Risk assessment of geohazards along Cheng-Kun railway using fuzzy AHP incorporated into GIS

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\textbf{ABSTRACT}

This article presents a case study on the risk assessment of geohazards along Cheng-Kun railway line. Cheng-Kun railway passes through a region of highly varied elevation and faults and the operation of Cheng-Kun railway has been frequently interrupted owing to geological disasters. A hybrid method via integrating triangular fuzzy number (TFN) and the analytic hierarchy process (AHP) (hereafter simply call TFN-AHP) into a geographic information system (GIS) is employed in this study to perform the geohazards assessment. The assessment results showed that TFN-AHP with GIS can effectively predict the distribution of geohazards risk in the study region within the last 10 years. The results also showed that the TFN-AHP method is more efficient in identifying high-risk areas compared with using original AHP. Based on the assessment results, prospective management measures to prevent risk are recommended.

1. Introduction

With the development of the economy, the importance of railway systems that connect cities, shorten transportation time for people, and facilitate the exchange of goods is becoming more significant. According to data from the National Railway Administration up to 2019, China’s operating railway mileage has reached 139,000 km (NRA 2020). Railway accidents may threaten the safety of passengers, employees, road users, and surrounding residents within the railway area. Therefore, the safe operation of railway systems has become a major concern for the authorities. China is a country that experiences frequent geological disasters (geohazards) and contains almost all types of landforms (Lyu et al. 2018b) and, in China, geohazards have been identified as the main causes of damage to railway systems (Lyu et al. 2018a; Khalid et al. 2019). Geohazards and disasters occur under the influence of natural or human factors and result in the loss of human life and damage to property and the
environment. The main types of geohazards include landslides, slumps, mudslides, ground collapse, and earthquakes.

With the development of various theoretical methods, the risk assessment of geohazards has been more focused on quantitative evaluations based on field data (Zhao et al. 2017). The relevant evaluation factors of geohazards could be determined according to various disaster evaluation models, e.g., deterministic models, pattern recognition models, statistical analysis models, and subjective inference analysis models (Piacentini et al. 2012; Mackillop et al. 2018). The identified factors then can be quantitatively presented in GIS, e.g., the related factors of landslide occurrence and urban flood disaster risk (Peng and Peng 2018a, 2018b; Qiao et al. 2019a, 2019b; Ali et al. 2019; Wu et al. 2019; Peng et al. 2021). At present, there are a variety of theories to analyse the relationship between the geohazards and their influencing factors, such as the artificial neural network (ANN), the probability model with logistic analysis, and the analytic hierarchy process (AHP) (Dou et al. 2015; Wang et al. 2017; Lyu et al. 2018a). In these methods, the AHP is a popular multi-criteria decision analysis method in the risk assessment of geohazards, which allows a flexible combination of data from different sources. The AHP-evaluation results can be incorporated into GIS well (Feizizadeh et al. 2014; Ali et al. 2019). However, the original AHP approach cannot deal with the ambiguity and uncertainty in the decision-making process (Kritikos and Davies 2011). Therefore, the fuzzy AHP was proposed to replace the crisp numbers obtained from decision-makers’ judgements in the original AHP method with the fuzzy numbers or fuzzy sets (Chen et al. 2011; Lyu et al. 2019). For the fuzzy AHP, it has been widely applied into risk assessment, such as the landslide susceptibility and soil slope stability (Zhang et al. 2018; Sur et al. 2020), which key process is the collection of experts’ judgements to determine the fuzzy numbers. Lyu et al. (2020d) proposed a new consulting process in fuzzy AHP by performing a risk assessment, which overcomes the deficiency of traditional pairwise questionnaires (Saaty 1977; Li et al. 2013a).

Cheng-Kun railway is one of the most important passenger and freight railway lines in the southwestern part of China, which has been threatened by many geological disasters. Figure 1 illustrates the number and types of geological disasters that have caused damage and interrupted operation along the Cheng-Kun railway from 2009 to 2019. As shown in Figure 1(a), during the past 11 years, there were 17 geological disasters along the railway and the frequency of geohazards has increased slightly in the past two years. The most frequent hazards are mudslide and landslide, at 35.29%, and the least frequent hazard is an earthquake, at 11.76% (Figure 1(b)). Owing to the low frequency of earthquake, only mudslide, landslide and slump are considered. These geohazards caused high casualties and economic losses (Zheng et al. 2019). At present, most risk assessment studies of geological disasters regard the geological bases as disaster-causing factors, and anthropic activities as exposure factors. However, with economic development and population growth, frequent anthropic activity appears to be the main causal factor in damaging landslides and floods, rather than natural factors (Baioni et al. 2011; Lira et al. 2014; Lyu et al. 2020b, 2020c).

In this article, mudslide, landslide and slump are recognized as different aspects of a generalized geohazard. The objective of this study is to evaluate the generalized geohazard
along the Cheng-Kun railway using GIS and fuzzy AHP and it also aims to propose sustainable management measures for this important railway. First, the background of the Cheng-Kun railway is presented. Subsequently, the assessment framework of fuzzy AHP is established. The assessment results are mapped by using GIS and discussed in detail. The sustainable management measures are then proposed based on the assessment results.

2. Background

With a total length of 1096 km, the Cheng-Kun railway starts at Chengdu station in Sichuan province at the northern end, terminates at Kunming in Yunnan province at the southern end, and serves 124 stations. Figure 2 shows the map of the areas along the Cheng-Kun railway and the surrounding cities. The route runs from the Sichuan

![Geological disasters along Cheng-Kun Railway that occurred from 2009 to 2019: (a) numbers and (b) percentage of types. Source: Author.](image)
Basin through the Hengduan Mountains to the Yunnan-Guizhou Plateau (Figure 2(a)). This line is laid along the first and second step edges of the Chinese terrain, where the terrain is complex, a fracture zone develops, and the valley is steep. The highest elevation is 2280 m, and the lowest is approximately 500 m (Yan and Wang 2006). According to the meteorological data, the annual precipitation in Sichuan, along the line, is approximately 900 mm, whereas the annual precipitation in Yunnan is approximately 600 mm. Therefore, this area is rich in hydraulic runoff of water due to abundant rainfall and unique terrain. The following eight cities that the railway passes through constitute the study area: Chengdu, Ya’an, Meishan, Leshan, Liangshan, Panzhihua, Chuxiong, and Kunming. Among them, the line from Chengdu to Panzhihua is under the administration of Sichuan province, and from Chuxiong to Kunming is administrated by Yunnan province. The total area along the railway is 130,000 km². Hence, eight cities were selected as the research area within the latitude of 24°00’ to 30°00’ and longitude of 100°00’ to 106°00’ (Figure 2(b)). All following datasets were clipped to the study area and resampled to a 1 km² raster size, thus all input grids were the same projection and cell size. The data collection and processing are explained below.

2.1. Topography

The topographic map in Figure 3(a) shows the elevation and the distribution of the river system and that in Figure 3(b) shows the distribution of slope in the area. The metadata of elevation, slope and the distribution of river system were generated from the DEM at a 30 m resolution, collected from the public records of Geospatial Data Cloud (http://www.gscloud.cn/). The Cheng-Kun railway extends from the west of the Sichuan Basin, with an average elevation of approximately 500 m to the central part of the Yunnan-Guizhou Plateau at an average elevation of approximately 1900 m (Yan and Wang 2006). Furthermore, the railway in Panzhihua, Liangshan, and Leshan was built along the banks of the Jinsha, Anning, and Niri rivers, respectively (Figure 3(a)). Along these rivers, the valleys on both banks are steep, with 35° to 70° slopes (Figure 3(b)). The gradient of slope has a significant influence on the susceptibility of the terrain to geohazards (Dai and Lee 2002) and topography plays a significant role in the development of geohazards along the Cheng-Kun railway.

2.2. Engineering geology

The regional geological structure in the study area is a multi-group fault cross. The lithology in the area is mutual layers with soft soil and hard rocks (REDCP 2020a). Deep soil is the geological basis for the occurrence of disasters (Wang et al. 2000).

1. Lithology

The stratigraphic lithology at the junction of Sichuan and Yunnan provinces is complex and diverse. According to the data from the Spatial Database of 1: 2,500,000 Digital Geologic Map of China (Ye et al. 2017), the study area contains mainly
mudstone, sandstone, conglomerate, siltstone, shale, dolomite, limestone, clastic carbonate, granite, diabase, and gravel. These rock types can be divided into eight categories.

Figure 2. Map of the eight cities along Cheng-Kun railway in the studied region. Source: Author.
Figure 3. Geographical map at the study area: (a) topographic map; (b) GIS slope gradient. Source: Author.
based on the global lithological map classifications (Hartmann and Moosdorf 2012). These are ice and glacier, water bodies, magmatic rock, loose sedimentary rock, metamorphic rock, carbonate clastic rock, pyroclastic rock, and clastic sedimentary rock. Figure 4 illustrates the distribution of the geologic formations in the study area, i.e., lithology (Figure 4(a)), faults (Figure 4(b)), and soil types (Figure 4(c)). Li (2001) divided the formation lithology into four categories according to the type of geological disasters, i.e., magmatic rock, metamorphic rock, pyroclastic rock and clastic sedimentary rock, and loose sedimentary and carbonate clastic rock (Li et al. 2001). Magmatic rock is relatively hard and corresponds to the area of the lowest incidence of geological hazards in this study. Metamorphic rock, pyroclastic rock, and clastic sedimentary rock correspond to the area with the highest incidence of geological hazards. Loose sedimentary and carbonate clastic rock correspond to the low- and high-risk areas, respectively.

Geological structures

As shown in Figure 2(a), the railway locates in the transition zone from the Sichuan Basin to the Yunnan-Guizhou Plateau, which lies on the south-eastern edge of the Tibetan Plateau. Hence, there are densely distributed fault belts (Figure 4(b)). The vector data of faults can be collected from National Earthquake Data Center (NEDC 2020). The active faults that the railway passes from north to south, include the Ebian, Ganzi-Zhuhe, Daliangshan, Xianshuihe, Zemuhe, Anninghe, and Lvzejiang faults. These faults (Figure 4(b)) all belong to the Quaternary active fault (Chen et al. 1991). The active faults with complex rock formations in the study area are some of the main natural factors that cause frequent geological disasters along this railway.

Soil types

Figure 4(c) shows the distribution of different soil types in the study area, which can be downloaded from the Resource and Environment Data Cloud Platform with 1 km grid size (REDCP 2020a). According to the soil classification of Chinese codes, the area contains 15 types of soils: alfisol, half alfisol, xerosol, primary soil, semi-hydromorphic soil, hydromorphic soil, anthrosols, high-mountain soil, iron bauxite, rocks, and four nonsoil types: urban, water, island, and glacier. Within the study area, alfisol, primary soil, anthrosols, and iron bauxite account for a large proportion. Xerosol and high-mountain soil are almost uniquely located on high elevation mountains. In the study area, yellow-brown earths and brown earths are the main subcategories of alfisol. The subcategories of primary soil are mainly red lime soils and purplish soils. The main subcategories of bauxite are red earths and yellow earths. Paddy soils are the main secondary classification of anthrosols. Wang et al. (2017) showed that red earths, yellow earths, purplish soils, and paddy soils are soil types closely associated with sudden mountain disasters (Chen et al. 2003).

2.3. Precipitation and hydrology

Figure 5 shows the distribution of precipitation and river density in the study area. The meteorological data from 2010 to 2019 was obtained from the China
Figure 4. Geological formation in the study area: (a) distribution of lithology; (b) distribution of faults; (c) Soil types. Source: Author.
Figure 5. Distribution of precipitation and rivers in the study area: (a) annual precipitation; (b) river proximity. Source: Author.
Meteorological Science Data Sharing Network (CMDN 2020) and the Rainfall Stations in the eight cities. Accumulated annual precipitation is calculated by daily rainfall which was collected from the Stations. Based on these data, the distribution of annual precipitation was calculated using Kriging interpolation. The junction between Sichuan and Yunnan is a subtropical climate region with an average annual rainfall from 600 to 1000 mm (Figure 5(a)). Precipitation near the western edge of the basin is higher than in other locations (Figure 5(a)). In addition, because Yunnan and Sichuan are in the upper reaches of the Yangtze River, its tributaries are densely distributed in the area (Figure 2(b)). There are large differences in elevation in this region. The canyons on both sides of the river are deep and the water flow is turbulent. River proximity demonstrates the distance to the closest river, which was obtained by the Multiple Buffer Operator. As shown in Figure 5(b), most of the railway sections were built on slopes close to rivers, especially in the Liangshanzhan region.

2.4. Anthropic activities

Both Sichuan and Yunnan provinces are now in a period of excessive agricultural industrialization, as agriculture and industry form the main part of the regional economy. Therefore, besides the natural factors, the anthropic activities along the railway line are also important factors to the occurrence of geological disasters. These anthropic activities include land use type (REDCP 2020b), population density (Xu 2017a), and gross domestic production (GDP) (Xu 2017b), which all can be downloaded from Resource and Environment Data Cloud Platform with 1 km grid size. Figure 6 illustrates the distribution of land use, population, and GDP in the study area. Figure 6(a) shows that most of the land types along the railway line are farmland, grass, and forest. Figure 6(b) shows the population density and Figure 6(c) shows GDP per km² in the study area. The population density along the railway line usually exceeds 100 people per km².

2.5. Railway operation management

Figure 7 shows the flowchart and content of existing railway disaster management systems, including safety management regulations (Li 2013) and accident emergency rescue and investigation regulations (Wen 2007). These two regulations were approved by the Prime Ministers. For the existing railway line, its safety management system is mainly related to the surrounding environment and railway operation safety. Therefore, the preventive measures for geological disasters primarily include environmental protection along the line, maintenance of railway operation equipment, and safety operation training for railway staff. The emergency rescue investigation follows the procedures in the disaster management regulations. Because the railway is operated by the same company, the values of these three factors are proposed to be evenly distributed along the route.

3. Methodology

The AHP method can be employed to determine the weight of evaluation indexes by (1) establishing an analytic hierarchy structure, (2) constructing a comparative
Figure 6. Distribution maps of the study area: (a) land use types; (b) population density; (c) distribution of GDP. Source: Author.
judgment matrix, and (3) calculating weight vectors and performing consistency checks (Lyu et al. 2020a, 2020b). However, when using a single value to construct the judgment matrix, the evaluation system may be subjective and biased (Lyu et al. 2020c). Therefore, this study adopts a triangular fuzzy AHP (TFN-AHP), which uses fuzzy numbers instead of single values to indicate the relative importance of evaluation indicators (Lyu et al. 2020d).

3.1. Assessment model

According to Roslee (2018), the main factors leading to geomorphological hazards in a certain area are natural factors (geology, topography, precipitation, etc.) and human factors (anthropic activities and lack of proper planning). Therefore, this study proposed an integrated AHP system to evaluate the risk of the different aspects of the generalized geohazard simultaneously by one weight. The assessment structure divides the main disaster factors into three parts: the railway’s natural environment ($E_i$), anthropic activities near the railway ($H_i$), and railway operation management ($M_i$), based on which an evaluation structure with corresponding indexes is established. Each index layer is composed of different factors. Therefore, the risk model can be defined as the system containing $E_i$, $H_i$, and $M_i$ as below.

$$F = f\{S_k\} = f\{E_i, H_i, M_i\}$$

(1)

where $F =$ risk and $k =$ the index classification number. When $k = 1$, $S_k$ is the natural environment index ($E_i$); when $k = 2$, $S_k$ is the anthropic activity index ($H_i$); when $k = 3$, $S_k$ is the railway management index ($M_i$). $S_k$ denotes each factor in the model and can be expressed by Eq. (2):
\[ S_k = \sum_{i=1}^{n} f_{k,i} R_{k,i} \quad (2) \]

where \( R_{k,i} \) = normalized value of index \( i \) of classification \( k \), \( f_{k,i} \) = weight of index \( i \) of classification \( k \), and \( \sum_{i=1}^{n} f_{k,i} = 1, f_{k,i} > 0 \). Therefore, the assessment model can be redefined in Eq. (3) (Chen et al. 2015):

\[ F = \sum_{i=1}^{n} e_i E_i + \sum_{j=1}^{n} h_j H_j + \sum_{k=1}^{n} m_k M_k \quad (3) \]

All the quantitative data in the evaluation model are drawn in the GIS. The geological hazard risk can be obtained from the calibration of the data and the related weights in the GIS. The weight calculated by the assessment system represents the comprehensive effect of one certain factor on the different aspects of the generalized geohazard. The risk level for the Cheng-Kun railway line can be obtained based on the result of the risk assessment. In addition, the judgements of experts have an important influence on the results of the risk assessment. To obtain expert opinions conveniently and intuitively, this study employed a new questionnaire method proposed by authors (Lyu et al., 2020d) recently, which employs a scale from 1 to 9 to express the importance of geological disaster events caused by a particular risk factor. The use of an interval value is conducive to TFN-AHP identification of the most important risk factor.

### 3.2. AHP structure

The AHP structure for assessment of geologic disaster risk is presented in Figure 8. As shown in Figure 8, the proposed AHP structure has three layers: object layer, index layer, and factor layer. The object layer is the geologic hazard risk of the Cheng-Kun railway (\( R \)). The index layer includes three aspects: the railway’s natural environment (\( E_i \)), anthropic activities (\( H_j \)), and railway management (\( M_k \)). The factor layer shows that each aspect has different disaster factors, which are expressed by indices with different weights. The railway’s natural environment includes seven-factor layers: elevation (\( E_1 \)), slope (\( E_2 \)), river density (\( E_3 \)), river proximity (\( E_4 \)), soil types (\( E_5 \)), lithology (\( E_6 \)), and rainfall distribution (\( E_7 \)). The anthropic activity includes three-factor layers: population density (\( H_1 \)), land use types (\( H_2 \)), and GDP (\( H_3 \)). The railway management also has included three-factor layers: environmental monitoring along the railway (\( M_1 \)), warning system (\( M_2 \)), and the risk judgement of the frontline workers (\( M_3 \)).

### 3.3. TFN-AHP

The TFN-AHP method uses triangular fuzzy numbers instead of crisp numbers in the judgment structure matrix. The replacement principle can be referred to from previous publications (Ziaei and Hajizade 2011). The triangular fuzzy number is denoted by \( P_i = (l_i, m_i, u_i) \) (\( l_i \leq m_i \leq u_i \)), in which \( l_i \) and \( u_i \) are the minimal and
maximal values, respectively, and $m_i$ is the most likely risk value. The fuzzy number $P_i$ can be represented by Eq. (4) (Ziaei and Hajizade 2011).

$$
\mu(x|P_i) = \begin{cases} 
0 & (x < l_i) \\
\frac{x-l_i}{m_i-l_i} & (l_i \leq x \leq m_i) \\
\frac{u_i-x}{u_i-m_i} & (m_i \leq x \leq u_i) \\
0 & (x > u_i) 
\end{cases} 
$$

The value of the extent of the fuzzy number element with respect to the $i$th object is defined by Eq. (5).

$$
P_i = S_i \otimes \left[ \sum_{i=1}^{n} \sum_{j=1}^{n} P_{ij} \right]^{-1}
$$

Based on the results of $P_i$, Figure 8 illustrates the membership between the two triangular fuzzy numbers $P_i$ and $P_j$. The area where the two fuzzy numbers intersect indicates the weight of the two factors ($P_i, P_j$) compared with each other, which can be expressed by Eq. (6). If $m_i (P_i) \geq m_j (P_j)$, the intersection area is calculated as 1; if $l_j (P_j) \geq u_i (P_i)$, the area is calculated as 0; otherwise, the area can be calculated according to Eq. (6).

$$
\mu(x|P) = \begin{cases} 
1 & (m_i \geq m_j) \\
0 & (l_j \geq u_i) \\
\frac{l_j-u_i}{(m_i-u_i)-(m_j-l_j)} & (otherwise)
\end{cases}
$$

For the factors in the same index layer, the $i$th factor is compared with all the factors in the index layer one by one, and the minimum value obtained is the weight ($\omega_p$) of the $i$th factor, which can be expressed by Eq. (7).
\[ P = \min \left( \frac{\Pi_i}{C_21} \right) \left( \frac{C_23}{P_k} \right) \tag{7} \]

4. Results

4.1. Weight calibration

Based on the AHP method, the judgment matrix of the index layer is shown in Eq. (8). The consistent ratio (CR) of the matrix \( F_{\text{index}} \) is 0.0176 (less than 0.1), which indicates that the judgement matrix is consistent. According to the consistency judgement matrix, the weights of the \( E_i \), \( H_i \), and \( M_i \) can be calibrated. Then, according to the principle of substitution between the crisp number and the triangular fuzzy number, the judgement matrix of the transformation index layer is obtained. Table 1 shows the judgement matrix for the index layer with the triangular fuzzy number obtained by TFN-AHP.

\[
F_{\text{index}} = \begin{pmatrix}
E_i & H_i & M_i \\
E_i & 1 & 2 & 3 \\
H_i & 1/2 & 1 & 1 \\
M_i & 1/3 & 1 & 1
\end{pmatrix}
\tag{8}
\]

Similarly, the triangular fuzzy number judgment matrix for each factor layer can be established. Then, according to Eq. (7), the weights between different factors in the same layer can be compared and calculated. Finally, the weight of each evaluation
factor is obtained. Table 2 shows the weight of assessment factors calculated by TFN-AHP.

4.2. Results of TFN-AHP

The analyzed results of the factor distribution are mapped by using GIS. Based on this, the data in these maps are normalized by GIS to convert them into data maps between 0 and 1. Then, the factor weights obtained (Table 2) and their corresponding normalized data are superimposed using the raster calculator in GIS according to Eq. (3). Figure 9 shows the spatial distribution of the geologic hazard risk of the whole research area obtained using the TFN-AHP method. The risk level is indicated from low to high using the risk index from 0 to 1. As shown in Figure 9(a), the high-risk areas are mainly distributed in Ya’an, Leshan, Liangshan, and Kunming, where it is found that the degree of risk around the railway is slightly higher than in other regions. Figure 9(b) shows the distribution of risks in the 5 km area around the railway line. The assessed risks were divided into five risk levels, i.e., lowest, lower, medium, higher, and highest. Lowest and lower can be combined into the term ‘Low’, and higher and highest can be combined into the term ‘high’. As shown in Figure 9(b), approximately 9.34% of sections have the highest risk, 23.82% of sections have higher risk; 29.43% of sections have medium risk, 24.92% of sections have lower risk, and 15% have the lowest risk.
5. Discussion

5.1. Recommendations

The railway network is an important part of today’s infrastructure, and the following recommendations have been made to improve its safety.

1. Early warning and data collection: The existing geological disaster warning system of the Chengdu-Kunming railway has been established and improved (Wu et al. 2012); however, the basic database still needs to be improved. For such a risk system, it is very important to collect and organize future operation data according to the concept of risk management (Liu and Dai 2013).

2. Establishment of a management flowchart: In addition to improving preventive measures before the occurrence of the disaster, it is also critical to integrate and analyze the known influencing factors after the occurrence of geological disasters.
Wu (2007) described the process of safety risk management in the operation stage of Hong Kong’s subway system, which consists of six parts: hazard identification and grading, hazard records and remediation recommendations, verification of hazards and remedial measures, remedial measures implementation, and monitoring and hazard update and risk review. Compared with the railway safety operation and emergency rescue regulations mentioned above, the subway safety risk process additionally includes the steps of hazard update and risk audit. Therefore, in the subway system, disaster feedback plays an important role, which could help improve and update the database to provide background analysis for subsequent disasters. Meanwhile, Lam and Tai (2020) proposed a network analytical framework to identify the factors and to reveal effects of railway incidents. The results show that the framework can not only analyze the influencing factors of each event, but also control and reduce the occurrence of railway accidents by dealing with interdependent and intermediate factors.

3. Management strategies: While establishing the disaster warning and feedback system, we should also develop new management strategies based on risk management. The Canadian railway complies with the railway safety management system (SMS) to promote the company’s safety and to better manage safety risk. Notwithstanding, a Canadian Pacific railroad derailment occurred in 2019, following which Lefsrud et al. (2020) introduced the adaptation of enhanced SMS implementation based on performance-based regulation and risk management approaches. Railroad workers and residents within high-risk areas are direct participants in the regulatory system. Therefore, the safety awareness of them should be paid attention to and improved upon. In Calabria, Southern Italy, a study focused on the degree of risk perception among citizens living in high hydro-geological risk areas and the risk perception gap between policymakers and residents (Antronico et al. 2019). The results show that it is necessary for local governments and experts to advance risk awareness and improve citizens’ safety through direct participation in disaster reduction activities.

5.2. Strengths and limitations

The research considers both the geological factors of geohazards and the vulnerability in the region studied. In addition, the study integrates railway management into the risk assessment system of geohazards. Figure 10 shows 15 geological disasters recorded along the Cheng-Kun railway line during the 10 years from 2009 to 2019. This map shows the general area of the geological disasters that occurred on the railway, which are marked with a green line and numbered from 1 to 15. Figure 10 also shows the risk levels assessed by the TFN-AHP method. As shown in Figure 10, seven disasters (numbers 2 to 5, 7, 9, and 10) occurred in the areas of highest risk as calculated by TFN-AHP. Three disasters (numbers 6, 8, and 13) occurred in the higher risk areas. Three disasters (numbers 1, 12, and 14) occurred in the medium risk areas. In total, 86.66% of geohazards were successfully recognized by integrating
TFN-AHP with GIS. This demonstrates that the proposed framework of the risk assessment system is effective and agrees with the real-world situation.

Figure 11 compares the percentages of different risk levels along the railway calculated using different methods. Figure 11(a) shows the percentage-based in the TFN-AHP approach, and Figure 11(b) is the percentage calculated by the original AHP. The highest-level risk from the TFN-AHP are 9.34% and 23.82%, which are higher than the results calculated by the original AHP method with the respective value of 8.17% and 22.77%. The result indicated that the TFN-AHP method was more efficient than the AHP approach in identifying high-risk areas. In addition, Figure 12 shows the calculated risk distribution in Ganluo County with three affected stations and railway sections where the disasters occurred. Disasters 5 to 8 were four geological disasters that occurred within the section from Ganluo Station and Lianghong Station of the Cheng-Kun railway line in 2019, Ganluo, Sichuan. The locations of the hazards coincide with the calculated high-risk areas. The AHP method requires the involvement of experts in the evaluation process. Although TFN-AHP method uses triangular fuzzy numbers to eliminate the uncertainty from the evaluation process, the results are still subjective and inevitably uncertain. Nevertheless, the results of the TFN-AHP method provide authorities with a supportive guide to the distribution of risk in the study area.

5.3. Future works

Although the operation and safety management of the Cheng-Kun railway are conducted in accordance with the relevant China regulations listed in Section 2.6, similar geohazards occurred from time to time and caused major casualties, which suggest that the management of the railway system still need improvement. This study considers a railway management index layer based on the regulations, and this layer contains three factors: environmental monitoring along the railway ($M_1$), warning system ($M_2$), and the risk judgement of the front-line workers ($M_3$). We also propose that, based on the same railway management system, the management training model should be consistent in different management sections. However, in the actual railway operating situation, the level of management is different in each station section. The
field factors of managements are influenced by a range of elements, the local economy, the workers’ education level and so on. In future work, how to assess the level of a management system needs to be considered.

6. Conclusions

This article summarized the types and number of geohazard events along the Cheng-Kun Railway within the past 10 years. Then, the relevant data from cities along the Cheng-Kun Railway were used to analyze the risk of geohazards using the TFN-AHP method. The main conclusions are summarized as follows.

The approach incorporating the TFN-AHP with GIS effectively predicted the distribution of geohazards risk in the study region. The high-risk regions are mainly distributed in Ya’an, Leshan, Liangshan, and Kunming. In addition, the risk level around the railway is higher than those in other regions. 86.66% of the 15 geological hazards statistical occurred in the railroad were in the higher-risk area and highest-risk area. This indicates that the assessment on geohazards risk is consistent with the field situation.

The percentage of each level of risk within the railway area calculated by the AHP and the TFN-AHP indicates that the TFN-AHP method is more efficient in identifying high-risk areas in this study. The percentage of high risk and above sections from the TFN-AHP was 33.16%, but only 30.94% of the high-risk sections calculated by the AHP.
To maintain the sustainability of this railway, the following management recommendations are proposed: effectively collecting data according to the framework of risk assessment of railway management; improving the postdisaster feedback and hazard factor analysis system; creating new management strategies (e.g., residents’ involvement) based on risk management.

Data availability statement (DAS)

| Availability of data | Template for data availability statement | Policy |
|----------------------|-----------------------------------------|--------|
| Data openly available in a public repository that issues datasets with DOIs | The data that support the findings of this study are openly available in Spatial Database of 1: 2,500,000 Digital Geologic Map of People’s Republic of China Geology in China at http://doi.10.12029/gc2017Z103, reference as (Ye et al. 2017). The data that support the findings of this study are openly available in Spatial Distribution of China Population: Kilometer Grid Data Set. Data Registration and publishing System of Data Center of Resources and Environmental Sciences at http://www.resdc.cn/DOI. 2017, DOI:10.12078/2017121101, reference as (Xu 2017a). The data that support the findings of this study are openly available in Spatial Distribution of China GDP: Kilometer Grid Data Set at http://www.resdc.cn/DOI. 2017, DOI:10.12078/20171211102, reference as (Xu 2017b). | All |
| Data openly available in a public repository that does not issue DOIs | The data that support the findings of this study are openly available in Geospatial Data Cloud at http://www.gscloud.cn/. The data that support the findings of this study are openly available in Spatial distribution data of soil types in China at http://www.resdc.cn/data.aspx?DATAID=145. reference as (REDCP 2020a). The data that support the findings of this study are openly available in Database of earthquake configuration in the key region of China at http://data.cea-ies.ac.cn/CSEMP/Home.aspx/. reference as (NEDC 2020). The data that support the findings of this study are openly available in China Meteorological Data Network at http://data.cma.cn/. reference as (CMDN 2020). The data that support the findings of this study are openly available in Chinese land use status remote sensing monitoring data in 2018 at http://www.resdc.cn/data.aspx?DATAID=184. reference as (REDCP 2020b). | All |

Disclosure statement

No potential conflict of interest was reported by the authors.

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