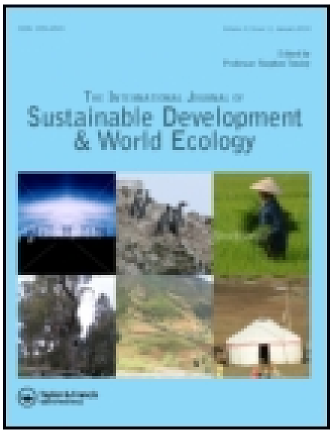

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A spatially explicit assessment and analysis of water-eroded desertification and its combating in Yunnan Province, China

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A spatially explicit assessment and analysis of water-eroded desertification and its combating in Yunnan Province, China

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In a study on water-eroded desertification in Yunnan Province, we used remote sensing and geographic information system (GIS) to determine the areas of water-eroded desertified land objectively, to analyze the spatial distribution and causes of desertification in association with the geologic background, and to propose the appropriate measures for prevention and control. We found that the area of water-eroded desertification in 2008 was 35,949.69 km^2, accounting for 9.39% of the total land area in Yunnan. The main reason of desertification is the combined impact of the development of geologic structures and specific lithology. Human factors exacerbate and sometimes induce the desertification. We recommend that the desertification prevention and control should focus on the desertification-prone areas, including the neighboring regions of active faults such as the Jinsha River–Hong River fault, Yuanmou–Luzhi River fault, Fuyuan–Mile fault, Wenshan–Malipo fault, Nanpan River fault, Xiao River fault, and Qujing–Zhaotong fault; the sedimentary and Quaternary regions covered by mudstone, clay stone, and carbonate rocks; and the neotectonic regions such as the fold-style uplift region in east Yunnan, the secondary uplift region in southeast Yunnan, and the large block-style uplift region in central Yunnan. The population pressure should be reduced and industrial activities such as construction and mining should be more strictly regulated to prevent human activities from exacerbating water-eroded desertification.

Keywords: water-eroded desertification; remote sensing survey; comprehensive geologic cause analysis; prevention and control; Yunnan

1. Introduction

Desertification is one of the global environmental problems which seriously affect the natural environment conservation and human development. According to the materials related to the 1997 'Desertification Convention' of United Nations, water-eroded desertification refers to the severe land degradation mainly caused by water erosion which leads to the loss or severe decline of land productivity. It is marked with sloping fields of scabland or gravels. Many human activities damage vegetation and make the soil more susceptible to water erosion.

For decades, many efforts have been made for the prevention of desertification. The survey and research of desertification using remote-sensing technology started as early as 1970s when countries such as Argentina and India surveyed their land desertification and evaluated the distribution of the desertified areas. Mann et al. (1984) proposed three indicators of desertification, i.e., the sand dune movement, salinization, and area expansion of bare rocks by using remote-sensing data combined with ground data. Hellden (1984) used remote-sensing method to monitor the impact of drought in the desertified areas in Kordofan, Sudan. A comprehensive study of desertification in the semi-arid regions of Sudan was done by applying the remote-sensing technology, geographic information system (GIS), and spatial modeling (Olsson 1985). The research demonstrated that the climate has a significant impact on desertification. Ringrose and Matheson (1991) investigated the grassland in the arid regions of Kalahari Desert, Botswana, during the drought from 1980 to 1987 by analyzing Landsat data. The land degradation in Mongolia was evaluated by combining satellite imagery data and ground data (Kharin 1992). In the research and monitoring of desertification in Gulbarga, India, the multi-temporal Landsat multi-spectral scanner (MSS) and Indian Resources Satellite (IRS) imagery data were utilized and ground ancillary information were integrated with GIS technology for the assessment of land degradation (Tripathy et al. 1996). In China, the survey and research of desertification using remote sensing began in the early 1980s. Zhu and Liu (1981) utilized the aerial photographs in their research of the desertification dynamics in Horqin, Inner Mongolia. Li and Zhou (2001) monitored the sandy desertification process in the western sandy region of Northeast China Plain according to the criteria established based on National Oceanic and Atmospheric Administration/Advanced Very High Resolution Radiometer (NOAA/AVHRR) data. They further investigated the development and cause of the sandy desertification using Landsat Thematic Mapper (TM) data and proposed the preventive measures specifically for the regional sandy desertification. A simulation was performed

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for the desertification trend from 1987 to 2000 in Beijing and its neighboring regions based on China-Brazil Earth Resources Satellite (CBERS) and Landsat TM imagery (Chen et al. 2004). A desertification prediction model was established. The status of the desertification in Beijing and its adjacent areas was discussed in terms of spatial distribution, desertification speed, and control. Taking West Hunan as their example area, Zhang et al. (2010) presented a hierarchical approach to extract land-cover information of water-eroded desertification based on the indices of normalized difference water index (NDWI), normalized difference vegetation index (NDVI), and normalized difference built-up index (NDBI), and spectral values of bands 3, 5, and 7 of Landsat Enhanced Thematic Mapper Plus (ETM+) data. Chen et al. (2010) suggested that the main influencing factors of water-eroded desertification in Guangxi are topography, geotechnical characteristics, and tectonics. Based on the GIS analysis, water-eroded desertification in Guangxi is mainly distributed in areas with carbonate rocks, granite, shale, sandy conglomerate, and sand shale. Qasim et al. (2011) used a structured questionnaire to collect information on different socio-economic parameters affecting land degradation and farmers' perceptions on the status of land degradation in Pishin sub-basin, Pakistan. Feng et al. (2011) assessed the land-use change characteristics in the past 30 years of an alpine-cold desertified area in the Qinghai-Tibetan Plateau, by interpreting remote-sensing satellite imagery acquired in 1976, 1996, and 2006 as well as change detection and analysis using GIS. Salvati (2012) suggested that the better understanding of the spatial linkage between the distribution of land vulnerable to degradation and long-term population growth would contribute to sustainable land management in dry regions. In summary, the previous studies listed above have laid a good theoretical foundation and provided technical references for the research of water-eroded desertification and its prevention.

Desertification, especially water-eroded desertification, is getting more severe in Yunnan, and the study on water-eroded desertification and its combating is urgently needed. At least 94% of Yunnan is covered with high mountains and deep valleys, making its land resources very precious. Complex geologic environment and improper use of resources have exacerbated water-eroded desertification development and made the shortage of land resources more severe. The Yunnan Department of Forestry did erosion surveys in 1987, 1999, and 2004 using remote sensing. The 2004 survey showed that the soil erosion covered 134,170 km^2 or 35.04% of total land in Yunnan. Meng et al. (2000) did a dynamic comparative study of the desertified land in Yunnan and analyzed the cause of desertification in terms of topography, climate, and human factors. Wan et al. (2005) compared the erosion trends of various watersheds in 1987 and 1999. Combining various factors such as geomorphology, vegetation coverage characteristics, the steep slope farmland ratio, and the agricultural population density, they performed the physical regionalization for soil erosion. However, previous researches of Yunnan water-eroded desertification were carried out by focusing on the desertified land or soil erosion instead of the specific water-eroded desertification. Their cause analysis was more concentrated on climate and geographic factors instead of geologic elements which could be the basic and important factor. Therefore, in this research, remote-sensing methods are used in the survey of water-eroded desertification for the entire province. The geologic causes of desertification are analyzed. The recommendations for the prevention and control of regional water-eroded desertification are proposed, which could provide valuable information and basic proofs for the government's decision-making in the field of land management and environmental protection.

2. Methods

2.1. *Water-eroded desertification classification*

The source data used in this research were Landsat TM imagery which acquired in Spring–Summer of 2008 with a map scale of 1:250,000. Spring–Summer time is the dry season in Yunnan and is the best time to obtain the high-quality cloud-free imagery in the region. Landsat bands 5, 4, and 3 were displayed in red, green, and blue colors, respectively, for interpretation. In addition, the band combinations like TM bands 4, 5, and 3 and TM bands 4, 7, and 1 were applied to enhance certain specific information related to water-eroded desertification such as vegetation, scabland or rocky slope coverage, and valleys.

Water-eroded desertification was classified into three classes in this research: mild, moderate, and severe. The interpretation on the remotely sensed imagery was mainly based on indirect features such as the proportions of the scabland or rocky slope land, valleys distribution, and landscape characteristics (Table 1).

2.2. *Remote-sensing interpretation and field investigation*

2.2.1. *Remote-sensing interpretation*

The satellite images were interpreted with the following steps:

(1) Establish the interpretation keys for vegetation, scabland or rocky slopes, and valleys.

On the remote-sensing imagery with color combination of TM bands 5, 4, and 3, the vegetation is shown as the green spots or patches. The scabland or rocky slope is mainly light purple–light gray or light white patches. The valleys appear to be undulating ravines, broken cuts, and dark shadows on the shade side of the slopes. On the color composite imagery of TM bands 4, 5, and 3 and 4, 7, and 1, the vegetation shows up as orange–reddish brown spots and patches. The scabland is gray green patches. The valleys have similar features as mentioned above.

Table 1. Water-eroded desertification classification.

Desertification level ID	Name	Proportion of scabland or rocky slopes (%)	Proportion of modern valleys (rill, gully) (%)	Vegetation coverage (%)	Landscape features
SS-1	Mild desertification	10	10	70～50	Patchy distribution of scabland or rocky slopes. Valley depth less than 1 m with sheet erosion and rill development. Scattered bare sand surface.
SS-2	Moderate desertification	10～30	10～30	50～30	Large distribution of scabland or rocky slopes. Valley depth 1～3 m. Widely distributed bare sand surface.
SS-3	Severe desertification	≥30	≥30	≤30	Dense distribution of scabland or rocky slopes. Valley depth larger than 3 m. Surface cut to pieces.

(2) Visually interpret and estimate the proportions of vegetation, scabland or rocky slopes, and valleys. Classify the areas based on the desertification levels in given Table 1.

If the vegetation coverage is 50–70%, the scabland or rocky slope less than 10%, and the valley less than 10%, the area could then be interpreted as the mild water-eroded desertification. For the moderate desertification, the vegetation coverage is 30–50%, the scabland or rocky slope 10–30%, and valley 10–30%. For the severe desertification area, the vegetation coverage is less than or equal to 30%, the scabland or rocky slope is larger than or equal to 30%, and the valley larger than or equal to 30% as well. Figures 1a, b, c show the sample images for different levels of water-eroded desertification in Yuanmou basin.

2.2.2. *Field investigation*

Field investigation had been done in 2008 to assess the classification accuracy. The total checking route was 2830 km long while 179 checking points which were distributed cross the whole study area had been used for verification. An overall accuracy of 86% was achieved.

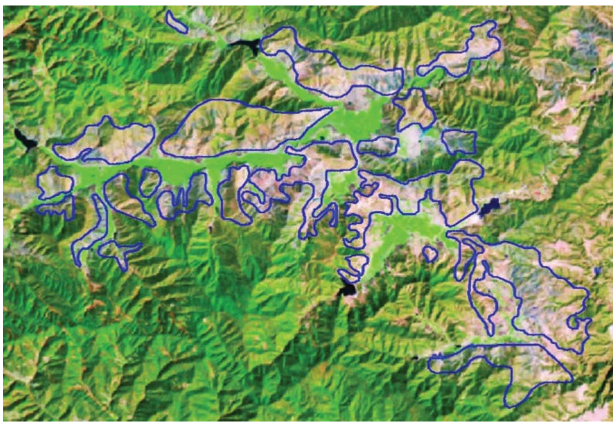

Figure 1a. Mild desertification (Quaternary mudstone).

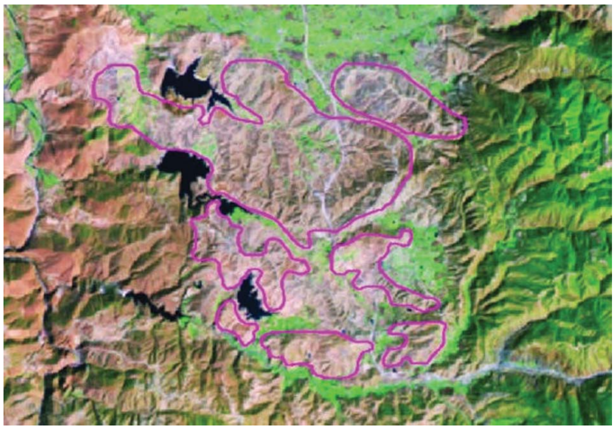

Figure 1b. Medium desertification (Quaternary).

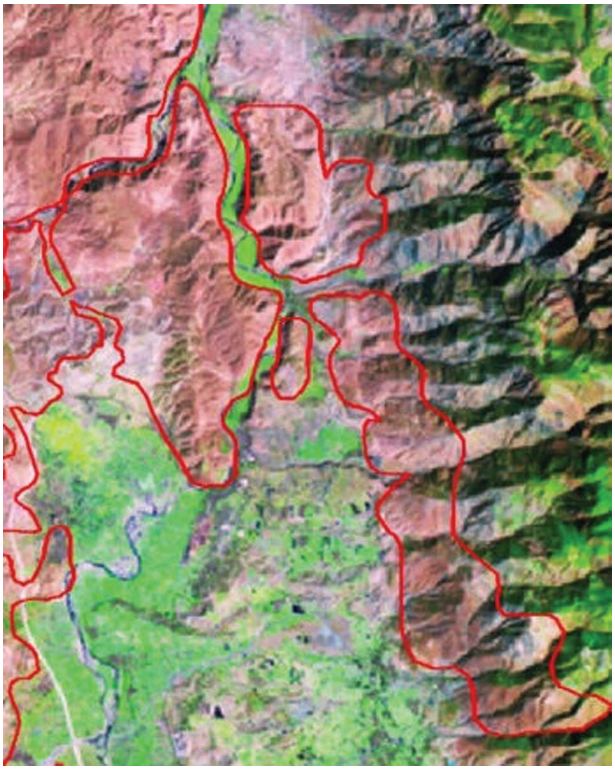

Figure 1c. Severe desertification (fault, granite).

3. Results

3.1. Spatial distribution of water-eroded desertification

Remote-sensing survey results demonstrated the various aspects of water-eroded desertification.

(1) The area of water-eroded desertification was 35,949.69 km^2, accounting for 9.39% of the total land in Yunnan Province. Among the desertified land, the mild, moderate, and severe desertification areas covered 14,363.84, 15,586.69, and 5,999.16 km^2, respectively; this reflected a serious situation in Yunnan (Table 2).

(2) For the regional distribution, the eastern Yunnan was more severe than the western part. The desertified land area in the east in 2008 was 30,690.17 km^2, accounting for 14.77% of the land in the east region, with higher concentration and higher degree of desertification. The counties or cities with severe desertification included Zhaotong City, Ludian County, and Qiaojia County in the northeast; Kunming, Xuanwei County, Fuyuan County, Luliang County, and Luoping County in the east; Gejiu City, Kaiyuan County, Mengzi County, Mile County, Jianshui County, Wenshan County, Yanshan County, Qiubei County, Guangnan County, and Xichou County in the southeast of Yunnan. The desertified land area in the west in 2008 was 5259.52 km^2, or 3.01% of the land in the west, distributed sparsely with lower degree of desertification.

(3) According to the watersheds, water-eroded desertification was mainly distributed in the Jinsha River, Nanpan River, and Yuan River basins. Lancang River also had some developed desertification while other rivers had limited desertification (Table 3).

3.2. Cause analysis of water-eroded desertification

The comprehensive comparative analysis of the spatial distribution, the geologic background, and the socio-economic conditions demonstrated that water-eroded desertification in Yunnan is resulted from the combined effect of natural and human factors. The natural factors included geologic, geomorphologic, climatologic, and hydrologic elements which provided the desertification the adequate source materials and set the tone for the overall spatial distribution and the degree of desertification. Human factors included population growth pressure, mining, and other related social economic activities, which could induce or worsen the desertification process under certain conditions.

3.2.1. Geologic elements

Along with the tectonic plate movement, a series of deep faults were developed in Yunnan. These faults shaped the block stress conditions, mold high mountains and deep valleys, and resulted in highly fractured rocks. They provided the adequate terrain conditions and abundant source materials for water-eroded desertification. The activities of

Table 2. Area distribution of Yunnan water-eroded desertification in 2008 (km^2).

Region	Cities or prefectures and areas covered	Mild	Moderate	Severe	Total
Eastern Yunnan	Zhaotong City, Qujing City, Kunming, Yuxi City, Honghe Prefecture, Wenshan Prefecture, Chuxiong Prefecture, Dali Prefecture. Area: 207,838.32 km^2	9893.05	14, 837.87	5959.25	30, 690.17
Western Yunnan	Diqing Prefecture, Nujiang Prefecture, Lijiang, Baoshan City, Lincang, Dehong Prefecture, Xishangbanna, Puer City. Area: 175,012.48 km^2	4470.79	748.82	39.91	5259.52

Table 3. Watershed distribution of Yunnan water-eroded desertification in 2008 (km^2).

		Mild		Moderate		Severe	
Name	Area	Water-eroded desertification	Proportion (%)	Water-eroded desertification	Proportion (%)	Water-eroded desertification	Proportion (%)
Jinsha River	106,055	3526.65	3.33	4597.61	4.34	1692.53	1.60
Lancang River	90,704	3100.64	3.42	394.24	0.43	13.64	0.02
Nu River	31,071	609.81	1.96	152.23	0.49	0	0.00
Yiluwadi River	18,979	192.3	1.01	22.01	0.12	0	0.00
Yuan River	74,063	4170.86	5.63	4117.92	5.56	1894.23	2.56
Nanpan River	58,654	2525.61	4.31	6245.77	10.65	2398.76	4.09
Chishui River	3211	237.97	7.41	56.91	1.77	0	0.00
Total	382,945	14, 363.84	3.75	15, 586.69	4.07	5999.16	1.57

geologic structures determined and influenced the development of water-eroded desertification.

3.2.1.1. Neotectonics. Separated by the deep fault along Muli River, Li River, Hong River, and Tengtiao River, the southeast of Yunnan was an orogenic zone from Qinghai–Tibet to three rivers (Nu, Lancang, and Jinsha) which was mainly marked by the NW–NNW-oriented orogeny. The north section of the mountains formed a relatively enclosed environment where water-eroded desertification was low. The south section had the scattered extensional environment with well-developed desertification. The central east of Yunnan was primarily the differential block movement that formed the overall terraced plateau environment. Water-eroded desertification is highly developed (Figure 2).

Water-eroded desertification was closely associated with following faults: Jinsha River–Hong River fault (F1), Yuanmou–Luzhi River fault (F3), Wenshan–Malipo fault (F7), Fuyuan–Mile fault (F5), Nanpan River fault (F6), Xiao River fault (F2), and Zhaotong–Qujing fault (F4).

(1) Jinsha River–Hong River fault (F1)

The Jinsha River–Hong River fault (F1) was divided into north (Jinsha River fault) and south (Hong River fault) segments. The north segment was a compression-shear fault, S–N oriented and active in Q_{1-2} era. The south segment was NW–NNW oriented and active in Q_{3-4} era with an annual movement of 0.4–7.5 mm. The Jinsha River–Hong River fault entered Yunnan at Deqin County, passed through Eryuan, Dali, Midu, Shuangpai, Yuan River, Hong River, and then left the region at Hekou. Less desertification was found at the northwest of Eryuan along the fault. The moderate desertification appeared in Eryuan County. The contiguous water-eroded desertification,

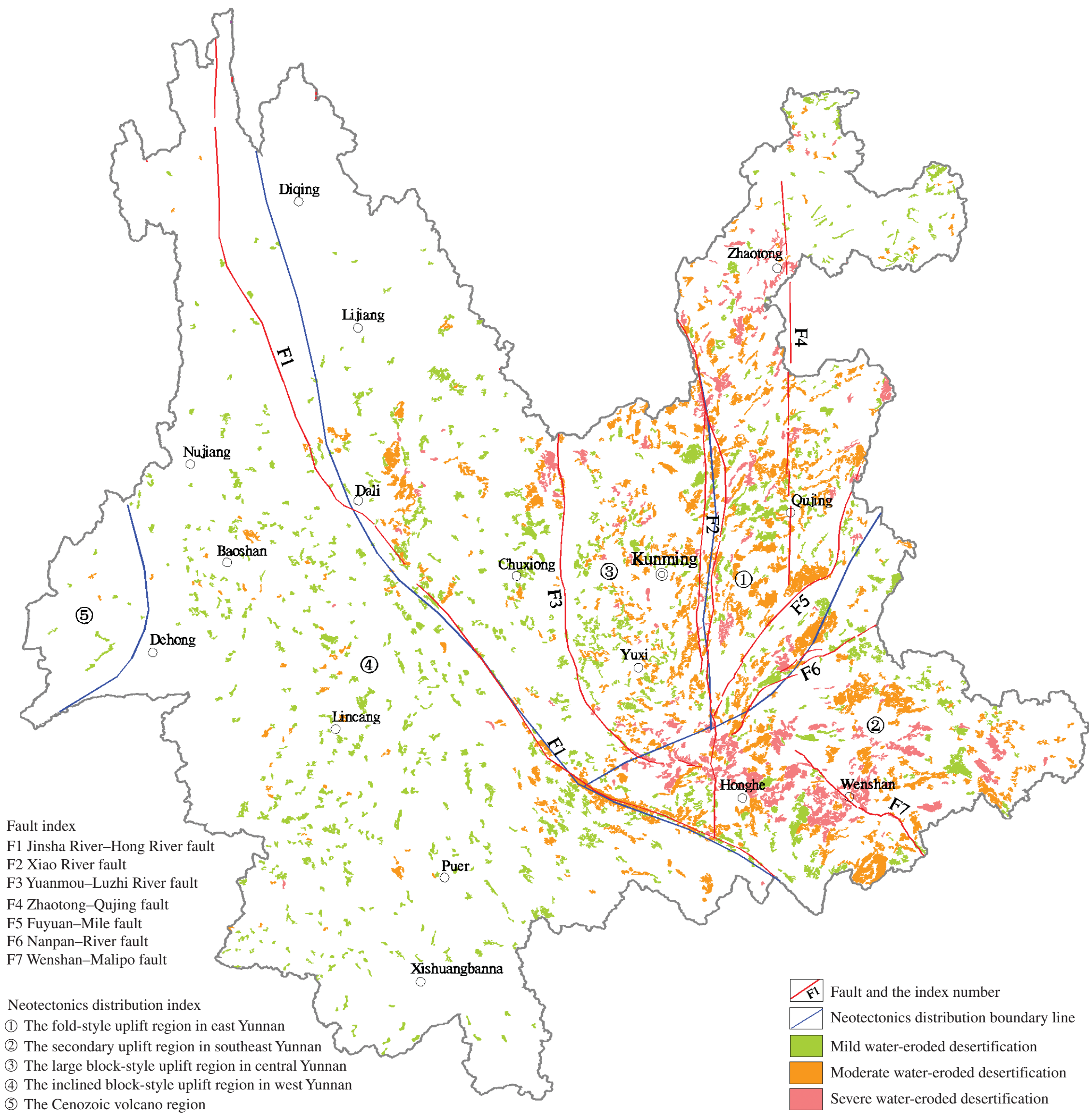

Figure 2. Relationship of water-eroded desertification, faults, and neotectonics.

mainly moderate or mild, occurred along the Xiangyun–Midu–Nanjian–southwest Nanhua of Dali City. Further south along the fault, the area of desertification became smaller and was distributed sporadically. Once the fault reached the southwest Xinping County–Yuan River–Hong River–Yuanyang, the large areas of moderate water-eroded desertification were developed with banded distribution on its two sides. The band width of desertification on the southwest side of the fault was larger than that on the northeast side. The desertification was mainly mild afterwards. In short, water-eroded desertification along the Jinsha River–Hong River fault was pretty serious. The degree of the desertification development was proportional to the segment activities of the fault. The enclosed tectonic environment in the north part of the fault had low activity which leads to less development of desertification. The central part and south part of the fault had higher activity which resulted in the more developed water-eroded desertification.

(2) Yuanmou–Luzhi River fault (F3)

The Yuanmou–Luzhi River fault (F3) was a strike–slip fault, S–N oriented and active in Q_{2-3} era. It formed the east border of the Yuanmou fault basin. Water-eroded desertification mainly appeared on the left side of the fault. Besides Yuanmou County, where one-fifth of its area was covered by the severe water-eroded desertification, other regions had moderate or mild desertification. The reason was that the activity was strong in this fault zone. The neotectonic movement had been intense since the Quaternary period. The Jinsha River and its tributary Longchuang River in Yuanmou County made downward cuts to form the river basin. The mean sea level at the bottom of the basin was 1000 m. The relative height was around 1000–2000 m. The basin was surrounded by mountains which blocked the entry of external moisture. With the additional foehn effect, the dry and hot valley climate was formed in the region, which led to the degradation of vegetation. The tectonic activities also led to highly fractured rocks. The favorable environment made water-eroded desertification widespread.

(3) Wenshan–Malipo fault (F7)

The Wenshan–Malipo fault (F7) was a strike–slip fault and NW oriented. The fault branching and merging were pretty common. Water-eroded desertification on both sides of the fault was mainly distributed in Wenshan County where more than 50% of its administrative area was desertified and more than 95% of water-eroded desertification was severe. There were concentrated pieces of the moderately desertified land in Malipo County and Maguan County. The serious desertification in these counties was due to a series of crisscrossed deformation faults of secondary blocks, fragmented rocks, and significant hydrochemical erosion and physical movement of, mostly, the Triassic, Carboniferous, and Devonian limestone.

(4) Fuyuan–Mile fault (F5) and Nanpan River fault (F6)

Large water-eroded desertified lands were developed between the Fuyuan–Mile fault (F5) and Nanpan River fault (F6). The desertification was mainly moderate and extended along the northeast direction. The most concentrated desertification was near the twisting section of the faults. These two faults intersected with the Xiao River fault (F2), Jianshui–Shiping fault, Mengzi–Nanxi River fault, and Wenshan–Malipo fault (F7). The intersections and affected regions such as Mengzi, Kaiyuan, Gejiu, and Jianshui had severe desertification. More than one-third of the administrative area was desertified. The area between these two faults is mostly consisted of sedimentary limestone. The geologic structures were more developed and the rocks more fractured around the twisting or intersecting sections of the faults. In addition, the terrain had significant height differences and slopes. The sufficient source materials and adequate hydrodynamic conditions made water-eroded desertification easy to happen.

(5) Xiao River fault (F2)

The Xiao River fault (F2) was a strike–slip fault, S–N oriented and active in Q_{3-4} era with an annual movement of 1.0–8.6 mm. Water-eroded desertification on each side of the fault was very significant and gradually increasing from north to south. Both sides had similar degree of desertification development. Around the fault were mostly the severe and moderate levels of water-eroded desertification. The mild level was limited. There existed large patches of desertification. The reason was that the area had widely distributed metamorphic rocks such as the black, gray, and purple slates, and phylites in Kunyang group of the Upper Proterozoic erathem. With well-developed joints and poor weatherability, these metamorphic rocks could be easily weathered and disintegrated into detritus under the influence of the strong activity of the Xiao River fault (F2), which provided the abundant source materials and becomes one of the important reasons why water-eroded desertification was well developed.

(6) Zhaotong–Qujing fault (F4)

The Zhaotong–Qujing fault (F4) was a tenso-shear fault, S–N oriented, active in Q_{2-3} era, and cross-cutting multiple northeast-oriented faults. Large areas of water-eroded desertification were distributed on both sides of the fault. A group of northwest-oriented faults passed through Ludian County and Zhaoyang District of Zhaotong City, which resulted in a large area of severely water-eroded desertification land. Large contiguous tracts of land of moderate desertification appear in the triangular region formed by the east side of Zhaotong–Qujing fault in Luliang County and the Mile–Shizong fault. The reason was that the strong activities in the Zhaotong–Qujing fault zone resulted in fractured rocks, especially in areas the faults intersected with one another, and led to the well-developed water-eroded desertification.

3.2.1.2. Stratum and lithology. Based on the statistic analysis of water-eroded desertification and lithologic distribution, water-eroded desertification in Yunnan was widely distributed in sedimentary rocks while a few areas of concentrated desertification were in basalt and granite (Table 4). The earlier the formation time of the sedimentary rocks was, the more porous their texture and structure became, and the easier they were weathered and water-eroded. The rocks with smaller particle size, for example, mudstones and shale, were more prone to water erosion. The limestone was also easily eroded as a result of its special chemical composition ($CaCO_3$). Some granite could also develop water-eroded desertification under the influence of human disturbances.

(1) In the carbonate rock region which was distributed in the east and southeast Yunnan, water-eroded desertification was well developed.

The area of water-eroded desertification in the carbonate rock region was 9172.21 km^2, accounting for 25.51% of all water-eroded desertified land in Yunnan. This region was located in the central and southeast sloping parts of the Yunnan–Guizhou plateau. It had the typical interlaced karst landscapes. The main component of the carbonate rocks was the calcium carbonate. It had unstable chemical properties and could be easily dissolved to form calcium bicarbonate when it encountered water with dissolved carbon dioxide. The carbonate rocks were powder-like, porous, and vulnerable to physical and chemical weathering and erosion, which led to the concentrated and well-distributed water-eroded desertification.

(2) In the granite region where the joints were well developed and vulnerable to weathering under favorable hydrothermal conditions, water-eroded desertification was also well developed.

The granite region appeared as broken shadow patterns on the remote-sensing imagery. The granite was a pluton which had dense texture and was not easy to be weathered into soil. However, due to the existence of granite cleavages and severe terrain cutting circumstances, the rocks were exposed; gullies and rills were formed; and the favorable conditions for water erosion were developed. The exposed rocks were weathered into loose materials such as sand and soil which became the material resources for the development of water-eroded desertification. For example, the Lincang granite belt, distributed along the west side of the Lancang River and extended in NNW direction, had an area of water-eroded desertification as large as 527.06 km^2, accounting for 6.2% of the entire rock area (8495 km^2). The rock mass in the belt was large scale but not complex in terms of lithologic characters. It was mostly monzonic granite with the loose weathered sandy crust on the top and the original impermeable rock underneath, which could easily produce the scattered surface flow and form water-eroded desertification.

(3) In the Quaternary region where sediments were relatively loose and easily eroded, water-eroded desertification was significant.

The exposed Quaternary region had 9623.71 km^2 of water-eroded desertification, accounting for 26.77% of all

Table 4. Lithology and lithologic compositions with water-eroded desertification.

Lithology and lithologic compositions	Rock type	Area of water-eroded desertification (km^2)
Shale, sandstone, mudstone, shale with coal seam; limestone, strip, or concretion containing flint	Sedimentary	2108.87
Compact shaped, patchy and almond-shaped calc-alkaline basalt with sand, shale, coal line, siliceous rocks, picrites	Igneous, sedimentary, metamorphic	1738.25
Limestone, dolomite, bottom-mottled shale	Sedimentary	1294.52
Particle limestone mixed with muddy limestone, calcareous slate (shale)	Sedimentary, metamorphic	1035.72
Micro-coarse grain limestone, biologic flock limestone	Sedimentary	815.34
Mudstone mixed with silty sandstone, fine sandstone, limestone	Sedimentary	781.30
Limestone, strip, or concretion containing flint	Sedimentary	719.33
Mudstone, calcium mudstone, quartz sandstone, mud limestone, slate, conglomerate	Sedimentary, metamorphic	600.85
Muddy stripped limestone mixed with mudstone, silty sandstone	Sedimentary	577.75
Strip containing flint, mass dolostone mixed with limestone	Sedimentary	559.88
Adamellite (Lincang granite)	Igneous	527.06
Mudstone, sandy shale mixed with quartz sandstone, calcium fine conglomerate	Sedimentary	519.75
Others	Others	24, 671.07

water-eroded desertification and 9.98% of all Quaternary areas. The main reason was that Quaternary sediments were formed in a short time and without an adequate diagenesis, which resulted in the rocks existing in the form of loose deposits such as sand, silt, and clay. Due to the changing slopes in the transitional areas between basins and mountains, even the relatively weak hydrodynamic elements could erode the Quaternary alluvial, diluvial, and slope sediments, carried away the weathered surface materials and left behind the barren or sandy land. As a result, water-eroded desertification was further developed.

3.2.2. Geomorphic elements

The succession, intermittency, and the top layer's lift ability of the neotectonics directly controlled the development of the landforms and resulted in the varieties of mountains, plateau landscape features, and micro-landforms such as terrace (<7°), gentle slope (7°–15°), medium slope (15°–25°), steep slope (25°–35°), and high slope (>35°) in Yunnan. The Yunnan neotectonic movement formed the fold-style uplift region in east Yunnan (①), the secondary uplift region in southeast Yunnan (②), the large block-style uplift region in central Yunnan (③), the inclined block-style uplift region in west Yunnan (④), and the Cenozoic volcano region (⑤) (Figure 2).

The fold-style uplift region in east Yunnan (①), the secondary uplift region in southeast Yunnan (②), and the large block-style uplift region in central Yunnan (③) had the typical plateau terrains with medium-height mountains, where the distribution of water-eroded desertification was pretty concentrated. The reason was that the medium-height mountain landscapes were formed and shaped by the stable but slow uplift in the plateau environment. The long-term erosion and leveling resulted in the micro-landforms featured by gentle and medium slopes, which laid a good foundation for water erosion. The slow but continuing water erosion produced abundant materials for water-eroded desertification, which was why water-eroded desertification was well developed. On the contrary, the inclined block-style uplift region in west Yunnan (④) and the Cenozoic volcano region (⑤) had strong rises which led to medium-high mountains. High mountains and steep slopes produced the well-developed micro-landforms featured by steep and high slopes. Even though water erosion condition was relatively strong, water-eroded desertification was limited, due to a lack of long-lasting erosion process and not so abundant materials.

3.2.3. Climate and hydrologic elements

Yunnan has the subtropical plateau monsoon climate. Different watersheds have different local climate characteristics which affect the occurrence and development of regional water-eroded desertification. For example, the Nanpan River watershed in southeast Yunnan has unbalanced hydrothermal resources. The temperature variation is significant and the annual mean temperature is from 12 to 23.1°C. The yearly precipitation is about 750–1250 mm; the storms are strong and widespread; and 85% of the rainfalls occurs in July and August. In addition, the water storage capacity is low, due to the thin layer and small total amount of soils. The karst region has large infiltration. The fluctuation of groundwater level could be tens of meters. Even the rain seasons often have dry periods when the evaporation is more than rainfalls, which produces the karst dry climate that is not suitable for vegetation growth. On such unique geologic and geomorphic landscapes, the hydrothermal advantages can quickly turn into strong damaging forces and lead to water-eroded desertification once the vegetation is destroyed. The west Yunnan region is located in the Lancang River watershed and Nu River watershed. Affected by India's monsoon, this region has abundant rainfalls. For instance, the western rainy districts of Longling, Yingjiang, Longchuan, and Ximeng have the annual mean temperature around 14.9–16.9°C and precipitation between 1600 and 1900 mm. The southern rainy districts of Jiangcheng, Luchun, Jingping, and Pingbian have the annual mean temperature between 14.9 and 16.9°C and precipitation between 2000 and 2300 mm. The northern Gongshan has the yearly mean temperature 16°C and rainfall 1600 mm. There are relatively balanced hydrothermal conditions, well-developed vegetation, and good conservation capacity for water and soil. Even though the rainfalls alternated between dry and wet seasons, water-eroded desertification was not well developed.

Water-eroded desertification was concentrated and advanced in Jinsha River, Nanpan River, and Hong River watersheds. The river systems of these watersheds were not well developed and had the density of 0.37, 0.42, and 0.47 km/km^2, respectively. The Nu River, Lancang River, and Irrawaddy River watersheds in the west had less-developed water-eroded desertification. The river systems in these watersheds were highly developed and had the density of 0.48, 0.54, and 0.59 km/km^2, respectively. The river density and water-eroded desertification had a negative but weak correlation. The reason was that, although water erosion condition was desirable in the dense river systems, water-eroded desertification was very much influenced by the combined effect of tectonics, geomorphology, precipitation, and human activities. Even if the river systems were not well developed in Jinsha River, Nanpan River, and Hong River watersheds in the central east Yunnan, the combined effect of various elements such as the adequate geologic structures was still more advantageous and made water-eroded desertification in this region more developed.

3.2.4. Human elements

Various irrational socio-economic activities exacerbated the process of water-eroded desertification and could even directly result in the desertification.

(1) Large and fast-growing population in central east part of Yunnan caused the overload of environmental capacity, the rise of human disturbances

and the escalation of water-eroded desertification. For instance, the central east Yunnan, including Chuxiong, Kunming, Zhaotong, Qujing, Honghe, Wenshan, and Dali, had a population density of 163 persons per km^2. The west Yunnan, including Diqing, Lijiang, Nujiang, Baoshan City, Lincang, Puer City, and Xishuangbanna, had a population density of 69 persons per km^2. While the density in the central east region was twice as much as in the west, water-eroded desertification was more than five times as much. There were apparent reasons. The huge demand for basic living conditions such as food, water, and housing created a big pressure on land, forest, water, and minerals which then led to the over-exploitation of natural resources. The damage to the structure and functions of ecosystems resulted in the land degradation, the frequent occurrences of secondary disasters in mountainous areas, and water-eroded desertification. For example, the eastern Sichuan region next to the Xiao River fault zone had the age-old human activities such as cutting wood for copper smelting which could damage the stability of the rock-soil mass and then indirectly caused water-eroded desertification. The reclamation on steep slopes in the northeast Yunnan caused serious soil erosion and loss. The excessive withdrawal of groundwater in the southeast Yunnan led to the imbalance between the groundwater and the surface water supply, and the decrease of water levels for some lakes and rivers. The exposure of the lake or river sediments could directly result in the formation of the sandy land and triggered the development of water-eroded desertification.

(2) Intense industrial activities exacerbated water-eroded desertification. Taking the mining activities as an example, the more the mining activities are, the more severe water-eroded desertification becomes. The central east region of Yunnan had a mining density as high as four mines per 100 km^2, while the west region had only one mine per 100 km^2. The former was four times as the latter but its area of water-eroded desertification was more than five times as much. In the industrial towns such as Mengzi, Gejiu, Kaiyuan, and Pingyuan Street in the karst basin in east and southeast Yunnan, there were large-scale productions for the black and non-ferrous metal mining and smelting, water-eroded desertification was pretty severe there. The reason was that the common approach of stripping mining of the black and non-ferrous metal ores directly led to large areas of bare rocks which formed the important foundation for water-eroded desertification. In addition, the mining and smelting discharged such as exhaust gas, waste water, and waste residues containing a lot of toxic components like lead, zinc, arsenic, mercury, and sulfur dioxide, which could produce a large amount of acid rain. The acid rain resulted in the ecologic damages such as the death of remaining trees, bushes, grass, algae, moss, and other vegetations in the karst mountain region, and thus intensified water-eroded desertification.

3.3. *Combating focus on water-eroded desertification*

Based on the cause analysis of water-eroded desertification in Yunnan Province, the prevention and control measures are proposed below.

(1) In the concentrated areas of water-eroded desertification, the prevention and control should be the high priority.

The prevention and control should selectively focus on some key areas near the active faults such as the Jinsha River–Hong River fault, Yuanmou–Luzhi River fault, Fuyuan–Mile fault, Wenshan–Malipo fault, Nanpan River fault, Xiao River fault, and Qujing–Zhaotong fault; the sedimentary and Quaternary regions covered by mudstone, clay stone, and carbonate rocks; and the neotectonic regions such as the fold-style uplift region in east Yunnan, the secondary uplift region in southeast Yunnan and the large block-style uplift region in central Yunnan. The strategy of 'spreading the knowledge gained on a few key points to the whole area' should be applied to promote the prevention and control of water-eroded desertification.

(2) Increasing the prevention and control awareness and reducing the human disturbances are important ways to achieve the effective prevention and control of water-eroded desertification.

In the concentrated areas mentioned above, we should greatly enhance the environmental protection awareness, take the necessary engineering means and measures to improve the vegetation coverage, strengthen the soil and water conservation, and do as much as possible to avoid the deepening of water-eroded desertification. Besides, we should do whatever we can to regulate mining, to reduce the human disturbances, to prevent the combined effect of human-induced water erosion and natural causes, and to avoid the further development of water-eroded desertification. The mining industry should improve its mining methods to avoid exacerbating the desertification.

4. Conclusions and suggestions

4.1. *Conclusions*

The study revealed not only the spatial distribution of water-eroded desertification but also the relation between water-eroded desertification and geological and human beings' activities. Water-eroded desertification in Yunnan Province is the result of the joint influence of natural and human factors while the natural elements are the main force and the human ones are secondary. The geologic environment and ecologic conditions lay the foundation. The human aspects induce or exacerbate the desertification process.

4.2. Suggestions

(1) This paper mainly focuses on the qualitative analysis of the comprehensive geologic causes for water-eroded desertification. The quantitative cause analysis is not intended. In order to better understand the distribution and progression of water-eroded desertification, the next step of our research is going to be the quantitative analysis of the desertification causes, to build relevant mathematical models, to propose more specific prevention and control measures for water-eroded desertification, and then to make the research results become more effective support to the strategies of land management and national development.

(2) There exists a weak negative correlation between the degree of water-eroded desertification and the river system density in different watersheds. The analysis above is mainly carried out qualitatively. The comprehensive cause analysis requires our further attention.

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