Research on the Identification of Typical Terrain Patterns in Yunnan Province Based on the K-Means Technology

Fangrong Zhou 1,2, Xiaowei Huai 3,*, Pengcheng Yan 4,*, Cailing Zhao 4, Xingliang Jiang 1,5, Hao Pan 2, Yutang Ma 2 and Hao Geng 2

1 School of Electrical Engineering, Chongqing University, Chongqing 400044, China; zhfr0508@sina.com (F.Z.); xljiang@cqu.edu.cn (X.J.)
2 Electric Power Research Institute, Yunnan Power Grid Company Ltd., Kunming 650217, China; yndwp@foxmail.com (H.P.); qj1277396850@163.com (Y.M.); whutgenghao@163.com (H.G.)
3 Hunan Disaster Prevention Technology Co., Ltd., State Grid Hunan Electric Power Company Ltd., Changsha 410129, China
4 Key Laboratory of Arid Climatic Change and Reducing Disaster of Gansu Province/Key Laboratory of Arid Climatic Change and Reducing Disaster of China Meteorological Administration, Institute of Arid Meteorology, China Meteorological Administration, Lanzhou 730000, China; zhaocl@iamcma.cn
5 Xuefeng Mountain Energy Equipment Safety National Observation and Research Station of Chongqing University, Chongqing 400044, China
* Correspondence: huaixw@foxmail.com (X.H.); yanpc@iamcma.cn (P.Y.)

Abstract: Wire icing is a prevalent challenge in both industrial and scientific domains, and it is widely acknowledged that terrain and water vapor are significant contributing factors in the formation of wire icing. Consequently, the identification of terrains that are prone to inducing water vapor uplift serves as the scientific foundation for predicting ice accumulation on power lines. Yunnan Province, a mountainous province in China, features a large elevation difference. In winter, this region is prone to wire, pole and tower icing, which can affect power transmission and cause economic and property losses. Therefore, it is necessary to conduct research on the identification of typical terrain patterns in this region. In previous terrain studies, more attention has been focused on slope and aspect, watershed analysis and terrain profile analysis. When the purpose of the terrain identification is to analyze which terrains are more prone to collecting water vapor, we hope to obtain slightly larger terrain blocks and analyze the water vapor sources for different terrains in order to identify typical terrains that are conducive to icing formation. A new technology for identifying terrain patterns based on the K-means clustering method is proposed in this study to explore the typical terrain in Yunnan province. Additionally, the influences of different terrain patterns on water vapor movement are also analyzed. The results indicate that the typical terrains in Yunnan are “Valley-Air Channel”, “Topographic Uplifting”, “Ravine”, “Mountain Pass” and “Alpine Divide” patterns. The results show that the identified typical terrain is consistent with observations from satellite images, which verifies the effectiveness of this identification method. Among these five typical terrains, the “Valley-Air Channel”, the “Topographic Uplifting” and the “Mountain Pass” terrains are prone to collecting water vapor and forming ice cover. The “Alpine Divide” terrain is also prone to accumulating water vapor on both sides to form ice cover. The identified typical terrain demonstrates that typical terrain patterns near water bodies are more prone to the occurrence of wire, pole and tower icing because these areas are abundant in water vapor, and the extensive water vapor is easily condensed under the effects of terrain uplifting and cooling. In these key areas, existing wires and towers, as well as those to be constructed in the future, deserve our special attention.

Keywords: typical terrain pattern; wire icing; K-means method

1. Introduction

Typical terrain patterns reflect typical geomorphological characteristics, such as steep slopes, concave–convex terrain, ravines and water bodies, which are widely applied in
ecological environmental protection, natural disaster prevention, land use planning, water resource management and wire icing research [1,2]. Therefore, the identification research on typical terrain patterns is of great significance for engineering applications. At present, the typical terrain pattern identification technology relies on the digital elevation model (DEM) to obtain elevation data. The elevation data can be gained by combining multi-source data from lidar, multispectral image analysis, surface measuring, topographic survey, remote sensing, etc., with a high spatial resolution and wide coverage, playing an essential role in research on urban disaster risk [3], terrain and landform reconstruction [4] and glacier evolution [5].

Currently, the main methods for investigating typical terrain patterns include the analysis of slope gradient and slope aspect, watershed analysis, topographic profile analysis and terrain classification. Specifically, the analysis of slope gradient and slope aspect can reveal the characteristics of typical slopes, gullies and hills. Watershed analysis can distinguish water bodies [6], contributing to understanding hydrology and river paths. The topographic profile analysis is mainly applied to investigate the spatial undulation characteristics of landforms [7], and terrain classification is used to distinguish mountains, plains, river valleys and others [8]. These methods can help us to understand the spatial distribution and continuity of typical terrain, as well as the interactive relationship between typical terrain and the environment (e.g., water bodies) [9]. On this basis, we propose a typical terrain pattern identification method based on the DEM data in this research.

The method we used to identify typical terrain is the K-means clustering technique, which is mainly based on the Euclidean distance between different data and regards them as belonging to the same category by calculating the minimum Euclidean distance [10]. Currently, the K-means clustering technique is widely used in the fields of machine learning [11], image processing [12], climate change [13] and market analysis [14]. For example, in market analysis, K-means can be used to classify customers in order to better understand their needs and behavioral patterns; in the field of image processing, K-means can be used for image segmentation, clustering similar pixels together to form objects. The method is suitable for scenarios that require automatic classification and clustering of data, and it has wide applications in big data processing and data mining. By identifying typical terrain, we can analyze the impact of the terrain on the ascent of water vapor, thus enabling us to assess the typical icing effects under these terrains.

A previous study [15] has demonstrated that icing is affected by mountain trend and slope aspect. Icing is heavy in windward slopes and wide-open areas but light in leeward slopes and closed areas. Moreover, the extent of wire icing varies in different parts of a mountain, i.e., icing is more severe in mountain tops, alpine divide areas and mountain passes than in mountain foothills, mountainsides and mountain basins. Icing tends to be more intense near water bodies such as rivers and lakes with abundant water vapor, while this phenomenon is less severe in areas far from water bodies where the air is dry. This means that when the terrain elevation facilitates the collection of more water vapor, it is more likely to result in icing. Therefore, identifying typical terrain patterns and confirming areas where wire, pole and tower icing is more likely to occur is essential to address wire icing risk [16–18]. In previous terrain studies, more attention has been focused on slope and aspect, watershed analysis and terrain profile analysis. The purpose of our terrain identification is to investigate whether there is an uplift in larger terrain and whether it is easy to collect water vapor. We used the K-means clustering technique to identify the typical terrain. Yunnan Province has been taken as an example to investigate the features of typical terrain patterns. Yunnan Province is characterized by high mountains, rivers and high altitudes, and its special terrain is highly sensitive to wire icing.

The remainder of this paper is organized as follows. Section 2 introduces the study area, data and methods of this research. Section 3 shows the identified results of the typical terrain patterns in Yunnan and their analyses. Conclusions and discussion are presented in Section 4.
2. Study Area, Data and Methods

2.1. Study Area

Yunnan (97°31′ E–106°11′ E, 21°8′ N–29°15′ N) is located in a low-latitude inland region of China’s southwestern border (Figure 1), with a meridional span of 864.9 km and a zonal span of 990 km, covering a total area of 394,100 km². The elevation is higher in the northwest and lower in the southeast, showing a step-like decline pattern from the north to the south. Thus, Yunnan displays typical mountainous plateau terrain, where 88.64% of the total area is mountainous. Six major river systems flow through this province, i.e., the Yangtze, Pearl, Yuanjiang, Lancangjiang, Nujiang and Dayingjiang Rivers. Most of Yunnan is located in mid-altitude areas, with the area at 1000–3500 m altitudes accounting for 87.21% of the total area. In total, 56.46% of the province’s area has a slope gradient of less than 25°. In terms of landform types, plains, plateaus, hills and mountains account for 4.85%, 1.55%, 4.96% and 88.64% of the total area, respectively. Low air temperatures in winter and steep slopes in mountainous areas often cause wire and tower icing, posing a risk to power transmission.

Figure 1. Schematic diagram of the research area.

2.2. Data

DEM data are used in this study to identify typical terrain patterns. These data are from digital simulations of surface terrain through a limited number of elevation data produced by the Computer Network Information Center of the Chinese Academy of Sciences, which are publicly available (https://www.gscloud.cn, accessed on 16 January 2024). They are the digital representation of topographic surface morphology, which is a real surface model represented by a set of ordered numerical arrays. Generally, the DEM exhibits a geospatial image, describing the topographic relief by a numerical array information model. DEM information has three elements (x, y, z), where x represents longitude, y denotes latitude and z indicates altitude.

2.3. Typical Terrain Pattern Identification Method Based on the K-Means Method

The K-means method [19,20], an unsupervised learning algorithm, can cluster and classify samples according to their similarity. A typical terrain pattern identification method can be developed based on the K-means clustering algorithm. This method can identify one or several typical terrain patterns by fully considering the similarity among different
terrain patterns and classifying terrain with the same size at different locations. The specific steps are as follows (Figure 2a).

Data collection: Obtain regional high-resolution DEM data, such as 30 m elevation data, including longitude, latitude and elevation.

Data reconstruction: The DEM is partitioned into \( X \times Y \) subregions (\( X \) and \( Y \) represent the grid numbers), each of which has the same shape and size (Figure 2b).

Labeling samples: The subregions are labeled as different samples, and the total number of samples is recorded as \( N \).

Random sampling: \( K \) samples are selected from \( N \) samples by using the random method.

Deviation calculation: Calculate the deviation between any sample and \( K \) samples.

\[
\zeta_{i,k} = \sqrt{\frac{1}{\sigma^2_{ci} \cdot \sigma^2_{ck}} \sum_{x=1}^{X} \sum_{y=1}^{Y} \left( C_{i,x,y} - C_{k,x,y} \right)^2}, k = 1, K; i = 1, N
\]  

(1)

where \( C_{i,x,y} \) and \( C_{k,x,y} \) denote the elevation in samples \( i \) and \( k \), respectively, and \( x \) and \( y \) represent the grids in the horizontal and vertical direction, respectively, where \( x \in [1, X] \) and \( y \in [1, Y] \) indicate the standard deviations of all grids within samples \( i \) and \( k \), respectively.

Clustering: Topography with the same pattern is classified according to the deviations of the different samples from \( K \) samples. Since the classification results are obtained based on random centers, they are not completely accurate and need to be re-calculated cyclically.

Checking the initial results: If the results of the above typing cycle are not consistent between the former and the latter, the deviations of every sample from the typing results are calculated, and the steps of deviation calculation, initial typing and checking the initial results are repeated. If the results no longer change with the loop, the loop calculation stops, and the terrain typing is determined.

This terrain pattern identification technology adequately considers the similarity of different terrain patterns, and the identified terrain through this method is more representative. This algorithm converges quickly and is highly operational. Considering that previous studies often classified the terrain that affects typical icing into five categories, Valley Air Channel, Topographic Uplifting, Enlarged Type, Mountain Pass and Alpine Divide patterns, the parameter \( K \) of the K-means clustering method is set to 5.

Figure 2. Schematic diagram of terrain pattern identification technology. (a) Cluster method flowchart, (b) Schematic diagram of clustering method partitioning.
3. Identifying Typical Terrain of Yunnan Province
3.1. Features of Typical Terrain Patterns

Based on the above method, we carried out a study on the identification of typical terrain patterns in Yunnan. By analyzing the characteristics of typical terrain patterns at the 30 × 30 km² scale, Yunnan is divided into 438 terrain segments with an area of 30 × 30 km² (Figure 3b), and each terrain segment has 1080 × 1080 grid points. Taking a grid area in central Yunnan Province as an example (Figure 3c,d), the “mountain-valley-mountain” pattern is quite clear due to the 30 m high-resolution data, i.e., mountains stretch in the west, a hill towers out in the northeast and the terrain is flat in the southeast.

![Figure 3. Terrain segmentation of Yunnan Province.](image)

The 438 terrains are clustered by using the K-means cluster method, and five typical terrain patterns are obtained (Figure 4). One of the identified terrain patterns, denoted as pattern I and illustrated in Figure 4a, is recognized as the “Valley-Air Channel” pattern. In this particular pattern, the airflow from different directions is obstructed by the surrounding mountains, causing it to converge in river valleys, subsequently leading to the formation of localized convection as a result of forced topographic uplift. The “Valley-Air Channel” pattern plays a pivotal role in facilitating the convergence of water vapor from the southern regions, thereby creating favorable conditions for precipitation. Moreover, the gathering of water vapor in river valleys before it is uplifted by the terrain results in a larger amount of water vapor being directed to these areas. This specific terrain pattern covers a substantial 31.74% of the total area of Yunnan Province, signifying its significant influence on the region’s overall climate and hydrological conditions. Understanding the characteristics and implications of this pattern is crucial for effectively managing and adapting to the unique environmental conditions within the province. Regarding pattern II, known as the “Topographic Uplifting” pattern, the terrain is characterized by its relatively flat nature, with elevations at the edges ranging from hundreds to thousands of meters. In areas with relatively flat terrain, the straight airflow is minimally affected by terrain uplift, therefore making it less conducive to heavy precipitation. Conversely, terrain with significant uplift tends to create favorable conditions for precipitation. The “Topographic Uplifting” pattern
covers a substantial 28.54% of the total area of Yunnan Province. As for pattern III, the “Ravine” pattern, there are many north–south-oriented gullies that can lead airflow to uplift over the ridge part, thus contributing to precipitation. However, since the topographic relief does not vary considerably (about 100 m), precipitation generation is more limited. The “Ravine” pattern accounts for 21.23% of the entire Yunnan region. Pattern IV is the “Mountain Pass” pattern, accounting for 12.10% of the total area. This pattern shows a transition zone from wide-open terrain to narrow terrain, where large amounts of water vapor tend to converge. Thus, strong wind and severe convection are prone to occur in this terrain pattern. In terms of pattern V, namely the “Alpine Divide” pattern, there are large-scale mountain barriers (up to 10 km wide) in central regions, and the elevation is relatively high (over 3500 m). East–west water vapor uplifts and converges in this terrain pattern to form a divide in different directions. The “Alpine Divide” pattern accounts for 6.39% of the total area.

**Figure 4.** Typical terrain patterns in Yunnan Province: (a) “Valley-Air Channel” Pattern, (b) “Topographic Uplifting” Pattern, (c) “Ravine” pattern, (d) “Mountain Pass” pattern and (e) “Alpine Divide” pattern.

Overall, at the scale of 30 × 30 km², the Yunnan terrain is classified into five categories, “Valley-Air Channel”, “Topographic Uplifting”, “Ravine” Pattern, “Mountain Pass” and “Alpine Divide” patterns, which are in decreasing order of proportions. It is noteworthy that the typical terrain patterns are not isolated, and sometimes, different terrain patterns intersect with each other. For example, the “Valley-Air Channel” pattern can overlap with the “Topographic Uplifting” pattern, and it may also intersect with the “Mountain Pass” pattern, i.e., there may be different configurations for the same terrain.

The forced effects of different typical terrain patterns on water vapor and their influence on icing conditions are analyzed in detail by comparing satellite images.

### 3.2. Features of Representative Typical Terrain Patterns

#### 3.2.1. “Valley-Air Channel” Pattern

Valleys are the representative feature of the “Valley-Air Channel” pattern. As the distributions of valleys and gullies are widespread in Yunnan, this terrain pattern is the most common one. For instance, the north side of the mountains peaks more than 2500 m in Jinsha River bend (Figure 5), near Xiagan Village, Yongsheng County, Lijiang City, where the southerly wind passing through the river valley near Shangliu Village converges with the easterly wind from Jinsha River. The converging airflow is uplifted by the terrain forcing. Since this area is located in low latitudes, warm wind blows all year round, and the climate is dry. Many high-voltage lines pass through areas of this terrain pattern, such as the No. 36 pole of the 110 KV Liuping line in Nanpanjiang Valley, the No. 282–283 poles of the 220 KV Yikun line in Dakeishan Valley wind trough, and the No. 76–77 poles (in the valley wind channel of Tuje Town) of the 500 KV Mankun line in Ailao Mountain. Note that water bodies can bring more water vapor in this terrain pattern. Affected by the terrain
uplifting effect, icing may become more intense. Therefore, this terrain pattern may result in an increase in water vapor, as in the case of the Ailao Mountain section of the 500 KV Dakun line, which is influenced by the reservoir of the Laohu Mountain power station.

![Figure 5](image1.png)

**Figure 5.** A case of the “Valley-Air” Channel pattern (left) and its satellite image (right). The horizontal and vertical coordinates in figure a represent longitude and latitude respectively, not the actual coordinates. The red arrow in the figure represents the potential water vapor path.

3.2.2. “Topographic Uplifting” Pattern

The “Topographic Uplifting” pattern is shown in Figure 6. As air passes through the large-scale terrain, the terrain forcing can lead to the uplift and cooling of water vapor. This process easily triggers precipitation, impacting the region’s hydrological cycle. The uplifted terrain creates favorable conditions for the formation of clouds and subsequent rainfall. This pattern not only influences the distribution of precipitation but also plays a vital role in shaping the overall climate of the region. For instance, in Xiaojian Mountain of Yiliang County, Kunming City (Figure 6), the airflow moves over the wide-open area and then uplifts along the mountain ridge in the northwest (elevation of 1900 m), triggering precipitation easily. The annual mean temperature in Xiaojian Mountain is 13.5 °C, and the annual rainfall amount is 1055 mm. The Malage region at the edge of the Mengzi Basin in Yunnan also belongs to the “Topographic Uplifting” pattern.

![Figure 6](image2.png)

**Figure 6.** Same as Figure 5, but for the case of the “Topographic Uplifting” pattern.

3.2.3. “Ravine” Pattern

The “Ravine” pattern is primarily defined by its irregular and undulating underlying surface, featuring numerous ravines and gullies. The relief of the terrain varies from several kilometers to tens of kilometers, creating an uneven underlying surface that is also conducive to limited small-range precipitation. This pattern’s unique characteristics play a significant role in defining local hydrological conditions and influencing the distribution of precipitation within the region. For example, the satellite image of Dakonghai Village, Jinggu Dai and Yi Autonomous County, Pu’er City (Figure 7), shows irregular gullies. The maximum and minimum elevations in this village are 2920 m and 813 m, respectively, and the annual mean rainfall is 1354 mm.
3.2.3. “Ravine” Pattern

The “Ravine” pattern is primarily distributed at higher elevations, which can block airflows on both sides to form an obvious precipitation boundary. In Figure 5, but for the case of the “Ravine” pattern.

3.2.4. “Mountain Pass” Pattern

The typical feature of the “Mountain Pass” pattern is that airflows converge in river valleys to result in strong wind. For instance, in Liantie Village, Eryuan County, Dali Bai Autonomous Prefecture (Figure 8), airflows move over the wide-open terrain and converge in northern Liantie Village, easily causing strong convection in this region and resulting in hail and snow disasters. The No. 53 pole of the 110 KV Yidong line in the Shibuka mountain pass and the 500 KV Dakun line in the Shiguanpo mountain pass are also typical examples of the terrain pattern, and the observations indicate that wire icing is likely to occur in these areas.

3.2.5. “Alpine Divide” Pattern

The “Alpine Divide” pattern (Figure 9) is often distributed at higher elevations, which can block airflows on both sides to form an obvious precipitation boundary. The Jade Dragon Snow Mountain in Lijiang City, where the elevation is 4000–5000 m and snow covers the area all year round, is located in the alternating control zone of the westerly circulation, southwest monsoon and southeast monsoon. In the rainy season, this region is controlled by the southwest monsoon and southeast monsoon. The annual precipitation is 935 mm in the Jade Dragon Snow Mountain. As shown in the satellite image, the western side of the mountain ridge is covered by snow, but the eastern side is not. Therefore, this area belongs to the typical terrain of the “Alpine Divide” pattern. In addition, the divide between the Jinsha River and the Xiaojiang River also falls into this terrain pattern.

Figure 7. Same as Figure 5, but for the case of the “Ravine” pattern.

Figure 8. Same as Figure 5, but for the case of the “Mountain Pass” pattern.

Figure 9. Same as Figure 5, but for the case of the “Alpine Divide” pattern.
4. Conclusions and Discussion

In the study of wire icing, terrain uplift is beneficial for accumulating more water vapor and releasing heat through the uplift effect, forming ice on the power wire. This situation is more common in Yunnan Province, where mountainous terrain is a typical representative. There are many low-temperature (high-altitude) mountainous areas in this area, which poses difficulties for studying typical ice cover. Therefore, identifying which terrains are prone to causing water vapor uplift is the basis of this research. In the past, more consideration was given to slope and aspect, watershed analysis and terrain profile analysis in research. For large-scale water vapor, it is necessary to identify typical terrain on a larger scale. Therefore, we adopt the K-means clustering method to study a new method considering longitude, latitude and altitude to identify typical terrain. Based on the K-means data-mining technology, we study the terrains of Yunnan. This technology adequately considers the similarities among different terrain patterns and clusters the terrain at different locations. The results indicate that on the scale of $30 \times 30 \text{ km}^2$, Yunnan is characterized by five terrain patterns, namely “Valley-Air Channel”, “Topographic Uplifting”, “Ravine”, “Mountain Pass” and “Alpine Divide” patterns, which are in decreasing order of proportions. Furthermore, the identified typical terrain patterns in the inversion images from the DEM data are found to be consistent with the satellite images, suggesting the effectiveness of the new identification method.

Finally, by analyzing the terrain and water vapor processes, it is concluded that the “Valley-Air Channel”, “Topographic Uplifting”, “Mountain Pass” and “Alpine Divide” patterns are near water bodies where water vapor is abundant. Wire, pole and tower icing is more likely to occur as large-scale water vapor uplifts, cools and condenses due to the topography. Additionally, we should also take into account that with the intensification of global climate change, the precipitation patterns in Yunnan Province may also undergo changes. Therefore, the study of the relationship between terrain patterns and water vapor is of great significance for addressing the challenges posed by climate change and ensuring the sustainable development of Yunnan Province. In scientific research and practical applications in our country, these factors should be fully considered to provide more accurate guidance for climate adaptation and water resource management in Yunnan Province.

The new method based on the K-means method proposed in this study is an attempt at terrain pattern identification. It is not sensitive to data types and can identify terrain patterns at various spatial scales. Even at smaller scales ($10 \times 10 \text{ km}^2$, $3 \times 3 \text{ km}^2$, or $300 \times 300 \text{ m}^2$), this method also can provide good identification results. Furthermore, the algorithm runs efficiently and does not require separate labeling of the data. Notably, in this manuscript, the number (K value) of typical terrain patterns, which is set according to the number of terrains related to ice cover in the past, is confirmed artificially due to the limitations of the K-means method itself. For research in other regions where typical terrain is uncertain, we can also use the elbow method [21,22] to determine the number of typical terrain patterns when we are unsure how many typical terrains we need to choose.

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