Flood inundation evolution of barrier lake and evaluation of regional ecological spatiotemporal response—a case study of Sichuan-Tibet region

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Abstract
The Himalayan volcanic earthquake zone has significantly impacted China’s Sichuan-Tibet region. Many barriers have formed as a result of the earthquake and secondary disasters, such as landslides, which have blocked the river. The breach of the barrier lake seriously threatens the lives and property safety of downstream personnel. There has been little research on the surrounding ecology for the later treatment of the barrier lake. This paper aims to scientifically predict the risk of dam break in a barrier lake as well as to explore its impact on the ecological environment and put forward controllable measures. Based on four major barrier lake events in the Sichuan-Tibet area, Diexihaizi, Tangjiashan barrier lake, and so on, we extract water bodies from remote sensing images and use the HEC-RAS (Hydrologic Engineering Center of River Analysis System) model to investigate whether there is a dam break risk and the route of the dam break is predictable. Simultaneously, from 1990 to 2020, the smallest administrative region is located. The InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) model is utilized to evaluate and analyze its habitat and create an evaluation based on flood inundation data. The results suggest that a stable barrier lake (such as Diexihaizi) has a sound effect on the habitat quality index following engineering treatment. The development of the barrier lake has altered the types of neighboring lands used and the natural patterns of the region’s landscape. The habitat quality index will marginally deteriorate within a 1-km radius of the barrier lake. However, the quality of habitats in the area ranging within 3 km and 5 km has improved. It is necessary to discharge and strengthen the barrier lake artificially. Human-controlled regions, according to studies, will recover higher habitat quality index values than other locations. Whether the barrier lake has a positive impact on the surrounding area, on the other hand, is primarily dependent on the original ecology. The development of barrier lakes is damaging and unprofitable in Tibet, where the actual ecology is better in the short term. Still, in Sichuan Province, where the habitat quality is relatively low, the appearance of dammed lakes has played a role in correcting the ecology.

Keywords Barrier lake · Regional ecology · Flood simulation · Habitat quality

Introduction
As early as 1786, there was a record of barrier lakes. The landslide in Moxi-mian dammed the lake induced by an earthquake, and floods inundated the lower reaches, causing the death of more than 100,000 downstream residents (Dai et al. 2004). In 1933, the Diexi barrier lake was formed by the Diexi earthquake landslide in the Minjiang River basin. Many scholars also studied it as a model. Through the application of fuzzy comprehensive evaluation to evaluate the risk of a landslide blocking the river, 10 participating factors were established, and the Diexi barrier lake is analyzed (Chai et al. 1997). Some scholars systematically introduced...
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Before 2008, we knew that the lake is mostly written, or visited the lake relics (just like Diexi lake). Since the “5.12” Wenchuan earthquake, the emergence of 34 quake lakes, many scholars were given the different types of lake dam research and the study of the flood, of which there is a lot of the Tangjia Shan barrier lake as the study area. The researchers summarized the risk of dam break of Tangjia Shan barrier lake and its impacts. On this basis, the key areas and suggestions for future research on the dam break lake were put forward (Kuang et al. 2008). The Wenchuan earthquake formed another major quake lake; there are also many scholars for the research area. The JetIndex method is used to measure the erosion of soil proposed by Hanson, and the dam break risk of Hongshi River barrier lake is evaluated (Chang et al. 2009). There are also scholars using multi-source remote sensing to study, and on this basis, to further determine the type of barrier lake, characteristics, and harm to provide a basis (Fan et al. 2008). Earthquakes form most barrier lakes, so it is necessary to sum up the rules of their formation and put forward solutions.

In recent years, several researchers have used the geomorphic dimensionless accumulation index method to differentiate the danger of a laterite dam breaking, estimate the flood of a barrier lake breaking, and estimate the flood of the downstream evolution process (Liu et al. 2016). By analyzing the risk assessment flow chart of the barrier lake, the collaborative work process and dynamic group control mechanism were designed to improve the efficiency of emergency response to the risk of dam failure of the barrier lake. The theory of distributed virtual reality and GIS is used to construct DVGE with technology, which supports the risk assessment and impact analysis of the dam failure of the barrier lake (Zhu et al. 2012). Some scholars also used quick and detailed procedures to assess the risk of inundation and used the case of a landslide dam in southern Taiwan to prove the usability of the systematic method (Yang et al. 2013).

In the past 5 years, quake lakes triggered by earthquakes and heavy rains have been numerous. In October 2018, the Jinsha River cut off the flow, leading to a barrier lake. After two landslides, a large area of road collapsed, the road was completely interrupted, and rescued difficulties, until November 14, 2018, only to successfully discharge, the inconvenience caused during the economic losses cannot be calculated (Zhan et al. 2017; Xu et al. 2018; Chen et al. 2020a).

Flow-3d software, MIKE11 model, and HEC-RAS model were used to calculate the burst flow and realize the flood inundation evolution (Hafiyyan et al. 2021), and visualization of the process is the main means of study on the dam break of the barrier lake (Liang and Zeng 2021; Li et al. 2021; Ma et al. 2021). More and more scholars are also using different fields of technology to study barrier lakes. Taking some more accurate data, more advanced means and more efficient data processing methods, such as the improved UAV tilt photography, and LiDAR method, were used to obtain the multi-resolution time series data of the weir body. Through optical remote sensing images and interferometric synthetic aperture radar, the dynamic process of landslides is analyzed (Ouyang et al. 2019). Coupling the publicity proposed by railway scientific research and Xie Renzhi’s progressive dam break model, an improved barrier lake progressive dam break model is proposed and verified its practicability. It was realizing the rapid acquisition and processing of high-precision terrain and image data. It provides numerical simulation support for the emergency rescue of the barrier lake (Sun 2021).

Barrier lake emergency rescue is necessary for us, and its surrounding ecology is equal. Many scholars study regional ecology. As early as 1985, some scholars evaluated the whole Minjiang River basin (Wang 1985). Then, according to different characteristics and research scales, the evaluation methods are divided into indicator species and index system evaluation methods (Chen et al. 2002). Based on the analysis of land use change, the paper puts forward that optimizing land use patterns in watershed can ensure ecological security (Yu et al. 2006). Some scholars also applied InVEST model in the field to verify the Miyun reservoir watershed (Li et al. 2013). Through the study of the treatment project, the ecological footprint calculation model is adopted, which provides the basis for the treatment project of Hongshiyuan barrier lake (Hu et al. 2017). For scholars to study the evolution of flood the lake has a lot of, for lake basin, habitat quality also has a lot of research scholars. Still, the combination of scholars is relatively less, and some scholars use relatively simple map superposition method and factor weight sum method for 2015 the Tangjia Shan barrier lake reservoir area is analyzed (Yang et al. 2014; Jian Yang 2017). However, it also has obvious shortcomings. First, it only uses data from 2015, and second, the method is not precise enough.

Because of the lack of current research, based on the four major quake lake events in the Sichuan-Tibet region of China, according to the parameter data of the quake lake in the existing papers, the HEC-RAS model was used to analyze the flood of the quake lake and judge the possibility of the bursting of the quake lake (Tian et al. 2012). If there is no barrier lake, the bursting situation of the barrier lake is simulated. Based on the ecological quality model, the long-term ecological impact of the lake basin was analyzed (Zheng et al. 2018). They were taking the typical barrier lake in southwest China as the research content, according to the difference of each region. The evaluation criteria of the ecological model in different regions are established, and

the basic characteristics of the Diexi ancient barrier lake and preliminarily discussed the geological environment information contained in Diexi ancient barrier lake by investigating the existing landslide (Wang et al. 2005).

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the submerged area of the barrier lake and its influence on the surrounding ecology are finally analyzed. The ecological changes in the region are monitored in a long time series.

Materials.

Study area and sample collection

Sichuan-Tibet region is located in southwest China, one of the seven subregions of China. The terrain in this region is undulating and complicated, and the natural environment is extremely harsh (Ji et al. 2019; Xu et al. 2021). Earthquake and landslide disasters frequently occur. The formation of quake lake after the occurrence of a landslide blocks the river, and while the lake burst, it greatly threatens the safety of people’s lives and property; the destruction of regional habitat is inestimable. The surface undulations in the region vary greatly, spanning first-level ladder and second-level ladder, among which lowland basins, plains, small undulating low mountains, and small undulating middle mountains have a larger area (Gan et al. 2017; Wang et al. 2020).

Corresponding to the topographical area, the Sichuan Basin presents a humid mid-subtropical monsoon climate. Due to the uplift of the Qinghai-Tibet Plateau, the temperature and precipitation in this area vary greatly from northwest to southeast. The average annual temperature in the east reaches 24 °C, and the average annual temperature in the west is the lowest. Below 0 °C, there are obvious dry and rainy seasons (Li et al. 2020; Xiang et al. 2020) (Fig. 1).

The primary data is shown in the table below (Table 1).

Barrier lakes in the study area

This article mainly studies the flood inundation evolution of barrier lakes in the Sichuan-Tibet area and the impact of barrier lakes on the ecology of the basin.

![Fig. 1 Location map of barrier lakes, Sichuan-Tibet region, China](image-url)
Table 1 Data source table

| Input data                  | Period          | Description                                                                 | Source                                      |
|-----------------------------|-----------------|----------------------------------------------------------------------------|---------------------------------------------|
| Land use/land cover         | 1990 1995 2000 2005 2010 2015 2018 2020 | Chinese remote sensing image interpretation data (1990–2018) produced by the Resource and Environmental Science Data Center of the Chinese Academy of Sciences and land use data produced by the Ministry of Resources of China (2020) | https://www.resdc.cn/ |
| Barrier lake parameter data | 1933 2008 2018 2018 | Integrate the data from the yearbooks and local chronicles of each administrative region and related documents to obtain relevant tables | Sorting out the literature on barrier lake |
| Digital elevation model data| 2017            | The data download comes from the Geospatial Data Cloud (China) with a resolution of 30 m × 30 m | http://www.gscloud.cn/sources/ |
| Extract data from water surface | 1990 2000 2010 2015 2018 | Extract data from water bodies, choose to extract water bodies in mountainous areas, and choose the revised normalized difference water index | http://www.gscloud.cn/sources/ |

**Diexi Haizi**

In 1933, a magnitude 7.5 earthquake occurred in Diexi, which formed Diexi Haizi. It is located in Maoxian County, Aba Tibetan, and Qiang Autonomous Prefecture, the largest settlement of Qiang in China. It has a long history, and it is of great research value (Fan et al. 2019; Xu et al. 2019; Wang et al. 2020; Xu et al. 2020; Wei et al. 2021).

**Tangjiashan barrier lake**

On May 12, 2008, a magnitude 8.0 earthquake occurred in Wenchuan County, Sichuan Province, China. A huge landslide occurred in Tangjiashan on the right bank of Tongkou River in Sichuan and 6 km away from Beichuan County. The landslide cut, blocked the river, and then formed the most severe barrier lakes in the earthquake. At present, this barrier lake has become a bay of still water (Zheng et al. 2015; Li et al. 2020; Zhu et al. 2021).

**Hongshi River barrier lake**

The Hongshi River barrier lake in Qingchuan County, Sichuan Province, is one of 34 large barrier lakes formed by the Wenchuan earthquake. It was formed by the Donghekou landslide blocking the Hongshi River. The Hongshi River barrier lake is in a group of barrier lakes. The upper reaches are the Shibangou barrier lake and the Donghekou barrier lake, and the lower reaches are the Libaisi barrier lake (Li et al. 2008; Chang et al. 2009; Shi et al. 2015).

**Baige barrier lake of Jinsha River**

On October 11 and November 3, 2018, two large-scale high-level landslides occurred on the right bank of the Jinsha River at the junction of Baige Village, Boluo Township, Jiangda County, Tibet Autonomous Region, and Zeba Village, Ronggai Township, Baiyu County, Sichuan Province. The Jinsha River formed a barrier lake. After the manual intervention, the dammed body began to discharge on November 12. Until the 13th, the water level of the upper and lower reaches of the dam body was through, and the danger of the barrier lake was lifted (Zeng et al. 2019; Zhou et al. 2019; Chen et al. 2020b; Zhang et al. 2020).

**Method**

We firstly determine the stability of the barrier lake after analyzing the impact of the dam break of the barrier lake, and then analyze the habitat quality of the barrier lake area. The specific process is shown in the following figure (Fig. 2).

**Flood dam break simulation method**

Hydrologic Engineering Center of River Analysis System (HEC-RAS) comprises four parts: unsteady flow simulation, water quality analysis, constant flow water surface line calculation, and movable boundary sediment transport calculation. The two-dimensional hydrodynamic model, with high accuracy and simple construction requirements, is more suitable for various scenarios such as flooding...
in plain areas and is used by many people. This research mainly uses the dam break calculation module and the flood evolution module (Chen et al. 2006; He et al. 2015).

The HEC-RAS two-dimensional hydrodynamic model uses the shallow water equation, which is a simplified two-dimensional form of the Navier–Stokes equation.

Continuous equation
\[ \frac{\partial H}{\partial t} + \nabla \times h \bar{V} + q = 0 \] (1)

Momentum equation
\[ \frac{\partial \bar{V}}{\partial t} + \bar{V} \times \nabla \bar{V} = -g \nabla H + v_T \nabla^2 \bar{V} - c_f \bar{V} + f_k \times \bar{V} \] (2)

where \( H \) is the water surface elevation, \( m \); \( h \) is the water depth; \( m \) is the flow velocity and the unit is \( m/s \); \( R \) is the hydraulic radius, \( m \); \( q \) is the side inflow single-width flow, \( m^2/s \); \( g \) is the acceleration of gravity, \( m/s^2 \); \( v_T \) is the kinematic viscosity in the horizontal direction, \( m^2/s \); \( c_f \) is the roughness of the bottom of the river bed; \( f \) is the Coriolis coefficient; \( k \) is the unit vector in the vertical direction; and \( n \) is the roughness.
The outflow from the breach is calculated on the assumption of a wide crested weir, and the calculation equation is

\[ Q = \sigma \epsilon m B' \sqrt{2g(Z_i - Z_{i+1})^{\frac{3}{2}}} \]  

In the formula, \( Q \) is the flow rate, \( m^3/s \); \( \sigma \) is the weir side collection coefficient; \( m \) is the flow coefficient; \( B \) is the width of the wide-crested weir, \( m \); \( s \) is the submergence coefficient; and \( Z_i, Z_{i+1} \) are the water levels before and after the weir, \( M \).

At present, there are more and more factors involved in water conservancy projects, and the amount of information that needs to be processed is also increasing. The HEC center has developed the GeoRAS module, combined with GIS software to effectively simplify the preliminary data preparation work and facilitate the establishment of river topographic geometric data.

### Habitat quality model

The habitat quality assessment method uses the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model developed by the US Natural Capital Project Group. InVEST 1.0 only includes two submodules: pollutant control, sediment, and unclassified biodiversity and carbon storage, wood yield, and crop pollination modules. Subsequent versions continue to refine the types of ecosystem service functions. As of April 2021, the InVEST model has been updated to version 3.9.0 (Yu et al. 2012; Pan et al. 2013). In this version, ecosystem service functions include three major modules: supporting ecosystem services. In addition to the final ecological service and urban ecosystem, there are two analysis modules: module operation aids and support tools (Yang et al. 2012; Wu et al. 2013) (Tables 2 and 3).

#### Table 2 Stress factor weight and maximum influence distance

| Stress factor           | Influence distance (km) | Weights | Decay function |
|-------------------------|-------------------------|---------|----------------|
| Paddy field             | 1                       | 0.5     | Linear         |
| Dry land                | 1                       | 0.5     | Linear         |
| Urban land              | 8                       | 1       | Exponential    |
| Rural settlement        | 5                       | 0.7     | Exponential    |
| Other construction land | 2                       | 0.5     | Linear         |

#### Table 3 Habitat suitability and sensitivity of stress factors

| Land use type          | Habitat suitability | Sensitivity to stress factors | Paddy field | Dryland | Urban land | Rural settlement | Other construction lands |
|------------------------|---------------------|------------------------------|-------------|---------|------------|------------------|-------------------------|
| Paddy field            | 0.4                 | 0                            | 1           | 0.7     | 0.5        | 0.4              |                         |
| Dry land               | 0.4                 | 1                            | 0            | 0.7     | 0.5        | 0.5              |                         |
| Have woodland          | 1                   | 0.5                          | 0.6          | 0.9     | 0.7        | 0.4              |                         |
| Bush forest            | 0.8                 | 0.4                          | 0.5          | 0.7     | 0.6        | 0.5              |                         |
| Sparse woodland        | 0.7                 | 0.5                          | 0.6          | 0.8     | 0.6        | 0.4              |                         |
| Other woodland         | 0.4                 | 0.5                          | 0.6          | 0.8     | 0.6        | 0.4              |                         |
| High coverage grassland| 0.8                 | 0.4                          | 0.45         | 0.6     | 0.45       | 0.7              |                         |
| Medium coverage grassland| 0.6              | 0.45                         | 0.5          | 0.65    | 0.5        | 0.7              |                         |
| Low coverage grassland | 0.4                 | 0.5                          | 0.55         | 0.7     | 0.55       | 0.7              |                         |
| River                  | 0.8                 | 0.6                          | 0.6          | 0.8     | 0.7        | 0.5              |                         |
| Lake                   | 0.9                 | 0.55                         | 0.6          | 0.9     | 0.7        | 0.4              |                         |
| Reservoir pond         | 1                   | 0.55                         | 0.6          | 0.9     | 0.7        | 0.5              |                         |
| Glacier                | 1                   | 0.65                         | 0.9          | 0.7     | 0.6        | 0.45             |                         |
| Tidal flat             | 0.7                 | 0.4                          | 0.5          | 0.6     | 0.6        | 0.6              |                         |
| Urban land             | 0                   | 0                            | 0            | 0       | 0          | 0                |                         |
| Rural settlement       | 0                   | 0                            | 0            | 0       | 0          | 0                |                         |
| Other construction land| 0.3                 | 0.3                          | 0.5          | 0.4     | 0.5        | 0                |                         |
| Bare land              | 0                   | 0                            | 0            | 0       | 0          | 0                |                         |
| Bare rock texture      | 0                   | 0                            | 0            | 0       | 0          | 0                |                         |
Result and discussion

Diexi Haizi

After the Diexi earthquake, 11 barrier lakes of varying specifications appeared. Over time, most of the barrier lakes have been broken. Only two barrier lakes, a large one and a small one remain. The occurrence of the Diexi Earthquake was quite a long time ago. However, we can also see the evolution trend of the barrier lake from the changes in the water area of the barrier lake in recent years (Table 4).

| Name        | Location                              | Average length (m) | Average width (m) | Depth (m) | Water surface area (mu) | Water accumulation (×10^5 m³) | Blocked river           |
|-------------|---------------------------------------|--------------------|-------------------|-----------|-------------------------|----------------------------|-------------------------|
| Dahaizi     | Jiaochang Township, Maoxian County    | 3600               | 360               | 81        | 2700                    | 7000                       | Minjiang River           |
| Xiaohaizi   | Jiaochang Township, Maoxian County    | 2350               | 290               | 42        | 2025                    | 5000                       | Minjiang River           |
| Diexihaizi  | Jiaochang Township, Maoxian County    | 2000               | 300               | 160       | -                       | 8000                       | Minjiang River           |
| Gongpenghaizi | Songpinggou Township, Maoxian County | -                  | -                 | -         | 403                     | 1000                       | Songping ditch           |
| Yuerzhaihaizi | Songpinggou Township, Maoxian County  | -                  | -                 | -         | 201                     | 100                        | Yuerzhai ditch            |
| Bailazhaihaizi | Songpinggou Township, Maoxian Country | -                  | -                 | -         | 101                     | 70                         | Songping ditch            |

Fig. 3 The submergence map of Diexi Dahaizi. (a) Diexi Dahaizi dry season chart; (b) Diexi Dahaizi wet season: artificially set overload; (c) start the dam break for 2 min and 30 s; (d) start the dam break for 5 min; (e) 7 min and 30 s from the beginning of the dam break; and (f) 10 min after the dam break.
At present, Diexi Haizi has been developed into a tourist area to bring economic benefits to the local tourism industry. It is necessary to conduct flood inundation studies to calculate whether the remaining two barrier lakes are at risk of collapse and the critical storage capacity of their collapse (Fig. 3).

Diexi Dahaizi is located in the upper reaches of Diexi Xiaohaizi. There is a narrow section in the upper reaches. The downstream is also connected to Diexi Xiaohaizi through a narrow section. Normal water levels and water levels during low-water periods generally do not break out. This article sets a possible. The number has more than doubled the value in the high water area of Diexi Dahaizi. Diexi Dahaizi was formed in 1933, and after successive heavy rains in the middle, there was no outburst, proving its strong stability (Wang et al. 2020).

Once the bursting occurs, however, the amount of water will scour out the Minjiang and flow into the Xiaohaizi, which will cause the collapse of this river. This article analyzes the Dahaizi and Xiaohaizi, respectively. The water storage capacity of Xiaohaizi is weaker than that of Dahaizi. Therefore, the former could burst while the latter not. The human protection in Xiaohaizi is better than Dahaizi because of the favorable terrain and the tourist areas surrounding it.

The landform of Xiaohaizi can be fully seen in dry season. In contrast to the Dahaizi, the protuberance of the center in Xiaohaizi serves as a buffer for a portion of the flood from upstream Minjiang to Xiaohaizi.

Due to the much smaller water storage capacity, once the Dahaizi bursting, the breaking path of Xiaohaizi will be in accordance with the Fig. 4, which is the Minjiang. Minjiang will be scoured If the overloading strikes Xiaohaizi, widening the channel and raising the water level.

Under normal circumstances, it is difficult to reach the capacity of artificially set breaching reservoirs. Since 1933, there have been no breaches in Dahaizi and Xiaohaizi in Diexi. In recent years, the development of tourist areas has made experts pay attention to the damage to the two barrier lakes. The treatment project also made the two barrier lakes more stable.

Diexi Haizi is located in the northeastern part of Maoxian County. During 1990–2020, Maoxian, as the severely affected area of the Wenchuan earthquake, also greatly impacted land use changes. The first was the change in the water area. Under the subdivision of the secondary land types, the area increased significantly compared to 2005. The larger ones are the area of river channels and the area of reservoir ponds, which are used to dredge the 34 barrier

![Fig. 4 Inundation of Diexi Xiaohaizi. (a) Diexi Xiaohaizi dry season map; (b) Diexi Xiaohaizi wet season: artificial overload; (c) dam break for 4 min; (d) dam break for 8 min; (e) 12 min after the beginning of the dam break; and (f) 16 min after the dam break](image-url)
lakes formed by the Wenchuan earthquake and prevent heavy casualties caused by the collapse of the Diexi barrier lake after the 1933 Diexi earthquake.

Between 2010 and 2015, there was a small decrease in grassland and arable land area, and the area of construction land changed from 5.64 to 11.63 km², an increase of about 106.2%, and the water area and the bare land area did not change much. During this period, the urbanization process in Maoxian County has been significantly accelerated, and construction land has gradually increased. Most of the

| Time  | Land type | Grassland | Arable land | Construction land | Woodland | Bare ground | Waters | Total |
|-------|-----------|-----------|-------------|-------------------|----------|-------------|--------|-------|
| 1990  | Grassland | 1578.1    | 19.2080     | 1.33155           | 110.032  | 3.1632      | 1711.85|       |
|       | Arable land| 20.031    | 128.5776    | 2.943267          | 14.269   | 0.6662      | 166.487|       |
|       | Construction land | 0.2974 | 0.2126 | 2.8905 | 0.3003 | 0.0787 | 3.7796 |       |
|       | Woodland  | 192.581   | 15.703      | 4.5878            | 1786.869 | 3.61729    | 2005.96|       |
|       | Bare ground | 0.00093 | 0.045       | 0.067797          | 0.00079  | 3.833       | 4.21147|       |
|       | Waters    | 0.26538   | 0.045       | 0.067797          | 0.00079  | 3.833       | 4.21147|       |
|       | Total     | 1791.29   | 163.746     | 11.7531           | 1911.5397| 3.61729    | 10.34  | 3892.288|

Fig. 5 Habitat quality changes in Maoxian County
increase in construction land is the increase in rural settlements. Tourist areas have also been established near the barrier lake, driving local tourism GDP increase (Table 5).

The distribution of habitat quality in Maoxian from 1990 to 2015 has obvious characteristics (Fig. 5). Areas above the intermediate level account for the majority. The low-level and lower-level areas are mainly concentrated in the southeast of Maoxian. The areas judged as high level will be within 25 years. The proportion is decreasing, but the higher-level tone area has increased significantly, and the low-level and lower-level areas have decreased year by year. It can also be seen that the country pays more attention to the protection of environmental quality. During the 5 years from 2010 to 2015, the overall habitat quality index did not change much.

Judging from the images from 1990 to 2015, the dammed lake did not impact the surrounding ecology, mainly because the Diexi earthquake occurred in 1933.

The barrier lake is equivalent to an inland lake after treatment and development. In addition to the impact on the surrounding ecology during tourist area development, it can be seen in the 2010 and 2015 photos that following the earthquake, the ecology around the barrier lake has degraded to some extent, which is related to the tourism area development. It is also related to changes in geological conditions. After comparison, the effect on ecology is equivalent to that of inland lakes.

We divided the 0–1 habitat quality into 5 categories evenly through the hierarchical breakpoint method.

**Tangjiashan barrier lake**

Tangjiashan barrier lake is located in Beichuan County and is the largest barrier lake formed by the Wenchuan earthquake. Therefore, its data records are also very accurate. The relevant parameters of the Tangjiashan dam are as follows (Table 6):

At present, due to the great changes in geological conditions, we have no way to simulate the collapse of the Tangjiashan barrier lake in 2008 based on DEM data. We can only rely on the data of the Tangjiashan barrier lake extracted this year. Based on the upstream and downstream positions of the Tangjiashan barrier lake, the water body data follow the river course to simulate the dam break of the barrier lake (Fig. 6).

After the natural flood discharge under artificial control in 2008, the Tangjiashan barrier lake has been very stable. It has now turned into a bay of “human”-shaped still water and has been listed as a famous national freshwater lake. It has good ecological value. Once the Jiashan barrier lake breaks, it will have the most impact on the “Fujiang,” the mother river of Mianyang. It will scour and widen the channel of the Fujiang River, breaking from upstream to downstream.

The land use changes in Beichuan County from 1990 to 2015 are shown in Table 7. The grassland area and arable land area have relatively little change. The size of construction land has changed from 4.7 to 12.09 km², and the growth rate is 157.4%. The rate of increase clearly shows the acceleration of urbanization, the increase in the water area, and the changes in the ecosystem. In 25 years, the period of greatest change was from 2005 to 2010. This period is a relatively significant period. The event was the 5.12 Wenchuan earthquake, and many dammed lakes were formed simultaneously. The largest dammed lake is the Tangjiashan dammed lake in Beichuan.

At present, this barrier lake has stabilized after being discharged by experts and has become an inland freshwater lake with considerable economic benefits.

The distribution characteristics of the habitat quality of Beichuan Qiang Autonomous County from 1990 to 2015 are obvious. Areas above the intermediate level account for the majority of the proportions. The low-level and lower-level areas are mainly concentrated in the southeast and central areas of Beichuan County. During the 15 years from 1990 to 2005, the overall habitat quality did not change much. However, in 2010 and 2015, we can see a significant increase in areas with lower habitat quality. The Wenchuan earthquake has caused ecological damage in Beichuan County, a very serious impact (Fig. 7).

**Hongshi River barrier lake**

The Hongshihe barrier lake is the only one of the barrier lake groups in this research. It is situated between the Libaisi and Donghekou barrier lakes. Upstream, there is also a Shibangou barrier lake. Relatively speaking, once one of the barrier lakes has a breach problem, all barrier lakes in the Beichuan area will be affected. The structure
Fig. 6 The inundation map of Tangjiashan barrier lake. (a) Tangjiashan barrier lake dry season map; (b) Tangjiashan barrier lake normal conditions; (c) Tangjiashan barrier lake wet season: artificially set overload; (d) dam failure for 10 min; (e) 20 min of dam failure; (f) 30 min of dam failure; (g) 40 min of dam failure; (h) 50 min of dam failure; and (i) end of dam failure.

Table 7 Land use change matrix in Beichuan County (km$^2$)

| Time | Land type    | 2015          |
|------|--------------|---------------|
|      | Grassland    | Arable land   | Construction land | Woodland | Bare ground | Waters | Total  |
| 1990 | Grassland    | 448.28        | 11.6159        | 0.09351  | 32.3415    | 0.11   | 0.00017 | 492.4337 |
|      | Arable land  | 22.374        | 400.257        | 5.13828  | 82.73533   | 3.62   | 1.6455  | 515.770   |
|      | Construction land | 0.0773     | 0.47655        | 3.689095 | 0.109196   | 7.4946 | 0.3528  | 4.705     |
|      | Woodland     | 29.096        | 105.368        | 3.12086  | 1718.227   | 7.4946 | 0.1205  | 1863.43   |
|      | Bare ground  | 0.071         | 0.4527         | 0.04703  | 0.11218    | 0.023  | 4.068   | 4.77385   |
|      | Waters       | 499.89        | 518.17         | 12.0888  | 1833.525   | 11.244 | 6.1872  | 2881.11   |
|      | Total        | 448.28        | 11.6159        | 0.09351  | 32.3415    | 0.106  | 0.0002  | 492.4337  |
of the barrier dam is filled with block stones; the block stones are interposed with clay, the density is low, and the permeability is high. When analyzing the stability of the Hongshi River barrier dam, the existence of high permeability areas should be considered. This is also why the Hongshi River barrier lake is relatively special.

Not many people have studied the barrier lake of the Hongshi River. There are currently recorded data on the barrier lake of Hongshi River at that time as shown in the table below (Table 8). Nowadays, some water conservancy projects to protect the barrier lake have caused changes in the vicinity of the barrier lake. The barrier dam has also been slightly adjusted.

The Hongshihe barrier lake is located in a group of barrier lakes, including the Shibangou barrier lake upstream, the Donghekou barrier lake connected to the Hongshihe barrier lake, and the Libaisi barrier lake downstream of the Hongshihe barrier lake. Among the lakes, the Shibangou barrier lake has the largest water storage capacity in this barrier lake group.

Fig. 7 Habitat quality changes in Beichuan County

Table 8 Related parameters of Hongshihe Barrage Dam (2008)

| Name                      | Hongshihe Barrage dam |
|---------------------------|------------------------|
| Water level difference (m)| 300                    |
| Width of dam bottom (m)   | 400                    |
| Dam height (m)            | 50                     |
| Barrier lake length (m)   | 200–300                |
| Rain catchment area (km²) | 70                     |
| Water storage capacity (m³)| 2 x 10⁸                |
| Maximum storage capacity (m³)| 4 x 10⁸               |
| Average flood flow (m³/s) | 152                    |

### Table 8: Related parameters of Hongshihe Barrage Dam (2008)
The failure of the barrier lake is very rapid; sometimes, it is about 10 min, and sometimes, it is 20 min. It is very necessary to scientifically predict the time of the dam failure of the barrier lake and notify the residents to evacuate in advance. Once a flood occurs, it will affect the surrounding Guang-Fuzhou Bridge and the G212 Lan-Yu Line. The path of the failure is shown in Fig. 8. We can follow the main direction of the failure to plan the evacuation path of the residents. Once the failure occurs, it will affect the downstream of worship temple barrier lake.

The land use changes in Qingchuan County from 1990 to 2015 are shown in Table 9. The grassland area and the cultivated land area both with a small decrease. The construction land area changed from 9.04 to 12.62 km², and the growth rate was about 39.6%; the bare land area changed from 38.1 to 28.82 km²; the reduction rate was approximately 24.7%; the water area changed from 11.43 to 32.17 km²; the growth rate was approximately 182.5%.

Since 1995, Qingchuan County has been in the process of urbanization. Between 1995 and 2000, the area of grassland,
woodland, and arable land decreased, and the growth rate of construction land was about 40.5% increase rapidly.

The distribution characteristics of the habitat quality of Qingchuan County from 1990 to 2015 are obvious (Figs. 9 and 10). Areas above the intermediate level account for most Qingchuan County; low-level areas are located in the northeast of Qingchuan County, and lower-level areas are located in the middle and middle of Qingchuan County. As time goes by, lower-level areas have increased in the northeast, high-level areas have also increased, and intermediate-level areas have decreased significantly. It can be seen that since 2005, the ecological quality index has dropped significantly.

**Baige barrier lake of Jinsha River**

The barrier lake of the Jinsha River is currently invisible in the image. We simulated the location of the first landslide to simulate the flooding of the existing Jinsha River. The current Jinsha River is very stable, and many protection have been established.

There have been two landslides in the Baige dammed lake of the Jinsha River, one in October 2018 and one in November 2018. Both landslides have a dammed body. Some parameters of the dammed body are shown in the table below (Table 10).

At present, due to artificial changes in elevation, we cannot use HEC-RAS to simulate the two failures in 2018. We can only simulate the disaster at that time with limited data.

The process of simulating the collapse of the Jinsha River barrier lake is shown in Fig. 6. The Jinsha River is the upper reaches of the Yangtze River in China. It has a drop of 3300 m and is rich in water resources. It is located at the junction of Tibet and Sichuan. An earthquake caused the Jinsha River to block the river again to form a barrier lake. With the rich water resources of the Jinsha River, it will inevitably be broken within a week. Make timely...
predictions for the formation of the barrier lake, which is the Baige barrier lake of the Jinsha River. Give us the best warning.

The Baige barrier lake is special. It is located in Baiyu County in Sichuan Province, and half of it is in Jiangda County in the Tibet Autonomous Region. Jiangda County belongs to Tibet Autonomous Region in Changdu. It is dominated by grassland and forest land. There has been no land type for construction land. Grassland has been decreasing year by year, and cultivated land has increased year by year. During 2005–2015, large areas of grassland were under manual intervention. Turned into forest land, part of the reduction of bare land turned into arable land, and part of it widened the water area. The urbanization process in Baiyu County is not rapid, and various types of land are relatively stable (Tables 11 and 12).

Baige barrier lake is the one formed by the 2018 earthquake that blocked the Jinsha River. The Jinsha River is also the boundary between the Tibet Autonomous Region and Sichuan Province. In the first 25 years of the formation of the barrier lake, the regional ecology has been stable. Changes for the better, while the region’s ecology is relatively stable. In 2015, areas with low habitat quality in Jiangda County accounted for less than 5%. The proportion of high-level

| Time   | Parameter name         | Parameter   |
|--------|------------------------|-------------|
| 2018.10.10 | Initial reservoir level (m) | 2932.5      |
|        | Initial bottom elevation (m) | 2929        |
|        | Inbound flow (m³/s)      | 800         |
|        | Lowest water level (m)   | 2910        |
|        | Minimum storage capacity (m³) | 9.02 × 10¹⁰ |
|        | Highest water level (m)  | 2935        |
|        | Maximum storage capacity (m³) | 2.784 × 10¹¹ |
| 2018.11.03 | Landslide height (m)     | 800         |
|        | Landslide top elevation (m) | 3670        |
|        | Top elevation (m)        | 3718        |
|        | Length along the river (m) | 1400        |
|        | Length across the valley (m) | 600         |
|        | Highest water level (m)  | 2956.4      |
|        | Original riverbed elevation (m) | 2861        |
|        | Actual maximum storage capacity (m³) | 5.79 × 10⁸ |

Fig. 10 The simulated inundation map of the Jinsha River dammed lake. (a) The flood season of the Jinsha River barrier lake: artificially set overload; (b) start the dam break for 5 min; (c) start the dam break for 10 min; (d) start the dam break for 15 min; (e) 20 min after the start of the dam break; and (f) the dam break is completed.
areas decreased, and higher-level areas accounted for most of Jiangda County’s entire (Fig. 11).

**Impact of barrier lake on habitat quality**

Before 2005, Diexi Haizi has always had a good impact on the quality of the habitat. When the habitat quality is extracted in the corresponding area, it can also be seen that there will be existing near the barrier lake. Water and soil erosion (Wei et al. 2011) has caused a slight decline in the quality of the habitat. Still, in general, the quality of the habitat is higher than the average habitat in the administrative region. Still, from 2005 to 2018, it was affected by the Wenchuan earthquake and its establishment due to the tourist area; the habitat quality within 1 km and 3 km is lower than the average quality, but within 5 km, the habitat quality is higher than the average. Since 2018, the Maoxian government has paid more attention to ecological aspects. It has also improved the treatment and improvement of the Diexi Haizi Tourist Area, and the overall quality of the habitat has been improved (Fig. 12).

After the formation of the Tangjiashan barrier lake and the 2008 Wenchuan earthquake, the average habitat quality of the smallest administrative area tended to be stable at 6 km away from the city. Near the site, the habitat quality within the scope has not been high, especially the closer to the barrier lake, the lower the habitat quality, which is about 63.4% of the average habitat quality. However, after 2008, the formation of the barrier lake and the artificially planned flood discharge project changed the land type of the barrier lake area. The quality of the nearby habitat was significantly improved, and the area was stable. However, due to the urbanization process, there are too much construction, insufficient vegetation coverage, and ecological damage caused by landslides and mudslides. The area around the barrier lake is still lower than the average habitat quality of the smallest administrative area, which is about 75% of the average regional habitat quality (Fig. 13).

The Hongshi River barrier lake is located in Qingchuan County. The average habitat quality of Qingchuan County has been relatively stable, but it is relatively low compared to the average habitat quality of other administrative regions in Sichuan Province. From 1990 to 2005, the habitat quality of the existing barrier lake in Hongshi River was far lower than the average habitat quality, and the soil erosion around the area was serious. The farther away from the dammed lake, the higher the habitat quality. However, after the Wenchuan earthquake, the treatment volume of the surrounding habitat has been significantly improved after the formation of the dammed lake. Within 1 km of the barrier lake, the quality of the habitat is only lower than 3% of the average quality (Fig. 14).

The Baige barrier lake in Jinsha River is produced in the past 5 years, and it is impossible to analyze the

### Table 11 Land use transfer matrix in Baiyu County (km²)

| Time   | Land type   | 2015            |
|--------|-------------|-----------------|
|        | Grassland   | Arable land     | Construction land | Woodland | Bare ground | Waters | Total   |
| 1990   | Grassland   | 6182.09         | 7.222            | 0.2806387 | 123.23      | 26.7   | 1.4541  | 6340.922|
|        | Arable land | 13.2151         | 46.454           | 0.744456  | 0.783       | 0.002  | 61.19889|
|        | Construction land | 0.22181 | 0.0354          | 2.344171  | 0.0132      | 0.0011 | 2.615692|
|        | Woodland    | 150.373         | 14.672           | 0.104421  | 3275.5      | 2.53399| 0.31863 | 3443.47  |
|        | Bare ground | 53.8521         | 2.2016           | 7.15934   | 3.3018      | 740.113| 1.21173 | 798.479  |
|        | Waters      | 0.67672         | 0.0637           | 0.455     | 0.15771     | 39.451 | 40.80463|
|        | Total       | 6400.43         | 68.447           | 3.4737577 | 3403.2      | 769.449| 42.436  | 10,687.49|

### Table 12 Land use transfer matrix in Changdu County (km²)

| Time   | Land type   | 2015            |
|--------|-------------|-----------------|
|        | Grassland   | Arable land     | Construction land | Woodland | Bare ground | Waters | Total   |
| 1990   | Grassland   | 886.76          | 70.412           | 1.52305  | 53.77       | 0.65   | 2.17685 | 1015.3   |
|        | Arable land | 57.5955         | 711.67           | 5.6766   | 21.8186     | 0.12   | 20.104967| 816.9876 |
|        | Construction land | 1.03164 | 1.866            | 4.63396  | 0.03171     | 1.472674| 9.036012|
|        | Woodland    | 35.2214         | 16.41            | 0.72519  | 994.061     | 0.2391 | 0.020596 | 1046.6751|
|        | Bare ground | 0.57276         | 1.6884           | 0.0599   | 0.0065      | 8.3922668| 11.4253 |
|        | Waters      | 1.27822         | 0.6805           | 12.6188  | 1079.35     | 28.8245| 32.1674  | 2937.47  |

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Fig. 11 Habitat quality change map of Baige dammed lake area

Fig. 12 Changes in habitat quality of Diexi Haizi

Fig. 13 Changes in habitat quality of Tangjiashan barrier lake
temporal and spatial changes of habitat quality in a long time series. Because the barrier lake is located on the boundary between Sichuan and Tibet, and the habitat quality of two adjacent administrative regions is quite different, it is analyzed separately (Fig. 15).

Before the barrier lake was formed, due to the large area and sparse population, high vegetation coverage, and the slow urbanization process in Tibet, the habitat quality has been relatively good and stable. In contrast, due to the rapid urbanization process, the Sichuan region has only 83% of the habitat quality in Tibet. Due to the scarcity of disasters in Tibet, the production of barrier lakes has caused great damage to the habitat. As the scope of impact increases, the regional habitat is still higher than the average habitat. However, the quality of the habitat in Sichuan has been low. After the barrier lake formation, the national treatment of the dammed lake has improved the quality of the regional habitat, with an increased rate of about 6% (Fig. 16).

**Discussion**

Most barrier lakes are located in mountainous areas. To develop and manage barrier lakes, measures should be taken according to local conditions. High-risk barrier lakes cannot be developed. Demolition of the barrier lake can only construct a project similar to the Baige barrier lake of the Jinsha River. Minimize damage to habitat quality. After simulating flood breaks of all barrier lakes, we learned that the five barrier lakes studied in this paper are currently unlikely to have dam breaks in the barrier lakes.

In 2017, Chinese scholar Yang Jian conducted a regional habitat analysis on the Tangjiashan barrier lake, but its limitations are very large. First of all, only DEM and remote sensing data are used, and only factors such as slope, aspect, altitude, vegetation coverage, and water bodies are used for analysis. Studies have shown that the impact of barrier lakes on the surrounding habitats outweighs the disadvantages under artificial control, especially for some areas with serious soil erosion. The barrier lakes have the function of conserving water sources and maintaining water and soil so that the quality of regional habitats has been steadily improved. Tend to be stable, not only in ecology, some non-high-risk barrier lakes can be compared to Diexi Haizi and become tourist areas through engineering construction, providing jobs and economic benefits for the local area. After becoming a tourist area, Diexi Haizi will be regional habitat. Still stable, with minimal damage to the ecology. High-risk barrier lakes (such as the barrier lake in Jinsha River) must have
early warning, prevented, and controlled. They have a strong destructive power on the surrounding ecology. Even if it is artificially maintained, the damage to the surrounding ecology is still very large, and it can only be after the collapse through the establishment of ecological engineering and policy protection to maintain and improve the regional habitat.

Conclusion

This paper examines the barrier lake events, employs the HEC-RAS model to examine flood inundation, and utilizes the InVEST model to examine regional temporal and spatial changes.

The study focuses on the failure of four barrier lake occurrences in the Sichuan-Tibet region and an examination of a 30-year time series of regional habitat changes. This paper is the first study to look at changes in the habitat quality of barrier lakes through the perspective of models. This work studies the habitat quality using the InVEST model, which many people repeatedly evaluated the surrounding area of the barrier lake using submerged membrane extraction.

The four barrier lake events are rather common. Diexihaizi arose from the 1933 Great Diexi Earthquake. During the dammed lake’s development in 1985, it required considerable time to fortify the dam body. At the moment, there is little chance of a collapse. It has tended to be stable following the formation of the Diexihaizi. Except for slight soil erosion in the adjacent area, the overall habitat quality is relatively high. They also have barrier lakes formed after the Wenchuan earthquake. Due to the serious disasters, the Tangjiashan barrier lake has a lot of human intervention. Although humans also controlled the Hongshihe barrier lake in the late period, there was a natural outburst time in the early stage, so even though it has a good impact on the habitat, the impact is not as strong as the Tangjia Shan barrier lake.

Moreover, before the formation of the two barrier lakes, the areas where they were located belonged to areas with slightly severe water and soil erosion, so after the formation of the barrier lakes, the quality of the habitat was significantly improved. The Baige barrier lake formed on the Jinsha River is located at the junction of Sichuan and Tibet. After the collapse, it will cause serious damage to the Tibet Autonomous Region, but it will positively impact the Sichuan region. The basic reason is that disaster frequently occurs in Sichuan, and natural disasters such as landslides and mudslides are severely damaged. After the formation of barrier lakes, they function as lakes in the region, which can conserve water sources, preserve water and soil, and improve the quality of habitats. However, the habitat quality in Tibet has always been high and stable. The stabilizing effect of the barrier lake after the formation of a lake is far less than its destructive effect. The main area of the barrier lake collapse is located in the Tibet Autonomous Region, so the habitat quality is significantly reduced. The lakes in Tibet are mainly glacial lakes, which are partly similar to barrier lakes. Once a disaster occurs, the habitat will be destroyed greatly.

The barrier lake in Jinsha River was dredged under human intervention in December 2018, and it no longer exists. We have done so far to imitate the location of the first landslide and simulate the formation and failure of the Baige barrier lake in Jinsha River. The Jinsha River section has always been famous for its rich hydraulic resources, accounting for more than 40% of the Yangtze River's hydraulic resources. The ability to predict the formation of the barrier lake in time is the best reflection on the Baige barrier lake in the Jinsha River. The Jinsha River has now reached a stable state. It is often difficult to build a barrier lake unless natural calamities such as landslides and earthquakes occur. The Jinsha River in Tibet, on the other hand, has less human activity, making disaster prevention and mitigation more challenging.

The current science and technology cannot completely predict the occurrence of dammed lakes. What we can do is to develop and utilize the barrier lakes more reasonably. This study proves that, under artificial control, the Tangjia Shan barrier lake has a beneficial impact on habitat quality change. Diexihaizi, which has been developed into a tourist area, had a beneficial impact on the local economy before the epidemic. At the same time, it maintained water sources for the environment and acted as a lake. This research seeks to achieve the ability to plan more scientifically the development of barrier lakes after formation and to give a basis for applicable environmental planning of barrier lakes. To provide a set, only more barrier lakes can be chosen. This paper still has some limitations in the data selection for the highly relevant barrier lake ecological planning plan. Although the dammed lake occurrences chosen are already fairly common, they are relatively lacking in quantity.

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Author contribution X. D. initiated and designed the research. F. J., T. X., S. Y., and G. Q. conducted the experiment. Z. X. and Z. H. aided in analyzing the results and guidance. Y. Z., S. Y., Z. Y., and J. X. contributed to the writing and development of the manuscript. All authors discussed the results and contributed to the final manuscript.

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Declarations

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