydrodynamic methods. This unified three-dimensional approach not only transcends methodological fragmentation in the current literature but also enables robust quantification across river basins.

Therefore, constructing a three-dimensional connectivity evaluation method that integrates surface water and groundwater systems can not only make up for the shortcomings of existing research, but also provide a more comprehensive and reliable scientific basis for water resource management and ecological protection. It has important theoretical innovation value and practical guidance significance.

2. Methodology and Data

2.1. Research Framework

To comprehensively assess surface water–groundwater connectivity within a three-dimensional framework, this study establishes an assessment system with six key indicators categorized into three drivers: hydrological processes (Water Flow Momentum, Penetration

Force, Single-width Traffic), hydraulic structural effects (Degree of Fragmentation, Influence Radius), and human activities (Consumptive Water Use). This integrated approach enables quantitative characterization of comprehensive water connectivity through coupled multi-factor mechanisms.

As these factors impact rivers differently across dimensions, their combined effect varies. This study employs the Analytic Hierarchy Process (AHP) to construct an integrated assessment system.

The method involves (1) dividing the river into sections; (2) calculating a connectivity index per section by normalizing each indicator and applying weights (determined via expert opinion and river conditions) to reflect their relative importance; (3) obtaining the section connectivity index by weighting the normalized indicators; (4) error analysis of weights; (5) assessment of overall connectivity of the watershed.

The overall procedure to calculate the connectivity is described as shown in Figure 1.

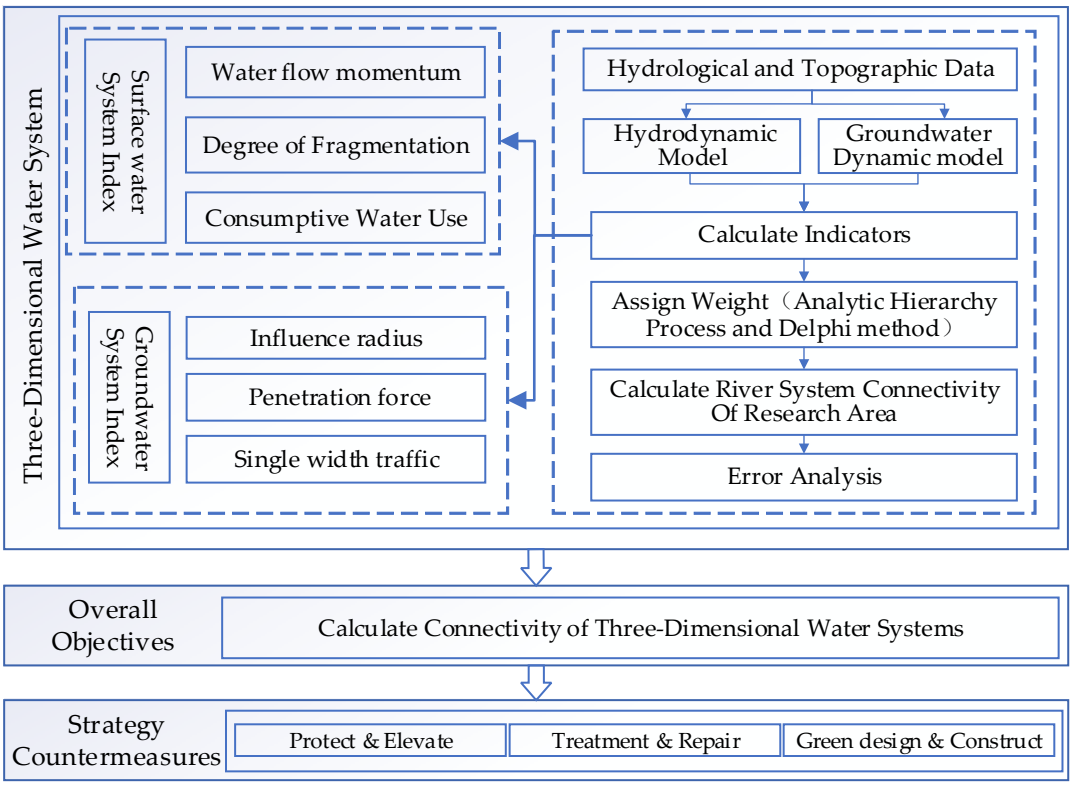


Figure 1. Calculation of Three-Dimensional Water Systems Framework.

2.2. Study Area and Data Types Sources

2.2.1. Study Area

The Luan River, a significant waterway in the northeast of the North China Plain, is well known for its numerous tributaries and distinctive landforms. Flowing from north to south, the river traverses a terrain that is high in the north and lower in the south, primarily consisting of plateaus, mountains, and plains. The river spans 888 km in length with a basin area of 44,750 square kilometers, covering three provinces: Inner Mongolia Autonomous Region, Hebei Province, and Liaoning Province [22]. Among the rivers in northern China, the Luan River is famous for its substantial water volume, providing a crucial source for industrial and agricultural production, as well as residential use within the basin. The precipitation pattern in the Luan River Basin exhibits significant temporal and spatial variability, largely influenced by the monsoon climate, which causes rainfall to be predominantly concentrated in the summer. The geographical context of the

study area is depicted in the Figure 2 (Partial Schematic Diagram of Luan River Basin).To enhance calculation accuracy and efficiency in model-based assessments, the research area was partitioned according to the spatial distribution of three key hydraulic control points—Panjiakou, Daheiting, and Taolinkou reservoirs—considering their dominant influence within the representative Luan River sub-basin, thereby ensuring modeling precision through localized reservoir impact quantification while enabling computational feasibility and maintaining structural relevance to actual water management divisions.

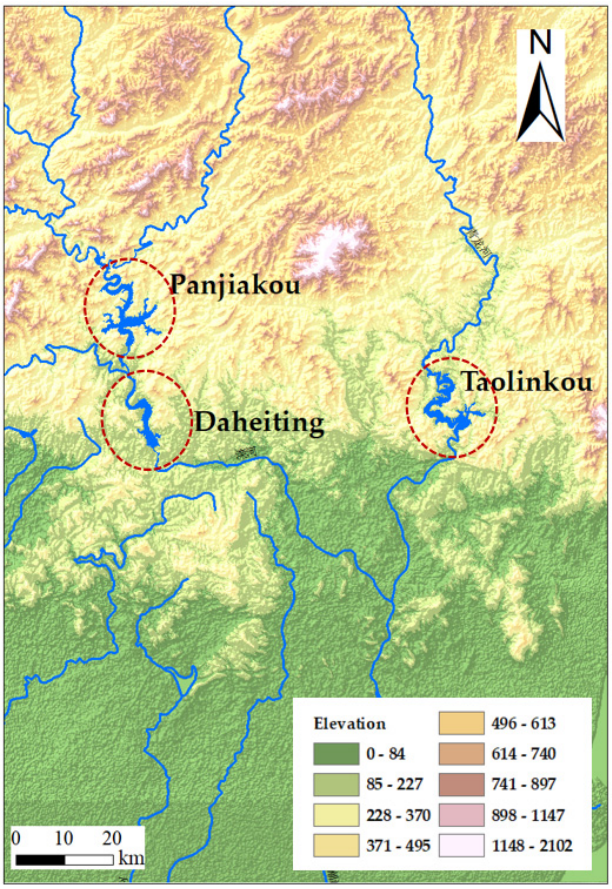


Figure 2. Partial Schematic Diagram of Luan River Basin.

The Luan River Basin has three important reservoirs, each with distinct characteristics and functions [23]: (1) The Panjiakou Reservoir, located at the junction of Qianxi County in Tangshan City, Hebei Province and Kuancheng Manchu Autonomous County in Chengde City has a main dam crest elevation of 230.50 m, and a normal water level of 222.00 m. It has a maximum capacity of 2.93 billion cubic meters, and controls a drainage area of 33,700 square kilometers, which constitutes 75.3% of the basin's total area. It is a key project for water resources development in the Luan River and a critical component of the Luan River to Tianjin water supply project. (2) The Daheiting Reservoir manages a watershed area of nearly 35,000 square kilometers, accounting for 79% of the basin's total area. The watershed between Panjiakou and Daheiting Reservoir covers approximately 1400 square kilometers, with a total storage capacity of 337 million cubic meters. The dam crest elevation is 138.80 m, the normal water level is 133.00 m, and the maximum dam height reaches 52.8 m. This reservoir is classified as a Type II annual regulating reservoir. (3) The Taolinkou Reservoir, located on the Qinglong River near Sandaohe Village, Qinglong Manchu Autonomous County, Qinhuangdao City serves as a large-scale water conservancy hub project. It controls a watershed area of 5060 square kilometers, with a normal water

level of 143.4 m, a dam crest elevation of 146.5 m, a maximum dam height of 74.5 m, and a total storage capacity of 859 million cubic meters. In summary, the Luan River Basin and its reservoirs play a crucial role in regional water resource management and economic development. However, the increasingly severe water resource conflicts and the impact of human activities underscore conflict and the urgent need for sustainable development and utilization of the Luan River's water resources.

2.2.2. Data Types and Sources

This study integrates multisource geospatial and hydrological data: Reservoir boundary coordinates information for Panjiakou, Daheiting, and Taolinkou reservoirs were delineated using Land Surface Viewer (LSV) within a longitude–latitude coordinate system to construct unstructured computational meshes. According to this, characteristic data of rivers is obtained in the study area, including river network morphology, river length, cross-section, riverbed elevation, and longitudinal changes. Bathymetric data originated from a 30 m resolution Digital Elevation Model (DEM) acquired on 1 June 2001, via the Geospatial Data Cloud platform (www.gscloud.cn (accessed on 1 June 2001)), which was interpolated into each reservoir's mesh file. Hydrological inputs were derived from 43-year observed records (1959–2002) of the Luan River Basin reservoir group, yielding average inflow discharges of 2063 m^3/s (Panjiakou), 1535 m^3/s (Daheiting), and 1852 m^3/s (Taolinkou). For hydrodynamic model calibration, observed water-level data were sourced from operational records of the Luan River Diversion Project Administration Bureau and Taolinkou Reservoir Administration Bureau.

2.3. Construction of Assessment System

2.3.1. Surface Water Connectivity Indicators

Based on the hydrodynamics principle of water system connectivity, three representative indicators are found from the three drivers of hydrological process, hydraulic structure effect and human activities: Water Flow Momentum (WFM) represents the flow potential energy of water; Degree of Fragmentation (DOF) quantifies the impact of hydraulic structures on river connectivity by measuring the extent to which these structures disrupt natural flow pathways. Meanwhile, Consumptive Water Use (USE) reflects the magnitude of human influence on the water system by indicating how much water is extracted and utilized, thereby affecting overall connectivity.

Water Flow Momentum (WFM): The speed of water flow is influenced by the slope of the riverbed. Together with the cross-sectional area, shape, and slope of the riverbed, these factors determine the river's flow capacity. Water flow momentum can be expressed using the following formula:

$$E_P = \frac{\rho_W g \sum \frac{h_i \left(h_{iup} - h_{idown}\right) D_i}{L_i}}{2A} \quad (1)$$

where ρ_W is the density of water (kg/m^3); g is the acceleration due to gravity (m/s^2); hi is the average depth of water above and below the selected cross-section (m); h_{iup} and h_{idown} are the water depths in front of and behind the dam, respectively (m). D_i is the water surface area of the river section (m^2); L_i is the length of the river section (m); A is the area of the region (m^2).

Degree of Fragmentation (DOF): The fragmentation indicator quantifies the impact of hydraulic structures on the connectivity of longitudinal physical, chemical, and ecological

processes in rivers. It accounts for alterations in natural flow patterns, nutrient transport, and migration of aquatic organisms. The DOF is calculated using the following formula:

$$DOF_j = 100 - \frac{\left|lgd_{bloc} - lgd_j\right|}{lgdrf} \times 100 \quad (2)$$

where DOF_j is the fragmentation index; d_{bloc} is the runoff volume at the location where hydraulic structures are obstructed (m); d_j is the average runoff of natural river channels (m^3); d_{rf} is the runoff variation factor; and 10 is taken as the research object.

Consumptive Water Use (USE): In the process of exploring the impact of water resource utilization on river ecology, the water resource utilization consumption rate has been identified as a matric for measuring the effectiveness of river blockage [24]. This metric indicates the proportion of water consumed relative to the total available water. Water consumption mainly includes domestic use, agricultural irrigation, and industrial production water. The formula for calculating the water resource utilization consumption rate is as follows:

$$P_{USE} = \frac{Q_{before} - Q_{after}}{Q_{before}} \quad (3)$$

where P_{USE} is the utilization rate of water resources consumption; Q_{after} is the average runoff after the obstruction position of hydraulic structures (m^3); Q_{before} is the average runoff before the obstruction position of hydraulic structures (m^3).

2.3.2. Groundwater Connectivity Indicators

When selecting groundwater connectivity indicators, it is important to consider the significant influence of hydraulic structures, particularly reservoirs, on groundwater dynamics. Given that the study area primarily includes three reservoirs, three representative indicators are found from the two drivers of hydrological process and hydraulic structure effect: the influence radius can be used to represent the spatial extent of hydraulic engineering impacts on surrounding groundwater. The penetration force reflects the groundwater's flow capacity, while single-width flow rate serves as an indicator of the groundwater's water-carrying capacity to a certain extent.

Influence of Radius: It is mainly used to evaluate the impact of large-scale water conservancy projects on post-construction surrounding groundwater. It is calculated as

$$R_0 = H\sqrt{\frac{K\left[1 - exp\left(\frac{-6Wt}{\mu H}\right)\right]}{2W}} \quad (4)$$

where R_0 is the radius of influence (m); H is the groundwater level (m); K is the permeability coefficient (m/d); W is the intensity of rainfall replenishment (d^{-1}); μ is the gravity water-supply degree; t is the storage time (d), with a long-term storage period of 365 days.

Penetration Force: When water infiltrates through the pore spaces of soil, it encounters resistance due to friction with surrounding soil particles. This interaction leads to energy dissipation and a corresponding loss in hydraulic head. The drag force exerted by the flowing water on the soil particles within a unit volume of soil is referred to as the penetration force (also known as seepage force or permeable force). It can be calculated using the following formula:

$$J = \gamma_w i \quad (5)$$

where $i = \frac{\Delta h}{L}$, J is the permeability; i is the infiltration gradient; γ_w is the bulk density of water, taken as 9.8 KN/m^3; L is the length of the river section.

Single-width Traffic: Diving is considered a stable motion, and in the case of uniform distribution in time and space, the single-width flow rate refers to the seepage rate per unit width, represented by the symbol q.

$$q = K\frac{h_1^2 - h_2^2}{2L} \tag{6}$$

where q is the single width traffic; K is the permeability coefficient (m/d); L is the length of the river section (m); h_1 and h_2 represent higher and lower groundwater levels (m).

2.4. Comprehensive Assessment Method

To comprehensively evaluate the connectivity of water systems, this article introduces a three-dimensional connectivity analysis method, which can capture the horizontal, vertical, and vertical connections between surface and groundwater hydrological elements.

The evaluation system calculation comprises four key steps: (1) basic data preparation, (2) hydraulic model construction to acquire indicator data, (3) indicator calculation and normalization, and (4) weighted calculation of surface–groundwater connectivity per region. This structured approach ensures systematic quantification of water system connectivity.

2.4.1. Model Construction

The connectivity index cannot be calculated solely based on hydrological and topographic data. Hydraulic modeling is required to calculate flow discharge and water depth within the study area. Furthermore, simulations of scenarios without hydraulic structures are necessary to quantify the impacts of water conservancy projects on hydrological characteristics (water depth and flow rate).

Flow discharge and water level of river channels within the study area were simulated using MIKE21. As a control group, select a section of river upstream of hydraulic structures that has not been affected by engineering construction to obtain the hydrodynamic characteristics. The numerical model is based on the two-dimensional Saint-Venant equations and employs the finite volume method. The governing equations are formulated as follows [25]:

$$\frac{\partial h}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} = hS \tag{7}$$

$$\begin{aligned}\frac{\partial hu}{\partial t} + \frac{\partial hu^2}{\partial x} + \frac{\partial huv}{\partial y} = fvh - gh\frac{\partial \eta}{\partial x} - \frac{h}{\rho_0}\frac{\partial p_a}{\partial x} - \frac{gh^2}{2\rho_0}\frac{\partial \rho}{\partial x} + \frac{\tau_{sx}}{\rho_0} - \frac{\tau_{bx}}{\rho_0} - \frac{1}{\rho_0}\left(\frac{\partial s_{xx}}{\partial x} + \frac{\partial s_{xy}}{\partial y}\right) + \\ \frac{\partial}{\partial x}(hT_{xx}) + \frac{\partial}{\partial x}(hT_{xy}) + hu_sS\end{aligned} \tag{8}$$

In the formula, t is time (s); η is the water level (m); h is the static water depth (m); uv is the component of the flow velocity in the x and y directions (m/s); ρ_0 is the density of water (kg/m^3) and f is the Coriolis force parameter; fu and fv are the accelerations caused by the Earth's rotation (m/s^2), respectively; T_{xx}, T_{xy}, T_{yx}, and T_{yy} are the horizontal viscous stress terms (Pa); S is the source and sink term.

This study uses the MODFLOW module in the Groundwater Modeling System (GMS) to calculate the groundwater level [26]. For non-homogeneous, anisotropic, three-dimensional spatial structures, and unstable groundwater flow systems, the governing equation is

$$\mu_s\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(k_x\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z\frac{\partial h}{\partial z}\right) + W \tag{9}$$

where μ_s is the water storage rate water level (m^{-1}); k_x, k_y, k_z are the permeability coefficients in x, y, and z directions, respectively (m/d), t is time (d), W is source, and sink term (d^{-1}). The initial conditions are as follows.

$$h(x, y, z, t) = h_0(x, y, z)(x, y, z) \in \Omega, t = 0 \quad (10)$$

where h_0 (x, y, z) is the known water level distribution; Ω is the simulation area of the model.

2.4.2. Weighted Calculation

Due to the different data units used for each indicator calculation, dimensionless processing is required before weighting the indicators. In this project, normalization methods are used to standardize the data. The calculation method is as follows [27]:

$$x_{ij}^{*} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} \quad (11)$$

where x^*_{ij} is the dimensionless standard value; x_{ij} is the value of the ith evaluated object on the jth indicator.

Use the Delphi method to determine the weights of indicators within each dimension [28,29]. This qualitative method based on expert knowledge adopts an iterative "rating feedback adjustment" cycle to allocate weights. In order to couple the connectivity of surface water and groundwater, the permeability coefficient of the groundwater model serves as a bridge. Calculate overall connectivity based on the percentage of water volume. The main objective of this study is to explore changes in watershed scale connectivity. Evaluate the surface water connectivity of the entire region by calculating a weighted sum based on the percentage of water surface area of each reservoir.

3. Results and Analysis

3.1. Calculate of Surface Water Connectivity

3.1.1. Calculation of Surface Water Indicators

In order to calculate the connectivity after the construction project, a control group needs to be set up. Therefore, a section of the river upstream of the three reservoirs that is not affected by engineering construction is selected to simulate a natural river channel, which facilitates the calculation of connectivity changes. The simulation of the hydrodynamic model is shown in Figure 3.

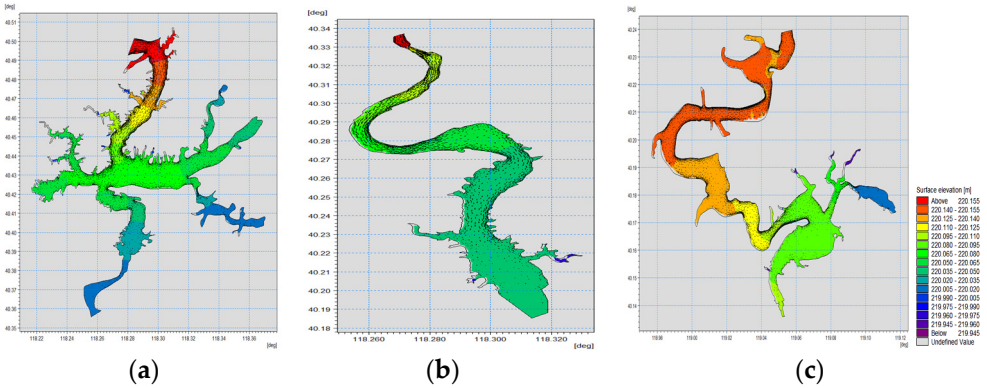


Figure 3. Surface Elevation of Reservoirs. (**a**) Panjiakou Reservoir; (**b**) Daheiting Reservoir; (**c**) Taolinkou Reservoir.

According to the operation results of the model, the water depths in front and behind the dams of the three reservoirs and the natural river channels, as well as the corresponding flow velocities at the detection points, are shown in Table 1.

Table 1. Hydraulic Model Simulation Results.

Study Area	H_up (m)	H_down (m)	Q_up (m/s)	Q_down (m/s)
Panjiakou	84.16	22.38	0.130	0.050
Daheiting	27.99	2.63	0.021	0.016
Taolinkou	49.89	21.99	0.260	0.150
Nature Channel	5.51	6.68	0.220	0.210

Water Flow Momentum: The water flow momentum has a direct impact on the river-blocking effect: the greater the momentum, the more pronounced the blocking. The flow potentials of Panjiakou, Daheiting, and Taolinkou are 0.70 kJ, 0.05 kJ, and 0.10 kJ, respectively, all greater than natural river channels.

Degree of Fragmentation: The higher the fragmentation index, the better the connectivity of the river. The dam area of Panjiakou, Daheiting, and Taolinkou reservoirs is 113,616.68 square meters, 41,422.68 square meters, and 20,220.88 square meters, respectively, while the dam area of the natural river channel is only 1064 square meters. According to the calculation formula, the fragmentation indices of Panjiakou, Daheiting, and Taolinkou are 62.53, 64.40, and 25.11, respectively. The fragmentation index of natural river channels is 91.52, which is significantly different from three reservoirs. Taolinkou has weaker connectivity than Panjiakou, and Panjiakou has weaker connectivity than Daheiting.

Consumptive Water Use: Calculate the average runoff before and after the obstruction position of hydraulic structures.

The research results show that as the utilization and consumption rate of water resources increases, its blocking effect on rivers becomes more significant. For natural rivers, the water resource utilization consumption rate is relatively low at 0.21 In contrast the rate for Panjiakou, Daheiting, and Taolinkou reservoirs are significantly higher at 0.98, 0.98, and 0.82, respectively. These findings highlight that the Panjiakou and Daheiting reservoirs have a stronger blocking effect on the rivers compared to the Taolinkou reservoir.

3.1.2. Calculation of Surface Water Connectivity

Regarding the quantitative evaluation of overall surface connectivity, this study further calculated the changes in connectivity of each reservoir based on the calculation of various relevant indicators. During this process, the weight allocation of each indicator is scientifically set based on the Delphi method. The calculation of surface water connectivity considered the proportional water surface areas of the reservoirs, with precise measurements obtained using LSV technology. The measured water surface area of Panjiakou Reservoir are 64.58 square kilometers, Daheiting Reservoir is 24.65 square kilometers, and Taolinkou Reservoir is 37.16 square kilometers. Based on this, the percentages of the water surface area of the three reservoirs are 51.10%, 19.50%, and 29.40%, respectively.

The weight allocation of water flow momentum, fragmentation index, and water resource utilization consumption rate in the study area are 0.50, 0.20, and 0.30, respectively. Table 2 lists the normalized standard values of each indicator (all dimensionless numbers) and calculates the surface connectivity of each reservoir. This provides reliable data for a comprehensive analysis of changes in project connectivity, supporting a deeper understanding of the impact of reservoir construction on surface water connectivity.

The calculation reveals that the overall changes in surface connectivity is 0.40. Among the reservoirs, Panjiakou Reservoir exhibits the most significant change, with a connectivity alteration of 0.57. In contrast, Daheiting Reservoir shows the smallest change at 0.18, while

Taolinkou Reservoir presents a moderate change of 0.25. These calculation results show a high degree of consistency with the actual scale and volume of each reservoir. A detailed analysis of pronounced connectivity change in Panjiakou Reservoir highlights several contributing factors. The dam's height and project's scale significantly exceed those of the other two reservoirs, with the watershed area it controls accounting for more than half of the total area. Additionally, the project's importance is relatively high. These factors collectively lead to a particularly significant interception effect of the Panjiakou Reservoir on water flow, leading to a marked reduction in surface connectivity. This study concludes that the higher the scale and level of the reservoir project, the greater its impact on surface connectivity, leading to a corresponding increase in the degree of reduction in surface connectivity. This discovery is of great significance for understanding and evaluating the impact of reservoir construction on surface water ecosystems.

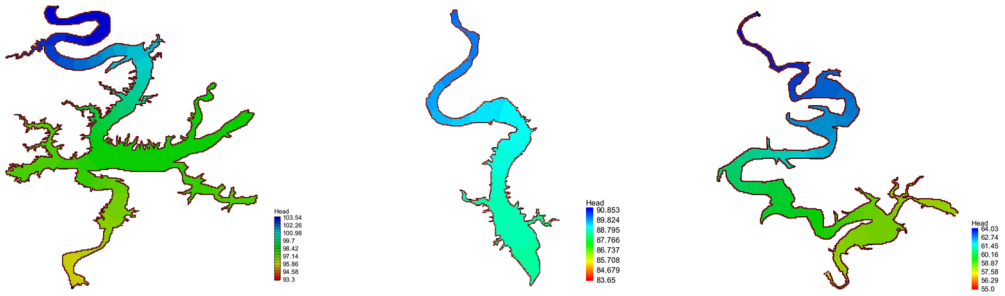
Table 2. Calculation of Surface Water Connectivity.

Study Area	WFM	DOF	USE	Proportion of Surface Water Control Area	Change in Connectivity
Panjiakou	0.82	0.24	0.36	0.51	0.57
Daheiting	0.06	0.22	0.36	0.20	0.18
Taolinkou	0.12	0.54	0.28	0.29	0.25

3.2. Calculate of Groundwater Connectivity

3.2.1. Calculation of Groundwater Indicators

The calculation indicators require data on the changes in groundwater level before and after dam construction. In order to obtain this data, a groundwater model is used to simulate the hydrodynamic process. The simulation of the groundwater model is shown in Figure 4.



(**a**) (**b**) (**c**)

Figure 4. Establishment of Groundwater Dynamics Model. (**a**) Panjiakou Reservoir; (**b**) Daheiting Reservoir; (**c**) Taolinkou Reservoir.

By analyzing the results of the model's operation, detailed information on the groundwater levels in Panjiakou, Daheiting, and Taolinkou were obtained. Before the implementation of water conservancy projects, the groundwater level in the Panjiakou area ranged from maximum of 100.47 m to a minimum of 93.3 m. In Daheiting, the highest level was recorded at s 85.95 m, and the lowest is 83.65 m. Similarly, in Taolinkou, groundwater levels varied between a maximum of 61.32 m and a minimum of 55.0 m. After the water conservancy projects were completed, a significant change in the groundwater level was observed. In the Panjiakou area, the highest level increased to 103.54 m and the lowest water level rising to 95.86 m The highest water level in the Daheiting area has risen to 90.85 m, and the lowest water level has also increased to 86.74 m. The highest value of

groundwater level in Taolinkou area has risen to 64.03 m, and the lowest value has also increased to 57.58 m. These findings highlight the substantial influence of water conservancy projects on the groundwater levels in three regions, (Panjiakou, Daheiting, and Taolinkou) leading to noticeable elevations.

Influence of Radius: Based on historical hydrological data, the permeability coefficient is 1.55×10^{-3} cm/s, and the rainfall recharge intensity is calculated based on the average rainfall in the basin. The annual average rainfall in the Luan River Basin is 553.2 mm, which is calculated as 0.000152 m/d in meters per day. The gravity water content is 0.2.

Calculations reveal that the radii of Panjiakou, Daheiting, and Taolinkou following the project's implementations are 5018.92 m, 3959.72 m, and 2429.46 m, respectively. This means that the impact of Panjiakou Reservoir on groundwater is greater than that of Daheiting Reservoir, and the impact of Daheiting Reservoir on groundwater is greater than that of Taolinkou Reservoir.

Penetration Force: The greater the permeability, the stronger the groundwater connectivity. According to calculations, the permeability of Panjiakou, Daheiting, and Taolinkou after the establishment of the project is 2.28 N, 1.73 N, and 1.67 N, respectively. The connectivity of groundwater in Panjiakou Reservoir is greater than that in Daheiting Reservoir, and the connectivity of groundwater in Daheiting Reservoir is greater than that in Taolinkou Reservoir.

Single-width Traffic: By calculating the single width flow before and after dam construction, the change in single width flow is calculated.

The larger the single width flow rate, the better the groundwater connectivity. According to calculations, the single width flow rates of Panjiakou, Daheiting, and Taolinkou after the project implementations are 0.03 m^2/s, 0.02 m^2/s, and 0.01 m^2/s, respectively. This suggest that groundwater connectivity in the Panjiakou Reservoir is better than that in Daheiting Reservoir, and the connectivity of groundwater in Daheiting Reservoir is better than that in Taolinkou Reservoir.

3.2.2. Calculation of Groundwater Connectivity

Same as the surface connectivity, to further calculate the changes in groundwater connectivity of each reservoir, using the Delphi method to set the weight allocation of each indicator, the weights of the three indicators are 0.50, 0.20, and 0.30, respectively, calculate the groundwater connectivity within the watershed based on the proportion of the area of the three reservoirs. Table 3 shows the normalized standard values for each indicator and calculates the groundwater connectivity of each reservoir.

Table 3. Calculation of Groundwater Connectivity.

Study Area	Influence Radius (m)	Penetration Force (N)	Single-Width Traffic (m^2/s)	Proportion of Groundwater Control Area	Change in Connectivity
Panjiakou	0.38	0.16	0.21	0.75	0.29
Daheiting	0.29	0.80	0.72	0.03	0.54
Taolinkou	0.33	0.04	0.06	0.11	0.19

After calculation and analysis, this study determined that the change in groundwater connectivity is 0.25. When considering only groundwater connectivity without accounting for surface factors, the results significantly differ from surface connectivity. The groundwater connectivity of Daheiting Reservoir has changed the most (0.52), Taolinkou Reservoir has changed the least, only 0.19, and Panjiakou Reservoir is at a moderate level (0.29). Exploring the causes of differences in changes, it was found that sediment played a key role. Due to the close geographical location of Panjiakou and Daheiting Reservoir, about

30 km apart, the upstream sediment first reaches Panjiakou Reservoir and settles at the bottom of the reservoir. This sediment settles at the reservoir's bottom, enhancing the impermeability of its foundation. However, the engineering scale of Panjiakou Reservoir is relatively large, which can intercept and deposit the vast majority of sediment. Therefore, the sedimentation of remains in Daheiting Reservoir is relatively small, and the increase in impermeability of its foundation is limited, resulting in a greater increase in groundwater connectivity. In contrast, the groundwater connectivity of Taolinkou Reservoir has the smallest change, which is closely related to its engineering scale and upstream environment. The engineering scale of Taolinkou Reservoir is between Panjiakou and Daheiting, but there are no other large-scale projects upstream, so the sedimentation situation is more severe compared to Panjiakou. In situations where the degree of sedimentation is similar, smaller reservoirs have relatively less leakage. Therefore, the groundwater connectivity change of Taolinkou Reservoir is the smallest. In summary, sedimentation and reservoir engineering scale significantly influence groundwater connectivity. These findings offer valuable insights into the impact of reservoir construction on groundwater ecosystems.

3.3. Calculation of Connectivity of Three-Dimensional Water System

The connectivity indices of surface water and groundwater were separately calculated, and the results for the three reservoirs are shown in the Figure 5.

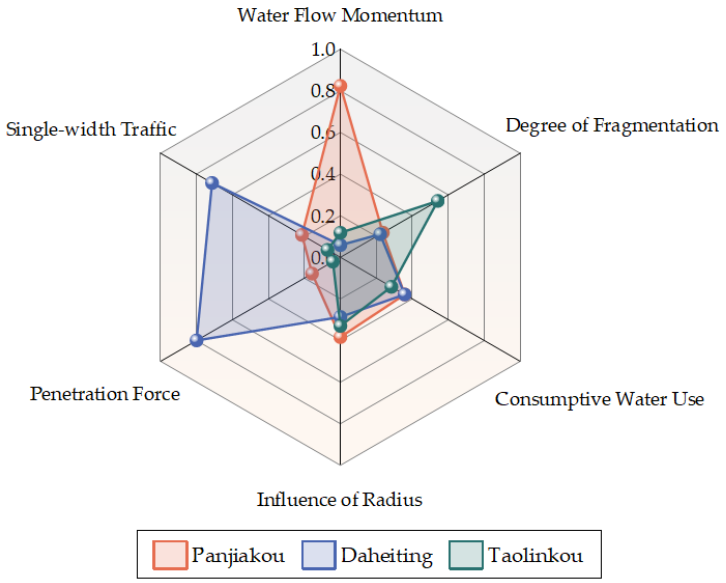


Figure 5. Calculation Results of Six Indicators for Three Reservoirs.

Given the complexity of water flow composition, the connectivity values of surface water and groundwater obtained earlier are not the final and accurate connectivity indicators. To address this, the concept of the permeability coefficient was introduced to determine the proportion of infiltrated water. Based on this, three-dimensional water systems were calculated considering the ratio of surface water to groundwater. As quantitatively visualized in Figure 6, the results show that the percentage of infiltration water is 3.93%, while the percentage of surface water is as high as 96.07%.

Therefore, by matching the percentage of water volume with the connectivity between surface and ground, as depicted in Figure 6, the change in surface water connectivity is 0.40, and the change in groundwater connectivity is 0.25. Due to the blockage of rivers caused by the construction of surface dams, the connectivity of surface water systems has decreased. After the dam is filled with water for a long time, water flow will seep into the underground, increasing connectivity for the groundwater part but decreasing connectivity

for the entire region. Therefore, the change in connectivity of the entire study area is 0.39, which means that the connectivity of the entire study area has decreased by 0.39.

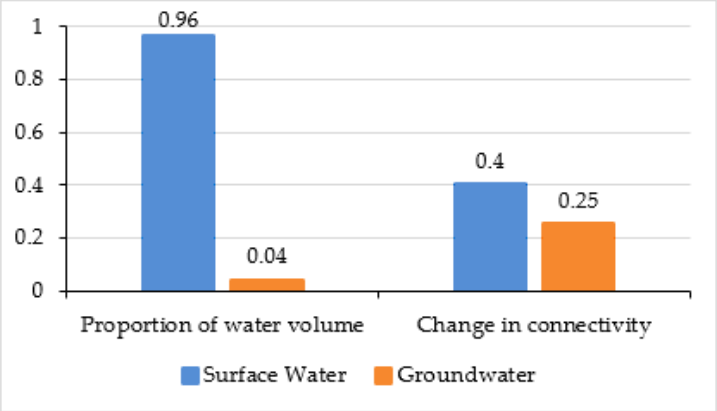


Figure 6. Calculation Results of Changes in Connectivity of Three-dimensional Water Systems.

3.4. Error Analysis

The main error in this project lies in assigning weights. In addition, water surface area, watershed control area, water volume, etc. are all objectively present, and only the weights based on the Delphi method are subjectively assigned. Therefore, the main analysis focuses on the errors caused by assigning weights. In order to analyze the impact of assigning weights on errors, different arrangements and combinations of weights assigned will be used to calculate connectivity. The allocation results for surface and underground are shown in Table 4.

Table 4. Weight Combinations of Surface and Underground Indicators.

Index	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Surface Water System						
Water flow momentum	0.50	0.50	0.20	0.20	0.30	0.30
Degree of Fragmentation	0.20	0.30	0.50	0.30	0.50	0.20
Consumptive Water Use	0.30	0.20	0.30	0.50	0.20	0.50
Groundwater System						
Influence of Radius	0.50	0.50	0.20	0.20	0.30	0.30
Penetration Force	0.20	0.30	0.50	0.30	0.50	0.20
Single-width Traffic	0.30	0.20	0.30	0.50	0.20	0.50

According to different weighting scenarios, the surface water connectivity, groundwater connectivity, and three-dimensional water system connectivity of each subregion area were calculated separately. The results are shown in Figures 7 and 8.

From Figure 7, it can be seen that changing the weights of various surface indicators may cause fluctuations in the surface connectivity of individual reservoirs such as Panjiakou, Daheiting, and Taolinkou. However, all of them conform to the conclusions of surface connectivity calculation. Among the three reservoirs, Panjiakou Reservoir has the largest change in surface connectivity, Daheiting Reservoir has the smallest change in surface connectivity, and Taolinkou Reservoir has the moderate change in connectivity. It can be concluded that the higher the scale and level of the project, the greater the decrease in surface connectivity.

As demonstrated in Figure 8, changing the weights of various groundwater indicators will also result in changes in the groundwater connectivity of individual reservoirs such as Panjiakou, Daheiting, and Taolinkou. However, the conclusions drawn are exactly the same as those obtained from the calculation of underground connectivity. Daheiting Reservoir

has the largest change in groundwater connectivity, Taolinkou Reservoir has the smallest change, and Panjiakou Reservoir has a moderate change.

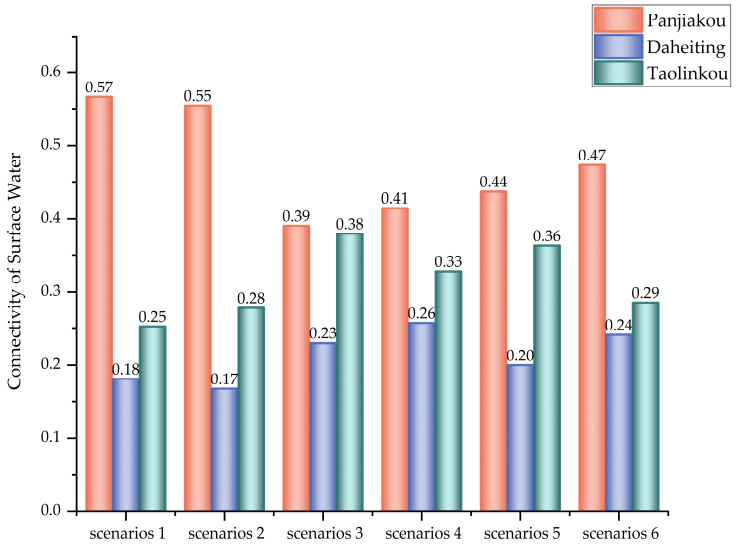


Figure 7. Comparison of Surface Water System.

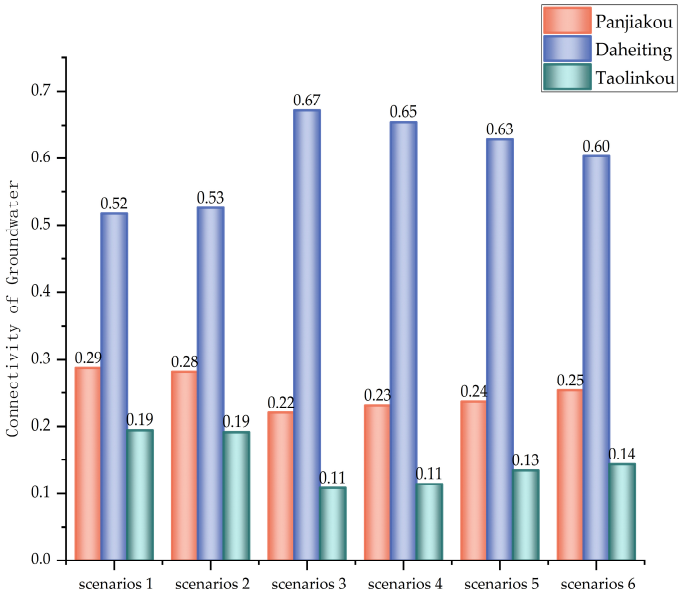


Figure 8. Comparison of Groundwater System.

In conclusion, changing the weights of each indicator does not have a significant impact on calculating the overall connectivity of the study area as evidenced in Figure 9. Therefore, it can be considered that the results of connectivity calculation are accurate.

After calculation, it can be concluded that the change in surface water connectivity in the study area is 0.40, and the change in groundwater connectivity is 0.25. The overall connectivity change of groundwater is relatively small. The change in connectivity of the entire study area is 0.39. The higher the scale and level of the project, the greater the decrease in surface connectivity.

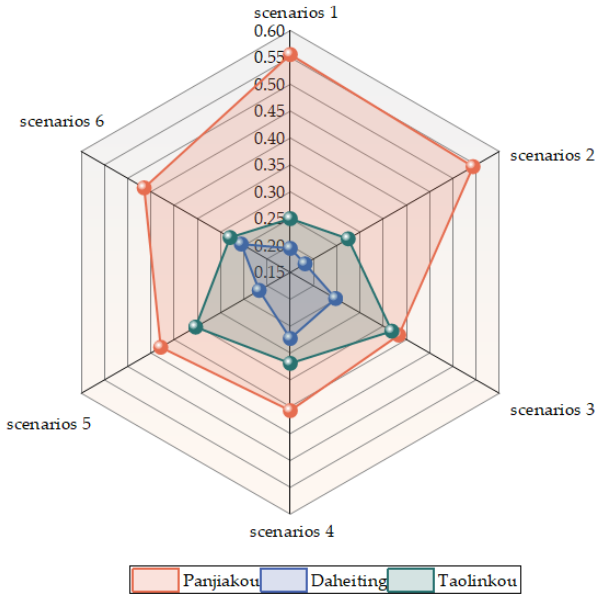


Figure 9. Connectivity of Three Reservoirs under Different Weighting Scenarios.

4. Discussion

According to the simulation results, the connectivity of the surface water system in the study area decreased by 0.40, while the groundwater connectivity increased by 0.25. Considering the overall regions, which link surface water and groundwater, the total connectivity of the study area decreased by 0.39. This indicates that water conservancy projects have a more pronounced negative effect on surface water connectivity compared to groundwater.

The construction of water conservancy projects such as surface interception dams will significantly reduce the connectivity of the surface water system. This decline is mainly due to changes in the natural structure and hydrological continuity of rivers caused by engineering: the shape of the river channel has been reshaped, and the interception of water flow by reservoirs has weakened the natural hydrodynamic processes. At the same time, artificial water intake reduces the natural runoff in the river channel, further indirectly weakening connectivity. The reservoir case in this study further demonstrates that the scale of the project is a key factor affecting the degree of connectivity decline. Due to its prominent dam height and engineering scale, the Panjiakou Reservoir has undergone the most significant changes in the original river structure and water flow continuity, resulting in the largest decrease in connectivity (up to 0.57). In contrast, the Daheiting Reservoir with lower scale and water level has the smallest impact on connectivity, with a decrease of only 0.18. Therefore, this study shows that the larger the scale of water conservancy projects, especially dam height and controlled watershed area, the more significant the reduction effect on the connectivity of surface water systems.

Groundwater connectivity generally increases after reservoir construction, as water infiltrates into the groundwater system. Results show that the connectivity of groundwater in Daheiting Reservoir has increased the most, Taolinkou Reservoir has changed the least, and Panjiakou Reservoir has changed in the middle. The key factors causing differences are sedimentation and dam foundation anti-seepage treatment. Panjiakou Reservoir is geographically adjacent to Daheiting Reservoir (about 30 km), and the upstream sediment first reaches Panjiakou and settles, improving the bottom impermeability of the reservoir and reducing the leakage of Panjiakou. However, the scale of Panjiakou Reservoir intercepted the vast majority of sediment, with only a small amount entering the downstream Daheiting Reservoir. Therefore, the sedimentation at the bottom of Daheiting Reservoir is relatively

small, and the improvement of impermeability is limited, resulting in a higher unit leakage rate and a greater increase in groundwater connectivity. The scale of Taolinkou Reservoir is between the two, but the change is minimal. This is because there are no large-scale projects upstream to intercept sediment, resulting in a high degree of sedimentation. Meanwhile, when the degree of sedimentation is similar, the smaller the size of the reservoir, the less the total amount of leakage. The scale of Taolinkou Reservoir is relatively smaller than that of Panjiakou, so its groundwater connectivity changes the least.

The results indicate that by selecting evaluation indicators from multiple perspectives and using models to calculate regional data, it is possible to quantitatively analyze the impact of water conservancy projects on water systems, comprehensively reflect the degree of water system connectivity, improve the accuracy of connectivity assessment, and provide data support for strengthening water conservancy construction management.

5. Conclusions

River connectivity is a key aspect of river management, but its assessment methods still need to be improved. Therefore, based on existing research at home and abroad, this study developed a comprehensive method for quantitatively evaluating water system connectivity, and applied it to three reservoirs in the Luan River Basin: Panjiakou, Daheiting, and Taolinkou, to evaluate the impact of reservoir construction on water system connectivity in the region. The innovation of this method lies in the comprehensive consideration of changes in the connectivity between surface water and groundwater. This method comprehensively considers the three-dimensional structure of surface water groundwater in rivers and the functions of hydraulic engineering. Using the Analytic Hierarchy Process (AHP), six representative indicators are selected to construct a multidimensional comprehensive evaluation system for water system connectivity. A numerical model is constructed based on Mike21 (Flow Model) and GMS (modflow) software to calculate the data required for the evaluation indicators.

Research has shown that water conservancy engineering construction will significantly change the connectivity of regional water systems, and its impact is closely related to project scale. The impact on surface water is mainly reflected in river structure, hydrodynamic processes, and hydrological continuity. The impact on groundwater mainly comes from the effectiveness of sedimentation and anti-seepage treatment.

The quantitative methodology employed in this study constitutes a standardized assessment framework capable of not only facilitating cross-basin comparative analysis of water system connectivity but also precisely evaluating changes in water system connectivity before and after water conservancy projects within specific basins. By establishing a unified indicator system, it enables both the interpretation of connectivity differentials between target regions and other basins and the quantitative diagnosis of impact mechanisms on hydrological connectivity following the construction of hydraulic structures. Compared with traditional research, this method innovatively integrates the three-dimensional structure and function of river systems, introduces groundwater evaluation indicators and human impact factor indicators, and constructs a more complete comprehensive evaluation system. This evaluation method can provide a scientific basis for the assessment and restoration of river connectivity, and provide methodological support for the protection and restoration of river ecosystems. At the same time, in response to the practical problem of difficult data acquisition in quantitative evaluation of river connectivity, the comprehensive evaluation method constructed in this study mainly relies on publicly available data and is supplemented by conceptual model calculations. Although the accuracy is limited compared to high-precision specialized survey data such as rivers, lakes, and reservoir

shoreline surveys, this method has significant universality and is suitable for computational evaluation in large-scale areas.

The results of this study show that large-scale water conservancy projects significantly reduce water system connectivity, and the degree of impact is directly related to the scale of the project. Good water system connectivity is crucial for rivers, as it helps to enhance the ability to coordinate and allocate water resources, improve the water ecological environment, and strengthen the ability to resist water and drought disasters. Based on this, it is recommended that the Chinese government

(1) Incorporate connectivity impact assessments in the planning and design phase of water conservancy projects: Fully consider the potential impact of buildings on water system connectivity, and strive to minimize damage to the natural ecological environment.
(2) Promote and popularize quantitative assessment methods for water system connectivity: Require and support the application of quantitative methods in project evaluation to ensure that changes in connectivity of both surface water and groundwater systems are considered simultaneously.
(3) Strengthen sediment management and optimize anti-seepage measures: Develop effective sediment management strategies and optimize anti-seepage engineering design based on the sedimentary characteristics of different regions (such as the differences presented by Panjiakou, Daheiting, and Taolinkou reservoirs) to balance the connectivity between surface water and groundwater.
(4) Implementing adaptive management strategies: Given the significant regional differences in project impacts (as shown in the case of the three major reservoirs), it is encouraged to adopt management methods that are tailored to local conditions and have strong adaptability.

Ultimately, strong government leadership is crucial for achieving the transition from qualitative management to quantitative management, improving the accuracy of connectivity assessments, and promoting sustainable water development to ensure the ecological integrity of watersheds.

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