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Analysis of temporal and spatial distribution characteristics and influencing factors of alluvial fan geomorphology in the middle of the northern foothills of Qilian Mountains, northwest China

Abstract: Zhang Z., Zhang J., Zhang Z., Wei X., *Analysis of temporal and spatial distribution characteristics and influencing factors of alluvial fan geomorphology in the middle of the northern foothills of Qilian Mountains, northwest China.* (IT ISSN 0391-9838, 2024). Geomorphological analysis is central to alluvial fan studies, but research on the long-term evolution trends of alluvial fans and the interaction of spatial and temporal factors remains limited. This study aims to fill this gap by exploring the long-term evolution of alluvial fan morphology and the long-term impact of climatic factors on morphological changes. The research uses satellite images from 1983 to 2023, GDEMV3 30-metre resolution digital elevation model, and regional annual precipitation data, combined with Geographic Information Systems (GIS), remote sensing technology, and statistical methods (such as Sen's Trend Test and Mann-Kendall Test), focusing on three regions in the middle section of the northern Qilian Mountains foothills. The results show: (1) Spatially, there is a significant inverse relationship between the number and average area of alluvial fans. The northwest region has the most alluvial fans but the smallest average area, while the southwest has the fewest but the largest. As the rank of alluvial fans increases, their area grows, but their number decreases. The area and slope of alluvial fans follow a power function relationship with watershed area – larger watersheds tend to have larger and gentler alluvial fans. (2) Temporally, from 1983 to 2023, the overall area of alluvial fans has significantly decreased, especially in the northwest, while the overall slope has slightly increased. Both the area and slope of alluvial fans are strongly correlated with annual precipitation; increased precipitation promotes area expansion and reduces slope. This study enriches geomorphological literature and provides new perspectives for related research.

Key words: Alluvial fan, Geomorphology, Influencing factors, GIS, Qilian Mountains.

INTRODUCTION

Alluvial fans are formed in arid and semi-arid regions when temporary water flows out of mountain passes. Due to the steep drop in terrain, the slope decreases, and the water flow escapes its lateral constraint, dispersing the materials it carries from the mountain pass to the surrounding areas, forming a fan-shaped accumulation with the mountain pass as the apex. The larger the flow of the river between the mountains, the larger the resulting alluvial fan, the gentler the slope, and the more complete the fan's shape. The upper layer is usually composed of loess, with clear and distinct stratigraphy, while the lower layer contains better-rounded, larger gravel. Conversely, the smaller the flow of the river between the mountains, the smaller the alluvial fan, the steeper the slope, and the more disordered the stratigraphy. Based on the relationship between Melton's ruggedness number and the fan slope, as well as the morphometric threshold method, alluvial fans can be classified into three types: debris-flow fans, fluvial fans, and mixed fans (Marchi *et al.*, 1993; Bertrand *et al.*, 2013). Alluvial fans provide historical data on technology, environment, and climate change for regions or basins (White *et al.*, 1996; Lanckriet *et al.*, 2016) and serve as records of climate, physical geography, and tectonic environments. In some mountainous areas, alluvial fans have become important land resources for local communities (Mazzorana *et al.*, 2020), with some larger fans even developing into towns or cities (Santangelo *et al.*, 2012; Maghsoudi *et al.*, 2014; Chen *et al.*, 2017). Therefore, research on alluvial fans has significant practical value, focusing on their geomorphological characteristics (Sorriso-Valvo *et al.*, 1998), sedimentary processes (Sweeney and Loope, 2001), and the key influencing factors (Calvache *et al.*, 1997; Harvey *et al.*, 1999). The development of alluvial fans is influenced by a variety of factors (Goswami *et*

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al., 2009), including basin characteristics, tectonic activity, and climate conditions (Harvey *et al.*, 1999; Harvey, 2002a,b; Salcher *et al.*, 2010; Chen *et al.*, 2022). The main characteristics of the watershed, such as area, slope, bedrock type, and vegetation cover, can significantly impact the size and shape of the alluvial fan (Blair, 1999; Harvey *et al.*, 1999; Stock *et al.*, 2008; Goswami *et al.*, 2009; Birch *et al.*, 2016; Stokes and Gomes, 2020). Alluvial fans formed in smaller watersheds are typically smaller in size and steeper in slope, while those in larger watersheds are larger and have gentler slopes. Bedrock type also affects the development of alluvial fans. Easily weathered rocks, such as mudstone, gypsum, and limestone, generate large volumes of weathered material, which is transported by water flow to the fan, forming a larger fan area (Nichols and Thompson, 2005; Chen *et al.*, 2022). Tectonic activity, such as uplift and subsidence, can also influence the migration and morphological characteristics of alluvial fans by controlling the accommodation space in front of the mountain. Climate is a crucial factor in the formation of alluvial fans (White *et al.*, 1996), affecting the deposition and erosion on the fan surface through runoff and flood events (Harvey *et al.*, 1999). Precipitation impacts the relative size of sediment fluxes, and its intensity and frequency are particularly important for fan development (Lu *et al.*, 2010; Lu *et al.*, 2018; Chen *et al.*, 2022). Additionally, alluvial fans are influenced by historical wet-dry cycles (Chen *et al.*, 2022), with wet periods being larger than dry periods during the Central European period (Meinsen *et al.*, 2014). Runoff transports debris from the watershed to the alluvial fan, so the quantity, distribution, and sedimentary characteristics of fan components reflect environmental changes within the watershed (Sorriso-Valvo *et al.*, 1998; Crosta and Frattini, 2004; Harvey, 2012). The relationship between alluvial fan morphology and watershed characteristics has received significant attention, particularly the relationship between their morphologies, as the parameters are readily available (Crosta and Frattini, 2004; Stokes and Gomes, 2020) and provide valuable insights into fan development. In the volcanic islands of the Atlantic Ocean, empirical models have quantified the relationships between fan area/slope and watershed parameters, highlighting the importance of watershed morphology (Crosta and Frattini, 2004; Chen *et al.*, 2022). Research has found a strong positive power function relationship between fan area and basin area, and a negative power function relationship between fan slope and basin area (Mokarram *et al.*, 2014). Karymbalis *et al.*, studied the alluvial fans and watersheds in the Trichonis Lake Graben in western Greece and found a very strong positive correlation between the geomorphological parameters of the fans and their watersheds (Karymbalis *et al.*, 2022). Chen *et al.*, identified key factors influencing the development of alluvial fans in the Lhasa River basin of the Qinghai-Tibet Plateau, with basin characteristics accounting for 17.88% of the relative importance, while material factors (average rock hardness and NDVI) and hydrological factors (average annual rainfall, glaciers, and snow) contributed 14.42% and 10.98%, respectively (Chen *et al.*, 2022).

At present, no systematic and widely accepted theory on alluvial fans has been established. Previous studies on the morphological characteristics and influencing factors of alluvial fan deposition are often case-specific, and the resulting theories differ considerably, mostly applying only to the specific regions studied. A thorough review of literature reveals two major shortcomings in the research on the geomorphology of alluvial fans in the central part of the northern foothills of the Qilian Mountains: first, while previous studies have made valuable contributions to understanding the provenance system, sedimentary mechanisms, structural characteristics, and sedimentary environments of alluvial fans in northwest China, there has been limited research on the alluvial fans in the central part of the northern foothills of the Qilian Mountains, particularly regarding their geomorphological characteristics; second, research on the variation of geomorphological parameters and influencing factors often focuses on specific time periods and spatial locations, discussing the relationships between various parameters and external influences on the fan body based on geographical differences, with little research on the long-term trends in alluvial fan geomorphology, the relationships between parameters over many years, and their relationship with the regional annual rainfall over extended periods.

Therefore, analyzing the morphological characteristics and influencing factors of alluvial fans in the central part of the northern foothills of the Qilian Mountains at both temporal and spatial scales will address the gaps in the existing research. This comprehensive analysis will not only enhance our understanding of alluvial fan geomorphology in this region but also provide valuable insights for future water resource management, land use, and local economic development, with significant policy support and guidance.

STUDY AREA

The study area is located in the northeastern margin of the Qinghai-Tibet Plateau and the central part of the northern foothills of Qilian Mountain (fig. 1). Qilian Mountain stretches 1300 kilometers in length and 350 kilometers in width, with elevations ranging from 1800 to 5800 meters above sea level. The elevation gradually decreases from west to east, averaging about 4500 meters, which is approximately 3000 meters higher than Hexi Corridor in the north. Qilian Mountain has undergone several stages of tectonic activity from the early Paleozoic to the Cenozoic (Xiao *et al.*, 2009; Song *et al.*, 2013; Zuza *et al.*, 2018; Zuza *et al.*, 2019; Tong *et al.*, 2020). After a period of rapid uplift and erosion between 20 and 8 million years ago, it continued to rise and expand outward (Jolivet *et al.*, 2001; Duvall *et al.*, 2013; Wang *et al.*, 2016; Wang *et al.*, 2017a; Zheng *et al.*, 2017; Li *et al.*, 2019; Pang *et al.*, 2019), making it one of the youngest structural components of the Qinghai-Tibet Plateau (Huang *et al.*, 2021). Affected by the Mongolian anticyclone, Qilian Mountain experiences cold and dry winters, with relatively high summer temperatures and significant daily temperature fluctuations, ranging from -5 °C to 15.5 °C (He *et al.*, 2012). The annual average temperature is 0.6 °C (Rong *et al.*, 2019). The region receives between 108 and 255 mm of annual rainfall, increasing from west to east, typical of a continental climate (Li *et al.*, 2022). The intense uplift of the Qinghai-Tibet Plateau has led to the formation of vast undulating mountains and valleys in the arid and semi-arid transition zone (Molnar and Tapponnier, 1975; Tapponnier *et al.*, 1982; Harrison *et al.*, 1992; Molnar, 2005; Zheng *et al.*, 2013; Wang *et al.*, 2021), creating conditions for the formation of the Shiyang River, Heihe River, and Shule River in the Hexi Corridor. In this paper, the alluvial fan located in the central part of the northern foothills of the Qilian Mountains, the southern foothills of the Longshou Mountains, and the northern foothills of the Yumu Mountains, i.e., Ganzhou and Minle counties in the southwestern part of Zhangye city, Ganzhou and Shandan counties in the eastern part, and Gaotai and Linze counties in the northwestern part of Zhangye city, is taken as a study object.

The North Qilian Mountains, one of the three oldest orogenic belts on Earth recognized to date(Song *et al.*, 2009), is a northwest-southeast trending Caledonian orogenic belt. This orogenic belt has been in the process of uplift and is considered to be the material record of a typical marine-type subduction zone in the early Paleozoic era(Wu *et al.*, 1993; Du *et al.*, 2001; Zheng *et al.*, 2010; Hetzel, 2013), part of the Qinling-Qilian-Kunlun orogenic belt in west-central China (Hou *et al.*, 2006). The southern part of the region is characterized by Cambrian strata, while the northern part features Ordovician-Silurian strata. The dominant rock types in the region include slate, phyllite, metamorphic sandstone, limestone, and volcanic rock (Li *et al.*, 2013). The northern edge of the Qilian Mountains has developed a large number of small and medium-sized rivers, the larger rivers are the Changma River, the Black River, the Shiyang River, the Fengle River, the Maying River, the Beidai River, and the Liyuan River. flow along the northern edge of the Qilian Mountains. During the Late Pleistocene, these rivers deposited extensive alluvial fans at the foot of the mountains(Zhang *et al.*, 2024). These fans are characterized by their wide expanse and significant thickness.

Yumu Mountain is situated north of the Qilian Mountains, south of the Hexi Corridor, and northwest of Zhangye City. It is an independent fault block formed by the northeastern extension of the North Qilian Mountains during uplift (Tapponnier *et al.*, 1990). Yumu Mountain began its uplift approximately 3 million years ago. It exhibits a northwest-southeast trend and spans about 65 km. The overall elevation of the mountain is low, and the highest peak in the middle reaches an elevation of 3200 m above sea level (Tapponnier *et al.*, 1990; Hu *et al.*, 2019a; Hu *et al.*, 2019b; Hu *et al.*, 2022). The central part of Yumu Mountain is primarily composed of Silurian metamorphic sandstone and phyllite, Devonian sandstone, and conglomerate. The eastern part consists mainly of Cretaceous sedimentary rocks. The western part is dominated by Neogene and Pleistocene sediments (Hu *et al.*, 2022). The area is home to two relatively large rivers: Liyuan River and Bailang River, both originating from the Qilian Mountains (Hu *et al.*, 2022) and flowing into the Heihe River in the northeast and north directions, respectively. the Yu-

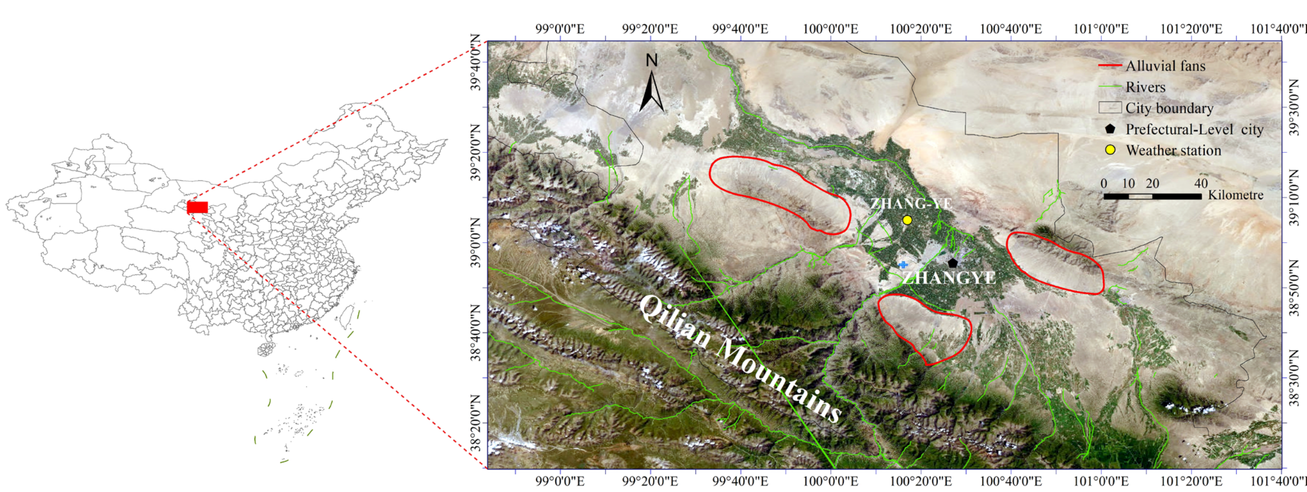


Figure 1 - Geographic location map of the study area.

mushan region has a dry climate, with the following key characteristics: the average annual rainfall is 200mm, the extreme low temperature is minus 28-30 °C, the extreme high temperature is 34-36 °C, the average temperature is 0-3 °C. This climate is classified as an arid and semi-arid grassland climate. Among the three regions of the study area, the area has developed fewer water systems, and the alluvial fans formed in front of the mountains are small in size, mostly in the form of narrow strips with greater thickness.

Longshou Mountain is located on the north side of the Hexi Corridor, north of the Qilian Mountains, on the southwest edge of the Alashan Block, east of Zhangye City. It borders the Hexi Corridor foreland basin to the northeast. Longshou Mountain's central region has a relatively low elevation, ranging from 2,500 to 3,000 meters. This places it approximately 1,400 meters above the Hexi Corridor Plain and 1,600 meters above the Alashan Plateau. The highest peak of Longshou Mountain reaches an elevation of 3,430 meters above sea level (Palumbo *et al.*, 2010). The climate is continental desert and continental steppe, with low rainfall and high evapotranspiration. Vegetation is scarce due to the arid conditions, with an average annual rainfall of less than 200 mm (Ta *et al.*, 2004; Palumbo *et al.*, 2010). The primary rock composition consists of ophiolitic mixed rock layers alternating with diamictic hornblende and various gneiss types. Minor occurrences of marble, quartzite, and schist are also present. Paleozoic formations are predominantly composed of quartz-rich metamorphic sandstones, with some Carboniferous granites. Metamorphic sandstone is occasionally interspersed with layers of limestone and dolomite. Hillsides are mainly exposed bedrock, with some areas covered by a thin (≤ 0.5 m) weathered layer. Rills on the slopes are partially filled with weathered material or bedrock debris. Alluvial fans formed by the rivers flowing from Longshou Mountain are larger in length, width, and volume compared to those in the Yumushan area. These fans also exhibit a more complete fan shape.

DATA SOURCE

The data used in this study include alluvial fan satellite images, GDEMV3 30-metre resolution digital elevation model, and regional annual rainfall records. Satellite imagery was obtained from Landsat 4-5 and 7-9 digital products and Global Mapper, covering the period from 1983 to 2023. GDEMV3 30-metre resolution digital elevation model were downloaded from the Geospatial Data Cloud, with the same time range as the satellite imagery. Annual rainfall data was sourced from Zhangye Hydrographic Station through NOAA (National Oceanic and Atmospheric Administration, USA) for the years 1983 to 2023.

METHODS

This study primarily uses geographic remote sensing, data interpretation, and statistical analysis methods. Based on topographic maps, alluvial fan satellite images, and DEM (Digital Elevation Model) data of the study area, remote sensing and interpretation techniques were applied. ArcMap, ArcScene and related auxiliary software were used to extract the three-dimensional model of the alluvial fans, to divide the alluvial fans and their watersheds in each region, and to obtain the area, slope and watershed area parameters of each alluvial fan in the study area on March 15, 2023, as well as the overall area and the overall slope values of the alluvial fans in each region for the 1983-2023 time interval of five years. The choice of a five-year interval is based on the following reasons: (A) Data Availability and Accuracy: The main reason for selecting a five-year interval is to consider the availability and accuracy of data. Satellite imagery and DEM data are typically updated every few years, making five years a suitable time scale. This interval allows us to avoid delays in data updates while providing a long enough period to observe changes in the geomorphological characteristics of alluvial fans; (B) Capturing Long-term Trends: A five-year interval helps capture long-term geomorphological trends of alluvial fans while minimizing the impact of short-term climate fluctuations and other sporadic events. For geomorphological evolution, five years is sufficient to reflect trends without being influenced by short-term variations; (C) Balancing Detail and Practicality: In selecting the time interval, I considered the balance between the operational feasibility of the analysis and the level of detail captured by the data. A five-year interval prevents the analysis from becoming too cumbersome due to excessive data volume while being sensitive enough to capture the long-term trends in the changes of alluvial fan morphology). Additionally, overall area and slope values for alluvial fans from 1983 to 2023 were calculated at five-year intervals. Using Excel and Origin software, we statistically analyzed the parameters of alluvial fans, watershed parameters, and regional rainfall data over many years. The main research objectives are as follows: (1) Analyze the number, area, and spatial distribution characteristics of alluvial fans. (2) Examine the relationship between the area and slope of alluvial fans and their respective basin areas. (3) Investigate the temporal variation trends of the overall area and overall slope of alluvial fans in each region, as well as the relationship between these two parameters. (4) Analyze the relationship between the overall area and slope of alluvial fans in each region and the annual rainfall over time.

The following are the methods for determining the sectors and modelling the three locations of the alluvial fans:

Method of determining sectors: Determination of the study area: alluvial fan in the central part of the northern foothills of the Qilian Mountains, the southern foothills of the Longshou Mountains and the northern foothills of the Yumu Mountains. Collecting data: collect geographic, climatic and hydrological data of the region. Including topographic maps, satellite images, meteorological data, river network data, etc. Drawing base maps: Use GIS (Geographic Information System) software to create shp surface files, identify the alluvial fan fan boundaries and draw alluvial fan contour range maps based on satellite image maps and extracted alluvial fan regional 3D model maps, as well as river network data.

The 3D model extraction methods for the nine periods of alluvial fans in each region are as follows:

Preparation of data

Firstly, prepare the following data: satellite image map (used to provide surface information of the study area), DEM (Digital Elevation Model) (providing topographic elevation data of the study area, usually a raster data)

Generating 3D Models in ArcMap

ArcMap is mainly used for two-dimensional map processing, but you can use raster data and 3D Analyst tools for three-dimensional view display. Steps: Load data: Open ArcMap and use the 'Add Data' button to load satellite images and DEM data; Prepare 3D view (3D Analyst extension): In ArcMap, click Customize→Extensions, make sure 3D Analyst has been selected; create 3D base layer: click DEM data layer, choose Properties→Symbology, and render the DEM data into different colour scales to better display the elevation differences; in Displays, click 'Add Data' button to load satellite images and DEM data; in Displays, click 'Add Data' button to load satellite images and DEM data; in Displays, click 'Add Data' button to load satellite images and DEM data. To display the elevation difference; In the Display tab, check the Use Surface Display option; To create 3D terrain: In the 3D Analyst toolbar, click Surface→Layer 3D To Display, and select the DEM data as the surface; To set the raster elevation of the data: Under the Elevation tab of Layer Propertie, choose the Elevation tab in Layer Propertie, select Surface, and set DEM as the surface elevation layer; Insert 3D Scene: Click Insert→New 3D Scene, and then select Add Data in the scene to add both the satellite image and the DEM layer to the scene view; Use the Scene toolbar to adjust the view angle and view the generated 3D terrain map.

Generating 3D models in ArcScene

ArcScene is a software specially designed for 3D data analysis and presentation. Compared with ArcMap, it provides richer 3D views and interactive functions. Steps: Load data: start ArcScene, click Add Data to add satellite images and DEM data to the project; set the surface of DEM layer: click on the DEM layer, choose Properties→Base Heights, and in this window, choose Floating on a custom surface, and then choose the DEM layer as the base ground; Superimpose the satellite image layer on the DEM: Satellite images are usually 2D images, which can be added as a layer to the 3D view; click on the image layer and select Properties→Symbology to adjust the image display effect; Adjust the 3D display settings: In the 3D Effects toolbar, select Scene Properties to set the lighting, shadows, viewing distance and other effects of the 3D scene; Rotate and adjust the viewing angle: use the 3D navigation tools in ArcScene to adjust the viewing angle, rotate and tilt the scene to view the 3D model of the study area from different perspectives; Export the 3D model: if necessary, you can export the 3D view to a 3D model file via File→Export Scene. 3D model file for further analysis or presentation.

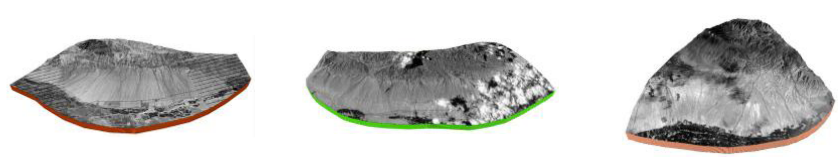
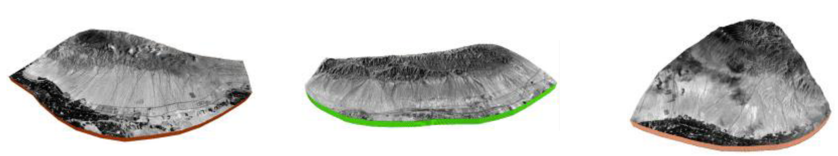
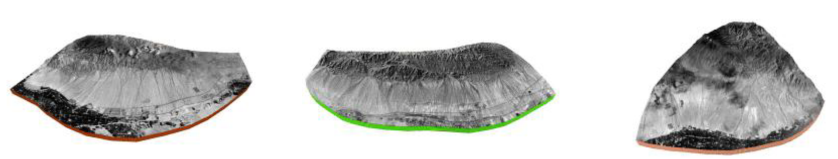
PARAMETER EXTRACTION

Alluvial fan area, slope, overall area, and overall slope

The collected data, including the regional topographic map, historical satellite images of alluvial fans, and DEM digital elevation model, were divided into three parts and processed separately to extract alluvial fan parameters. Topographic Map: The topographic map of the study area was processed using Adobe Photoshop, Adobe Illustrator, and ArcMap software. This involved cutting, describing, vectorizing, and geographically registering the map to assign it a coordinate system. Satellite Image Map: The geographic coordinate system of the satellite image map was converted to a projected coordinate system using ArcMap software.

DEM Digital Elevation Model: Using ArcMap software, the DEM digital elevation model plates for the study area were mosaicked, and the coordinates of the mosaic model were projected and transformed. Then the processed study area map, alluvial fan satellite image map and DEM digital elevation model were processed through mask extraction and 3D processing using ArcMap and ArcScene software to extract the 3D model of alluvial fans in the study area (Table 1), and then to delineate the location of the alluvial fans in each region and the fan margin boundary. Finally, using ArcMap, we generated vector files representing the area and slope of each alluvial fan, as well as the overall area and overal slope of alluvial fans in each region. These files were analyzed to obtain the area and slope of individual alluvial fans on March 15, 2023, along with the overall area and overal slope parameters for each region's alluvial fans from 1983 to 2023, in five-year intervals (1983, 1988, 1993, 1998, 2003, 2008, 2013, 2018, and 2023). (The 1983 satellite image, obtained from a USGS satellite, lacked a reference coordinate system. Despite undergoing geographic

Table 1. 3D model maps of alluvial fans in the eastern, northwestern, and southwestern regions.

Region / Year	East	Northwest	Southwest
1983			
1988			
1993			
1998			
2003			
2008			
2013			
2018			
2023			

alignment, the image remained distorted and deformed. Visual interpretation and comparison with the 1984 image revealed very similar geomorphological information. To minimize potential errors in parameter measurements, the 1984 satellite image was chosen for this study).

Watershed area

As show in fig. 2, the study area contains 51 watersheds associated with alluvial fans located in the east, northwest, and southwest regions. Using three-dimen-

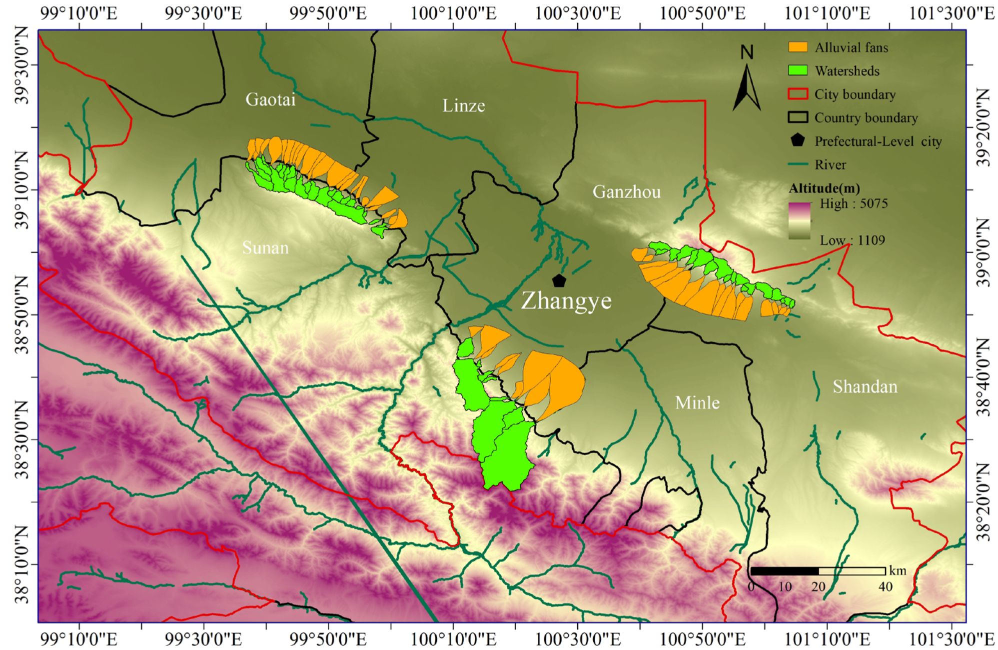


Figure 2 - Alluvial fan and watershed extraction results in the study area.

sional models of the alluvial fans, the latitude and longitude of the basin dumping points were identified with the coordinate positioning tool from 91 satellite map assistant software. Vector coordinate files for the basin dumping points were generated for each region. These vector files, along with the DEM (Digital Elevation Model) of the study area, were then imported into ArcMap. Hydrological analysis of the river basins was conducted in ArcMap, following steps such as sinkhole analysis, flow direction analysis, river network classification, grid vectorization, dumping point capture, and watershed analysis. Using the area identification function in ArcMap software, the basin area corresponding to each alluvial fan in the study area was calculated.

RESULTS

Based on satellite imagery analysis from March 15, 2023, the areas of alluvial fans in the three regions (Eastern, Northwestern, and Southwestern) were identified and measured using ArcMap software. The number of alluvial fans in the Eastern, Northwestern, and Southwestern regions are 18, 24, and 9, respectively. According to fig. 3, although the Southwestern region has the fewest alluvial fans, it has the largest total area, measuring 269.84 km². In contrast, the Northwestern region has the most alluvial fans but the smallest total area, measured at 225.11 km². Interestingly, there is an inverse relationship between the number of alluvial fans and their average area: regions with more alluvial fans tend to have smaller individual fans, while regions with fewer alluvial fans exhibit larger fans. In the Northwestern region, the average area of an alluvial fan is the smallest, at only 9.38 km², whereas in the Southwestern region, the average area is the largest, reaching 29.98 km². This distribution suggests that in the Eastern and Northwestern regions, despite the higher number of alluvial fans, the fans are generally smaller, linear, and less developed; whereas in the Southwestern region, despite having fewer alluvial fans, each fan is larger, fully developed, and more uniform in shape, width, and length (fig. 4).

According to fig. 5, the number of alluvial fans in Ganzhou District, Shandan County, Gaotai County, Linze County, and Minle County are 15, 12, 15, 9, and 0, respectively. Ganzhou District contains 94.58% of the Southwestern region's alluvial fans and 43.42% of the Eastern regions, accounting for 48.70% of the total alluvial fan area across the three regions. Shandan County contains 56.58% of the Eastern region's alluvial fans, accounting for 19.92% of the total area. Gaotai County contains 66.41% of the Northwestern region's alluvial fans, accounting for 19.57% of the total area. Linze County and Minle County contain 33.59% of the Northwestern region's alluvial fans and 5.42% of the Southwestern region's, with areas accounting for 9.90% and 1.91% of the total area across the three regions, respectively. Among these five counties, Ganzhou District has the largest number and area of alluvial fans, with 15 fans covering an area of 371.99 km², while Minle County has the smallest number and area, with 0 fans and 14.64 km², respectively. This distribution indicates that about half of the alluvial fans are concentrated in Ganzhou District, with the southwestern part of this district being occupied by three large alluvial fans.

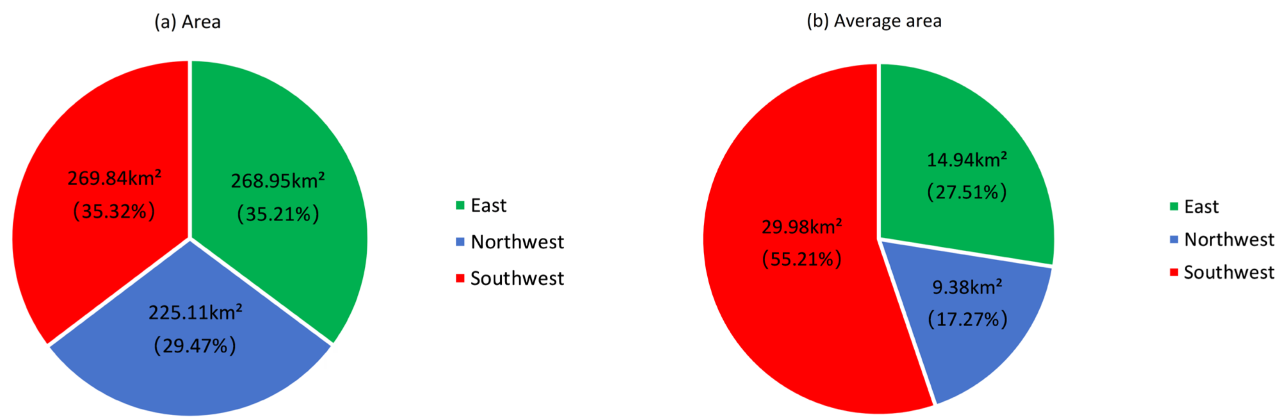


Figure 3 - Fan charts of overall area (left) / average area (right) of alluvial fans in the eastern, northwestern, and southwestern regions.

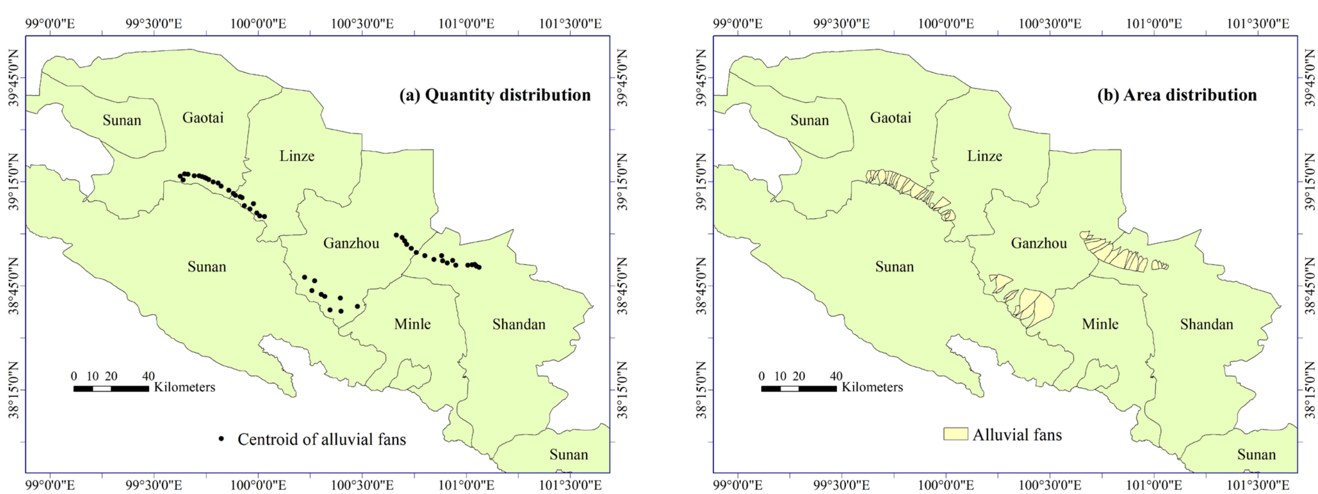


Figure 4 - Distribution map of the fan center and boundary of each alluvial fan in the study area.

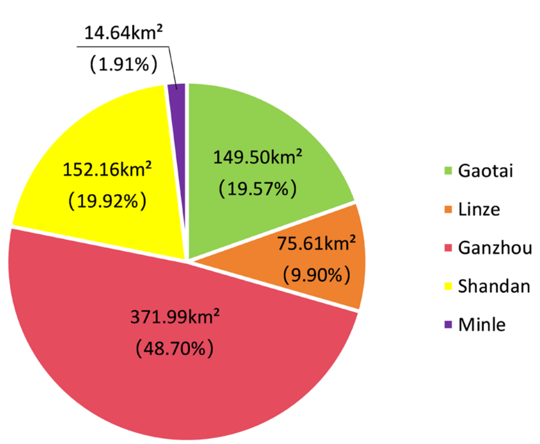


Figure 5 - Distribution map of alluvial fan area in each county

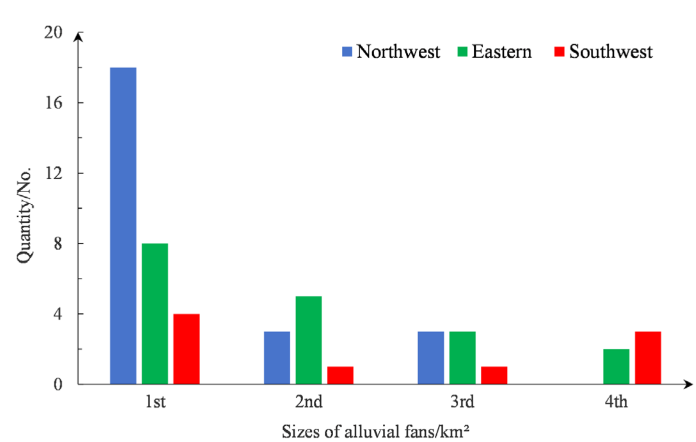


Figure 6 - Histogram of the number of grade 1-4 alluvial fans in the eastern, northwestern, and southwestern regions.

Number, area and spatial distribution of alluvial fans of different sizes

According to the alluvial fan area data from March 15, 2023, the alluvial fans in the study area are classified into four levels: Level 1 (1 km^2 ≤ area < 10 km^2), Level 2 (10 km^2 ≤ area < 20 km^2), Level 3 (20 km^2 ≤ area < 30 km^2), and Level 4 (area ≥ 30 km^2). See figs 4 and 6 for distribution of different levels in each region.

According to Table 2, the total areas of Level 1, Level 2, Level 3, and Level 4 alluvial fans are 138.74 km^2, 144.19 km^2, 169.47 km^2, and 311.50 km^2, respectively, accounting for 18.16%, 18.88%, 22.18%, and 40.78% of the total alluvial fan area in the study area. In the eastern region, the total areas of these levels of alluvial fans are 29.38 km^2, 77.02 km^2, 72.81 km^2, and 89.74 km^2, accounting for 10.92%, 28.64%, 27.07%, and 33.37% of the total alluvial fan area in the region, respectively. In the northwestern region, the total areas of these levels of alluvial fans are 96.68 km^2, 53.22 km^2, 75.21 km^2, and 0 km^2, accounting for 42.95%, 23.64%, 33.41%, and 0% of the total alluvial fan area in the region, respectively. In the southwestern region, the total areas of these levels of alluvial fans are 12.68 km^2, 13.95 km^2, 21.45 km^2, and 221.76 km^2, accounting for 4.70%, 5.17%, 7.95%, and 82.18% of the total alluvial fan area in the region, respectively.

Statistical analysis shows that the number of alluvial fans decreases from Level 1 to Level 4. In the eastern and northwestern regions, Level 1 alluvial fans are the most abundant, while Level 4 alluvial fans are the least. In the southwestern region, Level 1 alluvial fans are the most common, with fewer Level 2 and Level 3 alluvial fans. In terms of area, the total area of Level 1 alluvial fans in the eastern region is the smallest, and the total area of Level 4 alluvial fans is the largest; in the northwestern region, the total area of Level 4 alluvial fans is the smallest, and the total area of Level 1 alluvial fans is the largest; in the southwestern region, the total area of Level 1 alluvial fans is the smallest, and the total area of Level 4 alluvial fans is the largest.

Figs 7 and 8 show the geographical distribution of alluvial fans by size. The number and total area of Level 1 alluvial fans are the largest in Gaotai County and Linze County, while Level 4 alluvial fans are absent. In Ganzhou District, the number of Level 1 alluvial fans is the largest, and the number of Level 3 alluvial fans is the smallest; additionally, its total area of Level 4 alluvial fans is the largest, while the total area of Level 1 alluvial fans is the smallest. In Shandan County, the number of Level 1 alluvial fans is the largest, and the number of Level 4 alluvial fans is the smallest. The total area of Level 2 alluvial fans is the largest, while the total area of Level 1 alluvial fans is the smallest. Minle County contains a small portion of the Level 4 alluvial fans in the southwestern region, with a total area of 14.64 km^2. Overall, Level 1 to Level 3 alluvial fans are distributed across the four counties of Gaotai, Linze, Ganzhou, and Shandan, with the largest number of Level 1 alluvial fans in each county, and Level 4 alluvial fans are mainly distributed in Ganzhou District.

Regional distribution characteristics of alluvial fans in various regions (1983-2023)

Fig. 9 shows the temporal variation trends of the overall area and overall slope of the alluvial fans in the eastern, northwestern, and southwestern regions from 1983 to 2023. The southwestern region has the largest overall area of the alluvial fans, ranging from 269.84 km^2 to 281.76 km^2. The eastern region follows closely behind, with an area range of 266.42 km^2 to 278.66 km^2. The northwestern region has the smallest overall area, ranging from 221.90 km2 to 239.54 km^2. In contrast to the overall area, the overall slope values of the alluvial fans in the three regions exhibit the opposite size relationship. The northwestern region has the highest overall slope, ranging from 7.08% to 7.37%, followed by the eastern region, with an overall slope range of 5.24% to 5.28%. The southwestern region has the lowest overall slope, ranging from 4.94% to 5.02%. These results indicate that the changes in the overall area and overall slope values of the alluvial fans in the three regions have been relatively small over the span of more than 40 years. This is consistent with previous research, which has pointed out that in semi-arid and arid regions, the morphological changes of alluvial fans are relatively limited (Blainey and Pelletier, 2008; Shoshta and Marh, 2023; Lehmkuhl and Owen, 2024).

Table 2 - Distribution table of number and area of grade 1-4 alluvial fans in the eastern, northwestern, and southwestern regions.

Area range / Zone	First size		Second size		Third size		Fourth size	
	Number	Area (km^2)	Number	Area (km^2)	Number	Area (km^2)	Number	Area (km^2)
East	8	29.38	5	77.02	3	72.81	2	89.74
Northwest	18	96.68	3	53.22	3	75.21	0	0.00
Southwest	4	12.68	1	13.95	1	21.45	3	221.76
Gather	30	138.74	9	144.19	7	169.47	5	311.50

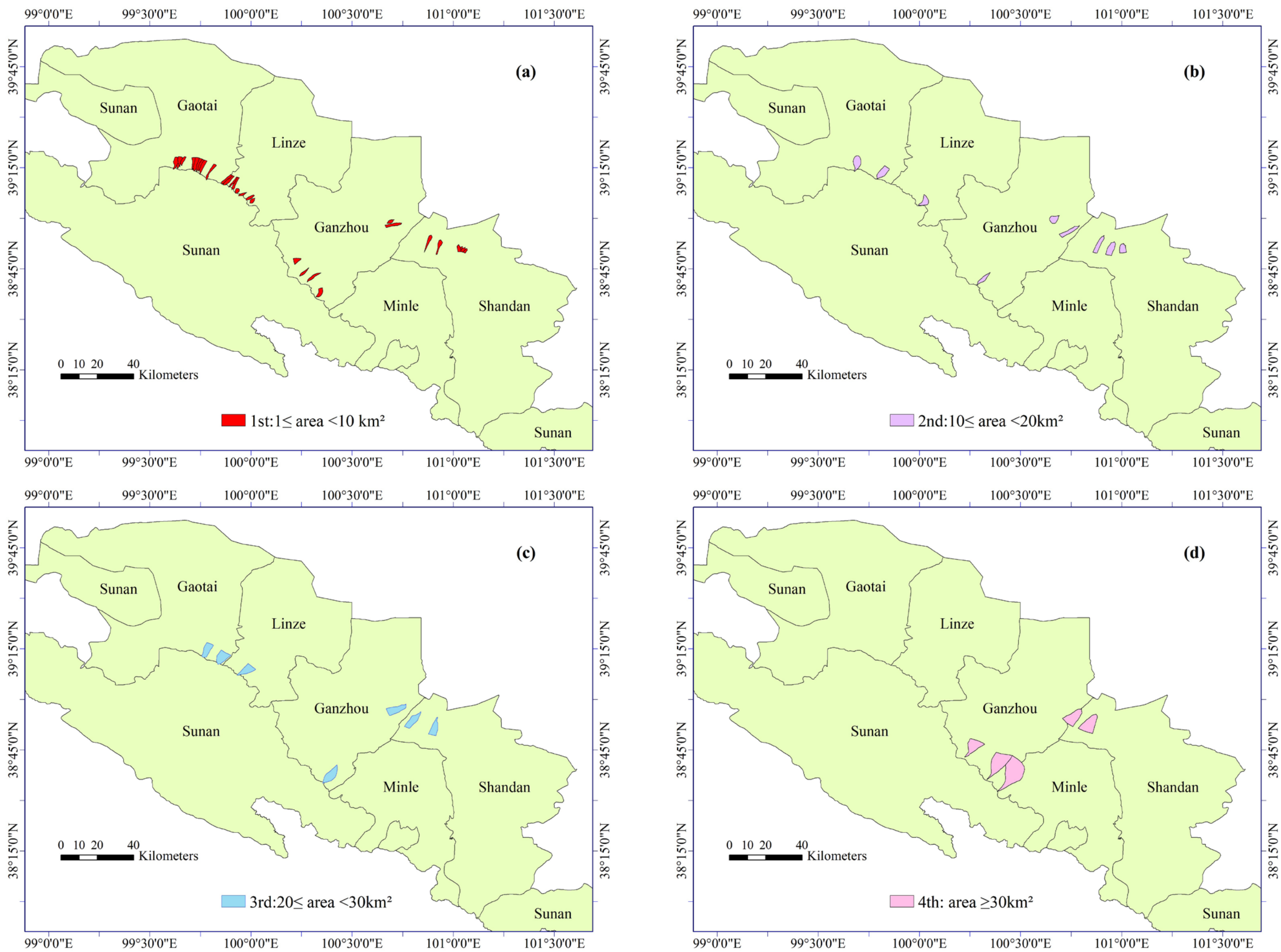


Figure 7 - Distribution map of grade 1-4 alluvial fans in each county.

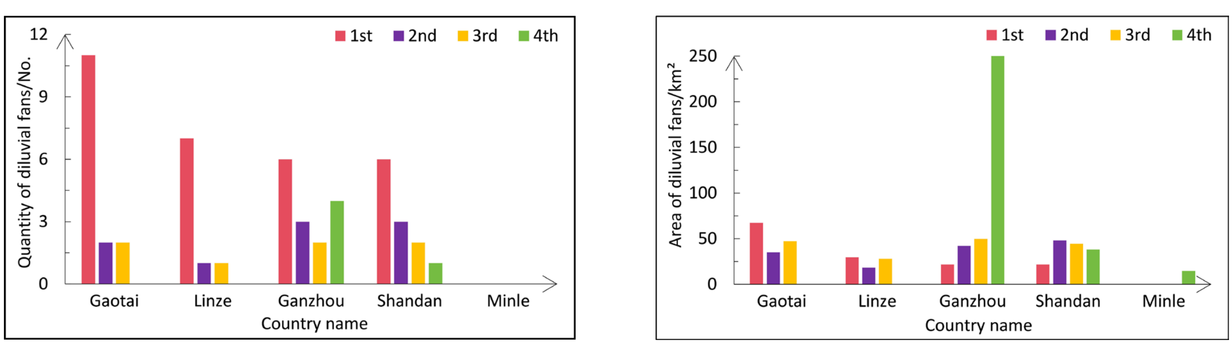


Figure 8 - Distribution of the number (left) / area (right) of grade 1-4 alluvial fans in each county.

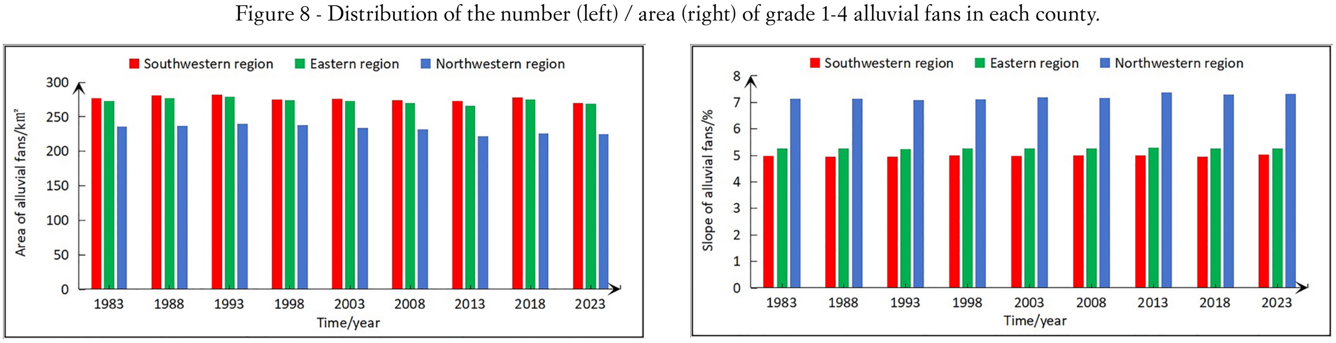


Figure 9 - Histogram of time-overall area (left) / overall slope (right) of alluvial fans in the eastern, northwestern, and southwestern regions.

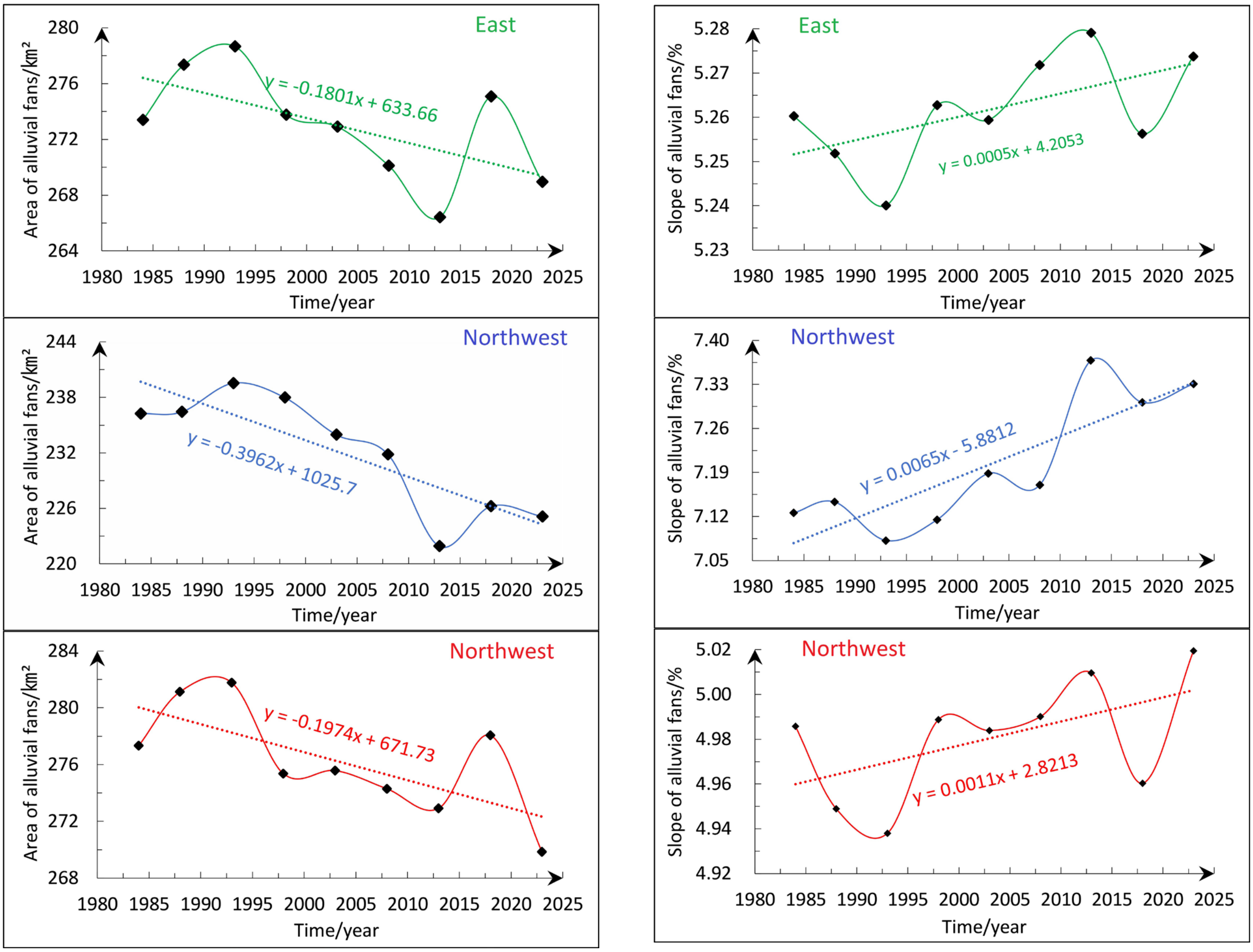


Figure 10 - Time-overall area (left) / overall slope (right) curves of alluvial fans in the eastern, northwestern, and southwestern regions (from top to bottom, respectively).

Sen's trend test, Mann Kendall test for overall area and overall slope of multi-year alluvial fans in each region

Fig. 10 shows the temporal variation trends of the overall area and overall slope of the alluvial fans in the eastern, northwestern, and southwestern regions from 1983 to 2023. The overall area of the alluvial fans in the three regions shows a trend of first increasing, then decreasing, then increasing again, and decreasing again. Specifically, the overall area of the alluvial fans gradually increased during 1983-1993 and 2013-2018, while it gradually decreased during 1993-2013 and 2018-2023. Overall, the overall area of the alluvial fans in the three regions shows a downward trend, with the northwestern region decreasing the fastest, followed by the southwestern region, and the eastern region decreasing the slowest. The slopes of the trend lines in the figure are -0.3962, -0.1974, and -0.1801, respectively.

From 1983 to 2023, the overall slope values of the alluvial fans in the eastern, northwestern, and southwestern regions fluctuated significantly, with the curve showing multiple stages of increase and decrease. The overall slope of the alluvial fans in the eastern and southwestern regions increased during the periods 1993-1998, 2003-2013, and 2018-2023, while it decreased during the periods 1983-1993, 1998-2003, and 2013-2018. The overall slope of the alluvial fans in the northwestern region increased during the periods 1983-1988, 1993-2003, 2008-2013, and 2018-2023, while it decreased during the periods 1988-1993, 2003-2008, and 2013-2018. Overall, the overall slope values of the alluvial fans in the three regions show an upward trend over time. The northwestern region has the fastest increase in overall slope, followed by the southwestern region, while the eastern region has the slowest increase in overall slope. The slopes of the trend lines in the figure are 0.0065, 0.0011, and 0.0005, respectively.

The analysis of the alluvial fan data from 1983 to 2023 indicates an inverse relationship between the overall area and the overall slope of the alluvial fans. Satellite image analysis shows that the scale of the alluvial fans in the three study regions has generally decreased. This ongoing morphological change of the alluvial fans is expected to have no significant impact on human activities in the alluvial fan areas in the near future.

Based on the analysis of the overall area and overall slope trends of the alluvial fans in each region (figs 10, 11), we observed the following.

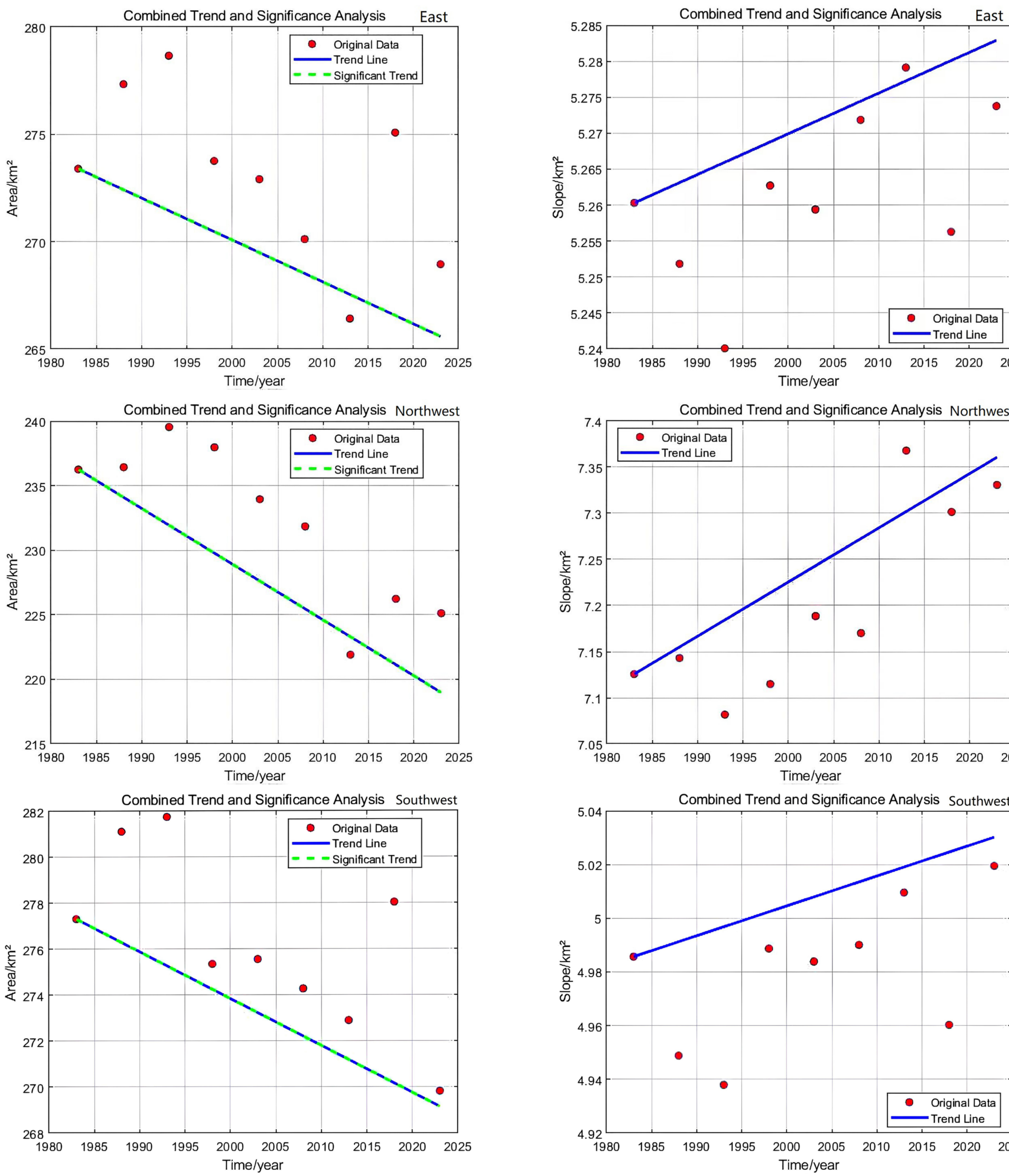


Figure 11 - Combined trend and significance plot of alluvial fan time-overall area (left)/ overall slope (right) for the eastern, north-western and south-western regions (from top to bottom, respectively).

As shown by the green line, the overall area of the alluvial fans in the eastern, northwestern, and southwestern regions shows a statistically significant decreasing trend, with P-values less than 0.05. This indicates that, during the study period (1983-2023), the overall area of the alluvial fans has continuously decreased. In contrast, the

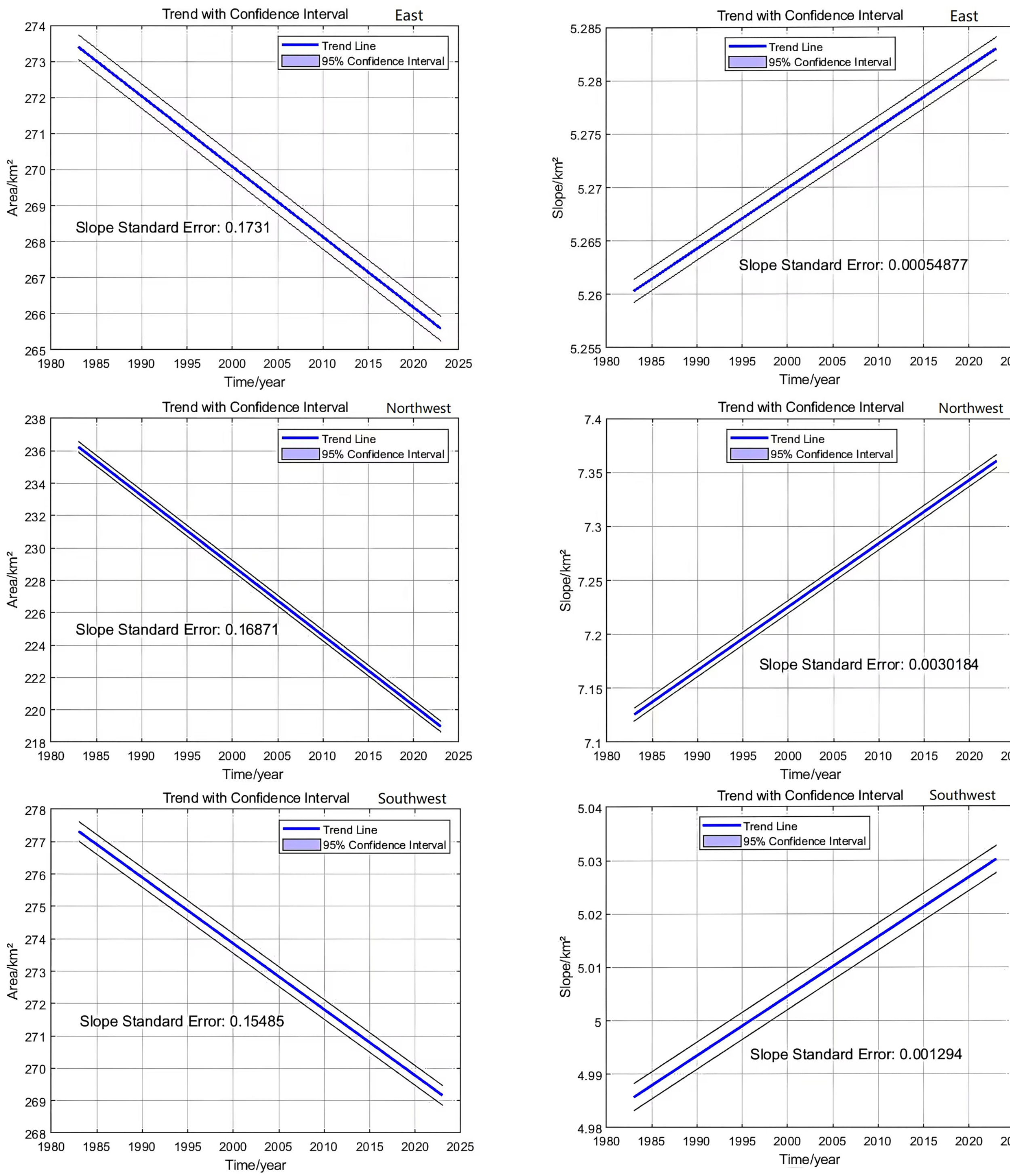


Figure 12 - Confidence interval plots for alluvial fan time-total area (left)/total slope (right) trends for the eastern, northwestern, and southwestern regions (from top to bottom, respectively).

overall slope of the alluvial fans in each region shows a non-significant increasing trend (P-value ≥ 0.05). The significant reduction in the overall fan area, particularly in the northwestern region, may be due to changes in regional precipitation patterns and human activities such as urban expansion. Studies have shown that the area of alluvial fans is often influenced by a combination of river erosion, changes in precipitation, and other environmental factors (Zygmunt, 2009; Clarke, 2015). The results of this study further validate that these factors may have led to the significant reduction in alluvial fan areas over the last 40 years or so.

Moreover, the non-significant change in overall slope also aligns with findings from similar studies in other regions. For instance, while some studies suggest that local slope may be influenced by topography, precipitation, and human activities, the changes are typically slow, and thus may not show a statistically significant trend over a short period of time (Zhang *et al.*, 2018; Fan *et al.*, 2019). This is also reflected in our study, indicating that changes in overall slope require longer monitoring to fully capture their trends.

These results provide valuable reference for understanding the long-term evolution of alluvial fans and may offer insights for the formulation of future alluvial fan conservation and management strategies.

Fig. 12 shows the trend line (in blue), confidence interval (the area between the two black lines), and standard error, providing the upper and lower bounds of the trend estimates. The main observations are as follows.

The confidence intervals for the overall area and overall slope of the alluvial fan in the northwestern region and for the overall area in the southwestern region are relatively narrow, indicating that the trends of these parameters in these regions are less affected by variability and are more stable over time. In contrast, the confidence intervals for the overall area, overall slope in the eastern region, and overall slope in the southwestern region are wider, reflecting greater volatility in the trend estimates. The wider confidence intervals in the eastern region and the narrower ones in the northwestern region may be related to the higher population density and frequent human activities in the eastern region, while the northwestern region has a more sparsely distributed population and a smaller total population.

The standard errors of the slope estimates are as follows: for the overall area, the standard errors for the eastern, northwestern, and southwestern regions are 0.1731, 0.16871, and 0.15485, respectively. The standard errors for the overall slope are 0.00054877, 0.0030184, and 0.001294, respectively. These values indicate that the trend estimates for the overall area are less precise compared to the overall slope, particularly in the eastern region. Since the overall area of alluvial fans in each region is around 250 km^2 over several years, the standard errors for both overall area and overall slope are very small, so in this case, it can be considered that the trend estimates are relatively precise.

These results are consistent with previous studies, where regions with narrower confidence intervals generally correspond to areas with more consistent and reliable environmental trends, while regions with wider confidence intervals indicate greater variability or complexity in the driving factors (Hu *et al.*, 2024). Areas with significant human influence or greater climate variability tend to show wider confidence intervals, indicating higher uncertainty in trend predictions (Thornton *et al.*, 2014; Seddon *et al.*, 2016; Borrelli *et al.*, 2020).

Correlation analysis of temporal changes in overall area and overall slope of alluvial fans across different regions

Previous studies have shown that there is a widespread inverse relationship between the area and slope of alluvial fans, particularly in semi-arid and arid regions (Goorabi *et al.*, 2021; Ghahraman and Nagy, 2024; Iacobucci *et al.*, 2024; Lehmkuhl and Owen, 2024). According to fig. 13, from 1983 to 2023, the overall area of the alluvial fans in the three regions has increased, while the overall slope has decreased. There is a strong negative power function relationship between the two parameters, with correlation coefficients of -0.9485, -0.9765, and -0.9416 in the eastern, northwestern, and southwestern regions, respectively. This further demonstrates that the inverse relationship between the area and slope of alluvial fans holds true across both temporal and spatial scales. Previous research indicates that the increase in the area of alluvial fans is generally accompanied by a decrease in slope, which is mainly attributed to the promotion of sediment accumulation under low-

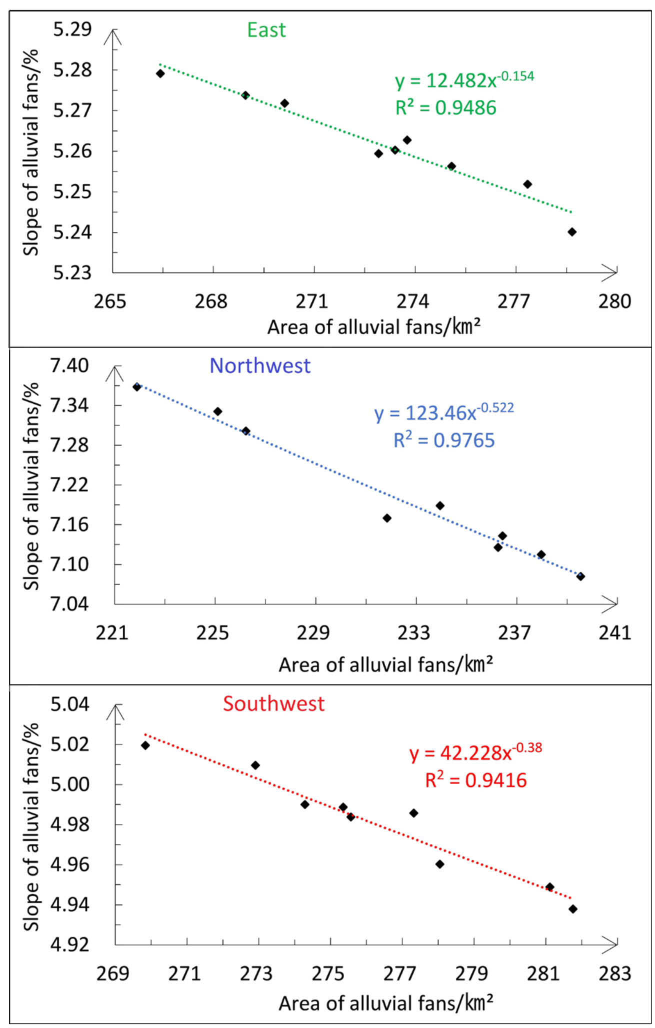


Figure 13 - Relationship between overall area and overall slope of alluvial fans in the eastern, northwestern, and southwestern regions over multiple years.

slope conditions (Reitz and Jerolmack, 2012; Patel and Pati, 2022). Additionally, in arid regions, due to the scarcity of precipitation, areas with lower slopes are more conducive to sediment accumulation, leading to the gradual expansion of alluvial fan areas (Ziadat and Taimeh, 2013). In this study, the strong negative correlation coefficients in the three regions (eastern -0.9485, northwestern -0.9765, southwestern -0.9416) further support this trend, indicating that factors such as precipitation and erosion play an important role in the morphological evolution of alluvial fans. These results provide strong evidence for understanding the evolution of alluvial fans under different climatic conditions.

The overall area and overall slope of alluvial fans in relation to annual rainfall (1983-2023)

According to fig. 14, from 1983 to 2023, there is a linear relationship between the overall area, overall slope, and annual rainfall of alluvial fans in the eastern, northwestern, and southwestern regions. The overall area of the alluvial fans increases with increasing annual rainfall, with strong correlations in the eastern (0.8604) and southwestern (0.8242) regions, and a relatively strong positive correlation in the northwestern region (0.7675). In contrast, as annual rainfall increases, the overall slope of the alluvial fans decreases. The eastern region shows a very strong negative correlation (-0.8758), while the northwestern and southwestern regions exhibit relatively strong negative correlations of -0.7404 and -0.7984, respectively. These results suggest that the temporal variation of precipitation in the same region has a significant impact on the developmental trend of alluvial fans. An increase in precipitation often leads to the expansion of alluvial fan areas because more water flow and sediment can promote the expansion of the fan (Whipple *et al.*, 1998; Curray *et al.*, 2002; Zhang *et al.*, 2016; Zhang *et al.*, 2020). The strong positive correlations in the eastern and southwestern regions (0.8604 and 0.8242) further support this point. In contrast, increased

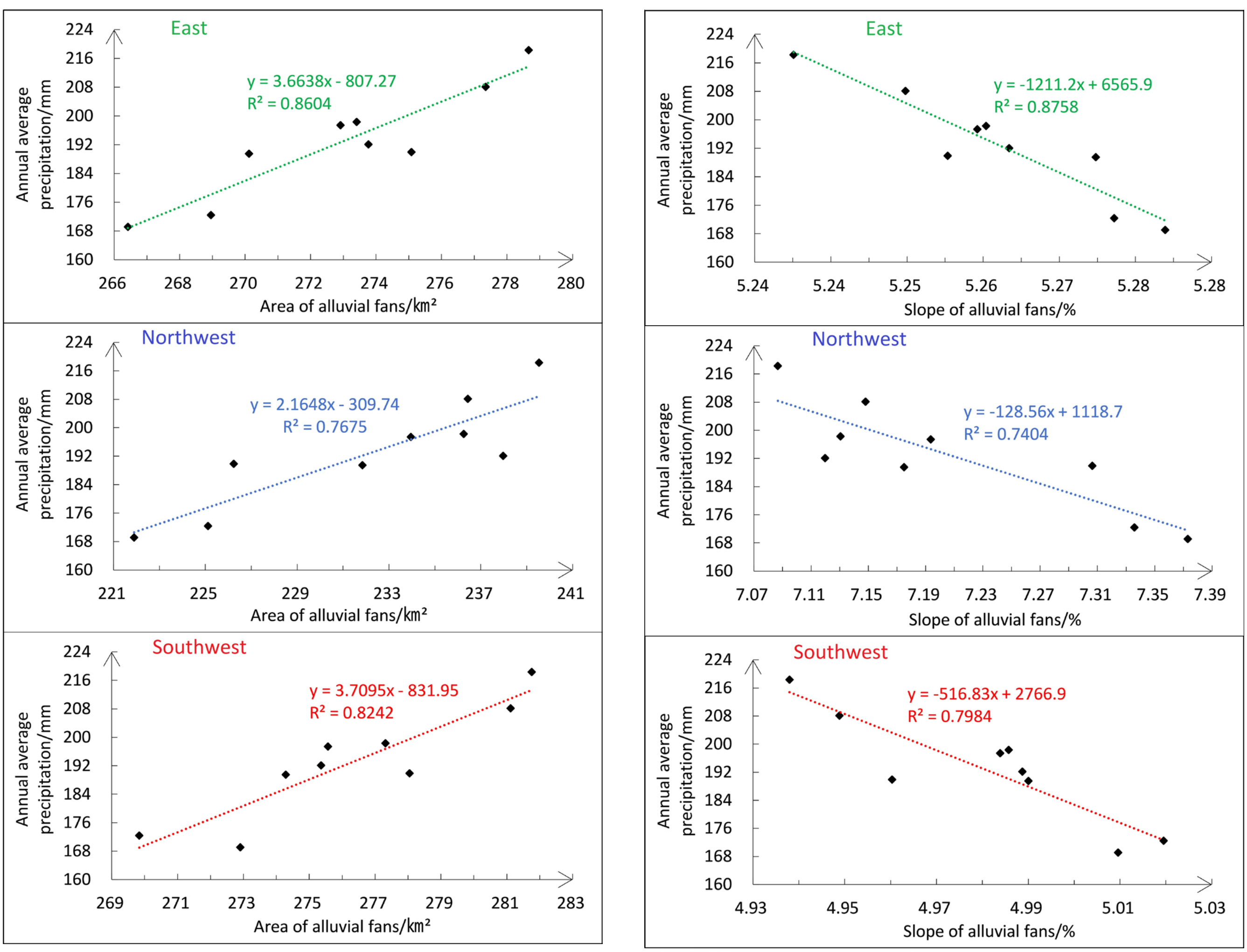


Figure 14 - Relationship between overall area (left), overall slope (right), and multi-year rainfall in the eastern, northwestern, and southwestern regions (from top to bottom, respectively).

precipitation leads to a reduction in the slope of the alluvial fans, which is consistent with findings from other studies (de Haas *et al.*, 2014; Silhán, 2014), indicating that erosion caused by precipitation may result in slope changes (Ziadat and Taimeh, 2013; Jiang *et al.*, 2014). Our results show that the eastern region exhibits the strongest negative correlation (-0.8758), which may be closely related to the strong seasonal variation of precipitation and the higher hydrological processes in this region.

Relationship among alluvial fan area, slope and watershed size

Fig. 15 shows that the areas of 18 alluvial fans in the eastern region, 24 in the northwestern region, and 9 in the southwestern region exhibit a positive power function relationship with the corresponding watershed area. The larger the watershed area, the larger the area of the alluvial fan, and the correlation is very strong, with correlation coefficients of 0.9774, 0.9682, and 0.9870, respectively. This positive correlation aligns with previous research, which indicates that larger watershed areas generally result in more extensive alluvial fans (Schick *et al.*, 1999; Field, 2001; Welsh and Davies, 2011; Fontana *et al.*, 2014; Zhang *et al.*, 2020). Moreover, the slopes of the alluvial fans in each of the three regions and their corresponding watershed areas also display a negative power function relationship. The larger the watershed area, the smaller the slope of the fan, the correlation coefficients are -0.9123, -0.9075, and -0.9345. This indicates that, with the increase of the basin area, the intensity of river runoff increases, and the sediment transport capacity also increases, the larger particles of sediment are first deposited in the root of the alluvial fan, and in the transition to the edge of the alluvial fan, the scouring effect is gradually weakened, and the grain size of the sediments gradually decreases. In the development of alluvi-

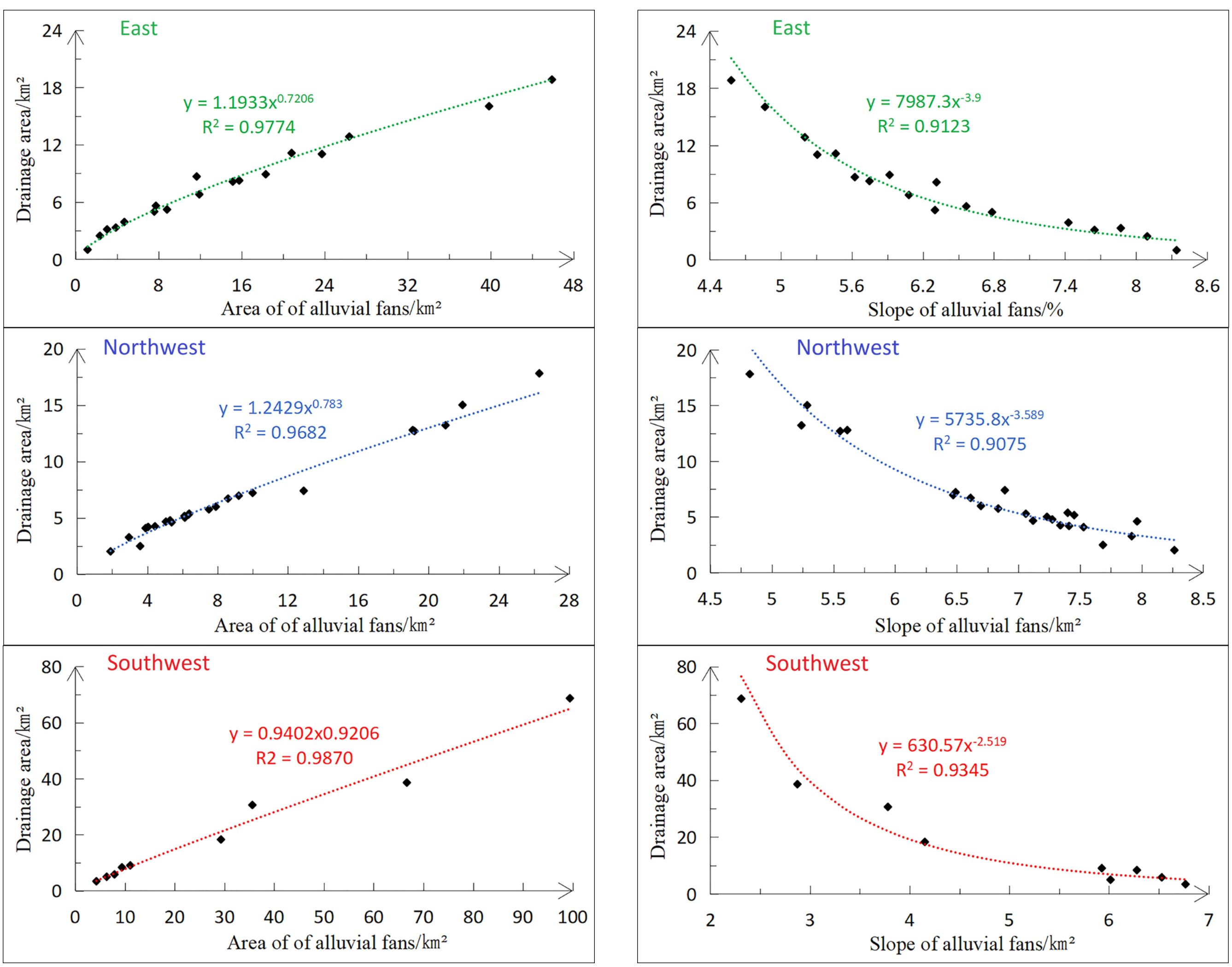


Figure 15 - Relationship between alluvial fan area (left), slope (right), and watershed area in the eastern, northwestern, and southwestern regions (from top to bottom, respectively).

al fan, sediment sorting plays an important role (Moreno and Romero Segura, 1997; Gómez-Villar and García-Ruiz, 2000; Crosta and Frattini, 2004; Miller *et al.*, 2014; Zhang *et al.*, 2020). As the overall area of the alluvial fan increases, the overall slope becomes gentler. Thus, watershed area is an important factor in the sedimentary development of alluvial fans. This finding contributes to a deeper understanding of alluvial fan morphology and emphasises that the complex relationship between watershed dynamics and sedimentary processes is influenced by a combination of climatic and geomorphological factors (Samaras and Koutitas, 2014; Zhang *et al.*, 2015; Hamidifar *et al.*, 2024).

DISCUSSION

Previous research on the alluvial fans in the Qilian Mountains area primarily focused on their spatial characteristics and influencing factors (Pan *et al.*, 2013; Yang *et al.*, 2014; Guo *et al.*, 2017; Su *et al.*, 2019; Lehmkuhl and Owen, 2024; Zhang *et al.*, 2024). Can we analyze the temporal trends in the geomorphological parameters of the alluvial fans along the central section of the northern slope of the Qilian Mountains and the relationships between these parameters, as well as the impact of multi-year precipitation on the fan's geomorphological features? The study shows that, based on GIS technology, using geographic remote sensing and interpretation, data statistics and analysis, as well as Sen's trend analysis + Mann-Kendall significance test methods, combined with satellite remote sensing imagery, GDEMV3 30-metre resolution digital elevation model, and multi-year precipitation data, parameters were extracted from the alluvial fans and their catchments on the northern slope of the Qilian Mountains (central part), the southern slope of Longshoushan, and the northern slope of Yumusshan. This led to the determination of the area, slope, and catchment area parameters of all individual alluvial fans in the study area as of March 15, 2023, as well as the overall area and slope parameters of the alluvial fans for each region from 1983 to 2023, with a five-year interval. Statistical analysis of the spatiotemporal distribution characteristics and influencing factors of the alluvial fans in the study area is feasible. This comprehensive analysis provides important insights into the spatiotemporal distribution characteristics of alluvial fans and their influencing factors. Understanding the spatiotemporal dynamics of alluvial fans is crucial for sustainable water resource management, land use planning, and urban development in the northern slope of the Qilian Mountains. It can also provide valuable information for understanding future land use scenarios, as precipitation and the spatiotemporal distribution of catchments are important indicators of alluvial fan development (Schick *et al.*, 1999; Wang *et al.*, 2017b; Chen *et al.*, 2022; Chen *et al.*, 2023; Yeh *et al.*, 2024). This study fills an important gap in the literature by providing detailed time-based analysis. Although most previous studies have focused on the spatial attributes of alluvial fans, few have explored how these features evolve over time and how climate and catchment factors influence these changes.

The northern slope of the Qilian Mountains is home to numerous alluvial fans, with many studies only focusing on typical alluvial fans associated with major large rivers, thus neglecting detailed investigations of the alluvial fans in the central section of the northern slope. This limits our understanding of the quantity, area, and geographical distribution characteristics of various types of alluvial fans in this region. In our study, we found that alluvial fans in the northwest region are generally small, with most of them having an area less than 10 km², while in the southwest region, larger alluvial fans are present, with fans larger than 30 km² accounting for 82.18% of the total area of alluvial fans in this region. In the eastern region, alluvial fans of various sizes are relatively evenly distributed in terms of number and area.

Research on the morphological parameters of alluvial fans has mainly focused on spatial relationships (Crosta and Frattini, 2004; Giles, 2010; Clarke, 2015; DeChant *et al.*, 2021), with few studies investigating the long-term changes in the area and slope of alluvial fans. In contrast, our study reveals a significant decreasing trend in the overall area of alluvial fans in the study area from 1983 to 2023, while the overall slope shows a non-significant increasing trend. These two parameters exhibit a clear negative power function relationship, indicating that the negative power function relationship between area and slope holds at both temporal and spatial scales. During the study period (1983-2023), the overall area of alluvial fans in the eastern, northwest, and southwest regions experienced continuous and significant reductions (fig. 11). Previous studies have shown that alluvial fans are highly sensitive to precipitation patterns, sediment supply, and external factors (Crosta and Frattini, 2004; Blainey and Pelletier, 2008; Clarke, 2015; Vincent *et al.*, 2022). Our findings are consistent with these results, especially in the northwest region, where the area of alluvial fans has significantly decreased. This change may be related to significant human activities such as agricultural expansion and urban sprawl in the region. In contrast, the overall slope changes in all study regions did not show statistical significance, indicating that the topographic changes of the alluvial fans were not significant over the past 40 years, and their slow change process may be associated with long-term geomorphological evolution. Factors such as vegetation cover, mild erosion processes, and sediment accumulation typically influence the slope of alluvial fans. However, these changes usually occur gradually and may not be noticeable within relatively short time frames. Slope changes are generally less sensitive to short-term climatic fluctuations and less pronounced compared to more dynamic features like alluvial fan area or river channel morphology. Although the slope trend in this study did not show significant changes, local changes may still have occurred in specific areas. For example, in regions where urbanization is rapidly increasing, such as the eastern area, human activities may have affected hydrology and sediment dynamics, leading to minor slope changes. However, due to the slow pace of geomorphological changes, these variations may not be directly detectable in a statistical sense. The difference between the trends of overall area and overall slope highlights the complex interaction between dynamic surface processes and the time scale required for significant changes. The reduction in the area of alluvial fans is a direct response to external factors such as precipitation variation, sediment transport, and human activities, while slope changes are more subtle and generally require long-term monitoring to detect statistically significant changes. These findings have important implications for future alluvial fan management. The significant reduction in overall area suggests that proactive measures may be needed to mitigate further loss caused by human activities, especially in the northwest region. On the other hand, the non-significant change in overall slope indicates that topographic evolution may not require immediate intervention but still requires continuous monitoring to identify progressive changes that could affect runoff discharge, sediment accumulation, and overall geomorphological stability.

The confidence intervals for the overall area and overall slope of the alluvial fans in the northwest region, as well as the overall area of alluvial fans in the southwest region, are relatively narrow, indicating that the trend of these parameters is relatively stable with low variability. This stability suggests that the driving factors in these two regions, particularly in the northwest, such as precipitation patterns, sediment supply, and human activities, have remained consistent over time, making trend estimates more predictable and reliable. In contrast, the confidence intervals for the overall area and overall slope of the alluvial fans in the eastern region, as well as the overall slope in the southwest region, are wider, reflecting higher uncertainty in trend predictions. This increased variability may be due to more complex driving factors in these areas, such as the higher level of human activities in the eastern region, including urbanization, agriculture, and land use changes. Compared to the relatively sparse population in the northwest, the higher population density and stronger human influence in the eastern region may result in greater fluctuations in trend estimates. This result is consistent with previous research, which suggests that areas more affected by human activities and climate change tend to have wider confidence intervals due to higher environmental process uncertainties (Whitmarsh, 2011; Orr *et al.*, 2015; Huang *et al.*, 2016; Borrelli *et al.*, 2020). In summary, the wider confidence intervals highlight the complexity of environmental processes and the influence of external factors, which may introduce considerable uncertainty into trend estimates. Future research should focus on identifying and quantifying the key driving factors behind these variations to improve the accuracy of trend predictions and provide more targeted guidance for alluvial fan ecosystem management strategies.

The standard error estimates of slope values provide additional insights into the precision of trend estimates. For the overall area of alluvial fans, the standard errors for the eastern, northwest, and southwest regions are 0.1731, 0.16871, and 0.15485, respectively; for the overall slope of the alluvial fans, the standard errors are 0.00054877, 0.0030184, and 0.001294. These values indicate that the estimation of trends in alluvial fan area is less precise than the slope trend, particularly in the eastern region. However, considering that the overall area of alluvial fans in each region is approximately 250 km2, the standard errors are relatively small, especially for the overall slope trend. Therefore, although the standard error for the overall area trend is relatively high, the trend estimates are still fairly accurate.

Most previous studies have emphasized the spatial relationships of alluvial fan morphology and short-term climatic effects (Harvey, 2012; Clarke, 2015; Li *et al.*, 2018; Leenman *et al.*, 2022), with few studies exploring the long-term impact of precipitation on alluvial fan morphology in the same region. We found that higher precipitation generally leads to larger alluvial fan areas and gentler slopes. However, climate change has destabilized the annual precipitation patterns in the region, weakening the correlation between multi-year precipitation variation and alluvial fan characteristics. As shown in our study results (fig. 14), the overall area and slope of alluvial fans in the eastern region, and the overall area of alluvial fans in the southwest region, exhibit a strong linear relationship with annual precipitation, with correlation coefficients of 0.8604, 0.8758, and 0.8242, respectively. However, the correlation between the overall area, overall slope of the alluvial fans in the northwest region, and the overall slope of the alluvial fans in the southwest region with annual precipitation is relatively weaker, with correlation coefficients of 0.7675, 0.7404, and 0.7984, respectively. This suggests that factors such as flow velocity, discharge, and the location, elevation, and cross-sectional shape of drainage outlets may also play a role in shaping the morphology of alluvial fans (Gibling, 2006; Lucà and Robustelli, 2020; Garcia-Estève *et al.*, 2021; Hou and Yu, 2023). In recent years, the persistent drought and low rainfall in northern China have gradually reduced the threat to the lives and production activities of people at the fan edges. People have increased their utilization of alluvial fans, such as agricultural expansion and water resource use, which to some extent also indicates that as the climate becomes drier and rainfall decreases, the size of regional alluvial fans is no longer increasing, which is consistent with the study results. Therefore, over long timeframes, changes in precipitation in the same region are positively correlated with the evolution trend of alluvial fans, which is of significant importance for land use planning.

As pointed out in previous studies (Fontana *et al.*, 2014; Clarke, 2015; Zhang *et al.*, 2020; Mokarram *et al.*, 2022), alluvial fans of different scales correspond to different catchment areas, and these catchments are usually stable over time. Our study results also demonstrate a strong power function relationship between the area, slope, and catchment area of alluvial fans (fig. 15), further supporting the conclusions of previous studies. With the increasing severity of climate aridity and the rapid development of regional economies, industries, and populations, the demand for land will continue to rise, particularly for large alluvial fans in large catchments, which may be extensively developed in the future (Zhang *et al.*, 2012; Zhao *et al.*, 2013; Taft and Evers, 2016; East and Sankey, 2020).

This study not only provides new insights into the dynamics of alluvial fans in the Qilian Mountains area, but also fills a critical gap in the literature by combining long-term temporal trends with spatial analysis, offering a new perspective on the evolution of alluvial fans. The research integrates both temporal and spatial dimensions, providing profound insights into the evolution of alluvial fans. It emphasizes the necessity of considering both spatial and temporal scales in future alluvial fan studies. Future research can further integrate long-term trends in climate change to analyze its far-reaching impact on alluvial fan morphology and evolution. Meanwhile, studies combining surface hydrology and vegetation changes will contribute to a more comprehensive understanding of the interaction between climate and catchment factors. Additionally, with the advancement of remote sensing technologies, future studies could use higher-resolution remote sensing data to investigate the spatiotemporal changes of alluvial fans on finer scales, providing more accurate scientific data for urban planning, disaster early warning, and ecological restoration in arid regions.

CONCLUSION

This study is based on satellite remote sensing images of alluvial fans and GDEMV3 30-metre resolution digital elevation model, from which the required data are extracted. Combining with relevant information, it thoroughly analyzes the spatiotemporal distribution characteristics of alluvial fan landforms in the study area and their interrelationship with watershed and climatic factors. The following important findings were obtained:

(1) In terms of regional distribution, there is a significant inverse relationship between the number and average area of alluvial fans. Specifically, the northwest region has the most alluvial fans, but their average area is the smallest; while the southwest region has the fewest alluvial fans, but their average area is the largest. As the grade of alluvial fans increases (from Grade 1 to Grade 4), the area of individual alluvial fans gradually increases, while their number gradually decreases. Analyzing the distribution of alluvial fans in five counties reveals that Ganzhou District has the largest number and area of alluvial fans, while Minle County has the smallest number and area. In addition, Grade 1 to Grade 3 alluvial fans are distributed in Gaotai County, Linze County, Ganzhou District, and Shandan County, with the largest number of Grade 1 alluvial fans in each county. Notably, Grade 4 alluvial fans are mainly concentrated in Ganzhou District. This finding suggests that the distribution of alluvial fans at different grades in each county exhibits distinct regional characteristics.

(2) Between 1983 and 2023, the overall area of alluvial fans in the eastern, northwest, and southwest regions showed a significant declining trend (p value < 0.05), with the northwest region experiencing the most pronounced decrease. However, the overall slope did not show a significant increasing trend (p value ≥ 0.05). By analyzing the time series data, it was found that there is a strong power function relationship between the overall area of alluvial fans and the slope in each region, with correlation coefficients of 0.9485, 0.9765, and 0.9416, indicating that the change trends of the two are highly consistent. In the analysis of confidence intervals, the confidence intervals for the overall area and slope of alluvial fans in the northwest region, as well as the overall area in the southwest region, are relatively narrow, indicating that the trends in these regions are more stable, especially in the northwest region, where external variation factors have less impact. In contrast, the confidence intervals for the overall area and slope of alluvial fans in the eastern region, as well as the overall slope in the southwest region, are wider, reflecting larger fluctuations in the trend estimates in these regions, particularly in the eastern region. This may be closely related to more complex climatic conditions and higher human activity disturbances. The standard error of the slope estimates suggests that the trend estimate for the overall area of alluvial fans in the eastern region is less precise, but the relatively small standard error still indicates that the overall trend estimate is highly accurate.

(3) Between 1983 and 2023, a significant positive correlation was observed between the overall area of alluvial fans and annual rainfall in the eastern, northwest, and southwest regions, with correlation coefficients of 0.8604, 0.7675, and 0.8242, respectively. This indicates that the increase in rainfall is closely related to the expansion of alluvial fan areas. At the same time, the overall slope of the alluvial fans in the three regions showed a significant negative correlation with multi-year rainfall, with correlation coefficients of 0.8758, 0.7404, and 0.7984, suggesting that increased rainfall may lead to a flattening of the slope.

(4) In the eastern, northwest, and southwest regions, a significant power function relationship exists between the area of a single alluvial fan and the corresponding watershed area, with the area of the alluvial fan increasing as the watershed area increases. Specifically, the correlation coefficients are 0.9774, 0.9682, and 0.9870, indicating that the size of the watershed largely determines the area of the alluvial fan. Meanwhile, the slope of alluvial fans in the three regions also shows a significant power function relationship with the watershed area, with the increase in watershed area being closely related to the decrease in the slope of alluvial fans. The correlation coefficients are 0.9123, 0.9075, and 0.9345, further emphasizing the profound connection between watershed size and alluvial fan geomorphological characteristics.

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AUTHORS CONTRIBUTION

All authors were involved in the conceptualization and design of the study. Zhengang Zhang was responsible for the preparation of the required materials. Junhong Zhang was responsible for data organization. Data extraction and analysis as well as the writing of the first draft of the manuscript were done by Zhenpeng Zhang. Xia Wei provided guidance for this study. All authors commented on a previous version of the manuscript. All authors read and approved the final manuscript.

CONFLICT OF INTEREST

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REFERENCES

Bertrand M., Liébault F., Piégay H., 2013. *Debris-flow susceptibility of upland catchments*. Natural Hazards, 67, 497-511. https://doi.org/10.1007/s11069-013-0575-4

Birch S.P.D., Hayes A.G., Howard A.D., Moore J.M., Radebaugh J., 2016. *Alluvial fan morphology, distribution and formation on Titan*. Icarus, 270, 238-247. https://doi.org/10.1016/j.icarus.2016.02.013

Blainey J.B., Pelletier J.D., 2008. *Infiltration on alluvial fans in arid environments: Influence of fan morphology*. Journal of Geophysical Research-Earth Surface, 113, 18. https://doi.org/10.1029/2007jf000792

Blair T.C., 1999. *Cause of dominance by sheetflood vs. debris-flow processes on two adjoining alluvial fans, Death Valley, California*. Sedimentology, 46, 1015-1028. https://doi.org/10.1046/j.1365-3091.1999.00261.x

Borrelli P., Robinson D.A., Panagos P., Lugato E., Yang J.E., Alewell C., Wuepper D., Montanarella L., Ballabio C., 2020. *Land use and climate change impacts on global soil erosion by water (2015-2070)*. Proceedings of the National Academy of Sciences of the United States of America, 117, 21994-22001. https://doi.org/10.1073/pnas.2001403117

Calvache M.L., Viseras C., Fernandez J., 1997. *Controls on fan development - evidence from fan morphometry and sedimentology; Sierra Nevada, SE Spain*. Geomorphology, 21, 69-84. https://doi.org/10.1016/s0169-555x(97)00035-4

Chen B.B., Gong H.L., Li X.J., Lei K.C., Zhu L., Gao M.L., Zhou C.F., 2017. *Characterization and causes of land subsidence in Beijing, China*. International Journal of Remote Sensing, 38, 808-826. https://doi.org/10.1080/01431161.2016.1259674

Chen T.D., Jiao J.Y., Wei W., Li J.J., Zhang Z.Q., Yang H.Z., Ma H.F., 2023. *Spatiotemporal variation in the land use/cover of alluvial fans in Lhasa River Basin, Qinghai-Tibet Plateau*. Agriculture-Basel, 13, 17. https://doi.org/10.3390/agriculture13020312

Chen T.D., Wei W., Jiao J.Y., Zhang Z.Q., Li J.J., 2022. *Machine learning-based identification for the main influencing factors of alluvial fan development in the Lhasa River Basin, Qinghai-Tibet Plateau*. Journal of Geographical Sciences, 32, 1557-1580. https://doi.org/10.1007/s11442-022-2010-9

Clarke L.E., 2015. *Experimental alluvial fans: Advances in understanding of fan dynamics and processes*. Geomorphology, 244, 135-145. https://doi.org/10.1016/j.geomorph.2015.04.013

Crosta G.B., Frattini P., 2004. *Controls on modern alluvial fan processes in the central Alps, northern Italy*. Earth Surface Processes and Landforms, 29, 267-293. https://doi.org/10.1002/esp.1009

Curray J.R., Emmel F.J., Moore D.G., 2002. *The Bengal Fan: Morphology, geometry, stratigraphy, history and processes*. Marine and Petroleum Geology, 19, 1191-1223. https://doi.org/10.1016/s0264-8172(03)00035-7

de Haas T., Ventra D., Carbonneau P.E., Kleinhans M.G., 2014. *Debris-flow dominance of alluvial fans masked by runoff reworking and weathering*. Geomorphology, 217, 165-181. https://doi.org/10.1016/j.geomorph.2014.04.028

DeChant L., Pease P., Tchakerian V.P., 2021. *Alluvial fan morphology: A self-similar free boundary problem description*. Geomorphology, 375, 7. https://doi.org/10.1016/j.geomorph.2020.107532

Du Y.S., Gong S.Y., Han X., Wang J.S., Gu S.Z., Lin W.J., 2001. *Silurian seismites in Hanxia, Yumen, North Qilian Mountains, and their tectonic significance*. Acta Geologica Sinica-English Edition, 75, 385-390.

Duvall A.R., Clark M.K., Kirby E., Farley K.A., Craddock W.H., Li C.Y., Yuan D.Y., 2013. *Low-temperature thermochronometry along the Kunlun and Haiyuan Faults, NE Tibetan Plateau: Evidence for kinematic change during late-stage orogenesis*. Tectonics, 32, 1190-1211. https://doi.org/10.1002/tect.20072

East A.E., Sankey J.B., 2020. *Geomorphic and sedimentary effects of modern climate change: Current and anticipated future conditions in the Western United States*. Reviews of Geophysics, 58, 59. https://doi.org/10.1029/2019rg000692

Fan Y., Clark M., Lawrence D.M., Swenson S., Band L.E., Brantley S.L., Brooks P.D., Dietrich W.E., Flores A., Grant G., Kirchner J.W., Mackay D.S., McDonnell J.J., Milly P.C.D., Sullivan P.L., Tague C., Ajami H., Chaney N., Hartmann A., Hazenberg P., McNamara J., Pelletier J., Perket J., Rouholahnejad-Freund E., Wagener T., Zeng X., Beighley E., Buzan J., Huang M., Livneh B., Mohanty B.P., Nijssen B., Safeeq M., Shen C., van Verseveld W., Volk J., Yamazaki D., 2019. *Hillslope hydrology in global change research and Earth system modeling*. Water Resources Research, 55, 1737-1772. https://doi.org/10.1029/2018wr023903

Field J., 2001. *Channel avulsion on alluvial fans in southern Arizona*. Geomorphology, 37, 93-104. https://doi.org/10.1016/s0169-555x(00)00064-7

Fontana A., Mozzi P., Marchetti M., 2014. *Alluvial fans and megafans along the southern side of the Alps*. Sedimentary Geology, 301, 150-171. https://doi.org/10.1016/j.sedgeo.2013.09.003

Garcia-Estève C., Caniven Y., Cattin R., Dominguez S., Sylvain R., 2021. *Morphotectonic evolution of an alluvial fan: Results of a joint analog and numerical modeling approach*. Geosciences, 11, 23. https://doi.org/10.3390/geosciences11100412

Ghahraman K., Nagy B., 2024. *Tectonic controls on the morphometry of alluvial fans in an arid region, northeast Iran*. Physical Geography, 45, 581-604. https://doi.org/10.1080/02723646.2024.2370653

Gibling M.R., 2006. *Width and thickness of fluvial channel bodies and valley fills in the geological record: A literature compilation and classification*. Journal of Sedimentary Research, 76, 731-770. https://doi.org/10.2110/jsr.2006.060

Giles P.T., 2010. *Investigating the use of alluvial fan volume to represent fan size in morphometric studies*. Geomorphology, 121, 317-328. https://doi.org/10.1016/j.geomorph.2010.05.001

Gómez-Villar A., García-Ruiz J.M., 2000. *Surface sediment characteristics and present dynamics in alluvial fans of the central Spanish Pyrenees*. Geomorphology, 34, 127-144. https://doi.org/10.1016/s0169-555x(99)00116-6

Goorabi A., Karimi M., Norini G., 2021. *Semi-automated method for the mapping of alluvial fans from DEM*. Earth Science Informatics, 14, 1447-1466. https://doi.org/10.1007/s12145-021-00616-3

Goswami P.K., Pant C.C., Pandey S., 2009. *Tectonic controls on the geomorphic evolution of alluvial fans in the Piedmont Zone of Ganga Plain, Uttarakhand, India*. Journal of Earth System Science, 118, 245-259. https://doi.org/10.1007/s12040-009-0012-y

Guo Q.N., Zhou Z.F., Wang S., 2017. *The Source, flow rates, and hydrochemical evolution of groundwater in an alluvial fan of Qilian Mountain, Northwest China*. Water, 9, 21. https://doi.org/10.3390/w9120912

Hamidifar H., Nones M., Rowinski P.M., 2024. *Flood modeling and fluvial dynamics: A scoping review on the role of sediment transport*. Earth-Science Reviews, 253, 14. https://doi.org/10.1016/j.earscirev.2024.104775

Harrison T.M., Copeland P., Kidd W.S.F., Yin A., 1992. *Raising Tibet*. Science, 255, 1663-1670. https://doi.org/10.1126/science.255.5052.1663

Harvey A.M., 2002a. *Effective timescales of coupling within fluvial systems*. Geomorphology, 44, 175-201. https://doi.org/10.1016/s0169-555x(01)00174-x

Harvey A.M., 2002b. *The role of base-level change in the dissection of alluvial fans: Case studies from southeast Spain and Nevada*. Geomorphology, 45, 67-87. https://doi.org/10.1016/s0169-555x(01)00190-8

Harvey A.M., 2012. *The coupling status of alluvial fans and debris cones: a review and synthesis*. Earth Surface Processes and Landforms, 37, 64-76. https://doi.org/10.1002/esp.2213

Harvey A.M., Silva P.G., Mather A.E., Goy J.L., Stokes M., Zazo C., 1999. *The impact of Quaternary sea-level and climatic change on coastal alluvial fans in the Cabo de Gata ranges, southeast Spain*. Geomorphology, 28, 1-22. https://doi.org/10.1016/s0169-555x(98)00100-7

He Q.S., Cao C.X., Chen E.X., Sun G.Q., Ling F.L., Pang Y., Zhang H., Ni W.J., Xu M., Li Z.Y., Li X.W., 2012. *Forest stand biomass estimation using ALOS PALSAR data based on LiDAR-derived prior knowledge in the Qilian Mountain, western China*. International Journal of Remote Sensing, 33, 710-729. https://doi.org/10.1080/01431161.2011.577829

Hetzel R., 2013. *Active faulting, mountain growth, and erosion at the margins of the Tibetan Plateau constrained by in situ-produced cosmogenic nuclides*. Tectonophysics, 582, 1-24. https://doi.org/10.1016/j.tecto.2012.10.027

Hou Q.Y., Zhao Z.D., Zhang H.F., Zhang B.R., Chen Y.L., 2006. *Indian Ocean-MORB-type isotopic signature of Yushigou ophiolite in north Qilian Mountains and its implications*. Science in China Series D-Earth Sciences, 49, 561-572. https://doi.org/10.1007/s11430-006-0561-8

Hou W.P., Yu G.A., 2023. *Debris-flow fan development and geomorphic effects in alpine canyons under a changing climate*. Earth Surface Processes and Landforms, 48, 3330-3346. https://doi.org/10.1002/esp.5699

Hu X.F., Chen D.B., Pan B.T., Chen J.J., Zhang J., Chang J., Gong C.S., Zhao Q.M., 2019a. *Sedimentary evolution of the foreland basin in the NE Tibetan Plateau and the growth of the Qilian Shan since 7 Ma*. Geological Society of America Bulletin, 131, 1744-1760. https://doi.org/10.1130/b35106.1

Hu X.F., Wen Z.L., Pan B.T., Guo L.Y., Cao X.L., 2019b. *Constraints on deformation kinematics across the Yumu Shan, NE Tibetan Plateau, based on fluvial terraces*. Global and Planetary Change, 182. https://doi.org/10.1016/j.gloplacha.2019.103023

Hu X.F., Wu J.K., Wen Z.L., Zhang J.X., Zhao Q.M., Pan B.T., 2022. *Fluvial evolution in a growing thrust-fold range of the Yumu Shan, NE Tibetan Plateau*. Earth and Planetary Science Letters, 594. https://doi.org/10.1016/j.epsl.2022.117704

Hu Y., Li X.Y., Wang S.K., Lv P., Yue P., Chen M., Zuo X., 2024. *Patterns and driving factors of functional traits of desert species with different elevational distributions in the Tibetan Plateau and adjacent areas*. Bmc Plant Biology, 24, 11. https://doi.org/10.1186/s12870-024-05080-x

Huang J.P., Yu H.P., Guan X.D., Wang G.Y., Guo R.X., 2016. *Accelerated dryland expansion under climate change*. Nature Climate Change, 6, 166-+. https://doi.org/10.1038/nclimate2837

Huang X.F., Gao R., Li W.H., Xiong X.S., 2021. *Seismic reflection evidence of crustal duplexing and lithospheric underthrusting beneath the western Qilian Mountains, northeastern margin of the Tibetan Plateau*. Science China-Earth Sciences, 64, 96-109. https://doi.org/10.1007/s11430-020-9677-y

Iacobucci G., Delchiaro M., Troiani F., Nadali D., 2024. *Land-surface quantitative analysis for mapping and deciphering the construction processes of piedmont alluvial fans in the Anti-Lebanon Mountains*. Geomorphology, 453, 18. https://doi.org/10.1016/j.geomorph.2024.109148

Jiang F.S., Huang Y.H., Wang M.K., Lin J.S., Zhao G., Ge H.L., 2014. *Effects of rainfall intensity and slope gradient on steep colluvial deposit erosion in Southeast China*. Soil Science Society of America Journal, 78, 1741-1752. https://doi.org/10.2136/sssaj2014.04.0132

Jolivet M., Brunel M., Seward D., Xu Z., Yang J., Roger F., Tapponnier P., Malavieille J., Arnaud N., Wu C., 2001. *Mesozoic and Cenozoic tectonics of the northern edge of the Tibetan plateau: Fission-track constraints*. Tectonophysics, 343, 111-134. https://doi.org/10.1016/s0040-1951(01)00196-2

Karymbalis E., Ferentinou M., Fubelli G., Giles P., Tsanakas K., Valkanou K., Batzakis D.V., Karalis S., 2022. *Classification of Trichonis Lake graben (Western Greece) alluvial fans and catchments using geomorphometry and artificial intelligence*. Zeitschrift Fur Geomorphologie, 63, 295-312. https://doi.org/10.1127/zfg/2022/0748

Lanckriet S., Asfaha T., Frankl A., Zenebe A., Nyssen J., 2016. *Sediment in alluvial and lacustrine debris fans as an indicator for land degradation around Lake Ashenge (Ethiopia)*. Land Degradation & Development, 27, 258-269. https://doi.org/10.1002/ldr.2424

Leenman A.S., Eaton B.C., MacKenzie L.G., 2022. *Floods on alluvial fans: Implications for reworking rates, morphology and fan hazards*. Journal of Geophysical Research-Earth Surface, 127, 17. https://doi.org/10.1029/2021jf006367

Lehmkuhl F., Owen L.A., 2024. *Alluvial fan types, distribution, and formation: a global perspective*. Zeitschrift Fur Geomorphologie, 64, 95-142. https://doi.org/10.1127/zfg/2024/0826

Li B., Chen X.H., Zuza A.V., Hu D.G., Ding W.C., Huang P.H., Xu S.L., 2019. *Cenozoic cooling history of the North Qilian Shan, northern Tibetan Plateau, and the initiation of the Haiyuan fault: Constraints from apatite- and zircon-fission track thermochronology*. Tectonophysics, 751, 109-124. https://doi.org/10.1016/j.tecto.2018.12.005

Li L., Wen Z.F., Wei S.G., Lian J.Y., Ye W.H., 2022. *Functional diversity and its influencing factors in a subtropical forest community in China*. Forests, 13. https://doi.org/10.3390/f13070966

Li Q.Y., Pan B.T., Hu X.F., Hu Z.B., Li F.Q., Yang S.Z., 2013. *Apatite Fission track constraints on the pattern of faulting in the North Qilian Mountain*. Journal of Earth Science, 24, 569-578. https://doi.org/10.1007/s12583-013-0350-1

Li Y.J., Armitage S.J., Stevens T., Meng X.M., 2018. *Alluvial fan aggradation/incision history of the eastern Tibetan plateau margin and implications for debris flow/debris-charged flood hazard*. Geomorphology, 318, 203-216. https://doi.org/10.1016/j.geomorph.2018.06.016

Lu H.H., Burbank D.W., Li Y.L., 2010. *Alluvial sequence in the north piedmont of the Chinese Tian Shan over the past 550 kyr and its relationship to climate change*. Palaeogeography Palaeoclimatology Palaeoecology, 285, 343-353. https://doi.org/10.1016/j.palaeo.2009.11.031

Lu H.H., Cheng L., Wang Z., Zhang T.Q., Lü Y.W., Zhao J.X., Li Y.L., Zheng X.M., 2018. *Latest Quaternary rapid river incision across an inactive fold in the northern Chinese Tian Shan foreland*. Quaternary Science Reviews, 179, 167-181. https://doi.org/10.1016/j.quascirev.2017.10.017

Lucà F., Robustelli G., 2020. *Comparison of logistic regression and neural network models in assessing geomorphic control on alluvial fan depositional processes (Calabria, southern Italy)*. Environmental Earth Sciences, 79, 18. https://doi.org/10.1007/s12665-019-8775-1

Maghsoudi M., Simpson I.A., Kourampas N., Nashli H.F., 2014. *Archaeological sediments from settlement mounds of the Sagzabad Cluster, central Iran: Human-induced deposition on an arid alluvial plain*. Quaternary International, 324, 67-83. https://doi.org/10.1016/j.quaint.2013.10.057

Marchi L., Pasuto A., Tecca P.R., 1993. *Flow processes on alluvial fans in the Eastern Italian Alps*. Zeitschrift Fur Geomorphologie, 37, 447-458.

Mazzorana B., Ghiandoni E., Picco L., 2020. *How do stream processes affect hazard exposure on alluvial fans? Insights from an experimental study*. Journal of Mountain Science, 17, 753-772. https://doi.org/10.1007/s11629-019-5788-x

Meinsen J., Winsemann J., Roskosch J., Brandes C., Frechen M., Dultz S., Böttcher J., 2014. *Climate control on the evolution of Late Pleistocene alluvial-fan and aeolian sand-sheet systems in NW Germany*. Boreas, 43, 42-66. https://doi.org/10.1111/bor.12021

Miller K.L., Reitz M.D., Jerolmack D.J., 2014. *Generalized sorting profile of alluvial fans*. Geophysical Research Letters, 41, 7191-7199. https://doi.org/10.1002/2014gl060991

Mokarram M., Pourghasemi H.R., Tiefenbacher J.P., 2022. *Identification of morphometric features of alluvial fan and basins in predicting the erosion levels using ANN*. Environmental Earth Sciences, 81, 14. https://doi.org/10.1007/s12665-022-10219-w

Mokarram M., Seif A., Sathyamoorthy D., Iop. 2014. *Use of morphometric analysis and self-organizing maps for alluvial fan classification: case study on Ostorankooh altitudes, Iran*. In: 7th IGRSM International Remote Sensing and GIS Conference and Exhibition, Kuala Lumpur, Malaysia.

Molnar P., 2005. *Mio-pliocene growth of the Tibetan Plateau and evolution of East Asian climate*. Palaeontologia Electronica, 8.

Molnar P., Tapponnier P., 1975. *Cenozoic tectonics of Asia: Effects of a continental collision. Features of recent continental tectonics in Asia can be interpreted as results of the India-Eurasia collision*. Science (New York, N.Y.), 189, 419-426. https://doi.org/10.1126/science.189.4201.419

Moreno C., RomeroSegura M.J., 1997. *The development of small-scale sandy alluvial fans at the base of a modern coastal cliff: Process, observations and implications*. Geomorphology, 18, 101-118. https://doi.org/10.1016/s0169-555x(96)00017-7

Nichols G., Thompson B., 2005. *Bedrock lithology control on contemporaneous alluvial fan facies, Oligo-Miocene, southern Pyrenees, Spain*. Sedimentology, 52, 571-585. https://doi.org/10.1111/j.1365-3091.2005.00711.x

Orr H.G., Simpson G.L., des Clers S., Watts G., Hughes M., Hannaford J., Dunbar M.J., Laizé C.L.R., Wilby R.L., Battarbee R.W., Evans R., 2015. *Detecting changing river temperatures in England and Wales*. Hydrological Processes, 29, 752-766. https://doi.org/10.1002/hyp.10181

Palumbo L., Hetzel R., Tao M., Li X., 2010. *Topographic and lithologic control on catchment-wide denudation rates derived from cosmogenic ^{10}Be in two mountain ranges at the margin of NE Tibet*. Geomorphology, 117, 130-142. https://doi.org/10.1016/j.geomorph.2009.11.019

Pan B.T., Hu X.F., Gao H.S., Hu Z.B., Cao B., Geng H.P., Li Q.Y., 2013. *Late Quaternary river incision rates and rock uplift pattern of the eastern Qilian Shan Mountain, China*. Geomorphology, 184, 84-97. https://doi.org/10.1016/j.geomorph.2012.11.020

Pang J.Z., Yu J.X., Zheng D.W., Wang W.T., Ma Y., Wang Y.Z., Li C.P., Li Y.J., Wang Y., 2019. *Neogene expansion of the Qilian Shan, North Tibet: Implications for the dynamic evolution of the Tibetan Plateau*. Tectonics, 38, 1018-1032. https://doi.org/10.1029/2018tc005258

Patel N.K., Pati P., 2022. *Evolution of terminal fans in the Indo-Gangetic foreland basin: A process-response model*. Geomorphology, 419, 21. https://doi.org/10.1016/j.geomorph.2022.108483

Reitz M.D., Jerolmack D.J., 2012. *Experimental alluvial fan evolution: Channel dynamics, slope controls, and shoreline growth*. Journal of Geophysical Research-Earth Surface, 117, 19. https://doi.org/10.1029/2011jf002261

Rong Z.L., Zhao C.Y., Liu J.J., Gao Y.F., Zang F., Guo Z.X., Mao Y.H., Wang L., 2019. *Modeling the effect of climate change on the potential distribution of Qinghai Spruce (Picea crassifolia Kom.) in Qilian Mountains*. Forests, 10. https://doi.org/10.3390/f10010062

Salcher B.C., Faber R., Wagreich M., 2010. *Climate as main factor controlling the sequence development of two Pleistocene alluvial fans in the Vienna Basin (eastern Austria). A numerical modelling approach*. Geomorphology, 115, 215-227. https://doi.org/10.1016/j.geomorph.2009.06.030

Samaras A.G., Koutitas C.G., 2014. *Modeling the impact of climate change on sediment transport and morphology in coupled watershed-coast systems: A case study using an integrated approach*. International Journal of Sediment Research, 29, 304-315. https://doi.org/10.1016/s1001-6279(14)60046-9

Santangelo N., Daunis-i-Estadella J., Di Crescenzo G., Di Donato V., Faillace P.I., Martín-Fernández J.A., Romano P., Santo A., Scorpio V., 2012. *Topographic predictors of susceptibility to alluvial fan flooding, Southern Apennines*. Earth Surface Processes and Landforms, 37, 803-817. https://doi.org/10.1002/esp.3197

Schick A.P., Grodek T., Wolman M.G., 1999. *Hydrologic processes and geomorphic constraints on urbanization of alluvial fan slopes*. Geomorphology, 31, 325-335. https://doi.org/10.1016/s0169-555x(99)00085-9

Seddon A.W.R., Macias-Fauria M., Long P.R., Benz D., Willis K.J., 2016. *Sensitivity of global terrestrial ecosystems to climate variability*. Nature, 531, 229-+. https://doi.org/10.1038/nature16986

Shoshta A., Marh B.S., 2023. *Alluvial fans of Trans-Himalayan cold desert (Pin valley, India): quantitative morphology and controlling factors*. Physical Geography, 44, 136-161. https://doi.org/10.1080/02723646.2021.1907883

Silhán K., 2014. *Chronology of processes in high-gradient channels of medium-high mountains and their influence on the properties of alluvial fans*. Geomorphology, 206, 288-298. https://doi.org/10.1016/j.geomorph.2013.09.032

Song S.G., Niu Y.L., Su L., Xia X.H., 2013. *Tectonics of the North Qilian orogen, NW China*. Gondwana Research, 23, 1378-1401. https://doi.org/10.1016/j.gr.2012.02.004

Song S.G., Niu Y.L., Zhang L.F., Wei C.J., Liou J.G., Su L., 2009. *Tectonic evolution of early Paleozoic HP metamorphic rocks in the North Qilian Mountains, NW China: New perspectives*. Journal of Asian Earth Sciences, 35, 334-353. https://doi.org/10.1016/j.jseaes.2008.11.005

Sorriso-Valvo M., Antronico L., Le Pera E., 1998. *Controls on modern fan morphology in Calabria, southern Italy*. Geomorphology, 24, 169-187. https://doi.org/10.1016/s0169-555x(97)00079-2

Stock J.D., Schmidt K.M., Miller D.M., 2008. *Controls on alluvial fan long-profiles*. Geological Society of America Bulletin, 120, 619-640. https://doi.org/10.1130/b26208.1

Stokes M., Gomes A., 2020. *Alluvial fans on volcanic islands: A morphometric perspective (Sao Vicente, Cape Verde)*. Geomorphology, 368. https://doi.org/10.1016/j.geomorph.2020.107356

Su Q., Yuan D.Y., Zhang H.P., Manopkawee P., Zhan Y., Zhang P.Z., Xie H., 2019. *Geomorphic evidence for northeastward expansion of the eastern Qilian Shan, northeastern Tibetan Plateau*. Journal of Asian Earth Sciences, 177, 314-323. https://doi.org/10.1016/j.jseaes.2019.04.003

Sweeney M.R., Loope D.B., 2001. *Holocene dune-sourced alluvial fans in the Nebraska Sand Hills*. Geomorphology, 38, 31-46. https://doi.org/10.1016/s0169-555x(00)00067-2

Ta W.Q., Xiao H.L., Qu H.J., Xiao Z., Yang G.S., Wang T., Zhang X.Y., 2004. *Measurements of dust deposition in Gansu Province, China, 1986-2000*. Geomorphology, 57, 41-51. https://doi.org/10.1016/s0169-555x(03)00082-5

Taft L., Evers M., 2016. *A review of current and possible future human-water dynamics in Myanmar's river basins*. Hydrology and Earth System Sciences, 20, 4913-4928. https://doi.org/10.5194/hess-20-4913-2016

Tapponnier P., Meyer B., Avouac J.P., Peltzer G., Gaudemer Y., Guo S.M., Xiang H.F., Yin K.L., Chen Z.T., Cai S.H., Dai H.G., 1990. *Active thrusting and folding in the Qilian-Shan, and decoupling between upper crust and mantle in northeastern Tibet*. Earth and Planetary Science Letters, 97, 382-&. https://doi.org/10.1016/0012-821x(90)90053-z

Tapponnier P., Peltzer G., Ledain A.Y., Armijo R., Cobbold P., 1982. *Propagating extrusion tectonics in Asia: New insights from simple experiments with plasticine*. Geology, 10, 611-616. https://doi.org/10.1130/0091-7613(1982)10<611:Petian>2.0.Co;2

Thornton P.K., Ericksen P.J., Herrero M., Challinor A.J., 2014. *Climate variability and vulnerability to climate change: a review*. Global Change Biology, 20, 3313-3328. https://doi.org/10.1111/gcb.12581

Tong K., Li Z.W., Zhu L.D., Tao G., Zhang Y.X., Yang W.G., Zhang J.L., 2020. *Fold-and-thrust deformation of the hinterland of Qilian Shan, northeastern Tibetan Plateau since Mesozoic with implications for the plateau growth*. Journal of Asian Earth Sciences, 198. https://doi.org/10.1016/j.jseaes.2019.104131

Vincent L.T., Eaton B.C., Leenman A.S., Jakob M., 2022. *Secondary geomorphic processes and their influence on alluvial fan morphology, channel behavior and flood hazards*. Journal of Geophysical Research-Earth Surface, 127, 16. https://doi.org/10.1029/2021jf006371

Wang W.L., Wu J.P., Fang L.H., Lai G.J., Cai Y., 2017a. *Sedimentary and crustal thicknesses and Poisson's ratios for the NE Tibetan Plateau and its adjacent regions based on dense seismic arrays*. Earth and Planetary Science Letters, 462, 76-85. https://doi.org/10.1016/j.epsl.2016.12.040

Wang W.T., Zhang P.Z., Yu J.X., Wang Y.Z., Zheng D.W., Zheng W.J., Zhang H.P., Pang J.Z., 2016. *Constraints on mountain building in the northeastern Tibet: Detrital zircon records from synorogenic deposits in the Yumen Basin*. Scientific Reports, 6. https://doi.org/10.1038/srep27604

Wang Y., Wu C.S., Wang F.F., Sun Q.Y., Wang X.F., Guo S.X., 2021. *Comprehensive evaluation and prediction of tourism ecological security in droughty area national parks-a case study of Qilian Mountain of Zhangye section, China*. Environmental Science and Pollution Research, 28, 16816-16829. https://doi.org/10.1007/s11356-020-12021-2

Wang Y.L., Yeh T.C.J., Wen J.C., Huang S.Y., Zha Y., Tsai J.P., Hao Y., Liang Y., 2017b. *Characterizing subsurface hydraulic heterogeneity of alluvial fan using riverstage fluctuations*. Journal of Hydrology, 547, 650-663. https://doi.org/10.1016/j.jhydrol.2017.02.032

Welsh A., Davies T., 2011. *Identification of alluvial fans susceptible to debris-flow hazards*. Landslides, 8, 183-194. https://doi.org/10.1007/s10346-010-0238-4

Whipple K.X., Parker G., Paola C., Mohrig D., 1998. *Channel dynamics, sediment transport, and the slope of alluvial fans: Experimental study*. Journal of Geology, 106, 677-693. https://doi.org/10.1086/516053

White K., Drake N., Millington A., Stokes S., 1996. *Constraining the timing of alluvial fan response to Late Quaternary climatic changes, southern Tunisia*. Geomorphology, 17, 295-304. https://doi.org/10.1016/0169-555x(96)00011-6

Whitmarsh L., 2011. *Scepticism and uncertainty about climate change: Dimensions, determinants and change over time*. Global Environmental Change-Human and Policy Dimensions, 21, 690-700. https://doi.org/10.1016/j.gloenvcha.2011.01.016

Wu H.Q., Feng Y.M., Song S.G., 1993. *Metamorphism and deformation of blueschist belts and their tectonic implications, North Qilian mountains, China*. Journal of Metamorphic Geology, 11, 523-536.

Xiao W.J., Windley F., Yong Y., Yan Z., Yuan C., Liu C.Z., Li J.L., 2009. *Early Paleozoic to Devonian multiple-accretionary model for the Qilian Shan, NW China*. Journal of Asian Earth Sciences, 35, 323-333. https://doi.org/10.1016/j.jseaes.2008.10.001

Yang R., Su Y.Z., Wang M., Wang T., Yang X., Fan G.P., Wu T.C., 2014. *Spatial pattern of soil organic carbon in desert grasslands of the diluvial-alluvial plains of northern Qilian Mountains*. Journal of Arid Land, 6, 136-144. https://doi.org/10.1007/s40333-013-0200-0

Yeh H.F., Lin X.Y., Huang C.C., Chen H.Y., 2024. *A meteorological drought migration model for assessing the spatiotemporal paths of drought in the Choushui river alluvial fan, Taiwan*. Geosciences, 14, 17. https://doi.org/10.3390/geosciences14040106

Zhang H.Y., Shi Z.H., Fang N.F., Guo M.H., 2015. *Linking watershed geomorphic characteristics to sediment yield: Evidence from the Loess Plateau of China*. Geomorphology, 234, 19-27. https://doi.org/10.1016/j.geomorph.2015.01.014

Zhang Q.Q., Xu H.L., Li Y., Fan Z.L., Zhang P., Yu P.J., Ling H.B., 2012. *Oasis evolution and water resource utilization of a typical area in the inland river basin of an arid area: a case study of the Manas River valley.* Environmental Earth Sciences, 66, 683-692. https://doi.org/10.1007/s12665-011-1276-5

Zhang X.F., Wang S.Q., Wu X., Xu S., Li Z.Y., 2016. *The development of a laterally confined laboratory fan delta under sediment supply reduction*. Geomorphology, 257, 120-133. https://doi.org/10.1016/j.geomorph.2015.12.027

Zhang X.Q., Hu M.C., Guo X.Y., Yang H., Zhang Z.K., Zhang K.L., 2018. *Effects of topographic factors on runoff and soil loss in Southwest China.* Catena, 160, 394-402. https://doi.org/10.1016/j.catena.2017.10.013

Zhang Y.F., Dai X., Wang M., Li X.X., 2020. *The concept, characteristics and significance of fluvial fans.* Petroleum Exploration and Development, 47, 1014-1026. https://doi.org/10.1016/s1876-3804(20)60113-6

Zhang Y.N., Hu X.F., Wang W., Pan B.T., 2024. *Evolution of the alluvial fan channel longitudinal profile and aggradation/degradation processes in the piedmont.* Quaternary Science Reviews, 331. https://doi.org/10.1016/j.quascirev.2024.108654

Zhao R.F., Chen Y.N., Shi P.J., Zhang L.H., Pan J.H., Zhao H.L., 2013. *Land use and land cover change and driving mechanism in the arid inland river basin: a case study of Tarim River, Xinjiang, China.* Environmental Earth Sciences, 68, 591-604. https://doi.org/10.1007/s12665-012-1763-3

Zheng D.W., Clark M.K., Zhang P.Z., Zheng W.J., Farley K.A., 2010. *Erosion, fault initiation and topographic growth of the North Qilian Shan (northern Tibetan Plateau).* Geosphere, 6, 937-941. https://doi.org/10.1130/ges00523.1

Zheng D.W., Wang W.T., Wan J.L., Yuan D.Y., Liu C.R., Zheng W.J., Zhang H.P., Pang J.Z., Zhang P.Z., 2017. *Progressive northward growth of the northern Qilian Shan-Hexi Corridor (northeastern Tibet) during the Cenozoic.* Lithosphere, 9, 408-416. https://doi.org/10.1130/l587.1

Zheng W.J., Zhang P.Z., Ge W.P., Molnar P., Zhang H.P., Yuan D.Y., Liu J.H., 2013. *Late Quaternary slip rate of the South Heli Shan Fault (northern Hexi Corridor, NW China) and its implications for northeastward growth of the Tibetan Plateau.* Tectonics, 32, 271-293. https://doi.org/10.1002/tect.20022

Ziadat F.M., Taimeh A.Y., 2013. *Effect of rainfall intensity, slope, land use and antecedent soil moisture on soil erosion in an arid environment.* Land Degradation & Development, 24, 582-590. https://doi.org/10.1002/ldr.2239

Zuza A.V., Wu C., Reith R.C., Yin A., Li J.H., Zhang J.Y., Zhang Y.X., Wu L., Liu W.C., 2018. *Tectonic evolution of the Qilian Shan: An early Paleozoic orogen reactivated in the Cenozoic.* Geological Society of America Bulletin, 130, 881-925. https://doi.org/10.1130/b31721.1

Zuza A.V., Wu C., Wang Z.Z., Levy D.A., Li B., Xiong X.S., Chen X.H., 2019. *Underthrusting and duplexing beneath the northern Tibetan Plateau and the evolution of the Himalayan-Tibetan orogen*. Lithosphere, 11, 209-231. https://doi.org/10.1130/l1042.1

Zygmunt E., 2009. *Alluvial fans as an effect of long-term man-landscape interactions and moist climatic conditions: A case study from the Glubczyce Plateau, SW Poland*. Geomorphology, 108, 58-70. https://doi.org/10.1016/j.geomorph.2007.08.021

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