

ORIGINAL RESEARCH ARTICLE

Evaluation method for assessing riverbank water intake suitability

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Abstract: The conjunctive use of groundwater and surface water near rivers can effectively balance both water quantity and quality, making the suitability of water source locations critically important. To address the issue of suitability for water intake from riverine terraces, this study develops a mathematical evaluation model based on the analytic hierarchy process (AHP) and establishes a comprehensive assessment system tailored to the optimal selection of riverside water intake sites. Based on a comprehensive analysis of the geomorphological and hydrogeological characteristics of the Weining–Yellow River alluvial plain, this study develops an evaluation model to assess the suitability of riverside water intake sites. The model incorporates eight key indicators: river low-flow discharge, riverbed siltation, aquifer permeability, aquifer thickness, presence of continuous impermeable interlayers, river water quality, groundwater quality, and groundwater depth. Indicator weights were determined using the AHP, and grading criteria were established for each parameter. Using the ArcGIS analytical platform, a suitability index was calculated, and the study area was categorized into different suitability zones based on the established classification standards. The results indicate that a substantial portion of the Weining Basin exhibits relatively favorable conditions for riverside water source extraction, with class I zones accounting for 8.63%, class II zones for 36.21%, class III zones for 17.54%, class IV zones for 23.18%, and class V zones for 14.44%. The comprehensive evaluation score for this water source site is 69 points, which can be classified as a class II (good suitability) zone. Both the theoretical framework and practical application demonstrate that the proposed evaluation method is well suited for assessing the intake suitability of riverside water intake sites.

Keywords: Groundwater; Riverside water intake sites; Suitability evaluation; Indicator system; Analytic hierarchy process; Weining basin

1. Introduction

Riverside water intake has been widely adopted in water supply systems owing to its advantages – such as high water quality, convenient access, and low

pollution risk. As an effective means of realizing the conjunctive use of surface water and groundwater, it has become an essential strategy for securing regional water supplies, especially in areas prone to seasonal water scarcity. Therefore, assessing the suitability of riverside

water intake sites is a critical prerequisite for ensuring adequate water quantity and quality, as well as the sustainable utilization of water resources. Developing a standardized and scientifically robust evaluation framework for site suitability not only enhances the reliability of planning and decision-making but also contributes to long-term water resource management. Despite increasing research attention, a universally applicable and practically implementable assessment system is still lacking.

International research in this field began relatively early, with a primary focus on hydrogeological processes, pollutant attenuation mechanisms, and sustainable management of river–aquifer interactions.¹⁻³ In terms of methodology, process-based numerical simulation models have been extensively used in Europe and North America to quantify surface water–groundwater exchange processes.^{4,5} These are often supplemented by hydrochemical and microbiological indicators to evaluate the safety and sustainability of riverbank filtration. Studies in major river basins such as the Rhine and the Danube have identified key parameters influencing water intake performance, including riverbed hydraulic conductivity, residence time, and redox conditions.⁶⁻⁸ International organizations such as the World Health Organization and the International Hydrological Programme have also developed comprehensive assessment frameworks that integrate quantitative and qualitative dimensions, addressing issues of climate change adaptation and emphasizing the importance of long-term monitoring.⁹⁻¹²

Moreover, recent trends in international research emphasize interdisciplinary integration, combining hydrological modeling, statistical analysis, and machine learning techniques (e.g., random forest and artificial neural networks) to improve assessment accuracy and predictive capacity.¹³⁻¹⁷ Risk-based models, such as improved versions of DRASTIC, have also been employed to evaluate groundwater vulnerability in intake areas, enhancing the scientific basis for site selection and water safety assurance.

In recent years, research on evaluation indicators and methodologies for riverside water intake in China has expanded, especially in the context of the Yellow River, which features unique riverbed sedimentation and bank morphology.¹⁸⁻²¹ Various evaluation frameworks have been proposed, incorporating hydrogeological, hydrodynamic, and environmental risk indicators. For example, Cui *et al.*²² examined the effect of sediment permeability on river recharge to adjacent aquifers, while Zacharie *et al.*²³ developed an urban river intake

suitability index system that integrates water quantity, water quality, and geological risk, using expert scoring and geographic information system (GIS)-based spatial analysis. Several studies have applied the analytic hierarchy process (AHP) to derive indicator weights and conduct multi-criteria evaluations – such as Jafar *et al.*,²⁴ who conducted a comparative analysis of different water sources, and Yang *et al.*,²⁵ who proposed a comprehensive system with 28 indicators to assess drinking water source suitability under legal and environmental constraints. Muktadir *et al.*²⁶ further developed a suitability model based on river morphological and hydrodynamic indicators.

However, a critical review of the literature reveals several research gaps. First, existing studies often adopt location-specific or empirical indicator systems, which lack generalizability and standardized grading schemes applicable to broader hydrogeological contexts.²⁷ Second, while advanced modeling techniques are widely applied, there is a lack of integration between spatial analysis tools and multi-criteria decision-making frameworks in site-level evaluations.²⁸ Third, few studies systematically consider the combined effects of multiple hydrological and geological parameters in a unified suitability index, which limits the applicability of results to real-world planning and engineering implementation.²⁹

To address these gaps, this study develops a suitability evaluation system for riverside water intake sites tailored to the hydrogeological characteristics of the Weining Yellow River alluvial plain. The system integrates eight quantitative indicators: low-flow river discharge, riverbed sedimentation, aquifer hydraulic conductivity, aquifer thickness, presence of continuous impermeable interlayers, river water quality, groundwater quality, and groundwater depth. Using the AHP to determine indicator weights and construct a comprehensive evaluation model, the study further employs GIS-based spatial analysis to assess intake suitability across the study area. The aim is to provide a scientifically grounded, spatially explicit tool for optimizing the site selection of riverside water sources, thereby contributing to more sustainable water resource development and management.

2. Hydrological and climatic overview of the study area

2.1. Climatic and meteorological conditions

The study area encompasses a 397 km stretch of the Yellow River, extending from southern Changtan

in Zhongwei City, flowing through the Weining and Yinchuan Plains, and exiting the region at northern Ma Huang Gou in Shizuishan City. This area accounts for approximately 7.3% of the river's total length. Based on a 40-year dataset (1956 – 1995), the average annual runoff at the Lower Heyang Hydrological Station is $317 \times 10^8 \text{ m}^3$ per year, while the outgoing volume at the Shizuishan Hydrological Station is $294 \times 10^8 \text{ m}^3$ per year, resulting in an annual net water loss of $23 \times 10^8 \text{ m}^3$. The average annual water consumption from the Yellow River is $32.0 \times 10^8 \text{ m}^3$ per year (Figure 1).

According to the data from the Zhongwei County Meteorological Station, the long-term average annual temperature is 8.9°C . The highest recorded extreme temperature is 37.6°C , while the lowest is -29.2°C . The average monthly temperature in summer exceeds 20°C . The long-term average annual precipitation is 183.3 mm, with rainfall mainly concentrated between July and September. The average annual evaporation rate reaches 1887 mm. The long-term average maximum wind speed is 16.3 m/s, with prevailing winds from the northwest. The maximum depth of frozen soil is 83 cm. Spring is short, dry, and windy; summer and autumn experience relatively concentrated rainfall; and winter is dry, with minimal precipitation and frequent sandstorms. The prevailing wind direction throughout the year is from the northwest.³⁰

2.2. Hydrogeological conditions

The study area is located within the Weining Basin, in the northern region of the Xiangshan Mountain Range.

The terrain is uneven, with alluvial plains on both sides of the Yellow River, characterized by relatively flat topography. The Yellow River flows through the region, and the river valley is classified as an anticlinal fault valley, forming the first-, second-, and third-level Yellow River alluvial terraces. The first- and second-level alluvial terraces are scattered along both banks of the Yellow River, with the main development areas located south of Enhe, Wusha, and Changle. The geological composition of these terraces primarily consists of silty sand, fine sand, and sandy gravel. Near Xuanhe and Baima, a segment of the second-level terrace extends approximately 40 km in length and 0.5 km in width, while the first-level terrace is sporadically distributed, featuring relatively flat surfaces. The third-level terrace stretches about 25 km long and 2 – 3 km wide, with terrace heights ranging from 2 to 10 m, and is mainly distributed south of Wusha, Enhe, and Changle.

As shown in Figure 2, the Weining Yellow river alluvial plain is located on both sides of the Yellow River, forming a narrow belt-shaped faulted basin. The basin has accumulated thick, unconsolidated sediments, providing favorable conditions for water storage. Within the alluvial plain, stratigraphic layers from different geological periods are stacked from top to bottom – including Miocene, Late Pleistocene, and Holocene deposits – which are primarily composed of coarse-grained, loose clastic materials. Within the upper 50 m, the strata mainly consist of gravel and pebble layers derived from Yellow River alluvium, with relatively stable lithology. The surface layer (0 – 10 m) is mainly

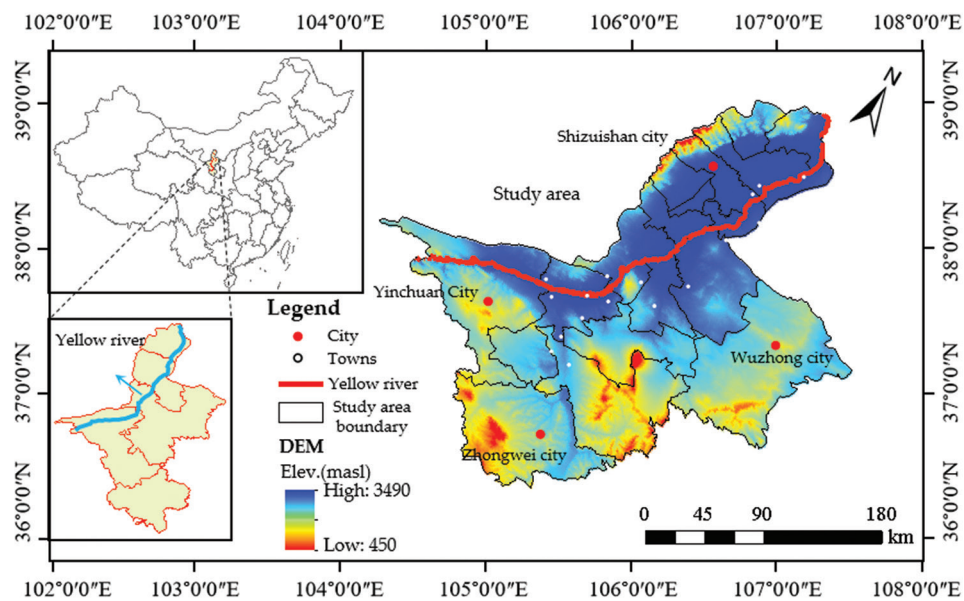


Figure 1. Location map of the study area

Evaluation of riverbank water suitability

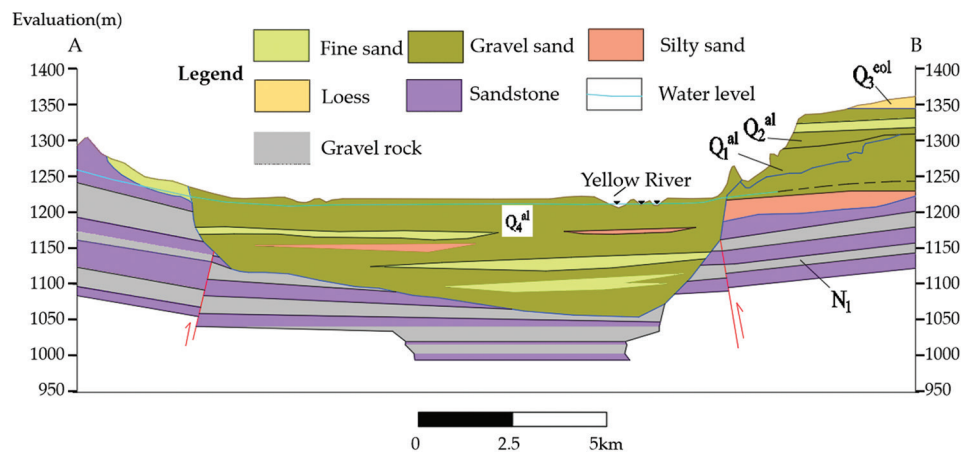


Figure 2. Hydrogeological profile of the study area, derived from the regional hydrogeological report. Q_1 represents Miocene deposits, Q_2 indicates Late Pleistocene deposits, Q_3 denotes Aeolian deposit, Q_4 signifies Holocene deposits, and N_1 refers to sand and gravel stratum.

composed of clay, while below 50 m, the deposits are mainly clay interspersed with gravel, pebbles, and sandy gravel, exhibiting relatively unstable lithological characteristics.

The groundwater types include both unconfined and confined aquifers. The unconfined aquifer is primarily composed of gravel and pebble layers, with localized medium to fine sand layers and clay lenses. The thickness of these layers generally ranges from 10 to 50 m, and the water depth typically lies between 1 and 5 m, increasing gradually from the riverbed to the surrounding mountainous areas. The abundance of groundwater resources generally decreases from upstream to downstream and from the riverbed toward the mountains.

From the perspective of regional hydrogeological conditions and macrogeomorphological characteristics, the northwestern part of the study area mainly comprises mountainous and hilly terrain, with groundwater predominantly replenished by runoff flowing from north to south. The central region lies within the Yellow River alluvial plain, where groundwater primarily flows toward the Yellow River. The southern part consists of floodplain terraces, where groundwater is mainly replenished by runoff from the southwest to the northeast.

3. Methodology for assessing the suitability of water intake

Selecting appropriate locations for riverside water intake sites is essential to ensure that the quantity and quality of withdrawn water meet supply requirements.

This study employed the AHP and selected relevant indicators based on the actual hydrogeological conditions of the case study area. By constructing and solving a judgment matrix, the weights of each indicator can be determined, thereby enabling the identification of suitable zones for the development of riverside water intake sites (Figure 3).

3.1. Selection of evaluation indicators

The selection of evaluation indicators is a fundamental step in assessing the suitability of riverside water intake sites. These indicators are categorized into qualitative and quantitative types. Qualitative indicators reflect expert judgments based on site-specific conditions, while quantitative indicators are derived from measurable hydrological and geological parameters.^{31,32} The AHP was employed to ensure consistency, objectivity, and scientific rigor in the assessment.

3.1.1. Qualitative indicators

In this study, the following qualitative indicators were selected:

- (i) **Aquifer characteristics:** The hydraulic properties of an aquifer are crucial for ensuring the efficiency and sustainability of groundwater intake. Aquifers with high permeability, substantial thickness, broad spatial distribution, and minimal occurrence of low-permeability interlayers or lenses are considered favorable and are assigned a score of 1. Conversely, aquifers with low permeability, limited thickness, discontinuous distribution, and the presence of impermeable features are considered less suitable and are assigned a score of 0. Favorable aquifers

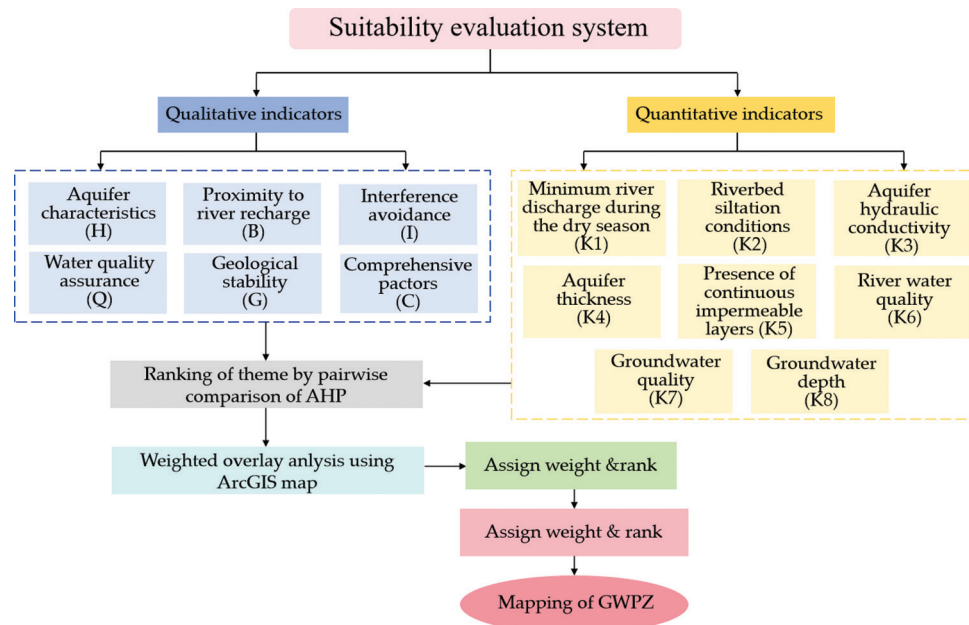


Figure 3. Flowchart of the methodology employed in this study

Abbreviations: AHP: Analytic hierarchy process; GWPZ: Groundwater potential zone.

provide high storage and discharge capacity, reduce technical challenges, and lower operational costs, thereby supporting stable, long-term intake operations.

- (ii) Proximity to river recharge: The distance between the groundwater source and the river directly influences the volume of induced recharge. Sites located closer to the river can effectively intercept recharge from river water and are assigned a score of 1. In contrast, sites farther from the river are less capable of capturing river recharge and receive a score of 0. Especially in zones with unconsolidated sediment, selecting intake locations adjacent to the river enhances recharge potential and overall water availability.
- (iii) Interference avoidance: Avoiding hydraulic and operational interference with existing water intakes and discharges is essential for sustainable resource management. Sites that are spatially separated from current water usage points (e.g., industrial or agricultural wells, municipal intakes, or drainage outlets) are assigned a score of 1, as they reduce the risk of resource conflicts, contamination, and mutual interference. In contrast, sites located near such facilities receive a score of 0 due to the potential for operational complications and increased management challenges.
- (iv) Water quality assurance: Ensuring high and stable water quality is a critical factor in site selection.

Ideal locations are those with minimal exposure to surface or subsurface contamination sources, such as positions upstream of industrial discharge areas or urban wastewater outlets. Areas with naturally good water quality and situated away from problematic lithologies (e.g., quicksand layers that may cause clogging or turbidity) are assigned a score of 1. In contrast, polluted or geologically vulnerable areas that require complex treatment or pose long-term reliability issues are assigned a score of 0.

- (v) Geological stability: The selection of a geologically stable site is vital to prevent hazards such as land subsidence, collapses, fractures, or landslides. Sites with stable lithological conditions and low geological risk are assigned a score of 1. In contrast, sites located in geohazard-prone areas are scored as 0 due to potential impacts on construction feasibility, cost, and operational safety. Geological stability ensures structural integrity and supports reliable groundwater development.
- (vi) Comprehensive factors: Beyond hydrological and geological considerations, comprehensive factors such as economic feasibility, safety, and potential for future expansion are also evaluated. Sites located closer to the target water supply area can reduce pipeline construction costs, while those with shallow or artesian aquifers have lower intake and pumping expenses. Options with favorable performance across economic, safety, and

scalability dimensions are assigned a score of 1, whereas those with significant limitations in these aspects are scored as 0. These indicators ensure the overall feasibility and long-term sustainability of the water source site.

3.1.2. Quantitative indicators

In this study, the quantitative evaluation system comprises eight indicators that reflect key hydrological, geological, and environmental factors influencing the suitability of riverside groundwater source development. These indicators are not entirely independent in practice, as they exhibit varying degrees of internal correlation and mutual influence. Understanding such interrelationships is crucial for enhancing the accuracy and robustness of the overall evaluation framework.

The following are the quantitative indicators employed in this study:

- (i) Minimum river discharge during the dry season (K1): Low-flow river discharge directly constrains the potential for induced recharge and the sustainable yield of riverside sources. During dry periods, river flow is predominantly maintained by baseflow contributions from regional aquifers, creating a bidirectional interaction between surface and subsurface systems. Moreover, insufficient discharge may reduce the hydraulic gradient necessary for lateral infiltration, thereby indirectly influencing aquifer hydraulic conductivity (K3) and riverbed permeability (K2).
- (ii) Riverbed permeability (K2): Sediment deposition on the riverbed alters the permeability and transmissivity of the hyporheic zone, serving as a critical control on the efficiency of river–aquifer interactions. Excessive siltation can form semi-permeable or impermeable layers, thereby limiting infiltration. Notably, this indicator is correlated with K3, as fine particles may migrate into upper aquifer layers, leading to clogging and a reduction in effective porosity and overall hydraulic performance. Hence, K2 and K3 should be considered in conjunction when assessing recharge potential.
- (iii) Aquifer hydraulic conductivity (K3): Hydraulic conductivity determines the capacity of the aquifer to transmit water both horizontally and vertically. In anisotropic or compositionally heterogeneous media, conductivity may vary by direction and depth. Together with K2, the presence of silt layers or interbeds can alter the vertical-to-horizontal conductivity ratio, affecting induced recharge dynamics. Furthermore, K3 influences the spatial propagation of infiltrated river water and thus has an indirect impact on both river water quality (K6) and groundwater quality (K7) by mediating transport and mixing processes.
- (iv) Aquifer thickness (K4): The thickness of the unconfined aquifer defines the available cross-sectional area for subsurface flow and controls the static storage capacity of the system. A thicker aquifer facilitates greater recharge volumes under a given hydraulic gradient and increases buffering capacity during periods of high demand or drought. While largely independent in formulation, K4 interacts with K3 in determining total transmissivity and modulates the influence of groundwater depth (K8) on pumping feasibility and long-term aquifer drawdown behavior.
- (v) Presence of continuous impermeable layers (K5): Impermeable or semi-permeable interlayers significantly affect vertical recharge and may compartmentalize the aquifer, reducing connectivity between the river and extraction zones. This spatial heterogeneity complicates conceptual models and may result in over- or underestimation of induced recharge. K5 is closely related to K2 and K3, as riverbed clogging and vertical flow resistance both contribute to reduced effective permeability. It also has a potential masking effect on the apparent relationship between K6 (river water quality) and K7 (groundwater quality), by acting as a selective barrier or hydraulic filter.
- (vi) River water quality (K6): As riverside water sources rely substantially on induced infiltration, river water quality is a critical determinant of overall source suitability. However, its impact does not operate in isolation. Infiltrated river water undergoes natural attenuation processes within the vadose and saturated zones, where its quality is modified by aquifer-specific physical and chemical properties. Therefore, the interaction between K6 and K7 must be carefully interpreted: high-quality river water may improve local groundwater conditions, while low-quality surface water may result in cumulative contamination, especially in shallow or highly permeable aquifers.
- (vii) Groundwater quality (K7): Groundwater quality reflects both the native geochemical background and anthropogenic influences, as well as the cumulative effects of river-induced recharge. Its interpretation should therefore consider upstream indicators, particularly K6 and K3. In certain settings, elevated pollutant concentrations in

groundwater may indicate ineffective attenuation capacity or legacy contamination, thereby undermining source suitability despite favorable hydraulic conditions.

(viii) Groundwater depth (K8): The depth to groundwater influences pumping costs, recharge rates, and the hydraulic connection with surface water bodies. Greater depths increase required pumping lift and may induce vertical flow from confining units, potentially affecting both K3 and the migration of contaminants. Moreover, as groundwater depth increases, the influence of river recharge becomes more attenuated, suggesting a nonlinear and site-dependent relationship between K8 and both K1 and K6 in practical intake performance.

These interdependencies underscore the importance of a systems-thinking approach in evaluation model construction. Rather than treating each indicator as independent, this study acknowledges key functional linkages – particularly between K2 and K3, as well as between K6 and K7. Although this version of the model applies additive weighting through AHP, future enhancements may incorporate correlation analysis, interaction terms, or multivariate statistical techniques (e.g., principal component analysis or factor analysis) to quantitatively capture these interrelationships and reduce redundancy. Such refinements would further improve the internal consistency and predictive reliability of the suitability assessment framework.

3.2. Determination of evaluation weights

3.2.1. Construction of the judgment matrix

Based on the qualitative indicators, one or more river sections are selected as potential groundwater source sites. Subsequently, a weighting analysis was conducted for all the identified quantitative indicators; however, the qualitative indicators were excluded from this process. The quantitative indicators were categorized into three groups: water quantity, water quality, and groundwater depth. The constructed judgment matrix for determining the weights is presented in Table 1.

Based on Table 1, K7, as the direct determinant of water supply site viability, exerts the most significant influence on site selection. If K7 fails to meet the required standards, the construction of a water source site is considered unsuitable. In contrast, river water undergoes natural purification during its infiltration into aquifers, thus exerting a relatively lower impact on site selection. The river’s low-flow runoff and the volume of groundwater reserves, as primary sources of recharge,

Table 1. Constructed judgment matrix for determining indicator weights

Analytic hierarchy process	K1	K2	K3	K4	K5	K6	K7	K8
K1	1	1/5	1/4	2	2	1/7	1/4	1/3
K2	5	1	3	7	5	1/3	2	3
K3	4	1/3	1	5	5	1/3	2	3
K4	1/2	1/7	1/5	1	1/3	1/5	1/3	1/2
K5	1/2	1/5	1/5	3	1	1/5	1/4	1/2
K6	7	3	3	5	5	1	2	3
K7	4	1/2	1/3	3	4	1/2	1	2
K8	3	1/3	1/3	2	2	1/3	1/2	1

Notes: K1 – K8 represent the following indicators: K1: Minimum river discharge during the dry season ; K2: Riverbed permeability; K3: Aquifer hydraulic conductivity; K4: Aquifer thickness; K5: Presence of continuous impermeable layers; K6: River water quality; K7: Groundwater quality; K8: Groundwater depth.

collectively determine the permissible groundwater intake capacity. In addition, K8 primarily affects the cost and operational stability of water intake, resulting in a moderate level of influence. A comprehensive analysis of the importance of the eight evaluation indicators reveals the following descending order of influence: K7 > K8 > K1 > K6 > K2 > K3 > K4 > K5.

3.2.2. Calculation of the judgment matrix

In this study, a judgment matrix constructed from statistical data is used to quantify the relative importance or influence of various factors. By conducting pairwise comparisons among the factors and assigning corresponding values, a positive reciprocal matrix is formed. Subsequently, the relative weight vector of each factor is obtained through weight calculation and a consistency check.

Based on the importance of the eight quantitative indicators, the judgment matrix is constructed:³³

$$A = [a_{ij}] = \begin{bmatrix} 1/4 & 1/3 & 1 & 1/7 & 1/5 & 1/4 & 2 & 2 \\ 2 & 3 & 5 & 1/3 & 1 & 3 & 7 & 5 \\ 2 & 3 & 4 & 1/3 & 1/3 & 1 & 5 & 5 \\ 1/3 & 1/2 & 1/2 & 1/5 & 1/7 & 1/5 & 1 & 1/3 \\ 1/4 & 1/2 & 1/2 & 1/5 & 1/5 & 1/5 & 3 & 1 \\ 2 & 3 & 7 & 1 & 3 & 3 & 5 & 5 \\ 1 & 2 & 4 & 1/2 & 1/2 & 1/3 & 3 & 4 \\ 1/2 & 1 & 3 & 1/3 & 1/3 & 1/3 & 2 & 2 \end{bmatrix} \quad (I)$$

The term a_{ij} represents the importance of the i -th indicator relative to the j -th indicator. Based on this, the eigenvalue M_i of the judgment matrix for each i -th row, corresponding to the j -th indicator, is calculated as follows:

$$M_i = \prod_{j=1}^m a_{ij} \quad (i, j = 1, 2, 3, \dots, n) \quad (II)$$

By calculating the eigenvalues and eigenvectors of the judgment matrix, the weight vector W_i for each indicator is obtained:^{34,35}

$$W_i = \sqrt[n]{M_i} \quad (III)$$

The consistency ratio (CR) of the judgment matrix is then calculated. If CR is <0.1 , the matrix is considered to exhibit satisfactory consistency; otherwise, it must be revised. Based on the weights of each indicator and their corresponding values, the comprehensive score is calculated:³⁶⁻³⁸

$$S = \sum_{i=1}^8 W_i \times X_i \quad (IV)$$

where X_i represents the specific value of the i -th indicator, while S denotes the comprehensive score of the i -th indicator.

The vector $W_i = (W_1, W_2, W_3, \dots, W_n)$ is normalized, as shown in Table 2.

$$W_i = W_i / (\sum_{i=1}^m W_i) \quad (V)$$

Based on Table 2, the total weight of the evaluation indicators is normalized to 1, with each weight reflecting the relative importance of the corresponding indicator within the overall assessment framework. The eight quantitative indicators, ranked in descending order of their weight proportions, are as follows: K7 (29%) $>$ K8 (22%) $>$ K1 (16%) $>$ K6 (13%) $>$ K2 (8%) $>$ K3 (5%) $>$ K4 (4%) $>$ K5 (3%). Among these, K7

plays a decisive role in determining the suitability of riverbank groundwater sources for water intake, thereby receiving the highest weight.

3.2.3. Calculation of the judgment matrix

In the AHP, consistency checking of the judgment matrix is a critical step to ensure the rationality of the weight assignment. In this study, the CR, consistency index (CI), and the average random index (RI) were employed to evaluate the consistency of the pairwise comparison matrix. The Delphi method was adopted for two rounds of anonymous scoring and feedback to ensure convergence. If the CR is <0.1 , the consistency of the judgment matrix is considered acceptable.

According to Table 3, the judgment matrix demonstrates satisfactory consistency ($n = 8$; $RI = 1.41$; $\lambda = 8.541$; $CI = 0.081$; $CR = 0.057$), indicating that the assigned weights are reasonable.

3.2.4. Indicator classification and scoring

Based on relevant domestic and international studies on the classification and scoring of impact indicators for water source site selection,³⁹ and taking into account, the specific characteristics of riverside water intake sites, a scoring standard for the evaluation index system of water intake adaptability in such areas has been established, as shown in Table 4.

3.2.5. Calculation of evaluation scores

Based on the classification criteria presented in Table 4, each quantitative indicator was categorized and assigned a corresponding score, resulting in an individual evaluation value for each indicator. Subsequently, a weighted summation was performed based on the indicator weights provided in Table 2. The comprehensive score S for all quantitative indicators of the riverside water intake site was then calculated using equation IV. Considering the geomorphological

Table 2. Weights of the evaluation indicators for riverside water intake suitability, derived from calculations based on equations I-V

Evaluation indicator	K1	K2	K3	K4	K5	K6	K7	K8
Weights	0.16	0.08	0.05	0.04	0.03	0.13	0.29	0.22

Notes: K1 – K8 represent the following indicators: K1: Minimum river discharge during the dry season; K2: Riverbed permeability; K3: Aquifer hydraulic conductivity; K4: Aquifer thickness; K5: Presence of continuous impermeable layers; K6: River water quality; K7: Groundwater quality; K8: Groundwater depth.

Table 3. Consistency evaluation of the judgment matrix

Order	1	2	3	4	5	6	7	8	9	10	11
Random index	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.52

characteristics and hydrogeological conditions of the study area, the Natural Breaks classification method in ArcGIS (Esri, Inc., USA) was employed to integrate the quantitative and qualitative evaluation results using a 1:1 weighting ratio. The final comprehensive suitability grading of the water source site is presented in Table 5.

4. Results of the suitability for water intake

Long-term hydrological monitoring data were used to determine the seasonal runoff variation patterns during the dry season. The dataset covered the period from 2013 to 2022, with 12 monitoring stations distributed across the study area and monthly average values recorded. The water quality sampling plan included

quarterly sampling and compliance with national standards – GB/T 14848-2017 for groundwater and GB 3838-2002 for surface water – with multiple types of parameters measured. Geological surveys provided information on the types and thicknesses of riverbed sediments, which were analyzed to assess their impact on lateral recharge capacity.

Based on borehole logs and pumping test data, the permeability characteristics of the aquifer were analyzed. Combined with terrain data and K8 measurements, the spatial distribution of K4 and K8 was calculated. Geological exploration was conducted to determine the distribution range and thickness of continuous impermeable layers and to evaluate their impact on aquifer permeability. For water quality analysis, samples from both river water and groundwater were collected,

Table 4. Scoring standards for evaluating the adaptability of riverbank water intake sites

K1 (10 ⁹ m ³ per year)	K2 (m/d)	K3 (m/d)	K4 (m)	K5 (m)	Score	K6 (/)	K7 (/)	Score	K8 (m)	Score
>150	>100	>100	>100	<0.3	100	I	I	100	<5	100
50 – 150	50 – 100	50 – 100	50 – 100	0.1 – 0.5	90	II	II	90	5 – 10	90
10 – 50	20 – 50	20 – 50	30 – 50	0.5 – 1	80	III	III	80	10 – 15	80
5 – 10	5 – 20	5 – 20	10 – 30	1 – 3	70	IV	IV	60	15 – 20	70
1 – 5	1 – 5	1 – 5	5 – 10	3 – 5	60	V	V	-150	20 – 25	60
0.1 – 1	0.1 – 1	0.1 – 1	2 – 5	5 – 10	30				25 – 30	30
<0.1	<0.1	<0.1	<2	>10	0				>30	

Note: K1 – K8 represent the following indicators: K1: Minimum river discharge during the dry season; K2: Riverbed permeability; K3: Aquifer hydraulic conductivity; K4: Aquifer thickness; K5: Presence of continuous impermeable layers; K6: River water quality; K7: Groundwater quality; K8: Groundwater depth.

Table 5. Comprehensive classification of water source site suitability based on combined quantitative and qualitative scores (1:1 ratio)

Comprehensive score <i>S</i>	Class	Suitability evaluation	Characteristic description
83 < <i>S</i> < 100	I	Excellent suitable area	The water quality meets potable standards and does not require additional treatment. The water supply is sufficient, and a strong hydraulic connection exists between surface water and groundwater, ensuring reliable water quantity and quality. The development and utilization of groundwater resources are deemed suitable, making the area appropriate for riverside water intake.
56 < <i>S</i> < 83	II	Good suitable area	
49 < <i>S</i> < 56	III	Moderate suitable area	
42 < <i>S</i> < 49	IV	Marginally suitable area	The water quality is poor and unsuitable for direct consumption, and the water supply conditions are relatively inadequate. However, with appropriate water treatment and controlled intake measures, the development of riverside groundwater resources remains feasible.
0 < <i>S</i> < 42	V	Unsuitable area	Poor water quality, high intake difficulty, and significant treatment costs, combined with an inadequate water supply, hinder sustainable water intake – making the area unsuitable for riverside groundwater intake.

and the comprehensive index method was employed to assess water quality conditions.

A systematic analysis and evaluation of eight key indicators were conducted across the study area to identify optimal zones for riverside water intake. Using the scoring standards for each indicator, ArcGIS was employed to generate scoring zonation maps for all quantitative indicators. In terms of spatial analysis, this study provides a detailed explanation of the interpolation method (Kriging), grid resolution (50 m × 50 m), and the logic behind classification and partitioning (Figure 4).

Based on the established evaluation indicator system, this study assessed eight quantitative indicators. A weighted sum was then calculated using the assigned weights for each indicator. Qualitative indicators – such as land use type and safety distance – were integrated in ArcGIS using a 1:1 weighting ratio. Raster layers were multiplied to compute the combined suitability. In the resulting output, areas with a value of 0 indicate zones unsuitable for the construction of riverside water intake sites. Finally, the quantitative and qualitative evaluation results were integrated. Raster data operations in ArcGIS

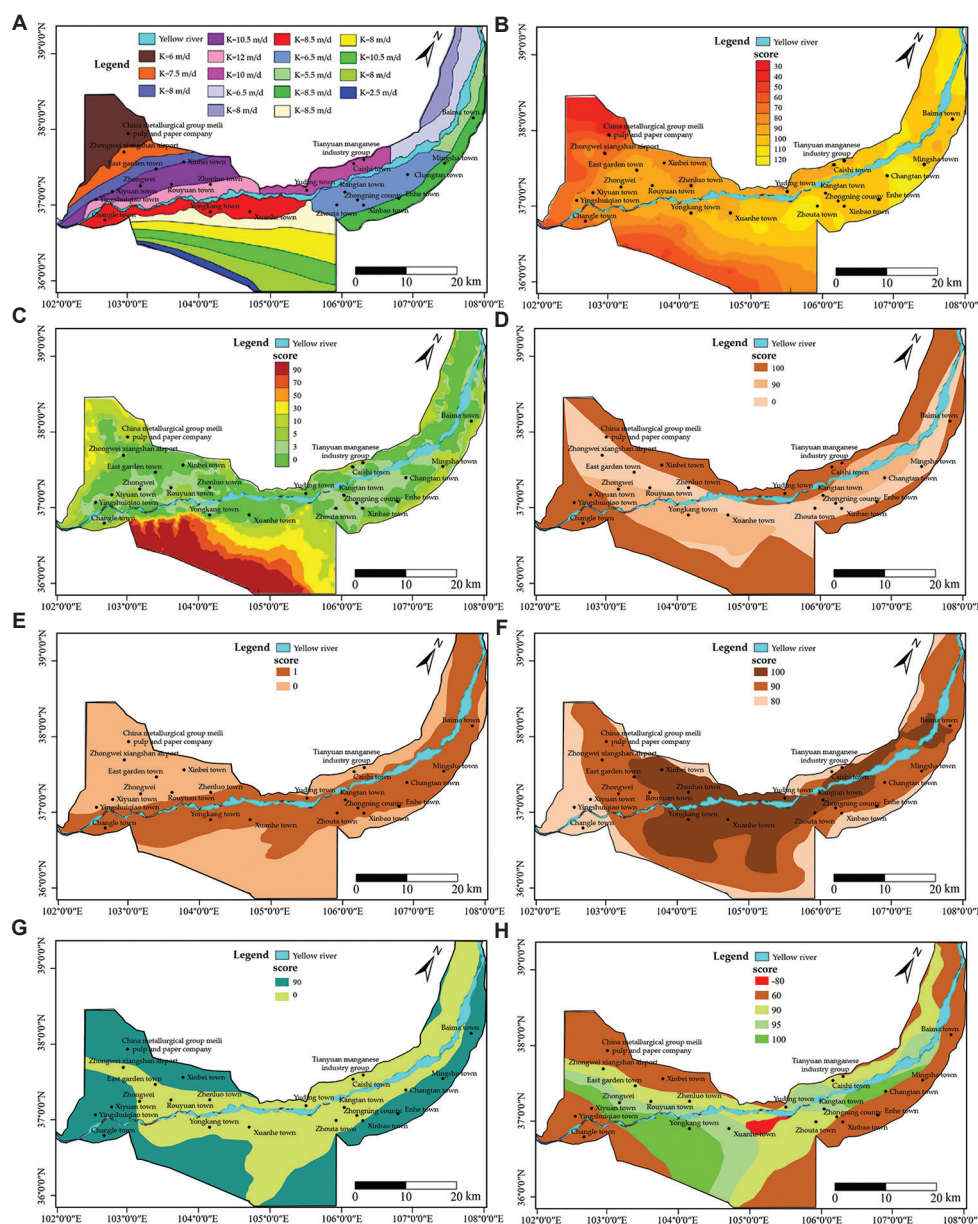


Figure 4. Scoring zones of the eight quantitative indicators in the study area: (A) Aquifer permeability; (B) Aquifer thickness; (C) Groundwater burial depth; (D) River discharge during dry season; (E) Riverbed sedimentation; (F) Continuous impermeable layers; (G) River water quality; and (H) Groundwater quality

were used to generate the comprehensive suitability map, which was then classified into zones according to the integrated scoring classification standard. The final suitability zoning of water source intake sites in the study area is shown in Figure 5.

Based on the spatial classification results shown in Figure 5 and supported by statistical analysis, it is evident that a significant portion of the study area is suitable for the development of riverside water intake sites. Specifically, the suitability classification reveals that 8.63% of the area falls under class I (most suitable), 36.21% under class II (good suitability), 17.54% under class III (moderate), 23.18% under class IV (poor), and 14.44% under class V (unsuitable). This distribution pattern reflects the combined influence of favorable hydrogeological conditions, topography, and water quality parameters across the study area.

Among these, class II areas – classified as having good suitability – are primarily concentrated along the riverbanks of Yongkang–Xuanhe Town and Shikong Town. A representative high-suitability zone is located along the Yellow River near Xuanhe Town, extending from the Qixing Canal inlet gate in the west to the estuary of the Qing Shui River in the east, bounded by Binhe South Road to the north and Weining Highway to the south. This zone features a ground elevation ranging from 1215 to 1190 m, with groundwater depths between 1 and 3 m, indicating shallow and easily accessible aquifers. The average annual river discharge at the bank intake station is $2.98 \times 10^{10} \text{ m}^3$, ensuring reliable water availability throughout the year.

Hydrogeologically, the aquifer in this region consists of alluvial sand and gravel with diverse lithological compositions and interbedded low-permeability layers, such as fine sand and silt. The average permeability coefficient is 2 m/d for the riverbed and 10 m/d for the aquifer, while aquifer thickness varies between 30 and 100 m. These characteristics indicate strong aquifer transmissivity and favorable recharge conditions.

In terms of water quality, the surface water of the Yellow River in this area is classified as class II–III, and the groundwater as class III–IV, both within acceptable limits for drinking water sources following appropriate treatment. The combination of stable aquifer structures, low pollution risk, sufficient water yield, and manageable depths renders this area highly favorable for riverbank water intake development.

In contrast, areas classified as class V (unsuitable) are characterized by one or more limiting factors – such as excessive groundwater burial depth, significant riverbed sedimentation, or the presence of continuous impermeable interlayers – that significantly hinder vertical recharge. Moreover, these areas often correspond with zones of lower aquifer permeability or compromised water quality due to anthropogenic influences. The spatial distribution of these unsuitable zones highlights the importance of integrating both natural and human-induced parameters into site suitability assessments.

The evaluation results obtained by the proposed suitability model have been validated against existing riverbank water intake projects within the study

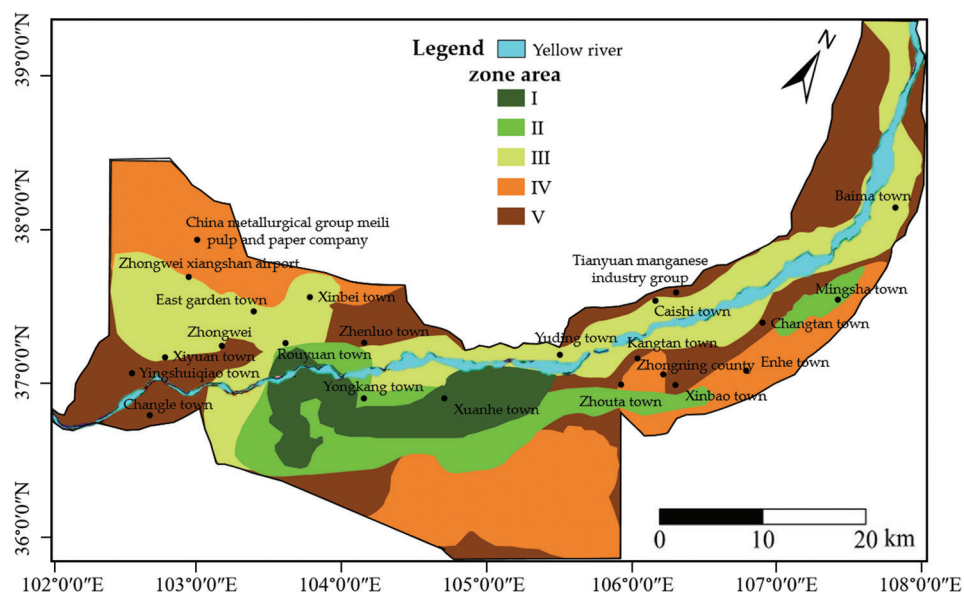


Figure 5. Suitability zoning map of riverside water intake sites in the study area

Table 6. The suitability index scoring results for riverside water intake sites

Project	K1	K2	K3	K4	K5	K6	K7	K8
Weight	0.16	0.08	0.05	0.04	0.03	0.13	0.29	0.22
Score	60	100	75	70	90	70	85	40
Individual score	9.6	8	3.75	2.8	2.7	9.1	24.65	8.8
Total	69							

Notes: K1 – K8 denote the following indicators: K1: Minimum river discharge during the dry season; K2: Riverbed permeability; K3: Aquifer hydraulic conductivity; K4: Aquifer thickness; K5: Presence of continuous impermeable layers; K6: River water quality; K7: Groundwater quality; K8: Groundwater depth.

area, particularly the intake site near Xuanhe Town. According to the comprehensive index evaluation (Table 6), this site achieves a suitability score of 69 points, corresponding to a class II classification, which indicates good exploitation potential. Field-based hydrogeological surveys and water quality monitoring data further confirm that the aquifer thickness, permeability, water depth, and surface–groundwater quality align with model predictions, thereby demonstrating the practical applicability and reliability of the evaluation system.

5. Discussion

Compared to previous studies that have primarily focused on individual aspects such as hydrological modeling, pollutant transport, or environmental risk assessments,^{40–42} this study proposes an integrated, multi-criteria evaluation framework that captures both surface and subsurface hydrological processes. The inclusion of indicators such as aquifer permeability, riverbed sedimentation, and groundwater depth reflects the hydrogeological complexity of the Weining–Yellow River alluvial plain and provides a more holistic basis for assessing intake suitability.

However, the applicability of this model beyond the current case study region remains a significant limitation. The Weining–Yellow River alluvial plain exhibits specific geological and climatic characteristics – such as semi-arid conditions, a relatively stable hydrodynamic regime, and a sediment-dominated riverbed – which may not be representative of other river systems. Thus, the generalizability of the evaluation model requires further validation before application to other regions. For instance, river systems in humid monsoon regions, mountainous catchments, or karst landscapes present fundamentally different geomorphic and hydrogeological conditions that may render certain evaluation indicators less relevant or require adjustments to indicator weights and thresholds.

Therefore, while this study offers valuable insights into the selection of riverbank water intake sites in similar alluvial plains, future research is essential to verify and adapt the evaluation model across diverse environmental settings. Comparative applications in various climate zones and morphodynamic contexts – such as the Yangtze River basin, inland arid regions, or tropical floodplains – would help evaluate its robustness and scalability. Moreover, to improve generalizability, researchers may consider integrating a modular indicator system that allows users to flexibly include or exclude parameters based on local hydro-environmental conditions.

In addition, this study employed static input parameters (i.e., fixed values for the quantitative indicators), which may not fully capture the dynamic nature of river–aquifer interactions. Temporal variations in river discharge, groundwater levels, and contaminant loading – particularly under the influence of climate change or upstream land-use alterations – could significantly affect suitability over time. Therefore, it is recommended that future research incorporates temporal simulation components or scenario-based assessments, potentially using hydrological modeling tools in combination with GIS to evaluate long-term sustainability.

In summary, this study presents a scientifically grounded and practically validated suitability evaluation framework that integrates key hydrological and geological indicators. It addresses the gap between theoretical assessment methodologies and on-the-ground planning needs. Nevertheless, to achieve broader applicability and operational robustness, the model requires further calibration, comparative validation, and adaptation across diverse environmental contexts.

6. Conclusion

This study employed eight quantitative indicators (K1 – K8) to evaluate the suitability of riverside water intake sites. The AHP was used to determine the

weights and grading methods for these indicators, and a suitability grading standard for groundwater source site exploitation was established. The Weining–Yellow River alluvial plain was selected as the study area. The constructed evaluation model for riverbank groundwater source suitability was applied in combination with ArcGIS to calculate the suitability index for riverbank water intake. Based on the grading standard, suitability zones in the study area were determined, identifying the Weining Basin water source area as a class II zone (good suitability). This zone extends from the Seven-Star Canal inlet gate in the west to the Qing Shui River mouth at the Yellow River in the east, bounded by Binhe South Road to the north and Weining Highway to the south. Verification using an existing riverside water intake site project confirms the evaluation system’s practical value and its accuracy in reflecting local suitability conditions for riverbank water intake in the study area. This framework provides practical guidance for the planning and development of riverbank water intake systems in similar hydrogeological settings.

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Conflict of interest

The authors declare that they have no competing interests.

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Availability of data

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