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Construction of a water resource suitability index for agricultural production and matching analysis of cultivated land in Lhasa, Tibet

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Water resources are essential for agriculture. In the spatial layout of agricultural production, quantitatively identifying the spatial differences in water resource conditions, including precipitation and irrigation water supply factors, is necessary. Here, a water resource suitability index for agricultural production (WRSIA) was constructed for agricultural development using irrigation water supply convenience (IWSC) and precipitation conditions. Considering Lhasa as the study area, water resource suitability index for agricultural production was calculated on a 100 m grid scale, and the spatial distribution relationship between water resource suitability index for agricultural production and cultivated land was analyzed using geographically weighted regression (GWR). The results showed that irrigation water supply convenience severely restricted agricultural production in Lhasa, and the high water resource suitability index for agricultural production values were mainly distributed in the valleys of the Lhasa River and its tributaries. Moreover, 47.7% of the cultivated land was distributed in 5% of the area having the highest water resource suitability. According to geographically weighted regression, the cultivated land area and water resource availability were strongly correlated ($R^2 = 0.904$). The distribution of the cultivated land was well explained by water resource suitability index for agricultural production, which could describe the differences in water resource suitability for agricultural production. Furthermore, the suitability of agricultural production was better evaluated when water resource suitability index for agricultural production was coupled with the land resource suitability index. Overall, water resource suitability index for agricultural production showed high applicability in Lhasa and other regions, thereby providing a scientific basis and technical support for the spatial layout of agricultural production.

KEYWORDS

water resource suitability index for agricultural production (WRSIA), irrigation water supply convenience (IWSC), cultivated land, geographically weighted regression (GWR), Lhasa

1 Introduction

Water is an essential resource for agricultural production and plays an important role in agricultural development (Wienhold et al., 2000; Cao et al., 2018). Both non-irrigated and irrigated agricultural lands require water. Particularly, non-irrigated farmlands require sufficient precipitation to ensure crop growth, whereas irrigated lands require needs suitable water supply

conditions. The contradiction of agricultural water use has become increasingly prominent and become a constraint for agricultural production in some areas (Li, 2019; Shi et al., 2016). Developing methods to measure the association between the sustainability of water resource conditions and agricultural production and to optimize the spatial layout of agricultural production according to the suitability conditions of water resources has become an increasing concern of having scientific and practical significance (Joerin et al., 2001; Chen et al., 2010; Ozkan et al., 2020).

Water resource suitability for agricultural production was initially studied by assessing agricultural production conditions in agricultural zones. In the 1930s, Soviet scholars first proposed agroclimatic zoning and conducted agroclimatic zoning by identifying and analyzing the most important climatic indicators for crop growth and development (Tian et al., 2008). In the 1960s, Japan conducted agricultural zoning based on the geographical zoning of statistical agricultural and forestry land, areal agricultural types, administrative regions, natural conditions, and production characteristics (Guo, 1989; Zhang et al., 2007). In China, integrated agricultural regionalization was studied from the 1950s to the 1960s using indicators, such as precipitation and dryness, to classify dry and wet partitions as the basis for agricultural regionalization (Huang, 1958; Chen, 1979; Shen et al., 1982; Shen and Li, 1983). Extensive climate resource surveys and agricultural climate zoning studies were conducted from the 1970s to the 1980s. Additionally, the Third National Agroclimatic Zoning was conducted from 1998 to 1999 by the China Meteorological Administration (Li, 1988; Zhang et al., 2009; Tao and Chen, 2014). In terms of indicator evaluation methods, crop production water requirements and precipitation processes were coupled and analyzed. Yang et al. (2005) constructed a water balance table simulation to assess the crop water requirement considering monthly precipitation, soil water, and deficit processes. Caldana et al. (2019) conducted agroclimatic risk zoning of avocados in the Paraná River Basin, Paraná State, Brazil, based on precipitation, water balance, and other conditions. Moreover, Zhang et al. (2022) proposed a stochastic simulation model by integrating the Monte Carlo, Copula and Markov process (MCMP-Copula) for agricultural water scarcity risk assessment based on indicators, such as crop water requirement and adequate precipitation. Masupha et al. (2016) measured the effect of drought on rainfed maize production in the Luvuvhu River Basin using the water demand satisfaction index. Furthermore, the influence of precipitation and temperature on agricultural development has also been widely studied previously (Henseler et al., 2009; Falloon and Betts, 2010; Silva et al., 2013; Elliott et al., 2014). Several complex factors affect agricultural production; therefore, many scholars have developed the framework of the indicator system based on the AHP model (Analytic Hierarchy Process Model) to assess the suitability of water resources for agricultural production (Ceballos Silva et al., 2003; Akinci et al., 2013; Bozdogan et al., 2016; Yalaw, 2016; Akpoti et al., 2019; Everest et al., 2021; Al-Hanbali et al., 2022; Shaloo et al., 2022). Although the analysis method based on indicator weights has a sizeable subjective factor, some scholars use machine learning models, such as random forest, to estimate the relative weights of the selected evaluation indicators (Taghizadeh-Mehrjardi et al., 2020; Singh R. et al., 2022).

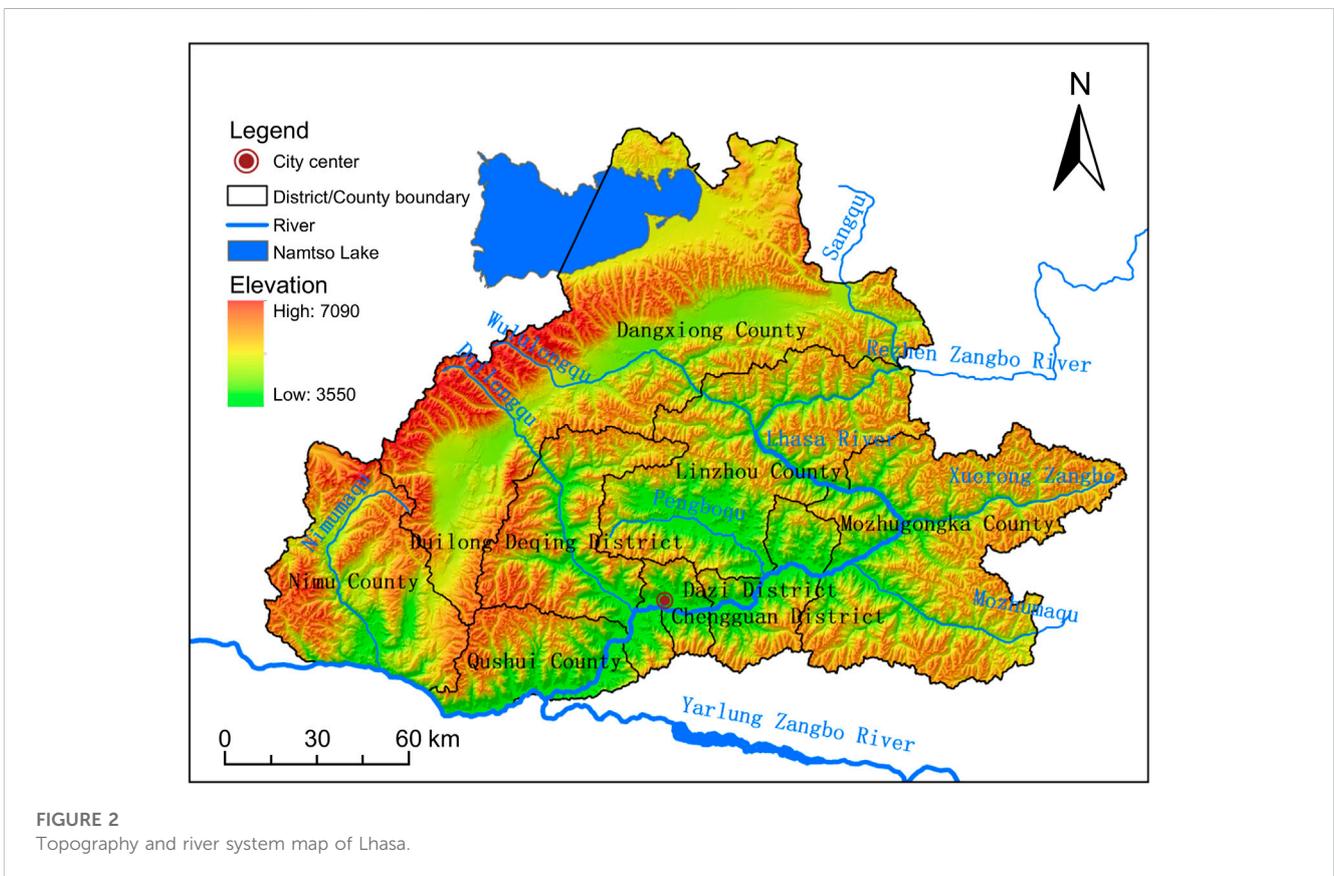
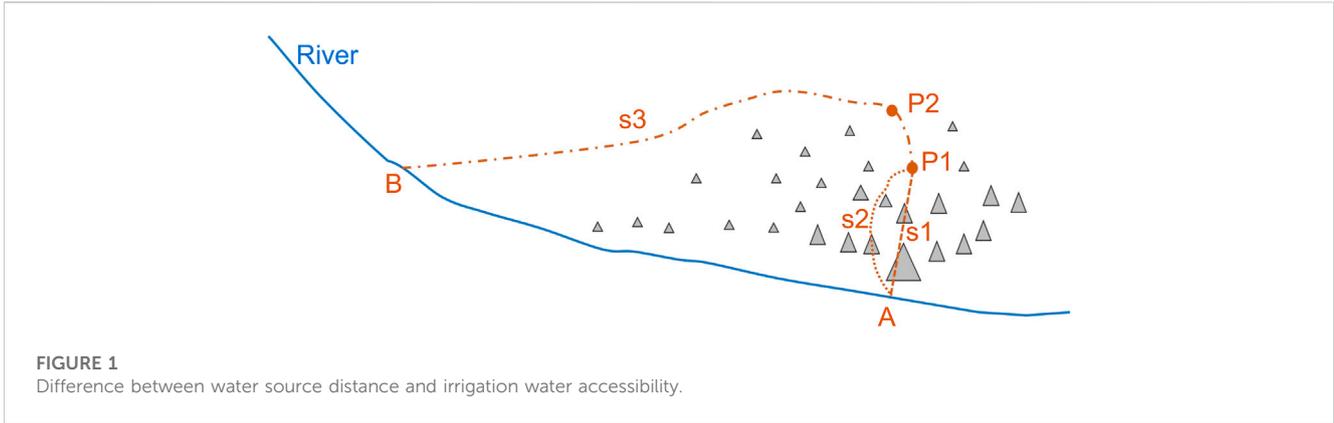
Water resources suitability studies are an essential basis for agricultural production layout and have been widely used in national and basin-wide agricultural development planning (Zolekar and Bhagat, 2015; Aldababseh et al., 2018; Hagos et al., 2022; Roy et al., 2022). Within watersheds, water resource suitability is also an important factor influencing the layout of agricultural development. In China's ongoing Territorial Spatial Planning, a high-precision water resource suitability assessment is required to reallocate agricultural, urban and ecological spaces on a grid scale. (Feng et al., 2018; Zhang et al., 2020; Li et al., 2021). However, most of the commonly used water resources indicators are statistical data, which cannot describe the differences in water resources conditions within a region and cannot meet the high precision requirements of Terrestrial Spatial Planning (Li et al., 2021; Liu and Zhou, 2021; Battisti et al., 2022). In some studies, water source distance is usually used to characterize the accessibility of irrigation water and to assess the water resource suitability for agricultural production (Lane, 2010; Wang, 2018; Shen et al., 2020; Hsu et al., 2021; Zhu et al., 2022). However, the distance to the water source does not equal to irrigation water accessibility. As shown in Figure 1, the optimal water supply path from water source A to P1 may be the curve s2 instead of the straight line s1, because s2 has fewer hills. Furthermore, the water supply path s3 from B may be better than s2 from A. Moreover, the irrigation water accessibility of Point P2 is better than that of Point P1, even though P2 is linear and far from the river source.

Thus, Lhasa City, which has a complex terrain and mainly been dominated by irrigated agricultural production, was selected as the study area. In this study, a framework for evaluating the suitability of water resources, including the convenience of water supply, was constructed to assess the water accessibility and suitability for agricultural production. Both distance to the water source and topographical influences in the water supply path were considered. Subsequently, the supporting capacity of irrigation water supply conditions and precipitation for agricultural production was comprehensively measured. The results provide a scientific basis for agricultural production in the territorial spatial planning of Lhasa and a reference for the layout of agricultural production in other areas with complex terrain.

2 Materials and methods

2.1 Study area

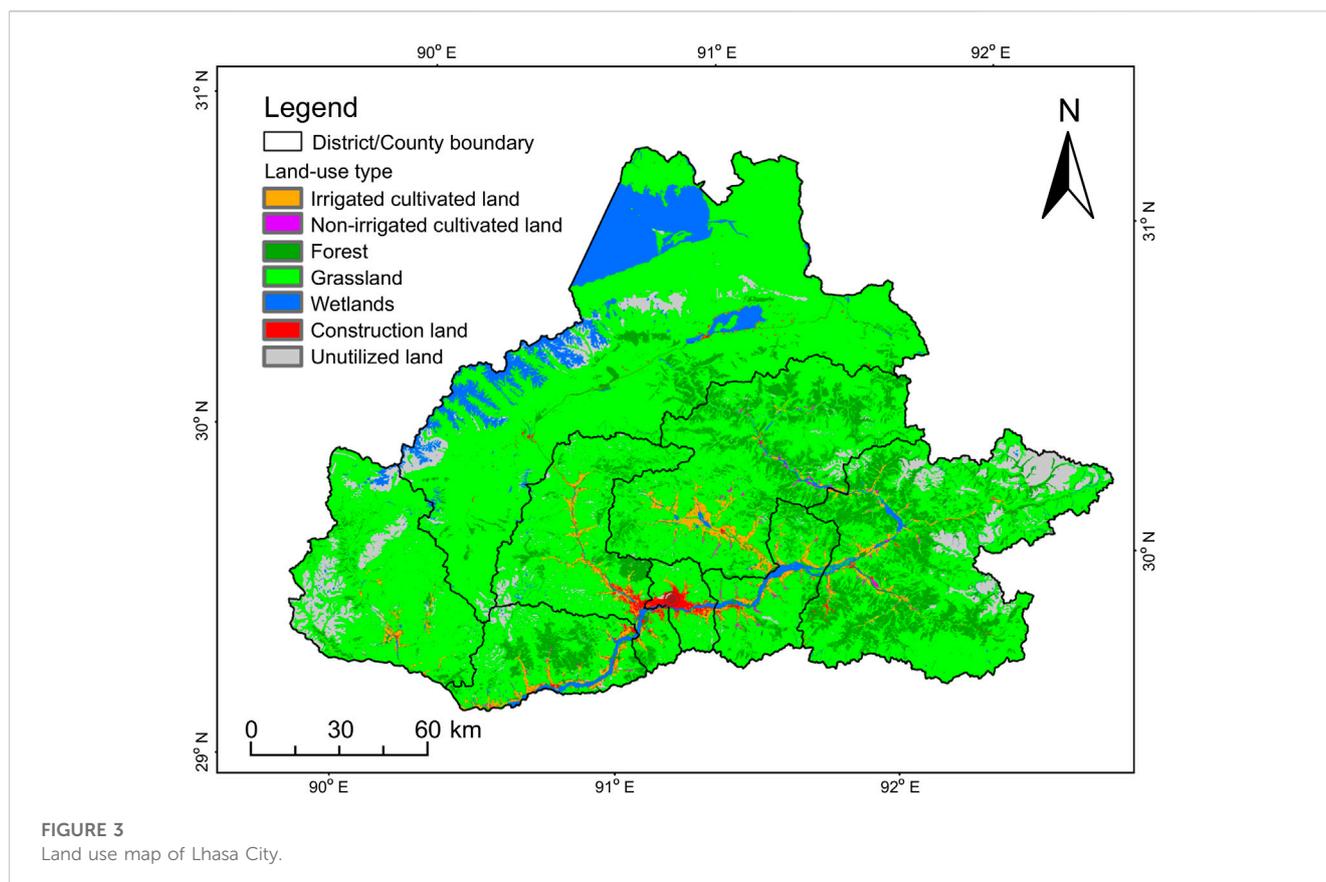
Lhasa City in Tibet, China, covers an area of approximately 30,000 km². The administrative divisions of Lhasa include three districts (Chengguan, Duilong Deqing, and Dazi Districts) and five counties (Linzhou, Damxiong, Nimu, Qushui, and Mozhugongka Counties). The average elevation of Lhasa is 4,852 m, with relatively higher elevation in the north than in the south. Lhasa mainly has a mountainous terrain, except for some river valleys and the northern Dangxiong Basin (Figure 2). The annual average precipitation is approximately 420 mm, which is mainly concentrated during June–September. The region is mostly located in the Yarlung Zangbo River Basin, and only a small part in the north belongs to the Namtso Lake Internal flow region. The main rivers include the Lhasa River and its tributaries (Sangqu, Wululongqu, Xuerong Zangbo, Mozhumaqu, Pengboqu, and Duilongqu Rivers) and



Nimumaqu River, a tributary of the Yarlung Zangbo River. The Lhasa River, which is the primary water source in Lhasa, is an important tributary of the Yarlung Zangbo River, with a total length of 495 km, drainage area of 32,500 km², and an average annual flow of 287 m³/s.

The land use types in Lhasa are mainly grassland and forest, and artificial ecosystems, such as cultivated land and construction land, comprise a relatively small proportion (Figure 3). Grasslands, which account for approximately 70% of the city's total area, are mainly distributed in the plateau valleys and mountains of medium elevated and highest. Grasslands are followed by forests dominated by natural shrubland and mainly distributed in Linzhou and Mozhugongka

Counties. The cultivated land area covers 61,824 ha, accounting for 2.1% of the total area. Owing to insufficient precipitation, the cultivated land in Lhasa includes mainly irrigated farmland, with a total area of 54,396 ha, whereas the remaining 7,428 ha includes non-irrigated farmlands. The irrigated farmlands are mainly distributed in the valleys of the Lhasa, Nimumaqu, Dui longqu, Mozhumaqu rivers, and other rivers, whereas the non-irrigated cultivated lands are dispersed around the irrigated cultivated land. Furthermore, rivers, which are the main water source for agricultural irrigation, are abundant in Lhasa. The average annual water resources comprise approximately 7.2 billion m³, with 8,600 m³ per capita and 116,000 m³/ha of cultivated land, which meet the agricultural



requirements. However, engineering conditions limit Lhasa's agricultural irrigation supply, indicating that the restrictions on water resources are mainly spatial rather than quantitative.

Lhasa City is one of the most suitable regions for human activities in Tibet; particularly, agricultural production in this region plays an important role in ensuring regional food security. Given the large population, the scale and spatial layout of agricultural production have been gaining attention. Irrigation convenience is a limiting factor for agricultural development. However, conventional indicators, such as distance of the water supply source, cannot represent the spatial differences because several factors other than the distance affect convenience in mountainous areas. Therefore, identifying new indicators that characterize the spatial differences in water resource suitability for agricultural production in Lhasa is necessary to provide a scientific basis for developing regional agricultural production layouts.

2.2 Data sources

A land use map with a 1:10,000 scale was obtained from the Second National Land Survey conducted in 2018. Precipitation and evapotranspiration data in a 1,000 m grid and digital elevation model (DEM) data in a 30 m grid were downloaded from the Resource and Environment Science and Data Center, Chinese Academy of Science (<https://www.resdc.cn>). The details of the data used in this study are listed in Table 1. The data were resampled to a 100 m grid in ArcGIS using a bilinear interpolation algorithm.

2.3 Methods

The Water Resource Suitability Index for Agricultural Production (WRSIA) model was constructed. It consists of two components: precipitation supporting capacity and Irrigation Water Supply Convenience (IWSC). Precipitation supporting capacity refers to the ability of precipitation conditions to support rain-fed agriculture and is assessed by the magnitude of precipitation. IWSC characterizes the suitability of water resources for the development of irrigated agriculture and is assessed using distance from potential water supply sources and lift elevation, as measured using the model, as shown in Figure 4.

2.3.1 Runoff model construction and river network extraction

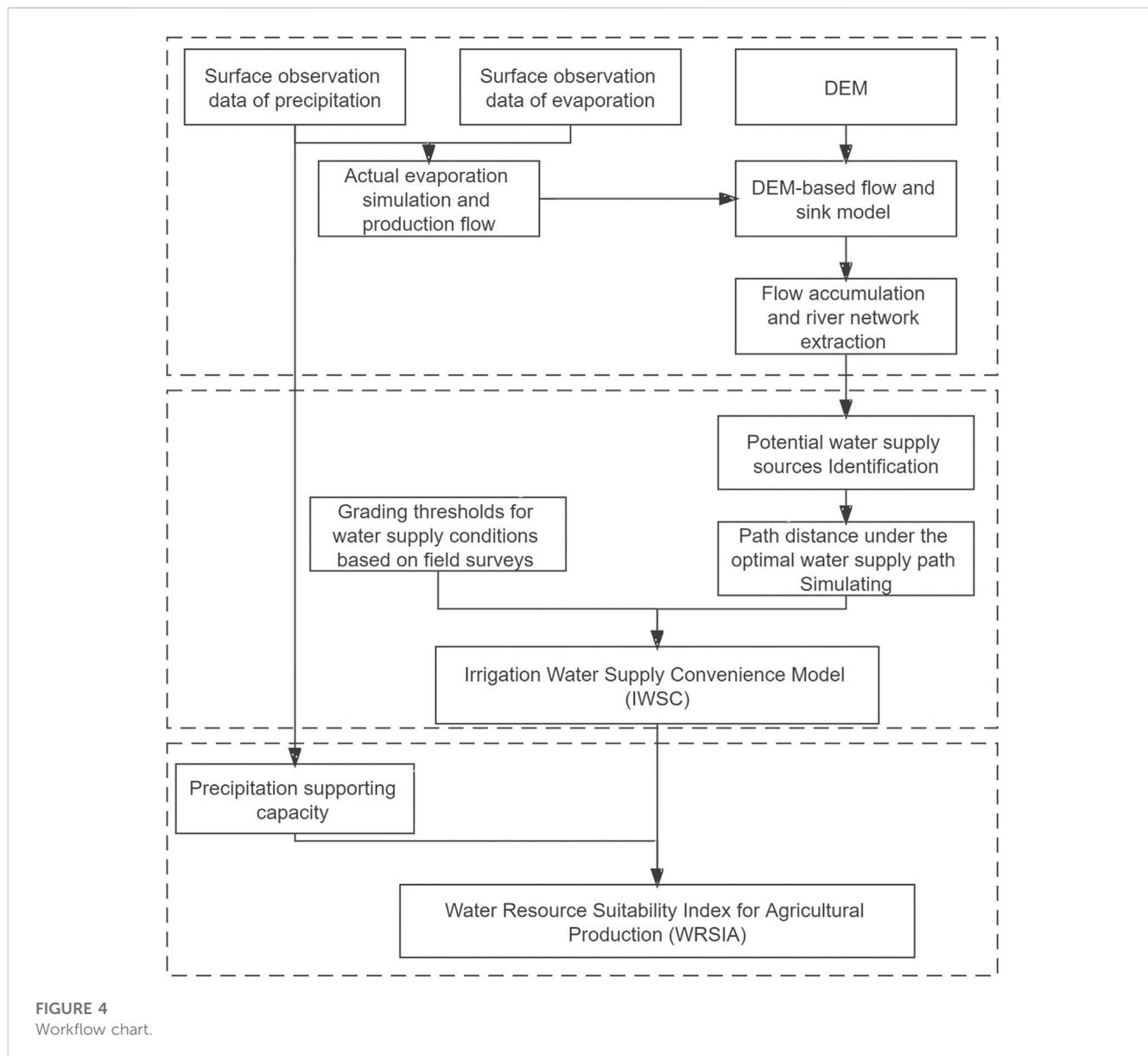
In order to identify potential water supply sources, a hydrological model needs to be constructed for flow simulation. The runoff of each grid was calculated by subtracting the actual evaporation from precipitation data. The actual evaporation was estimated using the formula (Zhang et al., 2001; Zhang et al., 2004) that is commonly used in areas where hydrological information is lacking, as shown below:

$$\frac{E}{P} = \frac{1 + \omega \frac{E_0}{P}}{1 + \omega \frac{E_0}{P} + \left(\frac{E_0}{P}\right)^{-1}} \quad (1)$$

Where, E is the actual evapotranspiration, p is precipitation, E_0 is potential evapotranspiration, and ω is the plant available water coefficient.

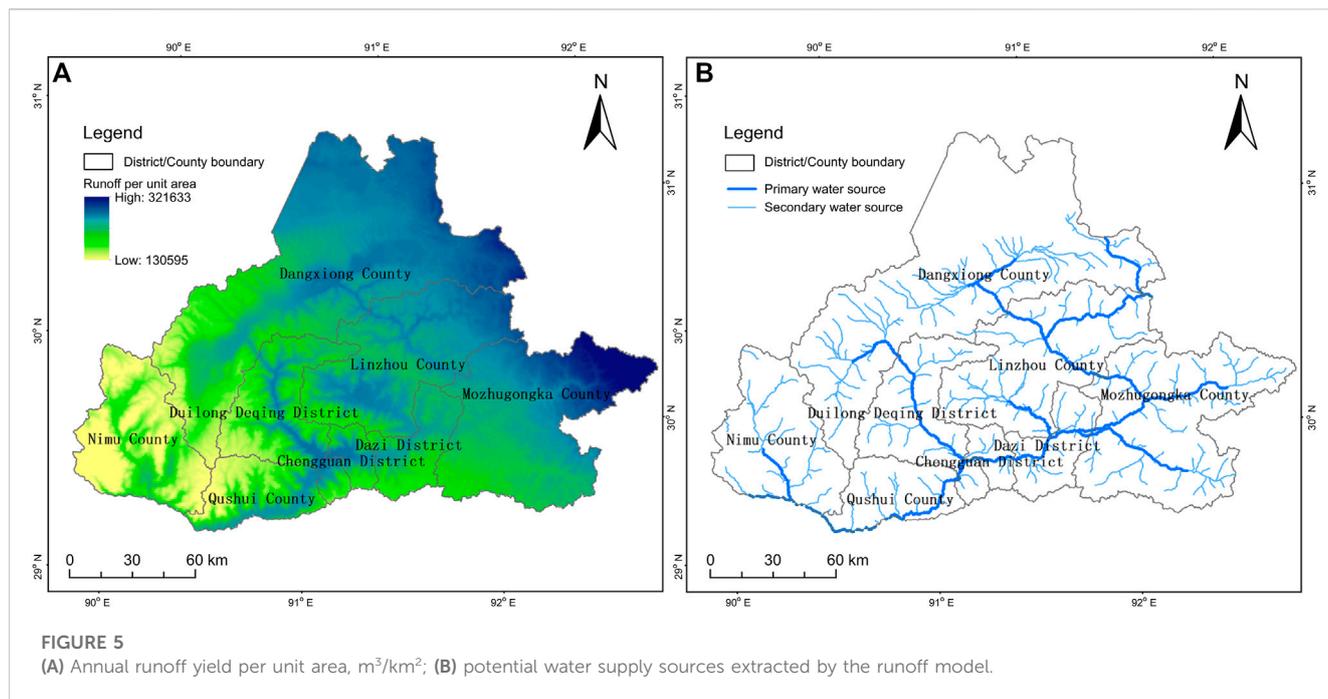
TABLE 1 Principal data sources in this study.

Data	Resolution	Source	Date
Land use type	1:10,000	National Land Survey	2018
Digital elevation model	30 m	Resource and Environment Science and Date Center, Chinese Academy of Science (https://www.resdc.cn/)	2007
Precipitation and evapotranspiration	1,000 m	Resource and Environment Science and Date Center, Chinese Academy of Science (https://www.resdc.cn/)	1980-2015



A 100 m grid scale runoff model was constructed for Lhasa. Potential water sources for Lhasa’s agricultural water supply were extracted from the DEM depression filling process, slope aspect analysis, flow accumulation, and river network extraction. The results of runoff per unit area calculated by Zhang’s formula show the characteristics of high runoff in the east and low runoff in the west

(Figure 5A), which is consistent with the actual situation of Lhasa city (Sun et al., 2019; Cai et al., 2021). The multi-year average yield flow in Lhasa City obtained from the model result statistics is 6.9 billion m³, which has an error of 4.2% with the observed value, and this error is acceptable for the extracted river network. Moreover, a field survey of Lhasa’s agricultural water supply sources was conducted to determine



the selection standard for primary and secondary agricultural water supply sources. The corresponding extraction results are shown in Figure 5B. The primary water source referred to the water source with the highest degree of water supply security that met the irrigation requirements of large scale irrigation areas, and the selection standard was rivers having an average annual runoff of more than 300 million m³. The secondary water sources referred to water sources with relatively low water supply security that met the requirements of small scale irrigated agriculture, and the selection standard was rivers with an average annual runoff ranging between 10 million and 300 million m³. According to the distribution of cultivated land, the water supply source selection standard was reasonable.

2.3.2 Irrigation water supply convenience (IWSC)

IWSC represents the convenience of irrigation conditions for agricultural development in irrigation areas, including irrigation water supply accessibility, and water source reliability. Water supply accessibility describes the magnitude of the cost of water supply and its affordability. This is determined by two factors, namely, the distance to the water supply source and the height of the required lift. The richer the water resources of the river water sources, the higher the degree of water supply security, and the more suitable the area is for the development of irrigated agriculture (Li, 2022). In this study, the level of reliability of the irrigation water sources was mainly distinguished based on the magnitude of river flow.

The convenience index of the irrigation water supply was calculated as follows:

$$I_P = 1 - \left(\frac{\sum_i d_{pi}}{D_{Pmax}} + \frac{\sum_i h_{pi}}{H_{Pmax}} \right) \quad (2)$$

$$I_S = 1 - \left(\frac{\sum_j d_{sj}}{D_{Smax}} + \frac{\sum_j h_{sj}}{H_{Smax}} \right) \quad (3)$$

$$IWSC = \text{Max} (0.6 + 0.4 \times I_P, 0.4 + 0.4 \times I_S) \quad (4)$$

Where, *i* and *j* refer to the points on the optimal water supply path, starting from the primary and secondary water supply sources, and simulated by the path distance module in ArcGIS. *I_P* and *I_S* refer to the irrigation water supply accessibility of the primary and secondary water sources, respectively. When *I_P* and *I_S* are <0, the area does not have irrigation water supply conditions, and the value is 0. *d_{pi}* and *h_{pi}* refer to the distance and water lifting height of pathway point *i*, respectively, and *D_{Pmax}* and *H_{Pmax}* refer to the maximum threshold distances of water diversion and the water lifting height of agricultural production in large scale irrigation areas, respectively. Furthermore, *D_{Pmax}* and *H_{Pmax}* were selected as 40 km and 60 m according to the irrigation agriculture survey in Lhasa City. *d_{sj}* and *h_{sj}* refer to the distance and water lifting height of pathway point *j*, and *D_{Smax}* and *H_{Smax}* are the maximum water transfer distance (20 km) and water lifting height (20 m) endured by agricultural production in small scale irrigation areas, respectively. Within the potential irrigation water supply range of primary water sources, the IWSC value range was 0.6–1, whereas it was 0.4–0.8 for secondary water sources. Notably, areas without irrigation conditions had a value of 0.

2.3.3 Water resource suitability index for agricultural production (WRSIA)

WRSIA represents the suitability of water resources for agricultural production. Considering the characteristics and agricultural water use of water resources in Lhasa, WRSIA was obtained by comprehensively evaluating precipitation and IWSC using the following equations:

$$C_P = \text{MIN} (P/2000, 0.6) \quad (5)$$

$$WRSIA = \text{MAX} [C_P, IWSC] \quad (6)$$

where *C_P* is the supporting capacity of precipitation for agricultural production. Areas with more abundant precipitation or higher

IWSC are more suitable for agricultural production; therefore the highest values of C_P and IWSC were taken as WRSIA. Natural precipitation uncertainty is high and seasonal deficits in agricultural water use can occur. Based on the field survey, the highest C_P value was determined to be 0.6, and the value is $[0, 0.6]$ according to the precipitation amount. In Lhasa City and the Tibetan Plateau region, precipitation above 1200 mm is sufficient for agricultural development; therefore, the C_P index is taken as the maximum value for areas above 1200 mm

2.3.4 Geographically weighted regression (GWR)

Brunsdon et al. (1996) built a GWR model that introduced the spatial location of the data into regression coefficients. The local estimator of the function was provided at each geographical location, and the spatial non-stationarity of the regression relationship was analyzed. Compared with the ordinary least squares method, GWR is more effective for analyzing data with spatial attributes (Lv and Zhen, 2010; Tang et al., 2012; Pang et al., 2014; Liu et al., 2022; Xu et al., 2022). Therefore, GWR was selected to analyze the correlation between cultivated land and WRSI. The GWR model formula was as follows:

$$y_i = \beta(u_i, v_i) \cdot x_i + \beta_0(u_i, v_i) + \varepsilon_i \quad (7)$$

where y_i is the dependent variable of the i^{th} grid unit, x_i is an independent variable of the i^{th} grid unit, (u_i, v_i) is the geographic coordinate of the i^{th} grid unit, $\beta(u_i, v_i)$ is the regression coefficient of the i^{th} grid unit, $\beta_0(u_i, v_i)$ is the intercept term at grid unit i , and ε_i is the random error term.

3 Results

3.1 WRSIA

According to the formula of irrigation water supply accessibility, the path distance and accessibility indicators of each grid from the primary and secondary water sources were measured using ArcGIS, and the corresponding results are shown in Figures 6A, B, respectively. High mountains and valleys dominated Lhasa, and areas with better accessibility were concentrated in the river valleys. The IWSC results are shown in Figure 6C. Irrigated agricultural land (19.0% of the total area) was mainly concentrated in the middle and lower reaches of the Lhasa River and tributary valleys, and the Dangxiong Basin in the north. Some of the Lhasa River tributary valleys had steep slopes on both sides; therefore, only narrow valleys exhibited irrigation water supply conditions. Agricultural production depending mainly on natural precipitation covered the remaining 81% of the total area. Moreover, the supporting capacity index of precipitation conditions for agricultural production was calculated based on the mean annual precipitation data (Figure 6D).

The WRSIA results are shown in Figure 7. The average value of WRSIA in Lhasa was low (0.312). Owing to inadequate precipitation in Lhasa, WRSIA was mainly determined by IWSC. The better-suited areas were distributed in the valleys of the Lhasa River and its tributaries, such as the Mozhumaqu, Pengboqu, and Duilongqu Rivers, and the Dangxiong Basin having a relatively flat terrain.

3.2 Relationship between WRSIA and cultivated land

3.2.1 Spatial adaptability of WRSIA and cultivated land

Figure 8 shows the double cumulative curve relationship between WRSIA and cultivated land. Cultivated land was more concentrated in areas with high WRSIA values, with 96.6% and 82.5% of the irrigated and non-irrigated cultivated land, respectively, distributed in the top 20% of the WRSIA areas. Moreover, up to 81.1% and 49.1% of the irrigated and non-irrigated cultivated land, respectively, were concentrated in the top 10% of the WRSIA areas, accounting for 77.3% of the total cultivated land. Furthermore, 50.8% and 25.0% of the irrigated and non-irrigated cultivated lands, respectively, were distributed in the top 5% of the WRSIA areas, accounting for 47.7% of the total cultivated land. In summary, WRSIA showed good spatial adaptability to cultivated land. Therefore, WRSIA is a critical factor in determining Lhasa's agricultural production layout.

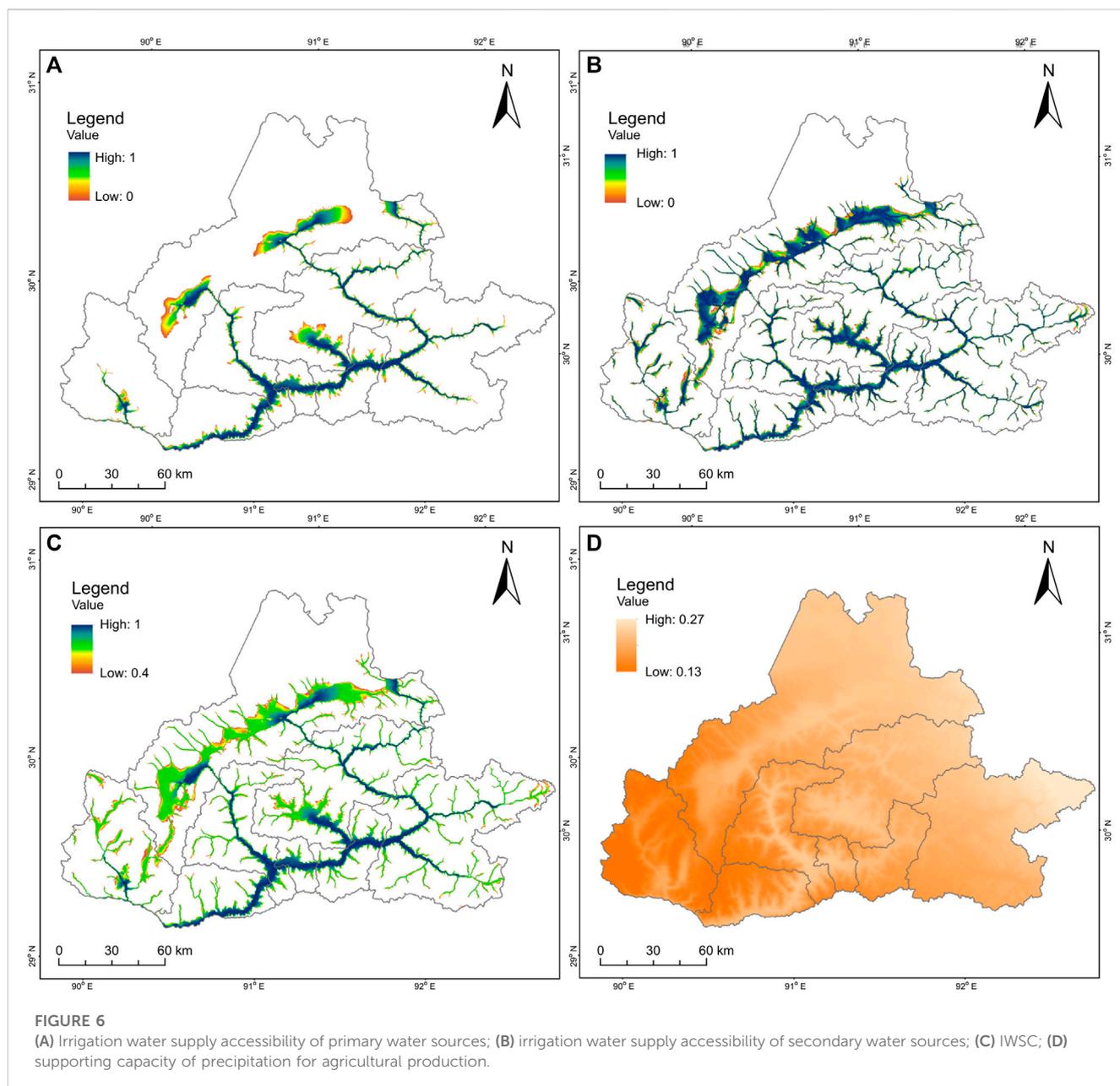
Table 2 shows the results of the cultivated land distribution in different WRSIA ranges. In areas with <0.4 WRSIA, the proportion of the cultivated land to the total land area was only 0.1%, which was lower than that of the entire city (2.1%). With increasing WRSIA, the cultivated land proportion increased. Among areas with WRSIA values within $[0.95, 0.99]$, the proportion of cultivated land reached 25.6%. Moreover, in the highest WRSIA interval $[0.99, 1]$, the cultivated land proportion decreased to 14.5% because of several construction lands and wetlands. By excluding 39.9 km² of construction land and 235.66 km² of wetland, the cultivated land proportion in the $[0.99, 1]$ interval was up to 28.0%.

3.2.2 Correlation analysis of WRSIA and cultivated land by GWR

The study area was divided into $5,000 \times 5,000$ m fishing net units, and the proportion of cultivated land and WRSIA in each unit was measured. Figure 9 shows the correlation results between WRSIA and cultivated land. Specifically, Figures 9A, B show the spatial distribution of the regression coefficient and correlation coefficient (r), respectively. The overall correlation was strong (0.904). In the southern Lhasa River and its tributary valleys, the regression coefficients were positive, and the correlation coefficients were >0.6 , thus, indicating a significant positive correlation. Thus, WRSIA could strongly interpret the spatial distribution of cultivated land. In the northern mountains and Dangxiong Basin, the correlation was weak because cultivated land is sparse, and the temperature could not meet the requirements of agricultural production.

3.3 Coupling analysis with land resource suitability

Agricultural production in Lhasa is restricted by topography, such as high altitude and steep slopes, which are unsuitable for agricultural production. We classified the suitability of slope and elevation, conducted spatial superposition with WRSIA, and analyzed the cultivated land density under different suitability levels of water and soil resources; the corresponding results are



shown in Tables 3, 4. The slope suitability level was divided into five grades: highly suitable (0–2), moderately suitable (2–6), relatively suitable (6–15), slightly suitable (15–25), and unsuitable (>25), and the corresponding cultivated land proportions were 18.05%, 23.91%, 10.09%, 0.40%, and 0.00%, respectively, showing a decreasing trend with increasing slope. Among them, the proportion of the cultivated land in the highly suitable area was lower than that in the moderately suitable area, and mainly wetlands and construction lands were abundant. The proportion of the cultivated land increased with WRSIA in each slope suitability level. For example, in the relatively suitable slope area, the cultivated land proportion was 10.09% on an average, whereas the proportions in the five WRSIA grades were 24.63%, 17.55%, 6.16%, 2.25%, and 1.54%, respectively. Similarly, in each WRSIA grade, the cultivated land proportion decreased with increasing slopes. For example, in the relatively suitable WRSIA

area, the average cultivated land proportion was 1.38%, whereas the proportions in the four slope grades were 10.99%, 6.16%, 0.93%, and 0.00%, respectively, without a highly suitable slope area. Overall, the coupling application of WRSIA and slope suitability appropriately explained the spatial distribution of cultivated land.

Elevation is also an important factor affecting agricultural production in the Qinghai-Tibet Plateau because lower temperatures in high altitude areas limit crop growth (Xu et al., 2022). According to the climatic conditions required for crops growing in Lhasa, the elevation suitability for agricultural production was divided into five grades: highly suitable (<3,600 m), moderately suitable (3,600–3,900 m), relatively suitable (3,900–4,200 m), slightly suitable (4,200–4,500 m), and unsuitable (>4,500 m) and the respective cultivated land proportions were 9.99%, 6.33%, 2.04%, 0.23%, and 0.02%,

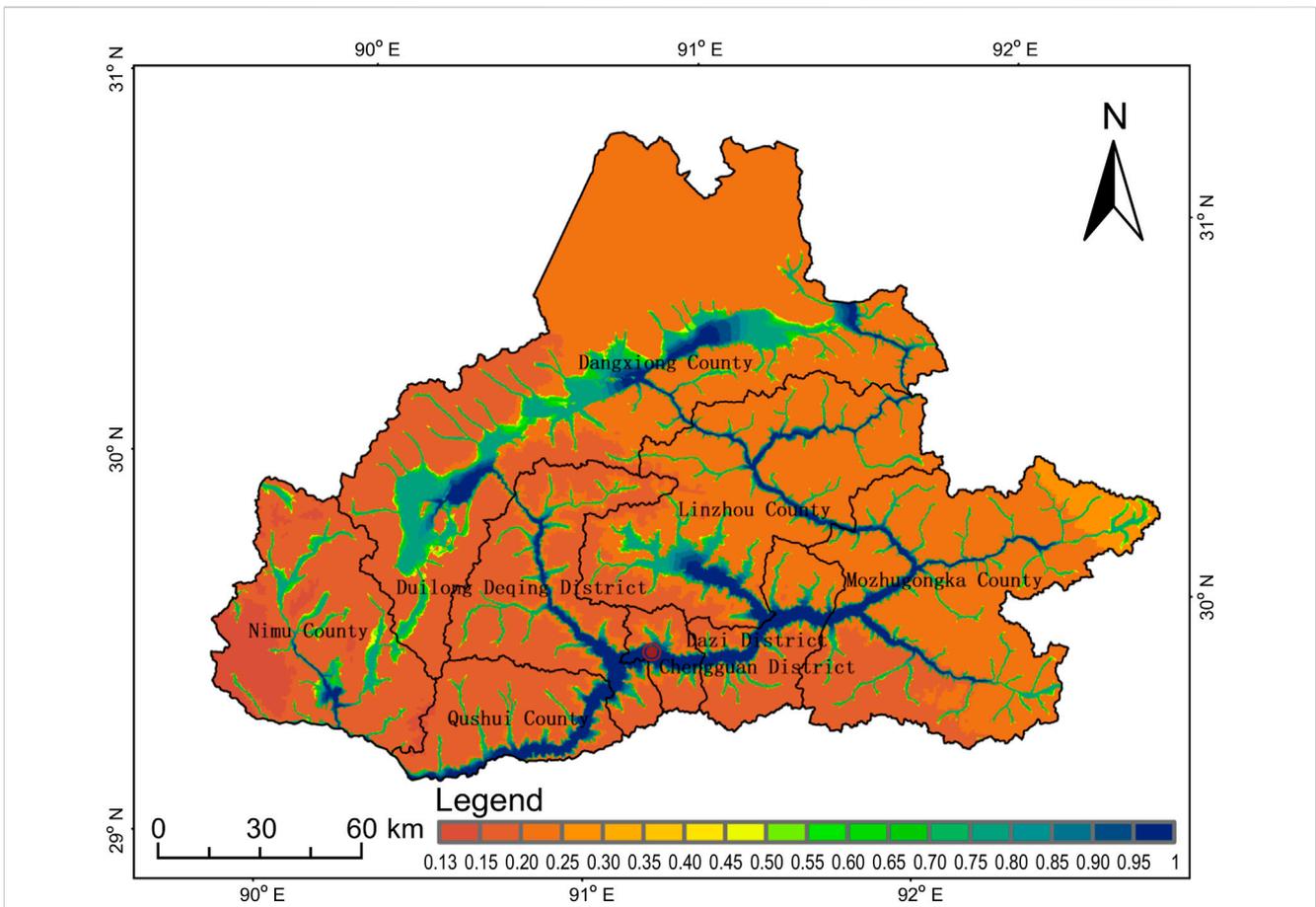


FIGURE 7 Wrsia in Lhasa city.

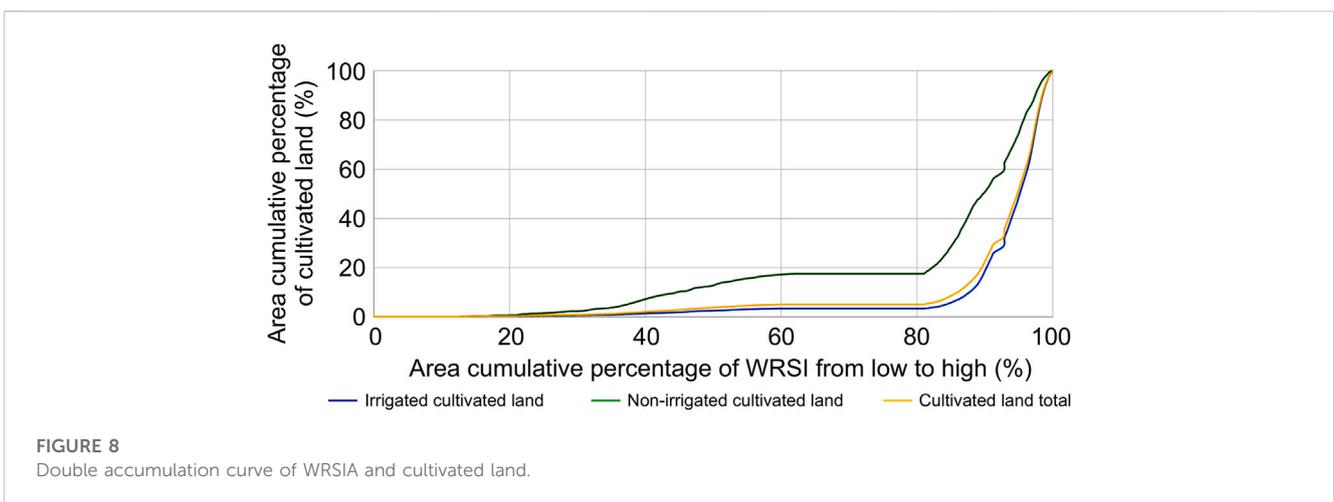


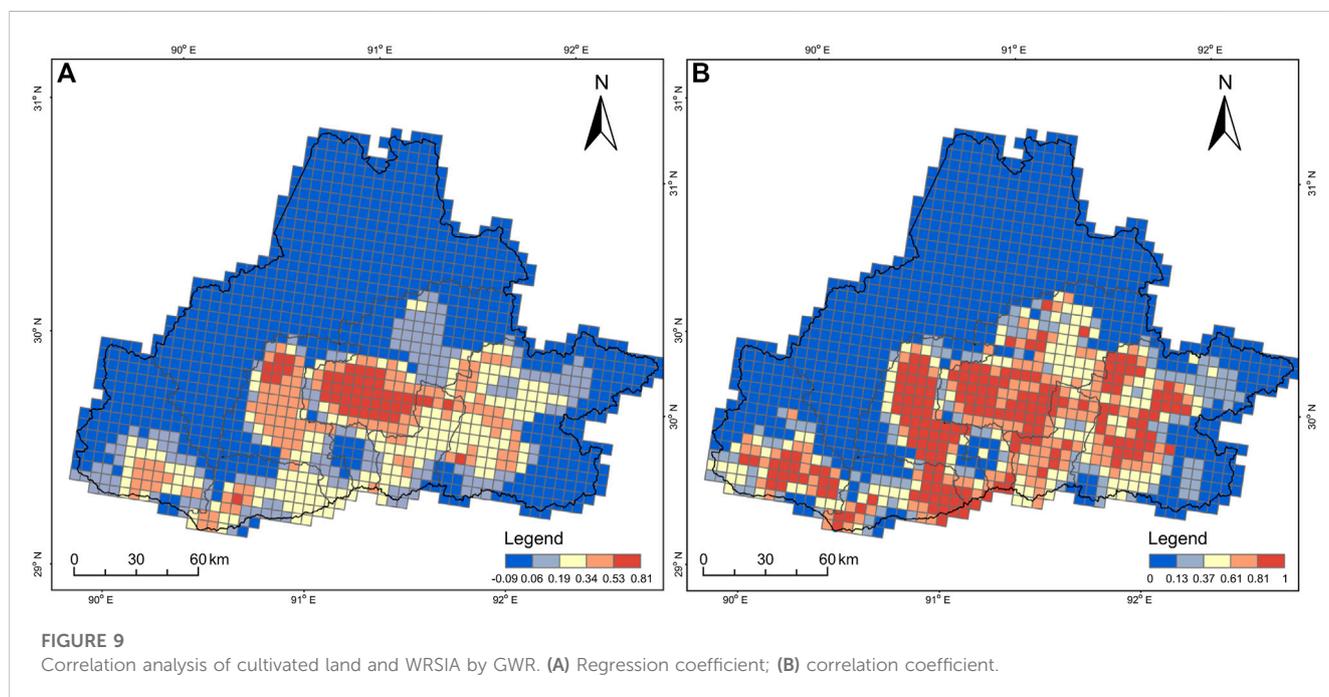
FIGURE 8 Double accumulation curve of WRSIA and cultivated land.

respectively, indicating a decreasing trend with increasing elevation. In each suitability elevation level, the cultivated land proportion increased with WRSIA. For example, the average cultivated land proportion in a relatively suitable elevation area was 2.04%, whereas the ratios in five WRSIA grades were 14.11%, 7.56%, 2.61%, 0.71%, and 0.20%, respectively. Similarly, in each WRSIA grade, the

cultivated land proportion decreased with increasing elevation. For example, the average cultivated land proportion in a moderately suitable WRSIA area was 5.88%, while the proportion in highly suitable, moderately suitable, relatively suitable, slightly suitable, and unsuitable elevation areas were 7.97%, 7.45%, 7.56%, 1.71%, and 0.20%, respectively. Thus, the coupling application of

TABLE 2 Cultivated land distribution in different WRSIA ranges.

WRSIA	Land area (km ²)	Irrigated cultivated land area (km ²)	Non-irrigated cultivated land area (km ²)	Total cultivated land area (km ²)	Irrigated cultivated land proportion (%)	Non-irrigated cultivated land proportion (%)	Total cultivated land proportion (%)
[0, 0.4)	24,005.1	18.2	13.0	31.2	0.1	0.1	0.1
[0.4, 0.6)	780.7	6.2	4.5	10.8	0.8	0.6	1.4
[0.6, 0.8)	2,692.6	131.7	26.5	158.2	4.9	1.0	5.9
[0.8, 0.9)	579.1	95.2	10.2	105.4	16.4	1.8	18.2
[0.9, 0.95)	361.6	58.5	6.4	64.8	16.2	1.8	17.9
[0.95, 0.99)	643.6	155.3	9.4	164.7	24.1	1.5	25.6
[0.99, 1]	572.1	78.8	4.3	83.1	13.8	0.8	14.5
Total	29,634.8	544.0	74.3	618.2	1.8	0.3	2.1



WRSIA and elevation effectively explained the spatial distribution of cultivated land.

4 Discussion

The ecosystem of the Qinghai Tibet Plateau is highly sensitive to anthropogenic activities and thus, its resources, environment, and spatial suitability require increased attention. The suitability of agricultural production and other anthropogenic activities is usually assessed by land resources, water resources, vegetation, and temperature. Previous studies have not considered water supply conditions; therefore, the identification results of suitable areas are extensive, thereby, limiting their application in agricultural development decision-making (You et al., 2020; Chen, 2022; Xu et al., 2022). Furthermore, although some

studies have used water source distance to measure water supply convenience, the spatial difference in water supply convenience has not been effectively and accurately described (Xu et al., 2020). Figure 10 presents an enlarged map of WRSIA and cultivated land distribution. High level WRSIA values were largely distributed in Lhasa and Pengboqu River Valleys and sparsely distributed in other river valleys having poor topographic conditions. The distribution of cultivated land was consistent with the WRSIA distribution characteristics (Figure 10). The results showed that WRSIA could explain agricultural production conditions and was evidently applicable in this region. Based on IWSC, WRSIA indicated whether the water supply cost was within the acceptable range. In this study, the water lifting height and water diversion distance, which determine the water supply cost, were adopted for valleys with a steep slope. Therefore, the WRSIA results could suitably describe the convenience of water

TABLE 3 Cultivated land proportions under different slope grades and WRSIA grades (%).

		Slope					Total
		Highly suitable (0–2)	Moderately suitable (2–6)	Relatively suitable (6–15)	Slightly suitable (15–25)	Unsuitable (>25)	
WRSIA	Highly suitable (0.8–1)	18.10	27.47	24.63	0.85	0.51	19.39
	Moderately suitable (0.6–0.8)	0.00	20.64	17.55	0.71	0.03	5.88
	Relatively suitable (0.4–0.6)	–	10.99	6.16	0.93	0.00	1.38
	Slightly suitable (0.2–0.4)	–	4.38	2.25	0.06	0.00	0.18
	Unsuitable (0–0.2)	–	6.93	1.54	0.18	0.00	0.07
	Total	18.05	23.91	10.09	0.40	0.00	2.09

TABLE 4 Cultivated land proportions under different elevation grades and WRSIA grades (%).

		Elevation					Total
		Highly suitable (<3,600 m)	Moderately suitable (3,600–3,900 m)	Relatively suitable (3,900–4,200 m)	Slightly suitable (4,200–4,500 m)	Unsuitable (>4,500 m)	
WRSIA	Highly suitable (0.8–1)	21.63	23.13	14.11	5.02	1.64	19.39
	Moderately suitable (0.6–0.8)	7.97	7.45	7.56	1.71	0.20	5.88
	Relatively suitable (0.4–0.6)	0.81	1.64	2.61	0.68	0.06	1.38
	Slightly suitable (0.2–0.4)	0.01	0.47	0.71	0.07	0.00	0.18
	Unsuitable (0–0.2)	0.13	0.22	0.20	0.04	0.01	0.07
	Total	9.99	6.33	2.04	0.23	0.02	2.09

resources for agricultural production than conventional factors, such as water supply distance.

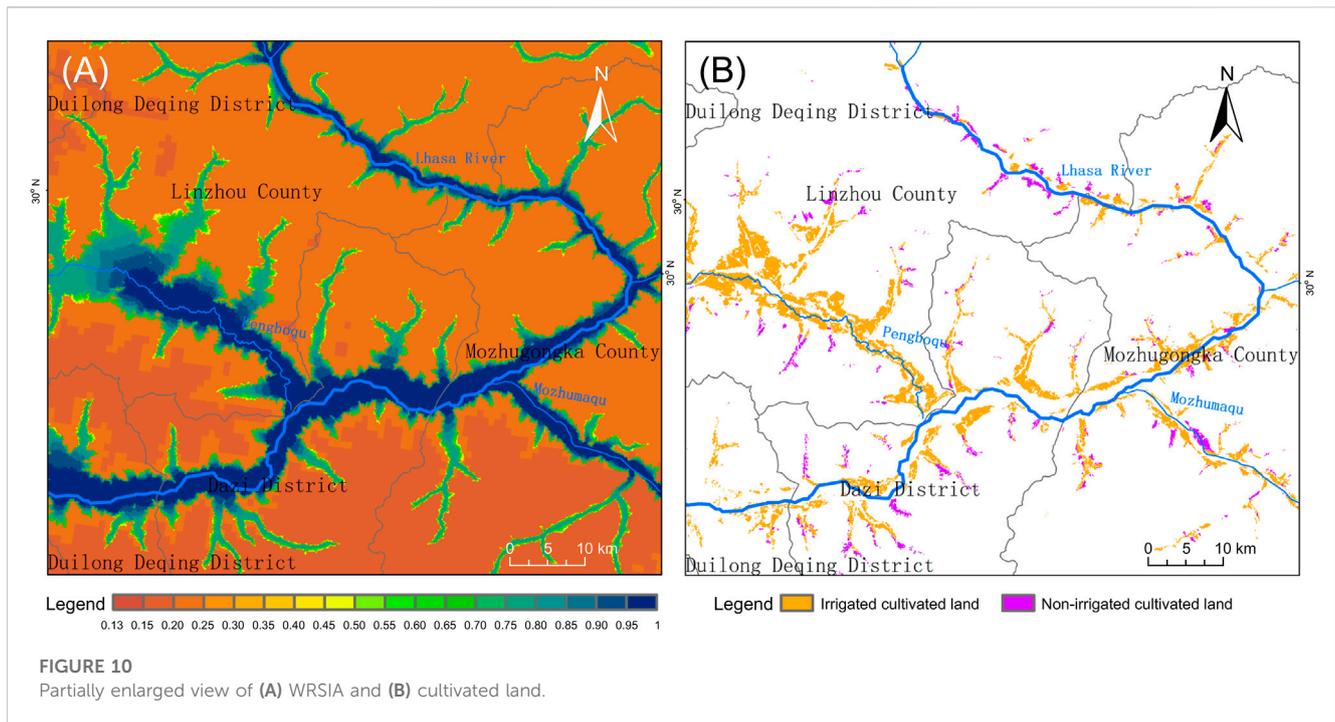
The constraints of water resources on agricultural production are mainly reflected in three aspects: whether the quantity of water resources is sufficiently abundant, whether the quality of water resources can be used for agriculture, and whether the engineering conditions for the development of irrigation are available. WRSIA focuses on the issue of engineering conditions. The spatial layout of agricultural production is an important research element in Territorial Spatial Planning carried out in China in recent years. In the mountainous regions of southern China, water resources are abundant, but they cannot be used to irrigate the arable land located halfway up the mountain. In the arid regions of Northwest China, where land resources are abundant, and water resources are insufficient, it is necessary to study areas that have low agricultural irrigation costs to develop a reasonable agricultural layout plan. In these areas, WRSIA can substantially improve the precision of evaluation and the accuracy of results, and in fact, the model has been practically applied in different

areas with relatively good results. It is worth noting that indicators such as topography, soil, and temperature are equally crucial in the layout of agricultural production and need to be used along with WRSIA.

Regarding the availability of data, factors such as water conservation sensitivity, meteorological disasters, and climate change risks were excluded from the selection of indicators. Agricultural production in some regions is strongly influenced by the above factors and requires model correction. For example, some arid areas need to consider the factor of groundwater, and some areas need to incorporate the effect of the intra-annual distribution of precipitation on agricultural production, etc.

5 Conclusion

Based on the convenience of irrigation water supply and natural precipitation conditions, WRSIA was constructed in this study. Owing to topographical conditions, only 19.0% of the land area in Lhasa exhibited



good irrigation and water supply conditions. Moreover, the over-all suitability of water resources for agricultural production was low because of insufficient natural precipitation, with the average value of the entire city being only 0.312. The statistical and spatial correlation analysis between the cultivated land and WRSIA in Lhasa showed that their spatial matching degree was relatively high. In the top 5% of the areas having the highest WRSIA, 50.8% and 25.0% of the total irrigated and non-irrigated cultivated lands, respectively were concentrated, accounting for 47.7% of the city's total land. Additionally, the correlation analysis based on GWR showed that the cultivated land and WRSIA were strongly positively correlated ($R^2 = 0.904$) in valley areas having concentrated cultivated land. On superimposing land resource elements (including slope and elevation), we found that the coupled application of water resources and land resource suitability explained the spatial distribution of cultivated land better. Therefore, WRSIA constructed in this study could appropriately represent the suitability of water resource conditions for agricultural production in Lhasa and can provide scientific support for future agricultural production planning in other Qinghai-Tibet Plateau regions.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: because it is the achievements of the Second National Land Survey in China. Requests to access these datasets should be directed to JL, lijuyi@igsnr.ac.cn.

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by YL, JY, ZW, and YW. The manuscript was written mainly by YL,

CW, JL, and LL. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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