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# Evaluation and Promotion of Alluvial Fan Land Suitability for Agriculture in the Lhasa River Basin, Qinghai–Tibet Plateau

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**Abstract:** Alluvial fans have been proven to have great utilisation potential in QTP, but to what extent they are suitable for agricultural development is unknown. Therefore, using the alluvial fan in the Lhasa River Basin (LRB) as a case study, this paper established an evaluation system of land suitability for agriculture (LSA). Principal component analysis (PCA) and the exhaustive method (EM) were used to define the minimum dataset (MDS) and then the LSA of the alluvial fan in the LRB was evaluated using a comprehensive index of LSA. Two scientific approaches were implemented to improve the LSA using a scenario simulation. The results showed that the MDS assessed by the EA was more representative compared to the PCA. Alluvial fans with suitable grades are mainly distributed in the Lhasa River's middle and lower reaches. Developing facility agriculture and repairing roads accessing the alluvial fans are effective approaches to improve the LSA, which can increase the suitable-grade area from 58.62% to 97.82% and 63.85%, respectively. Therefore, most alluvial fans in the LRB are suitable for developing agriculture, and under the influence of human activities, there will be more alluvial fans suitable for developing agriculture. Our research provides scientific methods for the sustainable development of land in alpine regions.

**Keywords:** land suitability for agriculture; alluvial fan; Lhasa River Basin; Qinghai–Tibet Plateau

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## 1. Introduction

At present, the world population is on a rising trend, and the surging population is expected to pose a threat to food security. The global food demand is anticipated to double by the middle of the 21st century [1]. Therefore, the human demand for land is dramatically increasing to meet the increasing food demand. However, the global land suitable for food cultivation and agricultural development is limited [2]. Moreover, the increase in urbanisation and industrialisation has led to additional problems, such as abandoned farmland, land pollution, and land degradation [1,3]. These issues strain the relationship between humans and the environment. Therefore, the efficient regional land use planning [4] and management of land resources is essential to ensure food security and sustainable agricultural development.

To rationally manage land resources, it is usually necessary to evaluate land suitability to determine which type of land use is most suitable for a specific location [5]. Land suitability evaluation is a planning method to avoid environmental conflicts by separating competing land uses [6]. Therefore, land suitability evaluation is regarded as the premise of land use planning and the foundation of sustainable land management [1,7]. Based

on the demand and the availability and suitability of land in various regions, many researchers have evaluated and analysed the land suitability for urban construction, forestry, or agriculture [8–10]. In particular, an agricultural suitability assessment is a process that needs spatial data, geographic information tools, and agricultural and computer scientists' professional knowledge to analyse complex information [11]. This process needs to consider many aspects, not only the local special environment but also the availability of data and the practicability and authenticity of the assessment results. Therefore, it is very complicated and systematic work. The studies have offered feasible and science-based approaches for land use planning.

Land suitability evaluation can be assessed by qualitative or quantitative methods. Qualitative methods are used to evaluate the land potential over a wider range and give qualitative results. Quantitative methods involve more detailed land attributes using parametric techniques, which incorporate various statistical analyses to quantify the potential of land for specific uses [3]. Therefore, quantitative methods have recently been widely used in land suitability evaluation. Since the 20th century, there have been many quantitative evaluation methods of land suitability developed. With the development of technology, there are many quantitative modern land suitability evaluation methods, such as the machine learning-based method and multi-criteria decision analysis method, which show their advantages in dealing with complex datasets [12,13]. However, those commonly used methods are still divided into four categories, namely, the FAO land suitability evaluation, land capability classification, stories index, and parametric method [6,14,15].

The FAO land suitability evaluation, the land suitability evaluation method of the Food and Agriculture Organization of the United Nations (FAO), has been an important tool for global land resources management and planning since it was first published in 1976. The framework provides a set of systematic guiding principles for evaluating the suitability of land for specific purposes, including agriculture, forestry, and urban development [16,17]. In practical application, the FAO method has been adopted by many countries or regions to support the sustainable management of their land resources [18]. For example, in Zambia, the land suitability of university farms was evaluated by using the FAO framework, and the most suitable crop types were determined, and the land use plan was made accordingly. In addition, the application of GIS technology has greatly improved the efficiency and accuracy of the land suitability evaluation, making the evaluation results better serve the decision-making of land use planning [16].

The land capability classification (LCC) is a land evaluation method widely used in the world, aiming at supporting the protection of soil and natural resources [19]. In practical application, the LCC needs to consider many factors, including the soil characteristics, slope, groundwater level, climate conditions, and socio-economic background of land. For example, in the surrounding area of the Aravalli fringes of southern Haryana, through detailed soil investigation and terrain analysis, the soil is divided into different grades to guide sustainable crop production [20]. Similarly, in the Gadagi-2 micro-watershed in Kenya, through the detailed study of soil-type units, suitable crop planting plans and soil and water conservation measures were put forward for different soil-type units [21]. The LCC is not limited to agricultural use but is also applicable to forestry, animal husbandry, and other types of land use. For example, the forest land capacity classification aims to classify forest land according to permanent physical factors so as to provide an index of land and crop management demand and potential [22]. In addition, the LCC can also be based on ecological conditions, which is considered to be a more reasonable and sustainable method [23]. The LCC system divides land into eight grades, but its application is limited by the lack of data input, storage, and management of digital platforms and the lack of technical ability to generate the required input in many areas [24].

In the land suitability evaluation, the application of the story index method is mainly reflected in the comprehensive consideration of various factors to evaluate the land suitability [25]. This method usually involves GIS and other data analysis techniques to ensure the accuracy and practicability of the evaluation results. For example, in the study of Pinglu

District, Shuozhou City, Shanxi Province, researchers used GIS tools and the comprehensive index method to evaluate the suitability of land resources. This method not only considered the data of land resources but also supported the evaluation process by establishing a management information system [26]. In addition, other studies have adopted different mathematical and technical methods to improve the accuracy of the land suitability evaluation. For example, some studies use vectors and matrices to express soil conditions and land use requirements and calculate the site suitability index of specific land use through the simple application of matrix algebra [27]. This method can flexibly deal with the positive and negative interaction between land characteristics and land use demand.

The parametric method is an important technical means in land suitability evaluation, which quantifies the various attributes and conditions of land by establishing mathematical models, thus providing a scientific basis for land use decisions. El Baroudy put forward an evaluation method of land suitability (MC-LSE) for wheat cultivation using a parametric method and evaluated the land suitability for agricultural activities in Egypt by using nearly 18 indicators in three soil aspects: physical and chemical properties and fertility [3]. The results showed that 71.44% of the total area is highly or moderately suitable for wheat cultivation. Vasu et al. also used the MC-LSE method to evaluate the land suitability for cotton, corn, peas, peanuts, and rice cultivation in southern India by using nearly 20 soil indicators, such as the cation exchange capacity, pH, and electrical conductivity [10]. Fuzzy logic is also a widely utilised approach that has been developed based on the parametric method. Fuzzy logic is an accurate tool because it can integrate various variables and explore the uncertainty related to land features [28]. For example, Amichev et al. used a fuzzy set method combined with principal component analysis and principal component regression [8]. They established a land suitability evaluation system with 50 indicators and evaluated regions with an area of 8.76, 7.90, and 9.77 Mha suitable for planting deciduous, coniferous, and shrub shelterbelts in Saskatchewan, Canada. Hoseini evaluated the land suitability for trickle irrigation in the Ardabil province of Iran using a fuzzy set method and found that about 2941.35 hectares (56.77%) and 159.81 hectares (3%) of land were highly suitable for drip irrigation and surface irrigation while about 246.43 hectares (4.7%) and 312.69 hectares (6%) were moderately suitable [29]. Abbasi et al. established a land suitability evaluation system consisting of eight indicators to evaluate the land suitability for agriculture in the Tando Allahyar district of Sindh Province in Pakistan [30]. Their research results closely aligned with the local real situation, confirming the superiority of the fuzzy set method.

The above methods have significantly advanced the research of land suitability evaluation. Still, they need a lot of indicators with high measurement costs, and most of them focus on the physical and chemical properties of soil, with little consideration given to other natural factors and societal factors. Evaluating the land suitability with a few indicators and low costs for their measurement and collection is a challenge in this field.

The Qinghai–Tibet Plateau (QTP) is the world's highest region, with a cold and dry climate, steep terrain, and limited land suitable for human life and agriculture [31]. Only river terraces, alluvial fans, and gentle slopes of mountains can support the local people's lives because of their relatively low altitude, suitable temperature, and sufficient water resources. However, there is very little land with such properties in the QTP [32]. Due to the increase in population in the QTP, the flat river terrace is currently highly developed [31,33]. Although the alluvial fan still has development potential, it is unclear which specific utilisation is suitable. The Lhasa River Basin (LRB) is an important traditional agricultural area in the QTP and a crucial local food crop-producing area, with many alluvial fans present in the region [33]. In the previous investigation and study [34], we found that this area has some special and effective experiences in developing the agriculture and agricultural practice of the alluvial fan surface. For example, alluvial fans have a certain slope, and terraces have been built on some alluvial fans to maintain the stability of farmland and thus obtain stable grain output. Due to the dry climate, some alluvial fans have also built irrigation facilities to irrigate farmland. Many alluvial fans have built paths

connected to highways, although alluvial fans appear at the toes of mountains and hills [34]. However, there are no prescribed criteria for these paths, and they are all built according to the terrain. These practical experiences provide great convenience for the agricultural development of the alluvial fan surface. In addition, the types of crops planted on alluvial fans are consistent with the widely distributed terraces in the local area, and basically all of them are planted with highland barley. The consistent reason may be that there is no significant difference between the soil quality of alluvial fans and terraces [32]. However, there are also some negative situations. For example, due to the imperfect drainage system, terraces are easily damaged in the rainstorm season, leading to greater land damage [34]. Therefore, an alluvial fan is a good reserve land resource. Terraces, irrigation facilities, and roads have improved the agricultural suitability of the alluvial fan, but more management practices need to be developed to ensure the durability of these practices on the surface of an alluvial fan.

Therefore, using the LRB as the region of study, this paper innovatively implemented the combination of the fuzzy set method (FSM), Analytic Hierarchy Process (AHP), principal component analysis (PCA), and exhaustive method (EM) to evaluate the land suitability for agriculture (LSA) of alluvial fans. The purpose was to perform the land suitability evaluation with a few evaluation indicators and propose a realistic approach to improve the LSA of alluvial fans by using a scenario simulation. This work will provide a scientific basis for the rational development of alluvial fans in the QTP and other parts of the world, as well as a new approach for evaluating land suitability.

## 2. Materials and Methods

### *2.1. Study Area*

#### 2.1.1. Location and Brief Introduction

The LRB is located in the south of the QTP, with an area of 32,471 km$^2$, at an altitude ranging from 3523 m to 7067 m (Figure 1). The LRB is the political and economic centre of the Tibet Autonomous Region and is also an important agricultural area. There are 9 administrative counties in this basin, including the Chushur, Chenguan, Seni, Taktse, Tolung Dechen, Chali, Dumshung, Lhundup, and Medro Gongkar counties (or districts). Animal husbandry is prevalent in the upper reaches of the Lhasa River, while agriculture, industry, and service sectors thrive in the middle and lower reaches [35]. Highland barley is the most widely planted food crop locally. In addition, potatoes, peas, and rapeseed are planted in a few areas. The total area of cultivated land in the LRB is 656.44 km$^2$ (in 2011), and the cultivated land is mainly distributed in the lower reaches and gradually decreases in the upper reaches. At present, the cultivated land has a tendency to gradually advance to areas with greater slopes and altitudes [36].

#### 2.1.2. Climate

The climate type of the LRB is the plateau monsoon semi-arid climate. Influenced by the semi-arid monsoon climate, the annual rainfall is between 340 and 600 mm, and the distribution of precipitation is uneven during the year, which is concentrated from June to September [32]. In addition, in many years, there is no precipitation from November to February. Affected by the altitude, the overall temperature in the basin is low, and the annual average temperature is between −1.7 and 9.7 °C, so agriculture and animal husbandry are vulnerable to freezing disasters in the winter and spring. Because the air in this area is relatively thin and there are less clouds, the solar radiation is strong. The total sunshine duration in the whole year is about 2800 h, and the average evaporation for many years can reach 1216 mm. In the winter and spring, due to the scarce precipitation, exposed riverbeds, and prevailing river valley winds, sandstorm weather is easily formed in some areas, which will do some harm to the local national economy.

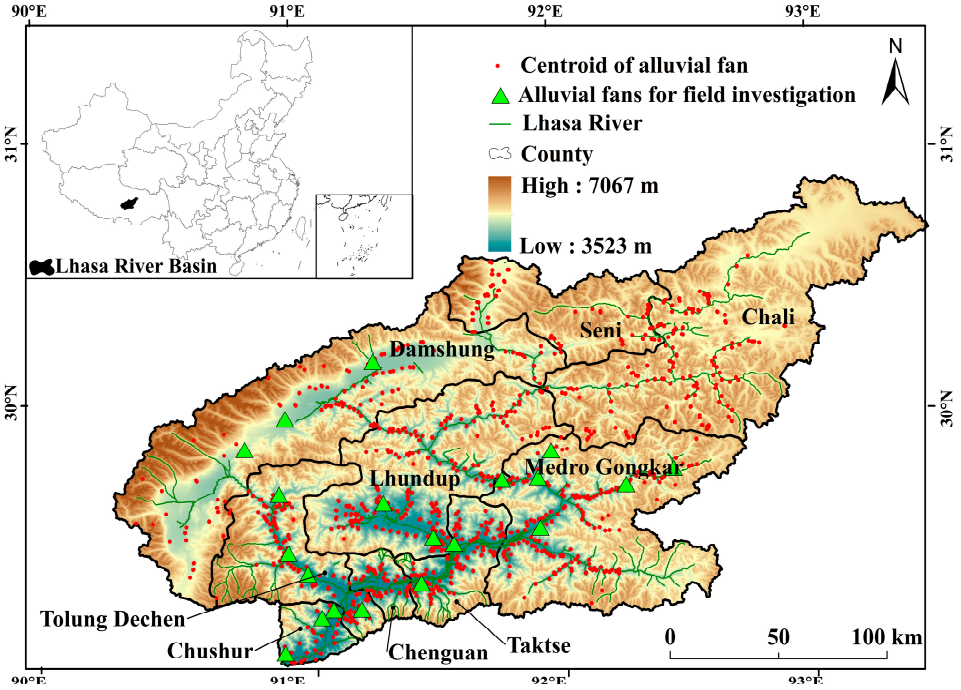



**Figure 1.** The administrative division and alluvial fans of the Lhasa River Basin [32].

### 2.1.3. Geomorphology

The terrain is dominated by mountains and river valleys. Along the banks of the Lhasa River, deep fluvial river terraces have developed, characterised by their gentle slopes and proximity to the river, so the main urban areas of the Lhasa city are on river terraces. There is a large number of alluvial fans (Figures 1 and 2) in the valleys on both sides of the Lhasa River, the number of which can reach up to 826, with an area of 1166.03 km$^2$ [33]. An alluvial fan is close to rivers, roads, and villages, and its soil quality is of a good grade compared to the local area; therefore, it has a significant utilisation potential [32,33].

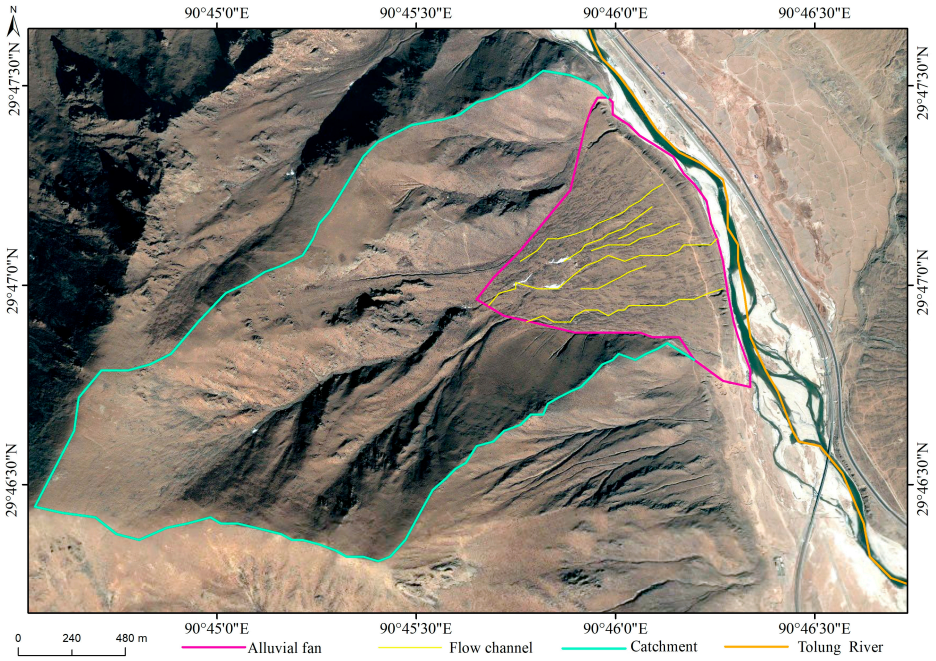



**Figure 2.** A typical alluvial fan located in the Lhasa River Basin [33]. The Tolung River is a tributary of the Lhasa River.

#### 2.1.4. Vegetation and Soil

The vegetation in the LRB has an obvious vertical distribution pattern, and the soil types mostly correspond to vegetation types. Above 5700 m, there is basically no vegetation (basically no soil development, with a rocky surface), 5200~5700 m is alpine mat vegetation (cold desert soil), 4700~5200 m is an alpine meadow (meadow soil), 4250~4700 m is alpine meadow soil, and below 4250 m is shrub grassland (shrub grassland soil) [37]. The alluvial fan has special soil and plant types. The upper part of the alluvial fan is mostly proluvial, and the soil is still in the development process. The toe part of the alluvial fan is mostly $CaCO_3$-deposited soil, and the soil profile is obviously differentiated [37]. The vegetation on the alluvial fan mainly includes *Populus szechuanica*, *Caragana sinica*, *Hordeum vulgare*, *Pisum sativum*, *Gnaphalium affine,* and *Sophora davidii* [35,37].

### *2.2. Evaluation Method and Process*

Highland barley is an economically important food crop in the LRB and even the whole QTP, and it is the most typical and widely planted crop in the study area. Therefore, this study used highland barley to evaluate the LSA of the alluvial fans in the LRB. Firstly, according to the field investigation data from 20 typical alluvial fans, the minimum dataset (MDS) for the LSA of the alluvial fans was determined by principal component analysis (PCA) and the exhaustive method (ME). Then, the MDS was used to evaluate the LSA of all the alluvial fans (826) in the LRB. The main steps include the establishment of an evaluating system of the LSA, the determination of the MDS, and the evaluation of the land suitability for agriculture.

#### 2.2.1. Establishment of an Indicator System for Evaluation

According to the investigation results of 20 typical alluvial fans in the field and previous research [32,33,38,39], the following evaluation system was established (Table 1). The criteria layer of the evaluation system comprised three indicators, namely, agricultural topographic suitability, agricultural environmental suitability, and agricultural production suitability, while the indicator layer comprised 17 indicators. The agricultural topographic suitability indicators include the area, slope, and altitude of alluvial fans, which will have an impact on the agricultural activities on the surface of the alluvial fans. If the slope is steep, the area is small, or the altitude is high, they are unsuitable for agricultural development. The agricultural environmental suitability indicators include the accumulated temperature, soil quality, vegetation coverage, rainfall gully density, and flood risk degree, which will affect the growth, development, and maturity of crops. The Qinghai–Tibet Plateau, including the Lhasa River Basin, has a dry and cold climate. If the accumulated temperature and rainfall fail to meet the minimum standards required by crops, crops will be difficult to grow. Soil is the key factor to ensure crop growth, and the content of the organic matter, carbon, nitrogen, phosphorus, and gravel in the soil will affect crop growth. According to the previous research [32], soil quality includes the above soil components, so soil quality is used to reflect the influence of soil on crops. The higher the soil quality, the better the crop yield. Vegetation coverage can reflect the environmental conditions that alluvial fans can support for crop growth, and the greater its value, the more suitable alluvial fans are for crop growth. An erosion gully will continuously erode the soil on the surface of an alluvial fan, which will lead to the decline in land productivity, so the greater its value, the less suitable it is for crop growth. The last agricultural environmental suitability indicator is the flood risk degree, and the greater its value, the less suitable it is for crop growth and agricultural activities. Agricultural production suitability indicators include the distance to a primary road, distance to a secondary road, distance to a tertiary road, distance to a river, distance to a village, distance to a town, distance to a county, and land use degree. Agricultural production conditions will also profoundly affect agricultural activities, for example, if the area is too far away from residential areas, roads, or rivers and agricultural development is challenging to planting, irrigating, and carry out. In addition, we also consider that the land use degree is also a good indicator of agricultural production

suitability. The land use degree is a comprehensive land use index. The higher the index, the higher the degree of land use, reflecting the more construction land and agricultural land distributed on the land [40], which can reflect that these land conditions are more suitable for agricultural production.

**Table 1.** Evaluation system of land suitability for agriculture of alluvial fan.

| Goal Layer | Criteria Layer | Indicator Layer | Unit |
|---|---|---|---|
| Land suitability for agriculture of alluvial fan | Agricultural topographic suitability | Area | $km^2$ |
| | | Slope | ° |
| | | Altitude | m |
| | Agricultural environmental suitability | Accumulated temperature | °C |
| | | Soil quality | - |
| | | Vegetation coverage | % |
| | | Rainfall | mm |
| | | Gully density | $km/km^2$ |
| | | Flood risk degree | - |
| | | Land use degree | - |
| | Agricultural production suitability | Distance to primary road | km |
| | | Distance to secondary road | km |
| | | Distance to tertiary road | km |
| | | Distance to river | km |
| | | Distance to village | km |
| | | Distance to town | km |
| | | Distance to county | km |

2.2.2. Acquisition of Data for the Evaluation Indicator

This research involved two scales of evaluation of the land suitability for agriculture (LSA). The first was to evaluate the LSA of 20 typical alluvial fans to determine the minimum dataset. The second was to assess the LSA of all the alluvial fans (826) in the LRB. The soil quality data and vegetation coverage are different when evaluating the two scales. In the first scale, the soil quality and vegetation coverage were obtained by calculating and investigating 20 typical alluvial fans [32]. In the second scale evaluation, due to the consideration of investigation and measurement costs, the vegetation coverage was replaced by the NDVI, which had been extracted in a previous study [39]. Soil quality was replaced by soil organic matter content. According to previous studies, the soil quality index of the alluvial fans in the Lhasa River Basin is significantly related to soil organic matter content [32]. The tiff data of the soil organic matter (with an accuracy of 1 km) were obtained from the National Earth System Science Data Center (http://soil.geodata.cn (accessed on 21 November 2021)). The average soil organic matter content of the 826 alluvial fans was obtained using the Spatial Analyst function in ArcGIS.

Other data sources are consistent with the two scales of evaluations and were obtained in previous studies [32,33,39]. The degree of flood risk and land use need to be further explained. A flood risk assessment generally requires high-precision rainfall process data and topographic data. However, these data are difficult to obtain in the LRB, so the catchment area of the alluvial fan was used to replace this indicator [39]. Generally, the larger the catchment area, the higher the risk of flooding in the alluvial fan. The catchment area was obtained as determined in a previous study [39]. The land use data of the alluvial fans was calculated in a previous study [38]. Then, the land use degree of the 826 alluvial fans was calculated using the method proposed by Zhuang [40].

2.2.3. Establishment of the Evaluation Index

A comprehensive index-evaluating model of LSA was established by using the weighted sum method, and the index of LSA (LSAI) was obtained after weighting [41], as shown below:

$$\mathrm{LSAI} = \sum_i^n W_{xi} f_{xi} \quad (1)$$

where LSAI is the land suitability for agriculture index, $W_{xi}$ is the weight of the xi indicator, $f_{xi}$ is the normalised score of the $xi$ indicator, and $i$ is the number of indicators from 1 to 17.

There are 17 evaluation indicators of the LSA of an alluvial fan, all of which were normalised by the standard scoring function (SSF), and normalisation can mitigate the impact of various factor indicators' dimensions on the results [42]. In this study, two types of SSF equations (M and L) were used to standardise the indicators. They were the "more is better" equation (M) and the "less is better equation" (L). According to the LSA evaluation purpose, the alluvial fan area, accumulated temperature, soil quality, vegetation coverage, rainfall, and land use degree were standardised by the M equation, and the slope, altitude, gully density, flood risk degree, distance to the primary road, distance to the secondary road, distance to the tertiary road, distance to the river, distance to the village, distance to the town, and distance to the county was standardised by the L equation. The two types of standardisation equations were as follows:

$$\mathrm{M}:\ \mathrm{f(x)} = \begin{cases} 0.1 & x < x_{min} \\ 0.1 + \frac{0.9 \times (x - x_{min})}{x_{max} - x_{min}} & x_{min} < x < x_{max} \\ 1 & x > x_{max} \end{cases} \quad (2)$$

$$\mathrm{L}:\ \mathrm{f(x)} = \begin{cases} 0.1 & x < x_{min} \\ 1 - \frac{0.9 \times (x - x_{min})}{x_{max} - x_{min}} & x_{min} < x < x_{max} \\ 1 & x > x_{max} \end{cases} \quad (3)$$

where f(x) is the score of the indicator between 0.1 and 1, and x is the value of the indicator.

### *2.3. Determination of the Optimal Minimum Dataset*

#### 2.3.1. Principal Component Analysis (PCA)

We selected 20 typical alluvial fans in the Lhasa River Basin [32] to evaluate the LSA of typical alluvial fans by the minimum dataset (MDS) obtained by the PCA combined with the LSAI (Equation (1)). The primary method for obtaining the MDS is the PCA. Multiple indicators are converted to fewer indicators, thereby reducing the statistical dimensions and minimising the correlations between the various indicators [43]. The evaluation indicators' principal components were analysed using SPSS22.0 software. The principal components with characteristic values of 1 were extracted, and the indicators with loading values of 0.5 in the same principal component were divided into groups. Each indicator's normalised value was determined after it was categorised into the group with the highest loading value if the loading of a particular indicator connected to each principal component was less than 0.5. When the normalised value of the indicator's loading value among all the principal components is larger, it indicates that the indicator can explain a significant percentage of the variation. The formula below was used to compute the norm value [43].

$$N_{ij} = \sqrt{\sum_1^j {U_{ij}}^2 \cdot \lambda_j} \quad (4)$$

where $N_{ij}$ is the combined loading value of the ith indicator on the first $j$ principal component with an eigenvalue $\geq 1$; $U_{ij}$ is the loading value of the ith index on the *jth* principal component; and $\lambda_j$ is the eigenvalue of the jth principal component.

The indicators within 10% of the highest total normalised value were chosen to further analyse the correlations of the selected indicators in each group. The indicators with the highest normalised values were included in the MDS if there was a strong correlation between them; otherwise, the indicators from the same group were included. Eventually, the MDS-PCA was obtained by this process.

In a PCA, the common factor variance indicates the proportion of the total variance contributed by each indicator, which is used as the weight for that indicator [32,43].

#### 2.3.2. Exhaustive Method (EM)

The EM, also known as the enumeration method, refers to investigating all possible situations of a certain type of event one by one to get accurate general conclusions. An EM

is also used to select the MSD to evaluate the LSA of alluvial fans. The specific process is as follows. The number of indicators determined in the MDS-PCA was taken as the target (for example, 4 indicators in the MDS-PCA), and the weight was calculated as the ratio of the common factor variance to the total variance of each indicator. Then, in Python, four indicators were randomly selected from 17 indicators and then were multiplied by the corresponding weights. The LSAI was calculated according to equation 1, and the results of all the combination types were used as the output. If the correlation coefficient between an MDS and the total dataset (TDS) evaluation was $\geq$0.9, it was initially selected as the MDS for the dataset. Then, the MDS with low or no correlation among the initial MDS indicators was chosen as the MDS-EM.

#### 2.3.3. Accuracy Verification of the Two Methods

The linear correlation coefficient (R) between the evaluation results of the MDS-PCA, MDS-EM, and TDS was used to verify the accuracy of the PCA and EA [43]. As R increases, the evaluation result of the MDS matches the TDS and represents a more viable substitute for the TDS. Then, the MDS was determined to evaluate the LSA of the alluvial fans in the Lhasa River Basin. The calculation formula of R was as follows:

$$R = \frac{\sum(x_{ij} - \overline{x_i})\ (y_{ij} - \overline{y_i})}{\sqrt{\sum(x_{ij} - \overline{x_i})^2 \sum\ (y_{ij} - \overline{y_i})^2}} \quad (5)$$

where R is the linear correlation value between two variables, with a value closer to 1 indicating a stronger linear correlation between the two variables. The $x_{ij}$ is the $j$ value for the i indicator of the TDS. The xi is the average value for the i indicator of the MDS. The $y_{ij}$ is the j value of the i indicator in the TDS. The $y_i$ is the average value of the $i$ indicator in the MDS. The i is the number of indicators, namely, 1, 2, 3,. . ., 17. The j is the number of typical alluvial fans in the field survey, which are 1, 2,3,. . .,20, respectively.

### *2.4. Classification of LSA*

The optional MDS (OMDS) was used to calculate the LSAI to evaluate the LSA of all the alluvial fans (826). To optimise the utilisation of the alluvial fans, the LSAI of the alluvial fans was classified into three grades: suitable, less suitable, and unsuitable. Because there is no relevant research in this area, it is difficult to classify the LSAI using experience or existing research. Therefore, this paper used the natural breakpoint classification method to classify the LSAI. Firstly, the LSAI was divided into two grades, suitable and less suitable, while unsuitable grades were directly selected from the less suitable grades by restrictive conditions. The classification method of the natural breakpoint method is a method to get the best grouping based on data similarity values. At the same time, it can ensure the most significant difference between groups [44]. This method has been integrated into ArcGIS and can be directly used to complete the classification to groups.

The alluvial fan in the LRB is located near water sources and roads, and its soil quality has been demonstrated to be good, so there are three main restrictions on agricultural production (taking highland barley as an example). First, as stipulated in the Soil and Water Conservation Law of the People's Republic of China, no reclamation is allowed in areas with a slope of $\geq$25°, so all alluvial fans with an average slope of $\geq$25° are unsuitable. Secondly, according to previous studies [45], highland barley in Tibet has a relatively stable yield only in the area with an accumulated temperature > 1000 °C, so all alluvial fans with an accumulated temperature $\leq$ 1000 °C are also regarded as unsuitable. Thirdly, the regional environment with an annual rainfall less than or equal to 250 mm is considered as dry and is also unsuitable for highland barley growth [45]. Therefore, alluvial fans with an annual rainfall less than or equal to 250 mm are also considered unsuitable alluvial fans. In the region, the rainfall is less than 25°, and the average annual rainfall in the LRB is more than >250 mm [39,46,47]. Therefore, the limiting condition of agricultural production of the alluvial fans in the LRB is only the accumulated temperature.

### *2.5. Determination of Factors Contributing to LSA Optimisation*

This study used a scenario simulation to determine the scientific paths to improve the LSA. The specific method was as follows. Firstly, the value of an indicator (a particular path) in the OMDS was modified to reach the optimal value. Then, the modified OMDS was calculated by equation 1 in 2.2.3, and the optimised LSAI was obtained. Finally, still using the classification method in 2.4, the area of the alluvial fan with a suitable grade was obtained, and the effect of the optimised path could be quantified by subtracting it from the area of the alluvial fan with a suitable grade before optimisation.

## 3. Results

### *3.1. The Determination of an Optimal MDS*

#### 3.1.1. MDS-PCA

Four principal components (PCs) were extracted from the PCA in SPSS, and their eigenvalues were greater than 1. The cumulative contribution of variance reached 83.29% (Table 2), which indicated strong explanatory power from the 17 indicators in the dataset. The norm values of each group were compared, and the indicators with larger norm values (within 10% of the maximum norm value) were included in the primary selection indicators. The first group's primary indicators included the altitude, accumulated temperature, soil quality, vegetation coverage, and rainfall. The second group's primary indicators included the area, flood risk degree, distance to a tertiary road, and distance to a river. The third and fourth groups only included the land use degrees and gully density, respectively. Combined with the results of the correlation analysis between the indicators (Figure 3), the indicators with large norm values and a low correlation with other indicators in the PCs were retained. Finally, the indicators included in the MDS-PCA were the area, gully density, land use degree, and distance to a town. If the MDS-PCA is used to evaluate the LSA, the indicators used are reduced by 76.47% (from 17 indicators to 4 indicators).

**Table 2.** PCA results and norm values of evaluation indicators.

| Indicators | Principal Component | | | | Common Factor Variance | Weight | Norm Value | Group |
|---|---|---|---|---|---|---|---|---|
| | PC1 | PC2 | PC3 | PC4 | | | | |
| Area | 0.082 | 0.952 | 0.207 | 0.110 | 0.968 | 0.068 | 2.079 | 2 |
| Slope | 0.169 | −0.653 | 0.593 | −0.001 | 0.806 | 0.057 | 1.642 | 2 |
| Altitude | 0.810 | 0.299 | −0.396 | −0.163 | 0.928 | 0.066 | 2.294 | 1 |
| Accumulated temperature | −0.756 | −0.298 | 0.474 | −0.003 | 0.885 | 0.062 | 2.178 | 1 |
| Soil quality | 0.896 | 0.059 | −0.178 | −0.017 | 0.839 | 0.059 | 2.384 | 1 |
| Vegetation coverage | 0.778 | −0.283 | 0.006 | 0.089 | 0.694 | 0.049 | 2.149 | 1 |
| Rainfall | 0.854 | −0.286 | 0.067 | 0.132 | 0.833 | 0.059 | 2.346 | 1 |
| Gully density | 0.431 | −0.137 | 0.189 | 0.678 | 0.700 | 0.049 | 1.386 | 4 |
| Flood risk degree | 0.086 | 0.930 | −0.111 | 0.178 | 0.916 | 0.065 | 2.027 | 2 |
| Land use degree | −0.363 | −0.231 | −0.514 | 0.581 | 0.787 | 0.056 | 1.384 | 3 |
| Distance to primary road | 0.794 | −0.350 | 0.264 | 0.098 | 0.832 | 0.059 | 2.256 | 1 |
| Distance to secondary road | 0.853 | −0.136 | 0.214 | 0.053 | 0.794 | 0.056 | 2.290 | 1 |
| Distance to tertiary road | 0.141 | 0.910 | 0.288 | 0.021 | 0.931 | 0.066 | 2.023 | 2 |
| Distance to river | −0.359 | 0.744 | 0.253 | 0.303 | 0.838 | 0.059 | 1.911 | 2 |
| Distance to village | 0.523 | 0.703 | 0.238 | −0.189 | 0.860 | 0.061 | 2.079 | 1 |
| Distance to town | 0.907 | 0.011 | 0.108 | 0.010 | 0.835 | 0.059 | 2.403 | 1 |
| Distance to county | 0.816 | 0.032 | −0.198 | −0.086 | 0.714 | 0.050 | 2.175 | 1 |
| Principal component eigenvalue | 7.00 | 4.63 | 1.49 | 1.04 | | | | |
| Contribution rate (%) | 41.15 | 27.23 | 8.79 | 6.13 | | | | |
| Accumulating contribution rate (%) | 41.15 | 68.38 | 77.17 | 83.29 | | | | |

X1–X17: Area, slope, altitude, accumulated temperature, soil quality, vegetation coverage, rainfall, gully density, flood risk degree, land use degree, distance to a primary road, distance to a secondary road, distance to a tertiary road, distance to a river, distance to a village, distance to a town, and distance to a county.

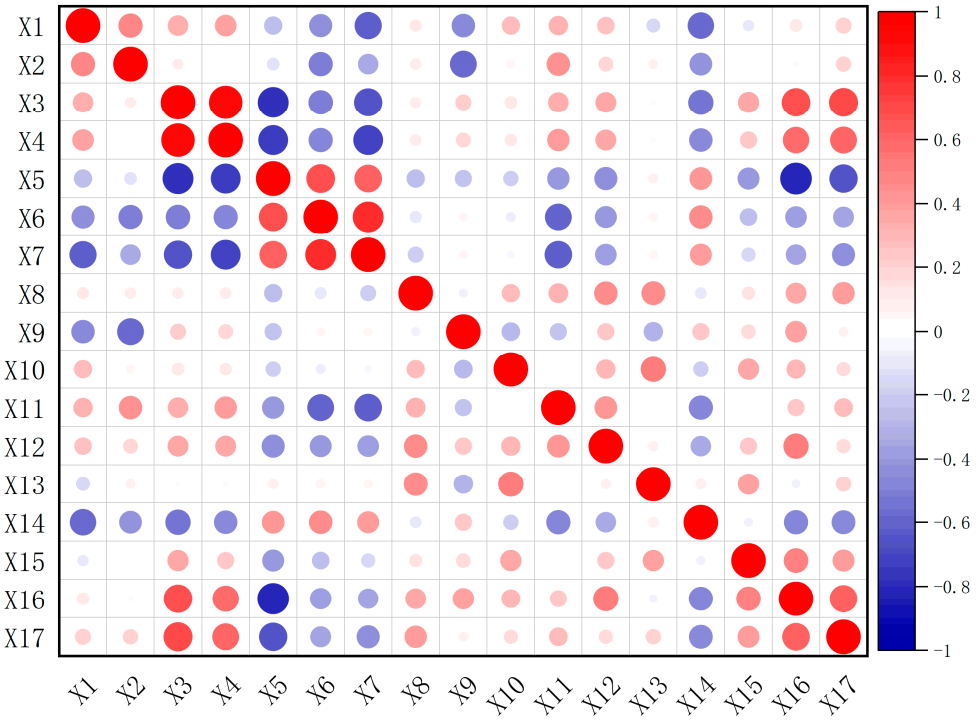



**Figure 3.** Correlation of evaluation indicators of 20 typical alluvial fans.

### 3.1.2. MDS-EM

The exhaustive method (EM) also had 4 indicators as a target, the same as the MDS-PCA, and randomly selected 4 indicators from 17 indicators. Then, it exhaustively tested all the possible combinations of these indicators in Python. At the same time, the weights were still calculated by the variance of common factors in the PCA. Random MDS-EMs were continuously combined and assessed, with equation 1 used for the calculation. The calculated results of the MDS-EM were correlated with the result of the TDS, and the combinations with a correlation coefficient (r) greater than 0.90 were the output. The results showed that there were 187 combinations with a TDS correlation coefficient $\geq$ 0.90 (Table 3). The No. 6 combination was selected as the final result of the MDS-EM combined with the evaluation system (Table 1) and the correlation analysis results (Figure 3), including the slope, accumulated temperature, the distance to a tertiary road, and the distance to town.

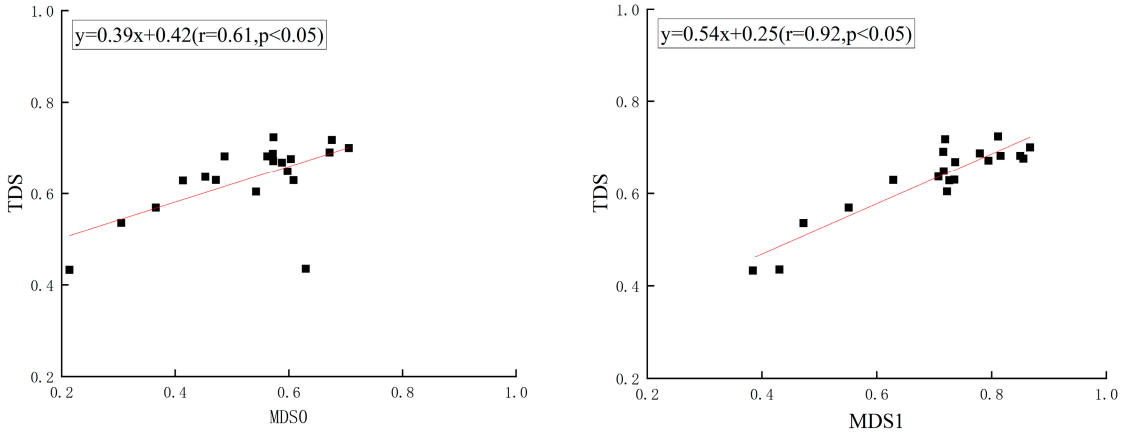
**Table 3.** Combinations with a correlation coefficient greater than 0.9.

| NO. | Combinations | Person Correlation Coefficient | NO. | Combinations | Person Correlation Coefficient |
|---|---|---|---|---|---|
| **1** | x1, x12, x13, x15 | 0.91 | 12 | x3, x5, x15, x16 | 0.91 |
| **2** | x1, x13, x15, x16 | 0.90 | 13 | x3, x6, x11, x13 | 0.91 |
| **3** | x2, x3, x9, x16 | 0.91 | 14 | x3, x6, x11, x15 | 0.92 |
| **4** | x2, x4, x9, x10 | 0.90 | 15 | x3, x6, x12, x15 | 0.92 |
| **5** | x2, x4, x9, x16 | 0.90 | 16 | x3, x7, x12, x15 | 0.90 |
| **6** | x2, x4, x13, x16 | 0.91 | 17 | x3, x11, x13, x14 | 0.91 |
| **7** | x3, x5, x8, x15 | 0.91 | 18 | x3, x11, x13, x16 | 0.92 |
| **8** | x3, x5, x10, x16 | 0.91 | 19 | x3, x11, x13, x17 | 0.90 |
| **9** | x3, x5, x12, x13 | 0.93 | 20 | x3, x12, x13, x16 | 0.93 |
| **10** | x3, x5, x12, x15 | 0.92 | ... | ... | ... |
| **11** | x3, x5, x13, x15 | 0.93 | 187 | x3, x4, x10, x16 | 0.91 |

Only a part of the results is shown; there were 187 groups in total. X1–X17: Area, slope, altitude, accumulated temperature, soil quality, vegetation coverage, rainfall, gully density, flood risk degree, land use degree, distance to a primary road, distance to a secondary road, distance to a tertiary road, distance to a river, distance to a village, distance to a town, and distance to a county.

#### 3.1.3. OMDS

The linear correlation coefficient (R) between the MDS-EM and TDS reached 0.92 (Figure 4). The linear regression coefficient between the MDS-PCA and TDS was significant ($p < 0.05$), but it was much lower than that between the MDS-EM and TDS. Therefore, the MDS-EM was selected instead of the TDS to evaluate the LSA of all the alluvial fans in the Lhasa River Basin.




(**a**)The linear regression relationship between the MDS-PCA and TDS

(**b**)The linear regression relationship between the MDS-EM, and TDS.

**Figure 4.** The linear regression relationship between the MDS-PCA, MDS-EM, and TDS.

### *3.2. Distribution of Alluvial Fans with Different Grades of Land Suitability for Agriculture (LSA)*

Using the MDS-EM and equation 1, the LSAI values of all the alluvial fans in the LRB were calculated and classified, and the distribution of the alluvial fans with different LSA grades was obtained (Figure 5). The alluvial fans with a suitable grade were mostly distributed in the middle and lower reaches of Lhasa River, consistent with the main distribution areas of agricultural land in the Lhasa River Basin. In total, 420 suitable alluvial fans were identified, with a total area of 683.58 km$^2$, accounting for 50.85% of the total number of alluvial fans and 58.62% of the total area of alluvial fans. They were mainly distributed in the Lhundup, Medro Gongkar, Taktse, and Duilong Deqing districts (Table 4). The number of alluvial fans in Chengguan District, Dumshung County, and Qushui County was relatively small (36, 26, and 24).

**Table 4.** Numbers and area of alluvial fans with different agricultural suitability grades in different counties.

| County (District) | Suitable Grade | | Less Suitable Grade | | Unsuitable Grade | | Total | |
|---|---|---|---|---|---|---|---|---|
| | No. | Area (km$^2$) | No. | Area (km$^2$) | No. | Area (km$^2$) | No. | Area (km$^2$) |
| Lhundup | 97 | 156.95 | 70 | 33.15 | 7 | 1.64 | 174 | 191.74 |
| Medro Gongkar | 80 | 62.76 | 68 | 26.38 | 8 | 0.81 | 156 | 89.95 |
| Tolung Dechen | 79 | 88.45 | 11 | 6.47 | 0 | 0 | 90 | 94.92 |
| Taktse | 77 | 58.00 | 10 | 3.32 | 0 | 0 | 87 | 61.32 |
| Chenguan | 36 | 25.98 | 0 | 0 | 0 | 0 | 36 | 25.98 |
| Dumshung | 26 | 226.63 | 58 | 249.39 | 4 | 8.86 | 88 | 484.88 |
| Chushur | 24 | 61.60 | 2 | 0.31 | 0 | 0 | 26 | 61.91 |
| Chali | 1 | 3.22 | 17 | 4.58 | 104 | 52.62 | 122 | 60.42 |
| Seni | 0 | 0 | 1 | 0.09 | 46 | 94.82 | 47 | 94.91 |
| Total | 420 | 683.58 | 237 | 323.69 | 169 | 158.76 | 826 | 1166.03 |

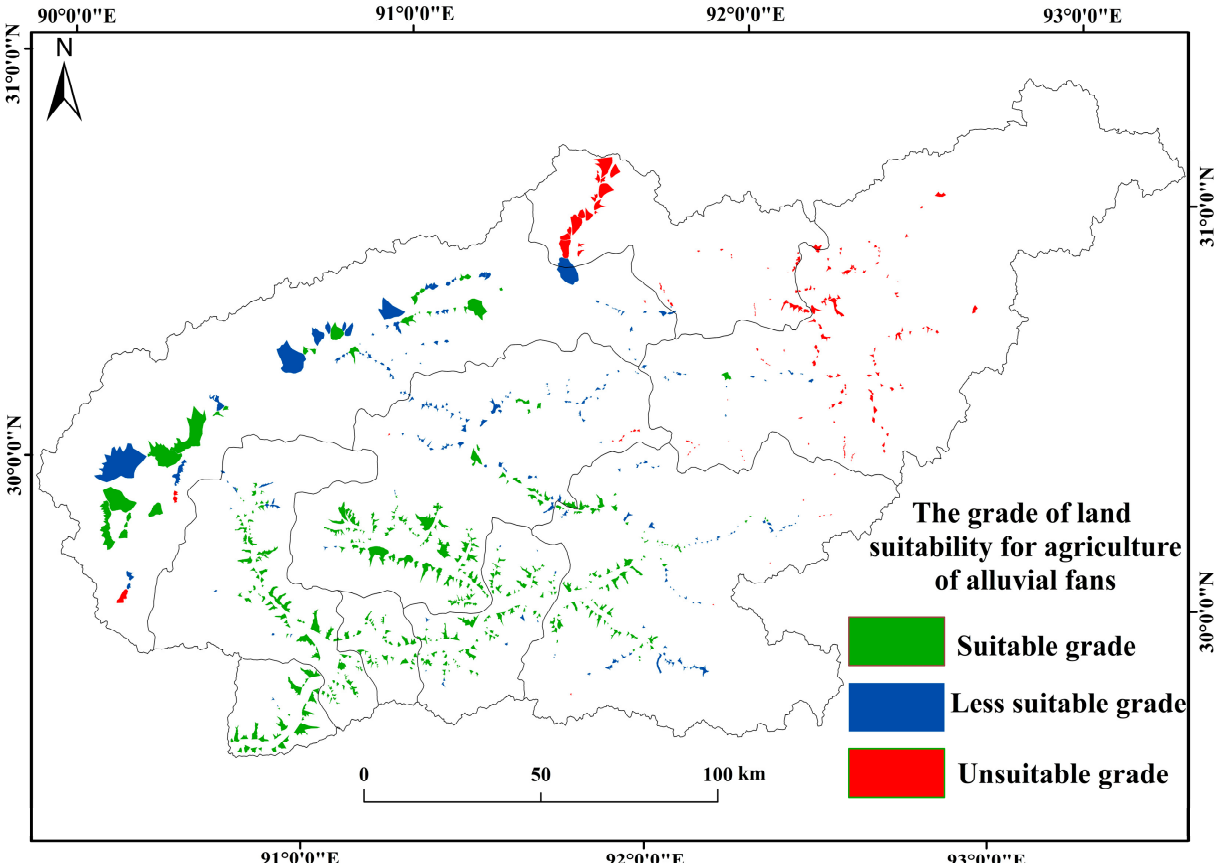



**Figure 5.** The distribution of the alluvial fans with different agricultural suitability grades in the Lhasa River Basin.

The alluvial fans with a less suitable grade were mainly distributed in the middle reaches of the Lhasa River (Figure 5), totalling 237 with a total area of 323.69 km$^2$ (Table 4), accounting for 28.70% and 27.76% of the total number and area of alluvial fans. They were mainly distributed in the Lhundup, Medro Gongkar, and Dumshung counties. Lhundup County had the largest number of alluvial fans with less suitable grades, totalling 70, accounting for 29.54% of the number of alluvial fans with less suitable grades. The Dumshung County had the largest area of alluvial fans with a less suitable grade, at 249.39 km$^2$, making up 77.05% of the total less suitable-grade area.

The alluvial fans with an unsuitable grade were mainly distributed in the upper reaches of the Lhasa River Basin (Figure 5), totalling 169 with a total area of 158.66 km$^2$ (Table 4), accounting for 20.45% and 13.62% of the total number and area of alluvial fans. The number (area) of alluvial fans with an unsuitable grade in Chali County and Seni District was high, with 104 (52.62 km$^2$) and 46 (94.82 km$^2$), respectively, accounting for 61.54% (33.17%) and 27.22% (59.76%) of the alluvial fans of an unsuitable grade.

The correlation analysis results between the LSAI and its influencing factors are shown in Table 5. The LSAI was significantly linearly correlated with four indicators (slope, accumulated temperature, distance to tertiary road, and distance to a town) in the MDS-EM used for LSAI establishment and also with 13 other indicators in the suitability evaluation system (Table 2). The LSAI was positively correlated with the area, soil quality, accumulated temperature, and land use degree but negatively correlated with the slope, altitude, vegetation coverage, rainfall, flood risk degree, gully density, distance to a primary road, distance to a secondary road, distance to a tertiary road, distance to a river, distance to a village, distance to a town, and distance to a county.

**Table 5.** The correlation coefficient matrix between the suitability scores (LSAI) and each index of the 826 alluvial fans in the Lhasa River Basin.

| | LSAI | X1 | X2 | X3 | X4 | X5 | X6 | X7 | X8 | X9 | X10 | X11 | X12 | X13 | X14 | X15 | X16 | X17 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LSAI | 1.000 | | | | | | | | | | | | | | | | | |
| X1 | 0.156 ** | 1.000 | | | | | | | | | | | | | | | | |
| X2 | −0.095 ** | −0.555 ** | 1.000 | | | | | | | | | | | | | | | |
| X3 | −0.907 ** | −0.166 ** | 0.101 ** | 1.000 | | | | | | | | | | | | | | |
| X4 | −0.408 ** | −0.265 ** | 0.353 ** | 0.460 ** | 1.000 | | | | | | | | | | | | | |
| X5 | 0.414 ** | 0.186 ** | −0.163 ** | −0.408 ** | −0.348 ** | 1.000 | | | | | | | | | | | | |
| X6 | 0.901 ** | 0.163 ** | −0.041 | −0.954 ** | −0.463 ** | 0.444 ** | 1.000 | | | | | | | | | | | |
| X7 | 0.879 ** | 0.201 ** | −0.098 ** | −0.956 ** | −0.450 ** | 0.454 ** | 0.940 ** | 1.000 | | | | | | | | | | |
| X8 | −0.103 ** | 0.730 ** | −0.460 ** | 0.128 ** | 0.004 | 0.012 | −0.109 ** | −0.092 ** | 1.000 | | | | | | | | | |
| X9 | −0.080 * | −0.686 ** | 0.503 ** | 0.097 ** | 0.242 ** | −0.096 ** | −0.104 ** | −0.117 ** | −0.539 ** | 1.000 | | | | | | | | |
| X10 | 0.656 ** | 0.245 ** | −0.214 ** | −0.688 ** | −0.261 ** | 0.314 ** | 0.673 ** | 0.683 ** | 0.056 | −0.149 ** | 1.000 | | | | | | | |
| X11 | −0.386 ** | −0.133 ** | 0.036 | 0.339 ** | 0.311 ** | −0.188 ** | −0.316 ** | −0.299 ** | 0.015 | 0.058 | −0.144 ** | 1.000 | | | | | | |
| X12 | −0.281 ** | 0.118 ** | −0.023 | 0.162 ** | −0.031 | 0.054 | −0.127 ** | −0.142 ** | 0.058 | −0.108 ** | −0.096 ** | 0.323 ** | 1.000 | | | | | |
| X13 | −0.288 ** | 0.098 ** | 0.002 | 0.154 ** | 0.009 | 0.016 | −0.137 ** | −0.142 ** | 0.040 | −0.087* | −0.121 ** | 0.265 ** | 0.844 ** | 1.000 | | | | |
| X14 | −0.108 ** | 0.202 ** | −0.168 ** | 0.041 | −0.208 ** | 0.079* | 0.002 | −0.008 | 0.118 ** | −0.186 ** | 0.051 | 0.222 ** | 0.400 ** | 0.289 ** | 1.000 | | | |
| X15 | −0.506 ** | 0.000 | 0.075* | 0.267 ** | 0.052 | −0.103 ** | −0.216 ** | −0.224 ** | 0.065 | −0.007 | −0.129 ** | 0.291 ** | 0.201 ** | 0.125 ** | 0.282 ** | 1.000 | | |
| X16 | −0.581 ** | −0.248 ** | 0.266 ** | 0.600 ** | 0.398 ** | −0.349 ** | −0.562 ** | −0.580 ** | 0.002 | 0.162 ** | −0.510 ** | 0.285 ** | 0.109 ** | 0.080* | 0.058 | 0.223 ** | 1.000 | |
| X17 | −0.727 ** | −0.131 ** | 0.082* | 0.805 ** | 0.397 ** | −0.426 ** | −0.762 ** | −0.781 ** | 0.103 ** | 0.070 * | −0.572 ** | 0.352 ** | 0.133 ** | 0.139 ** | −0.087 * | 0.147 ** | 0.500 ** | 1.000 |

** Spearman correlation coefficients significance at $p < 0.01$. * Spearman correlation coefficients significance at $p < 0.05$. X1–X17: Area, slope, altitude, accumulated temperature, soil quality, vegetation coverage, rainfall, gully density, flood risk degree, land use degree, distance to a primary road, distance to a secondary road, distance to a tertiary road, distance to a river, distance to a village, distance to a town, and distance to a county.

### *3.3. Factors That Can Increase Alluvial Fan Land Suitability for Agriculture*

The LSA of all the alluvial fans in the LRB was evaluated using the MDS-EM (including the slope, accumulated temperature, distance to a tertiary road, and distance to a town) and LSAI. Among these four indicators, the slope of the alluvial fan is difficult to change as a whole artificially. The development of towns is a long-term process, and it is also difficult to affect it quickly. At the same time, artificial measures can change the accumulated temperature and distance to a road. If facility agriculture (like building greenhouses) is developed on alluvial fans, the restriction of the accumulated temperature for agriculture can be removed. In this scenario, the area percentage of alluvial fans with suitable grades will increase from 58.62% to 97.82% (Figure 6). The distance to a road affects the convenience of human beings to use the alluvial fan. The closer it is, the higher the LSAI of the alluvial fan. Therefore, the LSA of the alluvial fan can be improved by shortening the distance between the alluvial fans and the roads. Assuming that all the alluvial fans are connected with the tertiary roads through the building roads, the area of the alluvial fans with a suitable grade will increase from 58.62% to 63.85% (Figure 7). Therefore, the development of facility agriculture and building roads can improve the land suitability for agriculture of an alluvial fan. Facility agriculture can improve it to a higher degree.

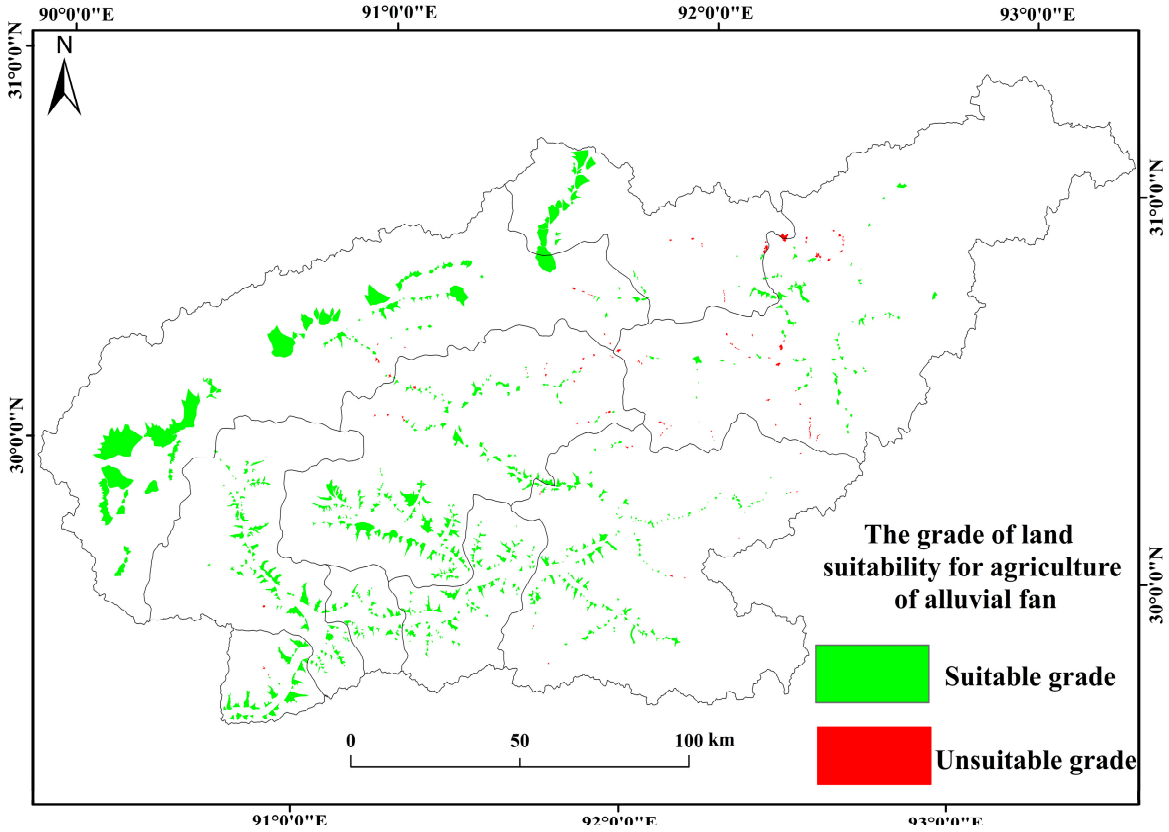



**Figure 6.** Distribution of different grades of agricultural suitability of alluvial fan when all alluvial fans are developed for facility agriculture.

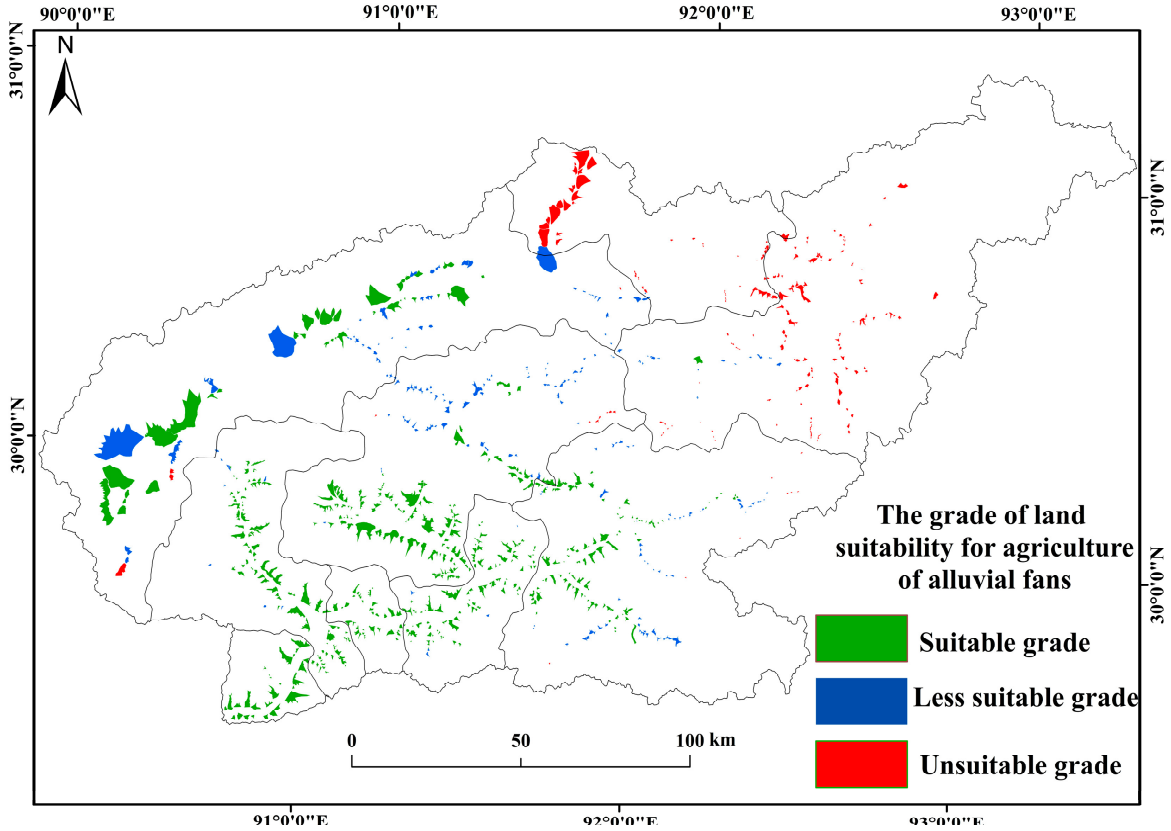



**Figure 7.** Distribution of different grades of agricultural suitability of alluvial fan when all alluvial fans are near roads.

## 4. Discussion

### *4.1. The Distribution of Alluvial Fans with Different Suitability Grades*

The number of alluvial fans with a suitable grade is mainly distributed in the Lhundup, Medro Gongkar, Taktse, and Duilong Deqing counties (or district). At the same time, there are fewer alluvial fans with a suitable grade in the Dumshung, Chali, and Seni counties (or district) (Table 4), which is consistent with the distribution area of traditional farming in the LRB [36]. It is worth mentioning that the alluvial fan in Dumshung County can be used as a potential cultivated land resource. There are several reasons leading to this suggestion. Firstly, according to the evaluation results, although the number of alluvial fans with a suitable grade in Dumshung County is relatively small (26), their area reaches 226.63 km$^2$, accounting for 33.15% of the total area of suitable alluvial fans. According to previous research, this basin's total cultivated land area is about 656 km$^2$ [36]. The area of a suitable-grade alluvial fan in Dumshung County alone reaches 35.55% of the total cultivated land area. Secondly, most alluvial fans are at a suitable altitude for crop growth. Altitude does not directly affect crop growth but does indirectly through temperature [48]. An alluvial fan located in Jiaduo Village, Yangbajing Town, Dumshung County, with an average elevation of 4462 m, is the largest alluvial fan in the LRB, covering an area of 82.99 km$^2$ (Figure 8). There are many farmlands distributed on the alluvial fan. The highest farmland can reach an altitude of 4600 m, higher than 84.14% of the alluvial fan land in the LRB and 96.60% of the alluvial fan land in Dumshung County. Thirdly, there is also cultivated land on the alluvial fans with a less suitable grade. An alluvial fan in Laduo Village, Yangbajing Town, Dumshung County, is classified with a less suitable grade, but about one-third of the alluvial fan is covered with cultivated land (Figure 9). Therefore, other alluvial fans with suitable and less suitable grades can be theoretically cultivated to grow highland barley. Thirdly, Dumshung County is rich in water resources, and most of the alluvial fans are distributed on both sides of the river, supplemented by the runoff

formed by melting snow in the alpine glaciers during the summer. The alluvial fans have an irrigation infrastructure (Figure 9), which can be used to appropriately develop irrigated agriculture. Fourthly, there is no significant difference between the soil quality of the alluvial fans in Dumshung County and that of the terrace farmland in Lhasa River's middle and lower reaches [32]. Therefore, if the population of the LRB increases in the future, the alluvial fans in Dumshung County can be used as the main reserve cultivated land resources due to the low land use degree and large area.

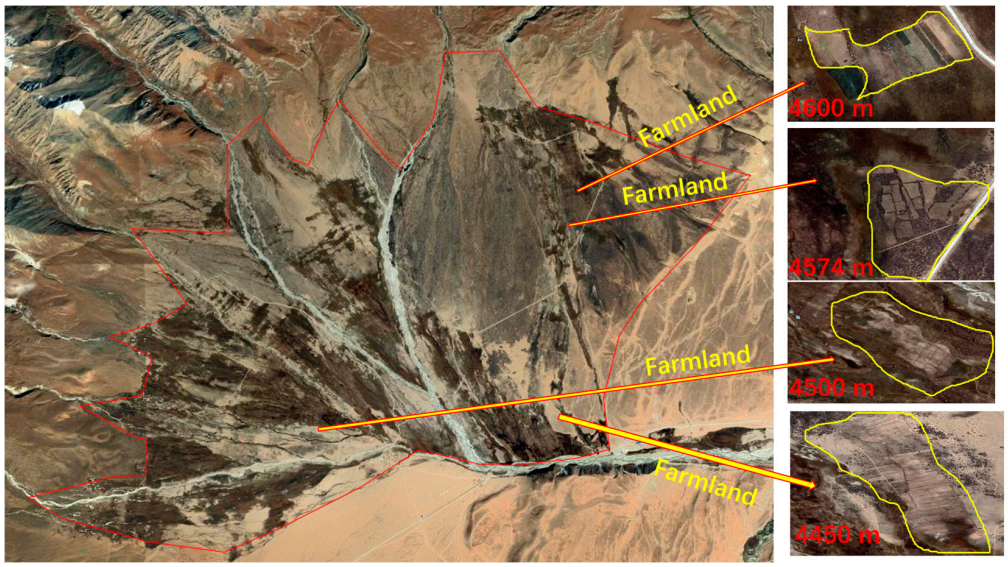



**Figure 8.** An alluvial fan located in Jiaduo Village, Yangbajing Town, Dumshung County.

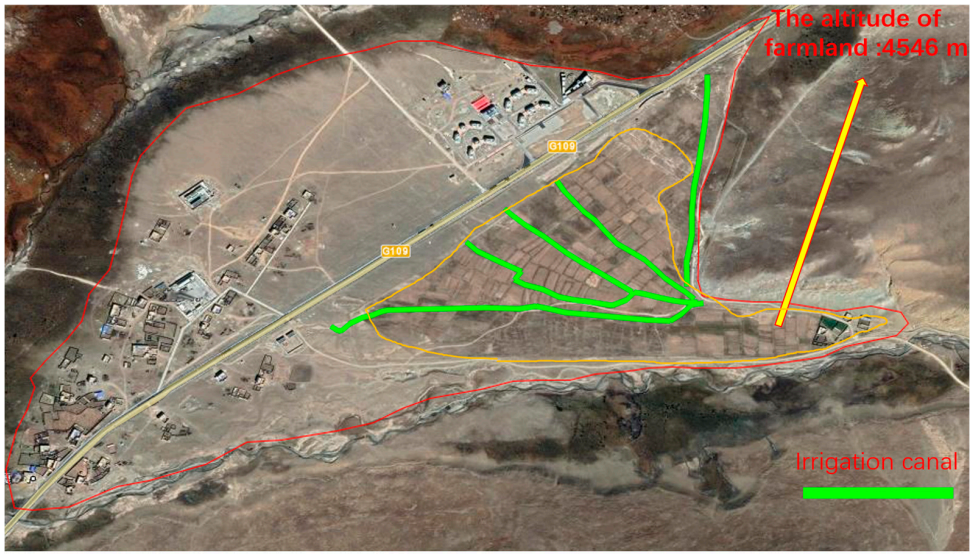



**Figure 9.** An alluvial fan located in Laduo Village, Yangbajing Town, Dumshung County.

### *4.2. Factors Influencing Alluvial Fan Land Suitability for Agriculture*

Certain measurable indicators can indirectly reflect the land suitability for agriculture (LSA), which is otherwise difficult to measure directly. Therefore, the land suitability for agriculture index (LSAI) of alluvial fans was established in this paper to reflect the LSA of alluvial fans. The results showed that the LSAI was significantly linearly associated with the 4 indicators in the MDS-EM (slope, accumulated temperature, distance to a tertiary road, and distance to a town), which were used in the establishment of the LSAI, and also significantly associated with the 13 indicators in all the other indicators in the evaluation

systems. This confirms that many factors affect the LSA of alluvial fans and the validity of assessment systems.

The LSA of alluvial fans was significantly associated with three topographic indexes (area, slope, and elevation) (Table 5) because land with a lower elevation, larger area, and smaller slopes is more suitable for agricultural production activities. Terrain factors such as altitude and slope can indirectly affect crop growth through temperature (accumulated temperature), oxygen content, moisture, and light [48,49].

The LSA of alluvial fans was positively correlated with soil quality and accumulated temperature but negatively correlated with rainfall and vegetation coverage, which is mainly related to the special topography and climate of the LRB, so it cannot be concluded that rainfall and the NDVI have an adverse impact on LSA. The rainfall and NDVI in the LRB gradually increase from southwest to northeast [39], and in the same direction, the altitude gradually increases (Figure 1) while the accumulated temperature decreases [39]. The LRB is an alpine region, and the crop types and distribution areas are generally substantially restricted due to the low accumulated temperature values [49]. However, different kinds of natural vegetation have different requirements for the accumulated temperature and other environmental conditions suitable for survival [32]. Therefore, the NDVI is higher in the northeast of the LRB with a high altitude, a low accumulated temperature, and high rainfall. At last, a region with a high NDVI and low LSA is more suitable for animal husbandry.

The LSA of alluvial fans was negatively correlated with gully density because gully erosion will continuously destroy the integrity of alluvial fans and affect the agricultural production activities on alluvial fans. For example, gully erosion can impede regular agricultural practices, impacting farming operations significantly, and even lead to the abandonment of cultivated land [50].

The LSA of alluvial fans was negatively correlated with the degree of flood risk. Flood risk evaluation usually needs accurate and high-resolution data on precipitation, water systems, disaster situations, and other aspects [51]. However, due to the limited relevant data in this area, this paper used the catchment area of the alluvial fan as a replacement for this indicator. Increased catchment areas lead to a higher flood risk for alluvial fans [52], resulting in a more significant negative impact on agricultural activities and production. In addition, glaciers or glacial lakes are distributed above some catchments of the alluvial fans in the LRB. With the increasing climate change in the Qinghai–Tibet Plateau, the melting of glaciers and glacial lakes also has a great possibility to increase the probability of floods [53], so the risk of floods on alluvial fans will also increase. This can be further studied in the follow-up study.

The LSA of alluvial fans was positively correlated with the land use degree but negatively correlated with the distance to primary roads, secondary roads, tertiary roads, rivers, villages, towns, and counties. The LSA of alluvial fans is closely related to human activities, which are generally more intense in areas with high suitability for agricultural activities [9]. Proximity to the river improves water availability in the alluvial fan [32], making irrigation easier and increasing its suitability. The alluvial fans closer to roads and residential areas generally have better environmental conditions and are easy to develop and utilise, so their LSA is higher.

To sum up, the LSAI calculated through the indicators screened by the MDS-EM are very effective. Our method is also used to evaluate the agricultural suitability of alluvial fans in other mountainous areas in the world. The MDS-ED method can significantly reduce the indicators for evaluating agricultural suitability and reduce the economic cost of data collection, which is very beneficial to the vast number of developing countries. However, we also need to admit that when using our method in other regions, we need to modify the indicators, because the background environment of each region is special.

### *4.3. Factors That Can Increase Alluvial Fan Land Suitability for Agriculture*

Developing facility agriculture (like building a greenhouse) and building roads are methodical approaches to improve the LSA of alluvial fans, which can increase the area percentage of suitable grades by 39.2% and 5.22%, respectively. In addition to the above indicators, other relatively easy-to-adjust indicators can also improve the LSA of alluvial fans. It is difficult to completely change the area, altitude, and slope of alluvial fans in the evaluation system. However, the slope can be changed partially and artificially in the alluvial fan. For example, terraces can be built in alluvial fans to reduce the partial slope of alluvial fans. Terraces have the functions of storing water, conserving soil, and increasing grain yield [54] to improve LSA. Agronomic measures can be taken to enhance the quality of soil, such as applying organic fertiliser, planting nitrogen-fixing plants, and crop rotation [55], to improve the LSA of alluvial fans. Although the rainfall and distance to a river are also difficult to change, irrigation agriculture can be developed by building reservoirs and irrigation canals to improve LSA. The erosion of gullies can be controlled by measures such as stone bundles, enclosures, terracing, and vegetation cover [56] to reduce the impact of gully erosion on agricultural activities. In addition, the agricultural activities of alluvial fans can be threatened by floods [52], so gully channels can be built to reduce the flood threat. These measures can be combined to effectively and reasonably utilise and protect the alluvial fan and realise the high-quality development of the land resources of the alluvial fan. However, it is difficult for our existing research to provide site-scale suitability criteria for the placement and siting of the terrace walls, which requires further research, which is the limitation of the current research.

These measures will provide a very good reference for improving the agricultural suitability of alluvial fans in other parts of the world, but they are also limited and cannot be directly copied. For example, if there is abundant rainfall in a certain area, there is no need to build reservoirs and terraces, because there is no need to store additional water resources for the development of agriculture in such areas, and it is enough to rely on natural rainfall. Therefore, when referring to the specific measures put forward in this study, other regions need to consider various local conditions.

## 5. Conclusions

In this paper, the minimum effective dataset was used to evaluate the land suitability for agriculture (LSA) of all the alluvial fans in the Lhasa River Basin (LRB), and scientific approaches to improve the LSA were outlined using a scenario simulation. The main conclusions were as follows:

The alluvial fans of a suitable grade for agriculture in the LRB are mainly distributed in the middle and lower reaches of Lhundup County, Medro Gongkar County, Taktse District, and Duilong Deqing District. This distribution range is consistent with traditional farming in this basin. Their number (area) reached 420 (683.58 $km^2$), accounting for 50.85% (58.62%) of the total number (area) of alluvial fans.

The land suitability for agriculture index (LSAI) of alluvial fans was significantly associated with all indicators in the evaluation system. The LSAI was positively correlated with the area, soil quality, accumulated temperature, and land use degree but negatively correlated with the slope, altitude, vegetation coverage, rainfall, flood risk degree, gully density, distance to a primary road, distance to a secondary road, distance to a tertiary road, distance to a river, distance to a village, distance to a town, and distance to a county.

Developing facility agriculture or building roads accessing alluvial fans will improve the LSA. Under the scenario of the complete development and adoption of facility agriculture, the area percentage of alluvial fans with suitable grades will increase from 58.62% to 97.82%. Under the scenario that all alluvial fans have access roads, the area percentage of alluvial fans with a suitable grade for agriculture will increase to 63.85%. At the same time, measures such as building terraces, improving soil quality, and controlling gully erosion can also improve the LSA of alluvial fans.

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