Catena 90 (2012) 53–62

Contents lists available at SciVerse ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

# Effects of land use, land cover and rainfall regimes on the surface runoff and soil loss on karst slopes in southwest China

Tao Peng [a,b,c], Shi-jie Wang [a,c,*]

[a] State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550002, China
[b] Graduate University of the Chinese Academy of Sciences, Beijing 100049, China
[c] Puding Karst Ecosystem Research Station, Institute of Geochemistry, CAS, Guiyang 562100, China

ARTICLE INFO

*Article history:*
Received 28 June 2011
Received in revised form 29 October 2011
Accepted 1 November 2011

*Keywords:*
Karst
Hill slopes
Limestone
Land use
Surface runoff
Soil loss

ABSTRACT

Surface runoff and soil loss from 2007 to 2010 related to land use and rainfall regimes in karst hill slopes in Guizhou Province, southwest China, were analyzed. Using the hierarchical clustering method, sixty-one rainfall events under the subtropical monsoon climate condition were classified into 5 types of rainfall regimes according to the depth, maximum 30-min intensity, and duration of rainfall. In our study, we first demonstrated that the amounts of surface runoff and soil loss on the karst hill slopes were very small compared to the non-karst areas, because the dual hydrological structure in the karst region, including ground and underground drainage systems, could influence the processes of rainfall recharge and runoff generation. Most rainfall water was transported underground through limestone fissures and fractures, while little was in the form of surface runoff. Second, the runoff and soil loss were affected by land use management and vegetation cover. Soil loss was intensified in a descending order to five types of land uses: pastureland > burned area > cropland > combination vegetation land > young forestland. Third, the runoff and soil loss exhibited remarkable variances among different rainfall regimes. Large runoff and soil loss were mainly created by heavy rainfall storms with a rainfall depth of more than 40 mm and a maximum 30-min rainfall intensity of over 30 mm $h^{-1}$. In addition, rainfall storms with large antecedent precipitations could also produce large runoff and soil loss. These observations indicated that limestone fissures and fractures play important roles in surface runoff generation on karst limestone slopes due to their large storage capacity and high infiltration rate. Lastly, the soil erosion risk in the karst pure limestone slope is quite high and should be paid particular attention, especially in regards to over-grazing because the soil loss created by a single heavy rainstorm in pastureland was 5 times the annual soil loss tolerance.

## 1. Introduction

Soil erosion has become a severe social and environmental concern throughout the world (Higgitt, 1991; Oldeman, 1994). Land use and land cover (LULC) are two of the most important factors that influence the occurrence and intensity of surface runoff and soil erosion (Kosmas et al., 1997; Morgan, 1995). Proper regulation of LULC can greatly improve soil properties (Kosmas et al., 2000) and reduce soil erosion (Fu et al., 2009; Zhang et al., 2004). Without exception, deforestation and improper regulation have led to severe water and soil loss on mountainsides (Francis and Thornes, 1990; Symeonakis et al., 2007), and have resulted in gully development, which in turn can increase the sediment load in rivers (Garcia-Ruiz and Valero-Garces, 1998; Kasai et al., 2005). Other factors, e.g. rainfall, could also result in raindrop splash and overland flow, and subsequently cause soil erosion (Kinnell, 2005; Nearing and Bradford, 1985; Nearing et al., 1991). Rainfall patterns and regimes play key roles in runoff generation and sediment yield (De Lima and Singh, 2002; Moody and Martin, 2009; Wei et al., 2007; Wei et al., 2009). LULC and rainfall regimes are important factors that control the intensity and frequency of overland flow and surface water erosion. Therefore, understanding the relationship of water and soil loss to rainfall and LULC is important for the management of land use and the conservation of soil and water.

In 1983, a soil loss study was conducted in a karst limestone upland region in western Ireland, which indicated that severe soil loss was caused by forest clearance and human activities (Drew, 1983). Since the beginning of the 1990s, some significant studies on runoff and soil erosion based on statistic and parametric models have been carried out from the perspective of the hydrology of limestone hill slopes in semi-arid or arid areas in the Mediterranean and Australia, using runoff field and simulated rainfall methods (Calvo-Cases et al., 2003; Cerdà, 1997a, b; Cerdà, 1998a, 1998b; Imeson et al., 1998; Kheir et al., 2008; Kosmas et al., 1997). Calvo-Cases et al. (2003)

---

* Corresponding author at: State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang, Guizhou Province 550002, China. Tel.: +86 851 5895328; fax: +86 851 5893400.
*E-mail address:* PengTao2020@gmail.com (S. Wang).

0341-8162/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.catena.2011.11.001

found that limestone slopes behave as a patchwork of runoff and run-on areas. The runoff generation mechanism on limestone slopes could be synthesized into two conceptual models: a Hortonian discontinuous runoff model that takes place in the most degraded slopes or during high intensity rain events, and a mixed runoff generation model where both excess infiltration runoff and excess saturation runoff can happen on the same slope. Runoff on limestone slopes was not continuous along the slope that was generated on degraded surfaces and quickly reinfiltrated in close soil patches with sufficient vegetation cover. However, the water and soil loss in semi-arid or arid limestone areas may not represent conditions in the subtropical humid karst region, and reliable data on water and soil loss is very limited for this type of area (Cao and Yuan, 2005; Ford and Williams, 2007). It has been suggested that karst landform development and its characteristics are determined by lithology, structure, geomography and climate (Williams, 2004). Aridity and extreme cold climate both constrain karst development, particularly, the epikarst where highly weathered carbonate bedrock, exposed at the surface or immediately beneath the surface soil, plays an important role in absorbing, storing and transmitting precipitation (Williams, 2008). Moreover, sub-humid and humid karst areas have a dual hydrological system of ground and underground drainage which can influence the hydrological process on slopes (Williams, 2008).

The Guizhou karst area, which covers ~109,084 $\text{km}^2$ with a population of 37.9 million in Guizhou Province in southwest China, is one of the largest continuous karst areas in the world in the humid climate zone. The karst area constitutes 73% of the total area in Guizhou Province, and 17.42% of the karst landforms are developed on continuously pure limestone (Li et al., 2003, 2006). The epikarst is well developed on the limestone bedrock and commonly is 2–5 m thick due to the sub-tropical climate conditions (Jiang et al., 2001). Most of the karst areas, especially limestone area, in Guizhou Province belong to the severe Karst Rocky Desertification (KRD) area (Wang et al., 2004). The soils formed from limestone bedrock are usually 20–40 cm thick on mountaintops and 50–150 mm thick on mountainsides (Chen, 1997). Previous studies have shown that 2000–8000 years would be required to produce 1 cm soil in pure and thick pure limestone areas, because the content of the insoluble residues in pure carbonate rocks is very small, usually less than 5% (Chen, 1997; Feng et al., 2009). Once vegetation is removed, extreme soil loss due to water erosion would occur (Zhang et al., 2011a), and it would be very difficult to regenerate vegetation in the region.

Because of population growth and economic development, many land use practices such as logging, over-grazing and agriculture activities are conducted, especially on hilly land with shallow soil. Approximately 29% of the mountain areas in Guizhou Province have slopes between 17 and 25° and 35% have slopes greater than 25° (Gan et al., 2002). At present, 80% of human activities (grazing and agriculture) in Guizhou Province are focused on slopes greater than 6°. The agricultural land on mountains is 691,800 ha for slopes >25°, and 281,800 ha for slopes >35°, which are about 20% and 6%, respectively, of the total dry land in Guizhou Province, respectively (Wang, 2003). While improper land use may cause severe soil erosion and karst rocky desertification in this region, rainfall in the sub-tropical wet monsoon climate could also cause runoff and soil erosion. The subtropical wet monsoon climate in humid Guizhou Province is characterized by spatial and temporal seasonal variability and wide yearly rainfall fluctuation. Extreme rainfall events, which are frequent in the rainy season, are very disruptive for fragile karst environments (Zhang et al., 2010).

In the 1990s, several studies suggested that soil erosion was very high in karst areas in southwest China due to the low soil formation rate from the carbonate bedrocks, steep slopes topography, high annual precipitation and poor vegetation cover (Lin and Zhu, 1999). Because of the low soil formation rate from the carbonate bedrocks, the rate of limestone soil formation was considered the soil loss tolerance in karst areas (Cao et al., 2008). The soil loss tolerance of the karst areas in southwest China has been calculated as 30–68 $\text{Mg km}^{-2}\,\text{a}^{-1}$ by different groups (Cao et al., 2008; Chai, 1989; Wei, 1995). A few studies have pointed out that, the petrologic assemblage in carbonate areas should be divided into three types which have different soil formation rates according to the amount of argillaceous material in formations. The soil formation rates of the homogenous carbonate rock area, the area of carbonate rock intercalated with clastic rock, and the area of carbonate/clastic rock alternations were 6.84 $\text{Mg km}^{-2}\,\text{a}^{-1}$, 45.53 $\text{Mg km}^{-2}\,\text{a}^{-1}$, and 103.46 $\text{Mg km}^{-2}\,\text{a}^{-1}$, respectively (Li et al., 2006). By monitoring the sediment yields in the main rivers in karst regions in southwest China, the soil erosion rates were found to range from 56 to 1047 $\text{Mg km}^{-2}\,\text{a}^{-1}$ (Zhu and Lin, 1995). Using large watershed monitoring data combined with the Geographic Information System (GIS) and the Revised Universal Soil Loss Equation (RUSLE), some other researchers studied soil erosion under different LULC conditions. These studies showed that the annual soil loss in the Maotiao River watershed was between 5 and 80 $\text{Mg ha}^{-1}\,\text{year}^{-1}$, with a mean value of 28.7 $\text{Mg ha}^{-1}\,\text{year}^{-1}$. The soil loss was closely related with land use, rainfall erosivity and topography (Xu et al., 2008). However, these results of the soil erosion rate in this area exhibited remarkable variations due to the different petrologic assemblages, monitoring methods, and scales. Moreover, since large scale studies can hardly indicate accurate water and soil loss rates at slope scales in the karst system, it is very difficult to quantify the processes of water and soil loss under different rainfall regimes.

In the present study, we investigated surface runoff and soil loss during rainfall events from 2007 to 2010 under 6 different land use conditions at the Puding Karst area (26°15′36″N, 26°15′36″E) of Guizhou Province. We analyzed the effects of land use on soil and water loss on karst limestone hill slopes to elucidate the relationship between surface runoff generation, soil loss on karst limestone hill slopes, and different types of rainfall regimes. We further assessed the soil erosion risk on karst limestone hill slopes in different LULC under the subtropical monsoon climate condition.

## 2. Materials and methods

### 2.1. Area of study

The studied area is a small catchment in Puding County (26°15′36″N, 26°15′36″E) in Guizhou Province, southwest China. This catchment is a ‘normal’ karst hill peak-cluster depression landform, with an area of 1.29 $\text{km}^2$ and an elevation of 1316–1500 m above sea level (Fig. 1). The studied area has a subtropical monsoonal climate with an annual precipitation of 1300 mm. Rainfall mainly occurs between May and October. The temperature of this area ranges from −1 °C to 28 °C, with an annual average of 14 °C. The highest monthly temperature is in July and the lowest is in January.

The dominant lithology in this catchment is the pure and thick limestone of the Guanling Formation of the Middle Triassic (Fig. 1b). The limestone has a less than 10° dip angle. Soil, commonly 20–50 cm in thickness, occurs on most slopes. The soil has a clay content of 24–32.5% and a density of 1.13 $\text{g/cm}^3$. The organic matter content of the soil is 69.8–136.6 g/kg. The vegetation in the catchment is mainly broad-leaved deciduous shrubs and evergreens. The agriculture fields and pastureland are mainly located from mountain slope side to bottom. Crops commonly grown are corn, soybeans, and rape oil seed.

Six types of field slope can be identified on the karst limestone hills of the catchment, including Burned Area Recovered (BAR), Burned Area Uncovered (BAU), Young Forestland (YFL), Cropland (CL), Pastureland (PL), and Combination Vegetation Land (CVL) (Table 1 and Fig. 2). The surface runoff and soil loss were measured for each slope type using the large runoff field method. The BAR is on the upper part of a mountain slope. The vegetation was burned out by a wildfire in February 2007, and the area was covered with new shrubs and grass the same year. The BAU, near the BAR, was also burned in 2007 and was

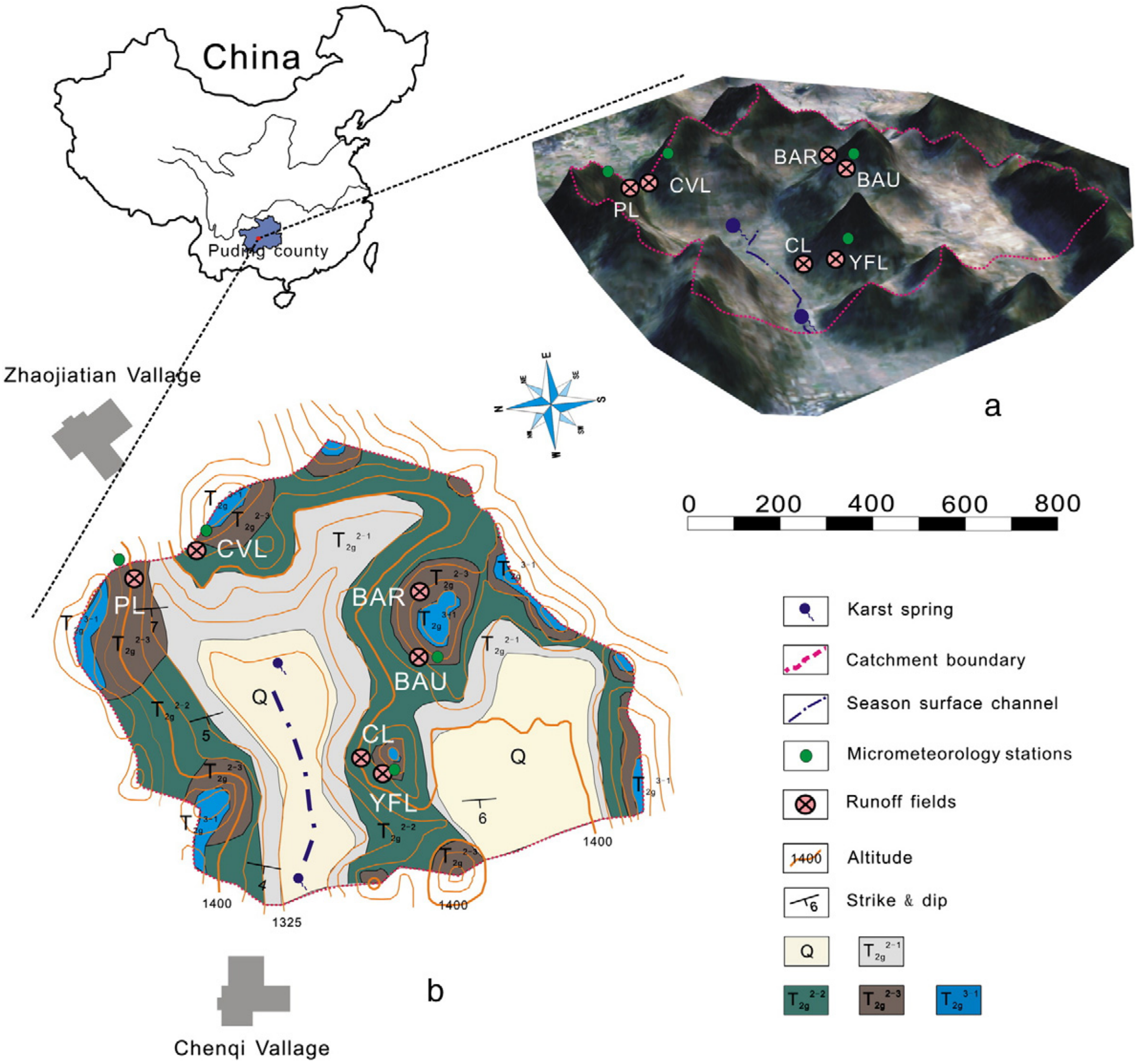

**Fig. 1.** Geographic map (a) and hydrogeological map (b) of the studied catchment. The geographic map was generated using ERDAS IMAGINE software based on the remote sensing image. Q: Quaternary deposits; $T_{2g}^{2-1}$: marl intercalated with limestone of the lower part of the middle part of the middle Guanling Formation of the Middle Triassic; $T_{2g}^{2-2}$: limestone intercalated with marl of the middle part of the middle Guanling Formation of the Middle Triassic; $T_{2g}^{2-3}$: limestone of the upper part of the middle Guanling Formation of the Middle Triassic; $T_{2g}^{3-1}$: dolomite of the upper Guanling Formation of the Middle Triassic. Large runoff fields were on karst limestone slopes in different LULC including Burned Area (Recover) (BAR), Burned Area (Uncover) (BAU), Young Forestland (YFL), Cropland (CL), Pastureland (PL), and Combination Vegetation Land (CVL).

recovered by shrubs and grass until 2008. However, all the recovered vegetation in the BAU was cleared again by cutting and burning between 2009 and 2010. The YFL is a mountain slope that was deforested in the 1980s and reforested in 2000. The CL field is located at the lower part of the mountain slope in the catchment where agriculture activities are very active. Corn is one of the main crops in this field from May to September, and rape oil seed from December to the following March. The PL field is a field over-grazed by cows since 1980; human activities are also so frequent that the vegetation coverage in this field is very poor. A stone coverage of more than 50% was classified

**Table 1**
Summary of characteristics of large runoff fields.

| Fields | Land use | Slope (°) | Position | Surface (m$^2$) | Wood (%) | Shrubs (%) | Grass (%) | Stone (%) | Main vegetation species |
|---|---|---|---|---|---|---|---|---|---|
| BAR | Burned (2007) | 37 | Upper | 1255 | 0 | 0 | 0 | 40 | Nothing |
| | Recover (2008–2010) | | | | 0 | 50 | 80 | | *Pyracantha fortuneana*, *Pteridophyta*, *Rosa cymosa* |
| BAU | Burned (2007) | 32 | Upper | 684 | 0 | 30 | 50 | 40 | Nothing |
| | Recover (2008) | | | | 0 | 50 | 80 | | *Pteridophyta*, *Rosa cymosa* |
| | Cutting (2009–2010) | | | | 0 | 10 | 20 | | Nothing |
| YFL | Reforest | 35 | Middle | 1146 | 85 | 50 | 20 | 30 | *Platycarya longipea*, *Lithocarpus*, *glaber Itea yunnanensis*, *Kalopanax septemlobus* |
| CL | Tillage | 30 | Foot | 2440 | 5 | 0 | 0 | 30 | Corn, soybeans, and rape oil seed |
| PL | Grazing | 33 | Foot | 2890 | 0 | 45 | 10 | 50 | *Pyracantha fortuneana*, *Rosa cymosa* |
| CVL | Wood (upper) | 36 | Foot | 2439 | 90 | 20 | 20 | 30 | *Quercus fabric*, *Platycarya longipea* |
| | Grass (lower) | | | | 0 | 10 | 80 | | *Kalopanax septemlobus* |

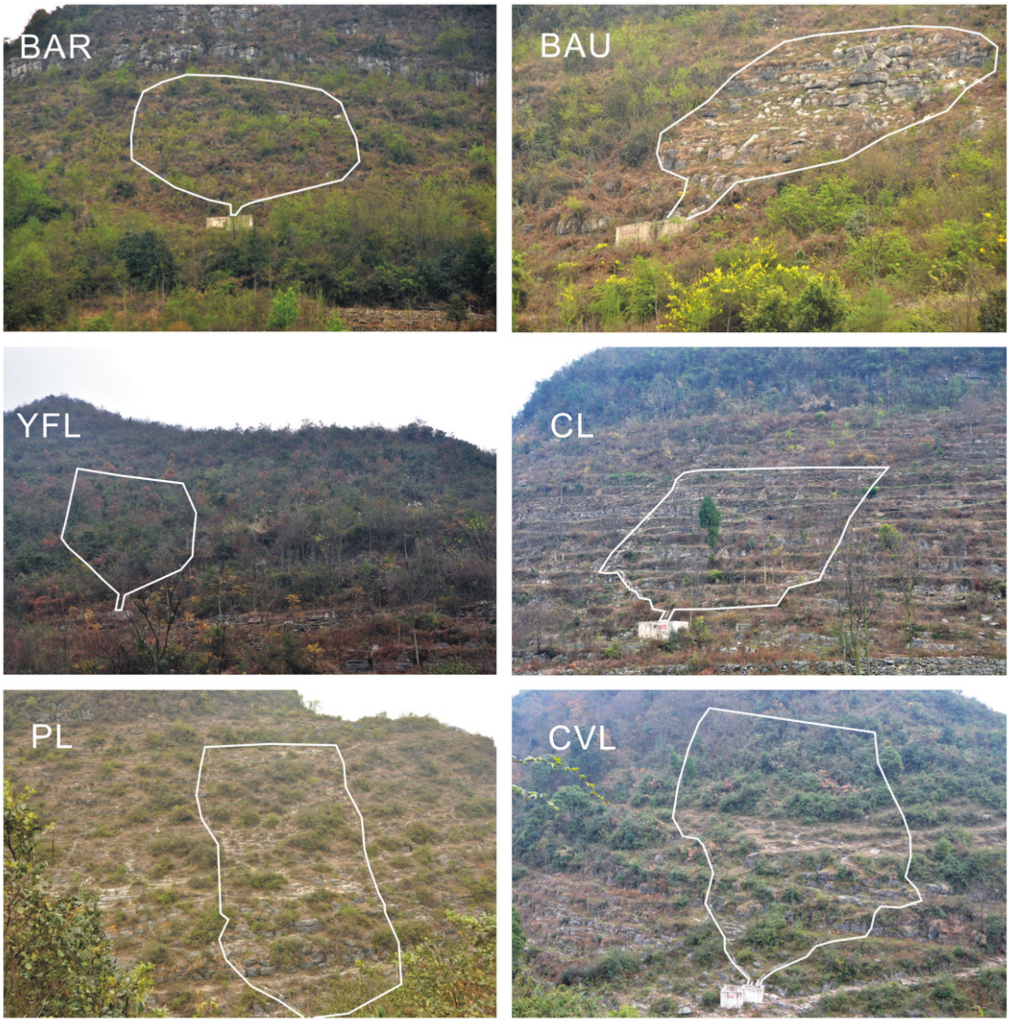

**Fig. 2.** Photos of large runoff fields and runoff tanks in different types of land use and land cover on limestone hill slopes.

as a moderate RKD area. The CVL is a field covered with a mixed vegetation, which consists of evergreens and broad-leaved deciduous vegetation on the upper mountain and grass and shrubs on the lower mountain. In accordance with the site-specific topography of the mountain slopes, each of these six large runoff fields was surrounded by concrete blocks projecting 10–15 cm above ground to prevent outside runoff from entering the studied fields (Fig. 2). Runoff and coarse soil materials were collected using sedimentation tanks installed in the outlet of each field type. Each tank was connected to a square shaped pool. The runoff in the square pool accounted for one-eighth of the total runoff generated in the field. The depth of the runoff in the tanks and square pools was measured after each rainfall event, and 500 ml runoff water was sampled in the square pools after stirring and mixing right after the rainfall event ended. After measurement and sampling, the runoff water in the tanks and pools was cleaned and the coarse soil materials in the tanks were weighed. Runoff samples collected in the square pools were filtered to measure the suspended-sediment concentration on a dry base and the suspended-sediment loss was calculated by the suspended-sediment concentration times the corresponding runoff volume. The total suspended-sediment loss plus the total coarse soil materials was referred to as the total soil loss in the large runoff field. Four individual meteorology stations were installed in the BAU, YFL, PL and CVL runoff fields (Fig. 1). The precipitation was automatically recorded using a tipping-bucket system at 2-min intervals.

### *2.2. Statistical analysis and clustering analysis*

Data of four consecutive years were used to study the surface runoff coefficients and soil loss on karst limestone slopes from 2007 to 2010. Surface runoff coefficients were calculated as follows:

$$C = (SR/P) * \%$$

where SR and P are the surface runoff depth and rainfall depth of a given rainfall event.

Clustering analysis is a convenient tool widely used in scientific fields. It groups objects based on their similarities. There are two clustering methods, k-means clustering and hierarchical clustering. The number of clusters is given before statistical analysis for K-means clusters, whiles the number of clusters obtained by automatically statistical analysis for the hierarchical clustering. We chose the hierarchical clustering method to divide the recorded rainfall events according to the depth, maximum 30-min intensity, and duration of the rainfall.

## 3. Result

### *3.1. Rainfall regimes*

Based on the depth, maximum 30-min intensity, and duration of the rainfall, the 61 rainfall events recorded from 2007 to 2010 were divided into five Rainfall Regime groups (Table 2) using the hierarchical clustering method (Perruchet, 1983). Rainfall Regime V represents the extreme rainfall storm with a very great rainfall depth and intensity. Rainfall Regime IV is the rainfall storm that has high rainfall depth and intensity, but shorter duration than Rainfall Regime V. Rainfall Regime III is the rainfall event with great rainfall depth and duration, but low rainfall intensity. Rainfall Regime II is the rainfall event with high rainfall intensity and very short duration, and the rainfall depth is not as great as in Rainfall Regimes IV and V. Rainfall Regime I is the moderate rainfall event that has a middle rainfall depth, intensity and duration.

During the measurement periods, Rainfall Regime I had 17 times events in the catchment, with a total rainfall depth of 452 mm. Rainfall Regimes IV and II occurred 19 and 16 times, respectively. Rainfall Regimes V and III only happened 5 and 4 times, respectively (Table 2). The distribution of the Rainfall Regimes showed remarkable variations (Fig. 3) among different years. For instance, Rainfall Regimes IV and V had very high proportions of annual rainfall depth every year, but their rainfall depth in 2010 were limited (Fig. 3a). Rainfall events were mostly for Rainfall Regimes I, II and IV in 2007, 2008 and 2009, while all rainfall events in 2010 were exclusively for Rainfall Regimes I, III and IV (Fig. 3b).

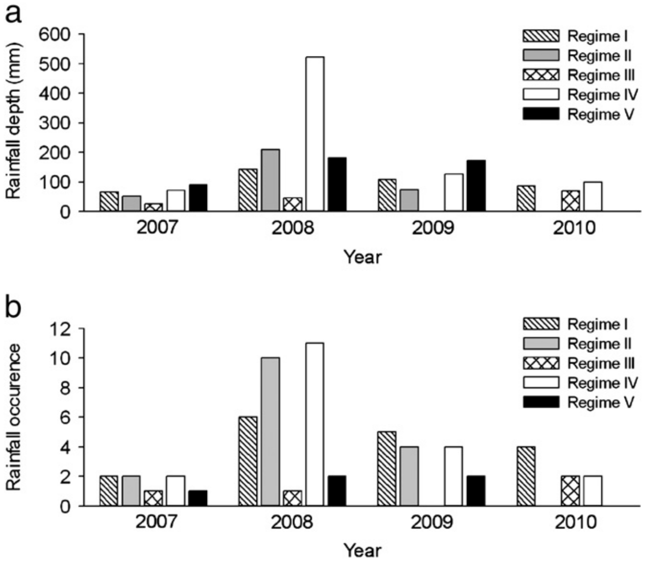

**Fig. 3.** 61 rainfall events from 2007 to 2010 in the catchment were divided into 5 types of Rainfall Regimes. (a) is the distribution of rainfall depth and (b) is the occurrence rates of rainfall events of different types of Rainfall Regimes.

### *3.2. Annual surface runoff and soil loss of different types of land use*

Tables 3 and 4 showed the results of annual surface runoff and soil loss on karst limestone hill slopes for the six types of land use from 2007 to 2010. Pastureland (PL) exhibited the greatest annual surface runoff ranging from 0.11% to 4.53%. The mean annual surface runoff of the other 5 types of land use descends in an order of CVL > BAU > CL > BAR > YFL. The mean annual soil loss, however, had a different trend from the annual surface runoff. The PL exhibited the greatest annual soil loss from 0.43 to 69.31 Mg km$^{-2}$. The BAU exhibited the second greatest loss of soil, followed by the CL and CVL, and then the BAR and YFL. The BAR and YFL both had very low annual surface runoff and soil loss, which was minimal compared to the other land use types. Interestingly, compared to the BAR, YFL and CVL, the BAU and CL generated lower annual surface runoff, but yielded greater soil loss. Also, the annual surface runoff of the CVL ranged between 0.11% and 3.08%, which was almost as great as the PL, while its soil loss was very low and ranged from 0.02 to 3.81 Mg km$^{-2}$.

The annual surface runoff and soil loss varied among different years (Fig. 4). The annual surface runoff and soil loss were correlated between the PL and CVL. For instance, the highest surface runoff coefficient and soil loss of the PL in 2008 were 4.53% and 69.31 Mg km$^{-2}$, respectively, while the lowest in 2010 were 0.11% and 0.43 Mg km$^{-2}$, respectively (Fig.4e and Fig.4f). The other types of land use were not correlated with each other. There was no large variation in annual surface runoff among the BAR, BAU and YFL. The soil loss of the BAR and YFL both showed a tendency to decrease from 2007 to 2010 (Fig. 4a and Fig. 4c). There was no significant change in the annual surface runoff of the BAU from 2007 to 2010, but its soil loss was first decreased to 4.35 Mg km$^{-2}$ in 2008 and then increased to 9.91 Mg km$^{-2}$ in 2009 (Fig. 4b). The greatest annual surface runoff of the CL was 0.85% in 2007 (Fig. 4d and Table 3), but its soil loss was as low as about 1.17 Mg km$^{-2}$. The highest annual soil loss of the CL was about 9.14 Mg km$^{-2}$ in 2008, but its annual runoff coefficient was just 0.68%.

**Table 2**
Statistical feature of the rainfall regimes.

| Rainfall regime | Eigenvalue | Mean | Std. dev | Sum | Frequency |
|---|---|---|---|---|---|
| I | P (mm) | 23.7 | 7.0 | 403 | |
| | $I_{30}$ (mm h$^{-1}$) | 8.32 | 6.9 | | 17 |
| | RD (min) | 730 | 393 | 13,870 | |
| II | P (mm) | 20.8 | 7.7 | 309 | |
| | $I_{30}$ (mm h$^{-1}$) | 23.1 | 5.6 | | 16 |
| | RD (min) | 208 | 173 | 3120 | |
| III | P (mm) | 35.3 | 12.8 | 141 | |
| | $I_{30}$ (mm h$^{-1}$) | 5.0 | 1.6 | | 4 |
| | RD (min) | 2686 | 482 | 10,745 | |
| IV | P (mm) | 43.0 | 14.7 | 818 | |
| | $I_{30}$ (mm h$^{-1}$) | 29.0 | 11.9 | | 19 |
| | RD (min) | 498 | 382 | 8965 | |
| V | P (mm) | 88.9 | 5.5 | 445 | |
| | $I_{30}$ (mm h$^{-1}$) | 39.6 | 9.0 | | 5 |
| | RD (min) | 1088 | 436 | 5440 | |

P: Rainfall depth.
$I_{30}$: Maximum 30-min intensity.
RD: Rainfall duration.

### *3.3. Water and soil loss under rainfall regimes on various karst limestone hill slopes*

Fig. 5 showed the characteristics of the mean surface runoff coefficients and the mean soil loss of Rainfall Regime events in different types of land use. In general, the runoff depth and soil loss among land use types were in decreasing order as follows: Rainfall Regime V > IV > II > I > III. Rainfall Regimes V and IV showed the most runoff and soil loss, while Rainfall Regimes I and III showed minimal water and soil loss. Rainfall Regime II showed more runoff and soil loss than Rainfall Regimes I and III, but less than Rainfall Regimes IV and V.

Under all types of Rainfall Regime, the water and soil loss in the BAR and YFL were very low. However, the water and soil loss in other slopes varied greatly among Rainfall Regimes. Rainfall Regimes V, IV and II created large runoff and soil loss in the CL, PL and CVL, while under other Rainfall Regimes the water and soil were relatively low. Although the surface runoff in the CVL was as large as in

**Table 3**
Annual surface runoff coefficients on limestone hill slopes in different land use type slopes (2007–2010).

| Year | Precipitation (mm) | Annual surface runoff coefficients (%) | | | | | |
|---|---|---|---|---|---|---|---|
| | | BAR | BAU | YFL | CL | PL | CVL |
| 2007* | 553 | 0.19 | 0.42 | 0.17 | 0.85 | 1.25 | 2.16 |
| 2008 | 1401 | 0.27 | 0.58 | 0.20 | 0.68 | 4.53 | 3.08 |
| 2009 | 861 | 0.23 | 0.60 | 0.21 | 0.13 | 2.81 | 1.92 |
| 2010 | 702 | 0.15 | 0.34 | 0.16 | 0.10 | 0.11 | 0.11 |
| Mean | 879 | 0.21 | 0.49 | 0.19 | 0.44 | 2.18 | 1.82 |

2007*:Surface runoff coefficients were recorded from July to December.

**Table 4**
Annual soil loss on limestone slopes in different land use types (2007–2010).

| Year | Annual soil loss (Mg km$^{-2}$ year$^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | BAR | BAU | YFL | CL | PL | CVL |
| 2007* | 1.04 | 12.59 | 0.84 | 1.17 | 19.19 | 2.06 |
| 2008 | 0.50 | 4.35 | 0.11 | 9.14 | 69.31 | 3.81 |
| 2009 | 0.03 | 9.91 | 0.04 | 0.04 | 57.61 | 2.17 |
| 2010 | 0.04 | 0.10 | 0.06 | 0.05 | 0.43 | 0.02 |
| Mean | 0.40 | 6.74 | 0.26 | 2.60 | 36.64 | 2.02 |
| Sum | 1.61 | 26.95 | 1.05 | 10.40 | 146.53 | 8.06 |

2007*:Soil loss was recorded from July to December.

the PL under Rainfall Regimes V and IV, its soil loss was limited. The BAU only created large runoff and soil loss under Rainfall Regime V.

The daily runoff coefficients and soil loss were recorded 8–30 times a year from 2007 to 2010. The number of runoff events included the rainy days with a daily rainfall greater than 10 mm (Fig. 6). The distribution of the daily surface runoff and total soil loss in the land use types changed greatly from 2007 to 2010, depending on the type of Rainfall Regime. In 2007 and 2008, most of the surface runoff and soil loss was from Rainfall Regimes II, IV and V. In 2009, water and soil loss were created only by Rainfall Regime V. In 2010, there was no Rainfall Regimes V or II, and Rainfall Regime IV was only recorded twice (Fig. 2). The surface runoff and soil loss in 2010 were very minimal for the 5 types of Rainfall Regime, and the daily surface runoff coefficients and soil loss were, respectively, <2% and 0.3 Mg km$^{-2}$ for all types of land use runoff fields (Fig. 6).

Under Rainfall Regimes I and III, the variations in the daily surface runoff coefficients and soil loss among all types of land use slopes were very small, ranging from 0 to 1.5% and 0 to 2.01 Mg km$^{-2}$, respectively (Fig. 6). Under Rainfall Regime V, however, the daily surface runoff coefficient and soil loss varied greatly among different land use types. The daily surface runoff coefficients in the PL and CVL were larger than in other land use slopes, and the daily soil loss in the PL was very high (Fig. 6). While the daily surface runoff and soil loss in all types of land use slopes were still very minimal for most rainfall events of Rainfall Regimes II and IV, some rainfall events of Rainfall Regimes II and IV created large daily surface runoff and soil loss in the CL, PL and CVL due to the influence of the rainfall amount, rainfall intensity, and preceding rainfalls right before the main rainfall storms (Tables 5 and 6). For instance, rainfall events on 05/26/2008, 05/27/2008, and 08/03/2008 had large preceding precipitations on the previous day (Table 5 and Fig. 6), and thus produced more surface runoff and soil loss than rainfall events of the same Rainfall Regime on other dates such as 7/30/2007 and 9/3/2008 (Fig. 6). The data showed that if the preceding precipitation was less than 40 mm (e.g. 4/19/2008) or if the maximum 30-min rainfall intensity of the main rainfall storms was less than 30 mm h$^{-1}$ (e.g. 5/23/2008), large surface runoff or soil loss would not be generated (Table 5 and Fig.6).

The independent rainfall storms of Rainfall Regime IV on 07/22/2007, 07/22/2008, and 08/16/2008 also caused large daily surface runoff and soil loss in the PL and CVL, when a rainfall depth of more than 40 mm and a maximum 30-min intensity of 30 mm h$^{-1}$ were both met (Table 6). Otherwise, Rainfall Regime IV did not create large runoff or soil loss on limestone slopes (Fig. 6).

## 4. Discussion

### 4.1. Effects of LULC on surface runoff and soil loss on karst limestone slopes

The amount of annual surface runoff and soil loss varied significantly for each type of land use (Tables 3 and 4). Thus, vegetation coverage might be one of the most important factors controlling surface runoff and soil loss (Francis and Thornes, 1990; Rogers and Schumm, 1991; Andreu et al., 1998). Increasing the vegetation coverage rate is usually a very effective strategy to reduce soil erosion in dry rangelands (Higgitt, 1993), because vegetation can enhance infiltration and reduce surface runoff (Cerdà, 1999). For instance, after a 10-year vegetation restoration effort on severely eroded land, the soil loss rate was dramatically reduced to 2–43 Mg ha$^{-1}$ year$^{-1}$, compared to the rate of 53–256 Mg ha$^{-1}$ year$^{-1}$ before the vegetation restoration (Zhang et al., 2004). Rainfall simulation experiments on limestone slopes in Israel also showed that plots located within shrubs cannot produce pounding and runoff. However, on the inter-shrub surface, pounding, surface runoff and sediments occurred, which eventually enriched the

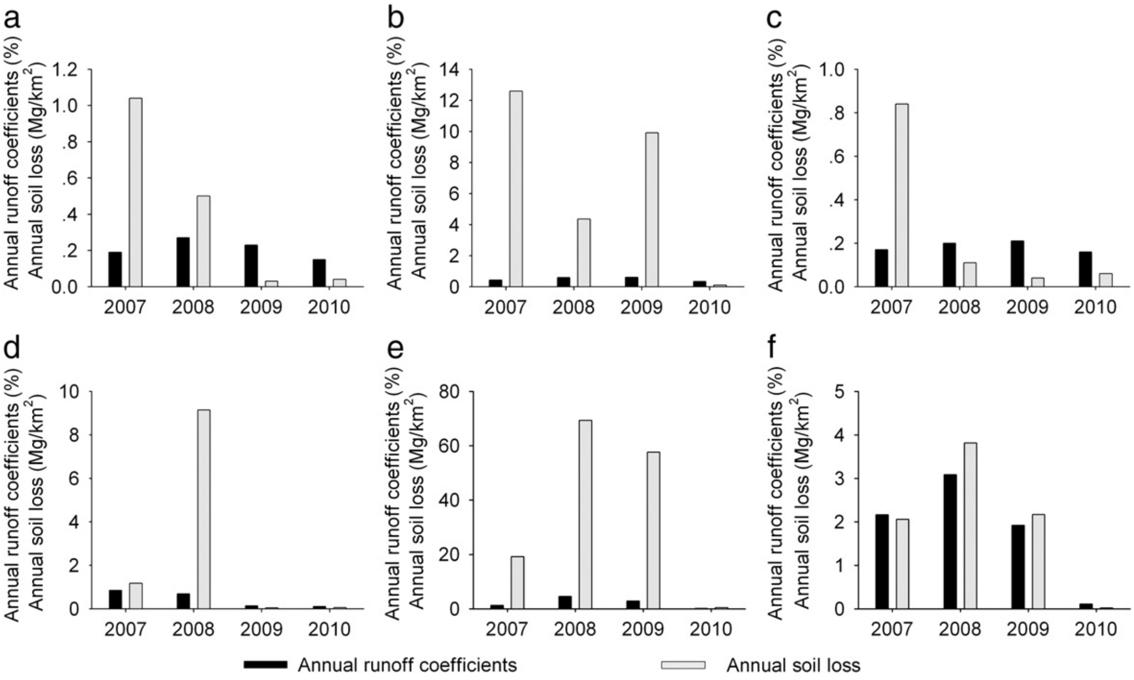

**Fig. 4.** Variation of annual surface runoff coefficients and annual soil loss in each runoff field from 2007 to 2010, (a): Burned Area (Recover), (b): Burned Area (Uncover), (c): Young Forestland, (d): Cropland, (e): Pastureland and (f): Combination Vegetation Land.

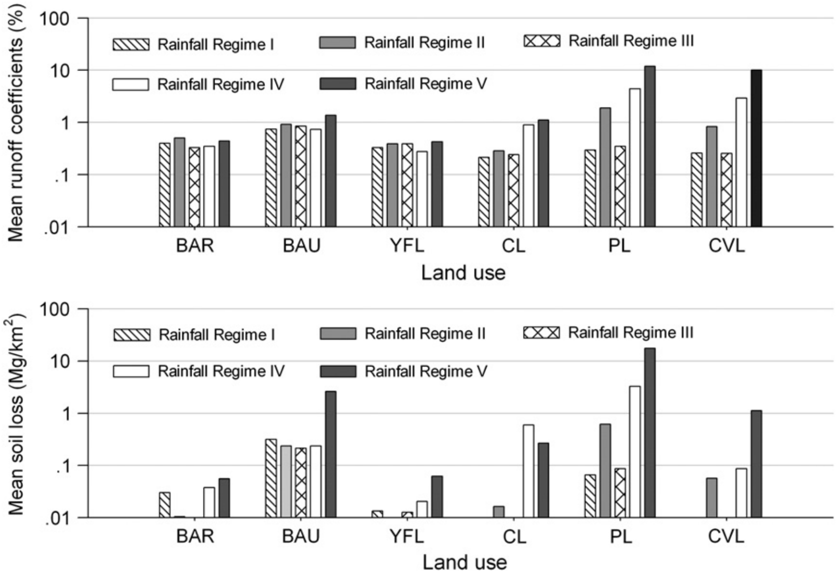

**Fig. 5.** Mean surface runoff coefficient and mean soil loss of each type of Rainfall Regime events in the land use of limestone hill slopes. Times of each type of Rainfall Regime were shown in Table 2.

shrub patches (Cerdà, 1998a, 1998b). Consistent with this notion, the present study indicated that since the vegetation in the BAR and BAU, most of which was pteridophyta and vines, continuously recovered after the wildfire in 2007, soil loss decreased dramatically from 2007 to 2008. However, after the second destruction of vegetation in BAU in 2009, the soil loss increased significantly. On the other hand, soil loss decreased to 0.03-0.04 Mg km$^{-2}$ in BAR as regenerative plants grew from 2007 to 2010 after 4 years vegetation restoration (Fig. 4). It was realized that increasing vegetation coverage plays an important role in protecting topsoil against rainfall splash and detachment on limestone slopes, and a well-developed root system can enhance soil porosity and thus increase the ability of soil to hold moisture and its infiltration capacity (De Baets et al., 2006; Gyssels et al., 2005).

In addition, human activities play an important role in surface runoff and soil loss. Our results indicated that surface runoff and soil loss in the pasturelands were the highest, because vegetation cover in the pasturelands is low and is distributed in a patched mosaic of shrubs. Inter-patch areas vegetated by grass, which suffers from overgrazing by cows, are dominant in this field, and the soil in the inter-shrub areas was frequently trampled, resulting in high soil bulk density,

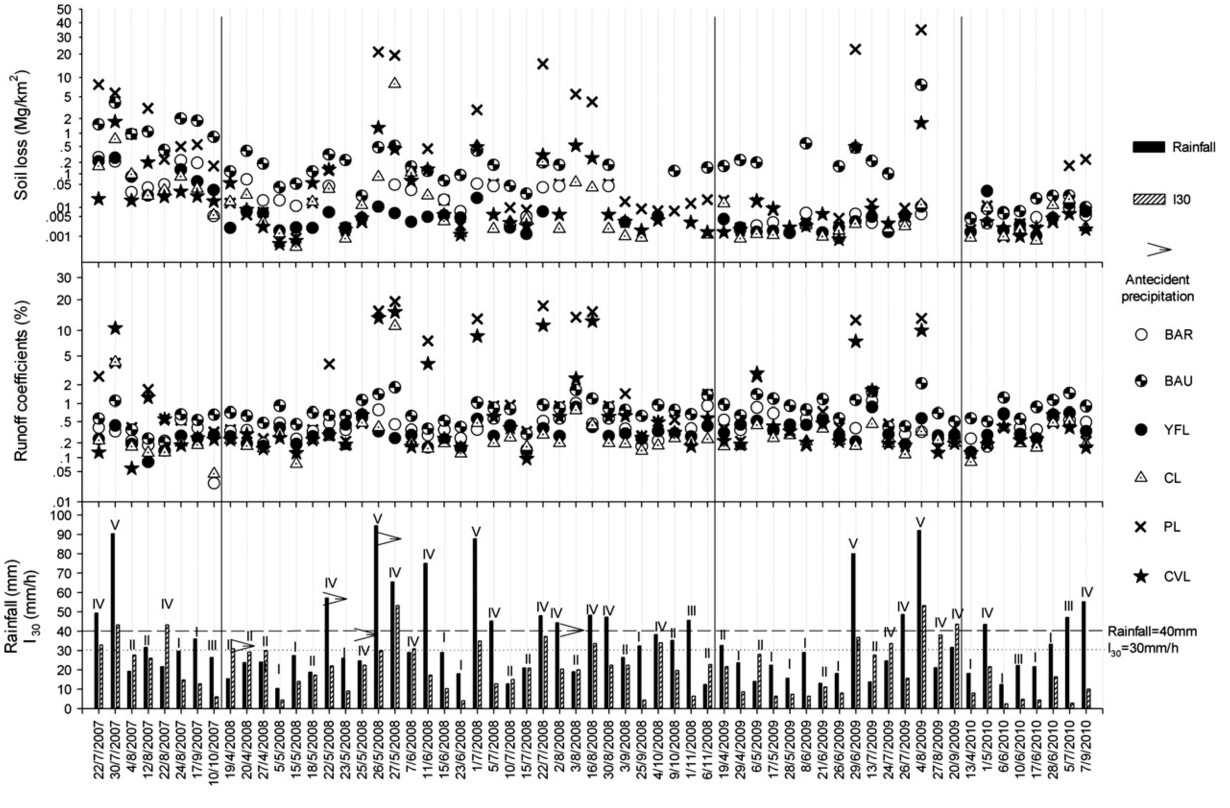

**Fig. 6.** Rainfall depth, I$_{30}$, runoff coefficients, and soil loss in each rainfall event in different land use types of slopes from 2007 to 2010. I$_{30}$ is maximum 30 min rainfall intensity, I–V: rainfall events with different types of Rainfall Regimes.

**Table 5**
Daily runoff coefficient and soil loss in Cropland, Pastureland and Combination of Vegetation Land for the rainfall storms with preceding precipitation.

| Date | P (mm) | $I_{30}$ (mm $h^{-1}$) | RD (min) | ATR (mm) | RR | Runoff Coefficients (%) | | | Soil loss (Mg $km^{-2}$) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | CL | PL | CVL | CL | PL | CVL |
| 4/19/2008* | 15.4 | 30.8 | 30 | 0 | II | 0.23 | 0.36 | 0.23 | 0.01 | 0.01 | 0.06 |
| 4/20/2008# | 23.8 | 29.2 | 130 | 15.4 | II | 0.17 | 0.30 | 0.29 | 0.02 | 0.01 | 0.01 |
| 5/22/2008* | 57.0 | 22.0 | 640 | 0 | IV | 0.26 | 3.93 | 0.28 | 0.04 | 0.13 | 0.13 |
| 5/23/2008# | 26.0 | 9.0 | 465 | 57 | I | 0.17 | 0.22 | 0.18 | 0.00 | 0.00 | 0.00 |
| 5/25/2008* | 24.6 | 22.4 | 485 | 0 | I | 0.47 | 0.47 | 0.66 | 0.01 | 0.00 | 0.00 |
| 5/26/2008#* | 78.8 | 30.0 | 555 | 24.8 | V | 0.39 | 15.81 | 13.55 | 0.08 | 21.20 | 1.30 |
| 5/27/2008# | 65.4 | 53.2 | 235 | 78.8 | IV | 11.19 | 19.33 | 15.44 | 7.99 | 19.33 | 0.43 |
| 8/2/2008* | 44.4 | 20.4 | 500 | 0 | IV | 0.20 | 0.92 | 0.61 | 0.00 | 0.05 | 0.01 |
| 8/3/2008# | 19.0 | 20.0 | 50 | 44.4 | II | 0.79 | 13.81 | 2.48 | 0.06 | 5.54 | 0.53 |

P: Rainfall depth; $I_{30}$: Maximum 30-min intensity; RD: Rainfall duration; ATR: Antecedent Precipitation the day before storms; RR: Rainfall Regimes. Date*: The antecedent precipitation; Date#: the main rainfall storms.

which has been suggested to reduce soil porosity and infiltration capacity (Boix et al., 1995; Dadkhah and Gifford, 1980; Mwendera and Saleem, 1997; Zhou et al., 2010). Similar results can also be found in the Israel simulation rainfall experiments — grazing modified the soil surface between shrubs, decreased the infiltration rates and caused the development of a surface crust. Overgrazing led to favored higher surface runoff and sediment concentration than on sites without overgrazing (Cerdà, 1998a, 1998b).

Croplands are strongly affected by agricultural activities (crops are usually sown in May and harvested at the end of July); plowing and tillage could improve soil infiltration capacity during the periods of heavy rainfall events. Therefore, surface runoff and soil loss in the croplands were very small for most rainfall events, and large runoff and soil loss in this type of field could only be generated by heavy rainfall storms with over 40 mm antecedent precipitation (e.g. 5/27/2008). The combination of LULC has obvious positive effects on controlling soil loss on limestone slopes, because it could change the hydrological process and the erosion system (Fu et al., 2009; Vandaele and Poesen, 1995). In CVL, the primary vegetation was forest land (at upper slopes) and grass land (at lower slopes), which had high runoff coefficients in most Rainfall Regime V storms but very low soil loss, indicating that a proper combination of different vegetation and land use types is an appropriate way to control soil loss on the karst limestone slopes.

### 4.2. Response of surface runoff and soil loss to the rainfall regimes

In our studied area, Rainfall Regime V was a less frequent type of rainfall event, but its annual rainfall depth was very great. The surface runoff and soil loss under Rainfall Regime V were much greater than those of other Rainfall Regimes, suggesting that those of Rainfall Regime V were the most destructive type of rainfall events on karst limestone slopes, especially on pastureland. Although the other Rainfall Regimes had large percentages of total rainfall events, their water and soil loss was very low. In other non-karst areas, such as the loess plateau of China and semi-arid regions, most of the water and soil loss was induced by rainfall events with high rainfall intensity within a short period thunderstorm (Rainfall Regime II) (Wei et al., 2007). Runoff generation has been commonly attributed to an infiltration excess mechanism (Yair, 1996). However, when the climate condition varies from arid to humid, both saturation and Hortonian mechanisms can be responsible for the generation of surface runoff (Calvo-Cases et al., 2003). The sediment concentration, erosion rates and surface runoff on limestone slopes usually have a negative relationship with the mean annual rainfall (Cerdà, 1998a, 1998b) because the presence of a dual hydrological structure that includes ground and underground drainage systems on humid karst limestone slopes increases the threshold of the surface runoff and changes the runoff generation mechanism.

Surface runoff and soil loss on karst limestone slopes were not simply related to one single rainfall eigenvalue (rainfall depth or intensity or duration). The inter-influence of these rainfall eigenvalues and other factors such as antecedent rainfall depth all contribute to the surface runoff and soil loss on karst limestone slopes. During rainfall storms with large antecedent precipitation, surface runoff and soil loss in pastureland or cropland were higher compared to rainfall storms without antecedent rainfall (Table 5). This phenomenon can also be observed in Rainfall Regime II, in which the surface runoff and soil loss in pastureland were as high as 13.81% and 5.54 Mg km$^{-2}$ (8/3/2008), respectively. These results suggested that antecedent precipitation had a strong impact on the generation of surface runoff and soil loss on limestone slopes during rainfall events. One explanation is that the antecedent precipitation increased the antecedent soil moisture before the main storms occurred and thus could reduce the water buffering capacity of the soil (Boix et al., 1995). One alternative possibility is that the antecedent precipitation could recharge and saturate the karst limestone fissures and fractures which usually reduce surface runoff. In the present study, our results indicated that if the antecedent precipitation event was large enough, e.g. 40 mm, it might be able to increase surface runoff and soil loss. However, in the case of rainfall intensity of less than 30 mm h$^{-1}$ for the main rainfall storm, the antecedent precipitation (e.g. 5/22/2008) could not significantly increase surface runoff or soil loss in the main rainfall storm (5/23/2008) even if it was large enough. Because the low intensity rainfall did not reach the saturation excess runoff phase in the karst limestone permeable slopes, recharge water rapidly infiltrated underground through fissures and fractures.

In addition, the results of daily runoff and soil loss in the independent rainfall events under Rainfall Regimes IV and V indicated that the co-effects of rainfall depth and intensity were very important for the generation of runoff and soil loss (Table 6). In karst limestone slopes in the sub-tropical humidity environment, the runoff generation mechanism may not be adapted to the conventional saturation excess runoff, thus the limestone fissures and fractures could influence the processes of infiltration and runoff generation during the rainfall. Runoff was generated in karst limestone slopes when both soil and limestone fissures and fractures were fully saturated with water. When the rainfall intensity was greater than the infiltration rates of limestone fissures and fractures during the soil and carbonate rock saturated phase, conventional saturation excess runoff would occur. In this area, rainfall events with a rainfall depth of more than 40 mm and a maximum 30-min rainfall intensity of over 30 mm h$^{-1}$ could maintain the saturation excess mechanism and create large runoff and soil loss (Table 6). However, this threshold might be affected by vegetation coverage, soil properties, and limestone infiltration rates.

### 4.3. The characteristics of soil loss and erosion risk on karst limestone slopes

The data of surface runoff coefficients and soil loss in all types of LULC on karst limestone slopes reported here was much lower than

**Table 6**
Daily runoff coefficient and soil loss in Cropland, Pastureland and Combination of Vegetation Land for the rainfall storms without preceding precipitation and with rainfall depth > 40 mm and maximum 30 min rainfall intensity $I_{30} > 30$ mm $h^{-1}$.

| Date | P (mm) | $I_{30}$ (mm $h^{-1}$) | RD (min) | ATR (mm) | RR | Runoff Coefficients (%) | | | Soil loss (Mg $km^{-2}$) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | CL | PL | CVL | CL | PL | CVL |
| 07/22/2007 | 49.4 | 32.8 | 780.0 | 4.4 | IV | 0.22 | 2.65 | 0.13 | 0.16 | 7.85 | 0.02 |
| 07/30/2007 | 90.4 | 43.2 | 825.0 | 4.8 | V | 4.16 | 4.05 | 10.61 | 0.73 | 5.78 | 1.73 |
| 07/1/2008 | 87.8 | 34.8 | 1120.0 | 0.0 | V | 0.47 | 13.23 | 8.66 | 0.51 | 2.94 | 0.48 |
| 07/22/2008 | 48.0 | 37.2 | 775.0 | 0.8 | IV | 0.29 | 17.68 | 11.37 | 0.21 | 15.23 | 0.31 |
| 08/16/2008 | 48.2 | 33.6 | 595.0 | 0 | IV | 0.43 | 15.57 | 12.56 | 0.04 | 4.10 | 0.26 |
| 06/30/2009 | 80.0 | 36.8 | 1265.0 | 1.8 | V | 0.17 | 12.89 | 7.55 | 0.00 | 22.59 | 0.49 |
| 08/4/2009 | 92.0 | 53.2 | 1700.0 | 0.0 | V | 0.33 | 13.43 | 10.04 | 0.01 | 34.95 | 1.63 |

P: Rainfall depth; $I_{30}$: Maximum 30-min intensity; RD: Rainfall duration; ATR: Antecedent Precipitation the day before storms; RR: Rainfall Regimes.

that of non-karst limestone hill slopes, indicating that the epikarst zone (subcutaneous zone) of carbonate bedrock could also play a very important role in runoff and soil loss. Because epikarst has a high porosity and permeability and is able to store and transport water, it might delay the rainfall impact and redistribute precipitation (Williams, 2008). The occurrence of epikarst is determined by lithology, structure, geomography history and climate (Williams, 2004). Cerdà et al. evaluated the effect of climate on surface flow and soil loss along a climatological gradient on limestone slopes in Israel. In the arid sites (<400 mm $year^{-1}$), direct surface runoff took place, the overland flow discharge and the soil loss were quite high, and the runoff coefficients ranged from 48 to 94%. However, under the wetter conditions (>500 mm $year^{-1}$) overland flow did not occur, or was negligible; the maximum runoff coefficients was 21% and the minimum was 0%. It indicated that vegetation cover is not the only thing retarding surface runoff and soil loss, and another important factor is epikarst development, which is influenced by the annual rainfall and temperature. The epikarst in southwest China under the subtropical monsoon climate is quite different from the arid and semi-arid karst regions in the world. The epikarst in our research area was usually 2–5 m thick with a porosity of 3.5% on the mountainside, and could store rainfall water from 53 to 159 mm (Zhang et al., 2011b). The highest infiltration rate of limestone fractures was up to $1.0 \times 10^{-3}$ m/s (8464 mm/d), but the stable infiltration capacity of soil was much lower, ranging from $1.91 \times 10^{-5}$ m/s to $1.85 \times 10^{-4}$ m/s. As a result of the high infiltration rate and storage capacity in the epikarst area, only extreme rainfall storms (e.g. Rainfall Regime V, or some storms with antecedent rainfall) could temporarily saturate the epikarst zone and induce large surface runoff and soil loss. Otherwise, most water in the rainfall events was transported to the underground system.

Soil loss on karst limestone slopes only occurs under extreme rainfall storms that usually have a low frequency occurrence, and the value of the annual soil loss is not as high as in other non-karst regions. However, its potential negative impact should not be ignored, especially on slopes with improper land management and poor vegetation cover, because the total amount of soil on karst slopes is very low and soil formation from limestone bedrock is very difficult. According to calculation based on insoluble residues and chemical dissolution rates of carbonate rocks in Guizhou Province, the true tolerance of soil loss is only 6.75 and 7.08 Mg $km^{-2}$ $a^{-1}$ in continuous pure limestone and dolomite areas, respectively (Li et al., 2006). In our study, a single extreme rainfall storm (e.g. Rainfall Regime V or rainfall events with antecedent precipitation) might induce soil loss more than 1–5 times the true annual soil loss tolerance in pastureland and burned limestone slopes. Although the large soil loss was created in the cropland only once in a rainfall storm with antecedent precipitation (5/27/2008) during the 4 year period, it might pose a potentially adverse risk. On the other hand, large soil loss on karst slopes mainly occurred during several extreme rainfall storms which might occur 1 to 2 times annually. Based on the historical date of daily precipitation from 1964 to 2005, statistical analysis illustrated that the daily rainfall depth, rainfall intensity and frequency of extreme storms from June to August exhibited an obvious trend of increasing, and were more significant in the karst pure carbonate rock region in southwest China (Zhang et al., 2007). Therefore, even though the amount of soil loss on karst limestone slopes might not be as great as in the non-karst area, the soil erosion risk is quite high and should be paid great attention.

## 5. Conclusions

Based on rainfall depth, intensity and duration, 61 rainfall events from 2007 to 2010 under the subtropical monsoon climate condition in a karst area in southwest China were classified into 5 types of Rainfall Regimes using the hierarchical method. We found that the surface runoff and soil loss varied remarkably among the different types of LULC and Rainfall Regimes on karst limestone slopes. The surface runoff and soil loss in Burned Area Recovered land and Young Forest land were very low in all types of rainfall events, and the water soil loss in fields with sufficient vegetation cover on karst hill slopes was very low. The runoff and soil loss in other LULC fields showed significant variations under different types of Rainfall Regimes. Rainfall events with a rainfall depth of more than 40 mm and a maximum 30-min rainfall intensity of over 30 mm $h^{-1}$ might induce large surface runoff in Pastureland and Combination Vegetation land. Large soil loss could only be found in Pastureland, indicating that over-grazing had seriously increased water and soil loss on the karst limestone slopes. The results also indicated that the combination of woodland and grassland had positive effects on controlling soil loss. The surface runoff and soil loss in Cropland were very low except for the extreme rainfall storms with large antecedent precipitation. Due to the antecedent precipitation, both the surface runoff and soil loss were increased significantly in Burned Area Uncover Land, Cropland and Pastureland.

The findings in this study provided reliable data of surface runoff coefficients and soil loss on karst limestone slopes under the subtropical monsoon climate condition. Our results indicated the soil erosion risk for the karst limestone slopes in different types of LULC. The findings also indicated that the generation of surface runoff in this area might not be attributable to the conventional saturated excess runoff mechanism. Due to the storage capacity and enhanced infiltration rate of limestone fissures and fractures, the runoff generation in karst limestone slopes exhibited a high threshold of recharge water and rainfall intensity to maintain the saturation phase. The detailed process and the runoff generating mechanism in this area remain to be further studied.

## Acknowledgment

This study was supported by the National Basic Research Program of China (no. 2006CB403200), the foundation of the Chinese Academy of Sciences for Innovation (no. kzcx2-yw-306) and the Strategic Priority Research Program — Climate Change: Carbon Budget and Related Issues of the Chinese Academy of Sciences (no. XDA05070400). We thank Dr. Michael J. Singer and Artemi Cerdà for their critical comments on the manuscript.

## References

Andreu, V., Rubio, J.L., Gimeno-Garcia, E., Llinares, J.V., 1998. Testing three Mediterranean shrub species in runoff reduction and sediment transport. Soil & Tillage Research 45, 441–454.

Boix, C., Calvo, A., Imeson, A.C., Schoorl, J.M., Soto, S., Tiemessen, I.R., 1995. Properties and erosional response of soils in a degraded ecosystem in Crete (Greece). Environmental Monitoring and Assessment 37, 79–92.

Calvo-Cases, A., Boix-Fayos, C., Imeson, A.C., 2003. Runoff generation, sediment movement and soil water behaviour on calcareous (limestone) slopes of some Mediterranean environments in southeast Spain. Geomorphology 50, 269–291.

Cao, J.H., Yuan, D.X., 2005. Karst Ecosystem Constrained by Geological Conditions in Southwest China. Geology Press, Beijing. in Chinese.

Cao, J.H., Jiang, Z.C., Yang, D.S., 2008. Soil loss tolerance and prevention and measurement of karst area in southwest China. Soil and water conservation in China, 321, pp. 40–44. in Chinese.

Cerdà, A., 1997a. The effect of patchy distribution of *Stipa tenacissima* L on runoff and erosion. Journal of Arid Environments 36, 37–51.

Cerdà, A., 1997b. Seasonal changes of the infiltration rates in a Mediterranean scrubland on limestone. Journal of Hydrology 198, 209–225.

Cerdà, A., 1998a. The influence of geomorphological position and vegetation cover on the erosional and hydrological processes on a Mediterranean hillslope. Hydrological Processes 12, 661–671.

Cerdà, A., 1998b. Effect of climate on surface flow along climatological gradient in Israel: a field rainfall simulation approach. Journal of Arid Environments 38, 145–159.

Cerdà, A., 1999. Parent material and vegetation affect soil erosion in eastern Spain. Soil Science Society of America Journal 63, 362–368.

Chai, Z.X., 1989. Soil erosion in karst area of Guangxi autonomous region. Moutain Research 7 (4), 255–260 in Chinese.

Chen, X.P., 1997. Research on characteristics of soil erosion in karst mountainous region environment. Journal of Soil Erosion and Soil and Water Conservation 3 (4), 31–36 in Chinese.

Dadkhah, M., Gifford, G.F., 1980. Influence of vegetation, rock cover, and trampling on infiltration rates and sediment production. Water Resources Bulletin 16, 979–986.

De Baets, S., Poesen, J., Gyssels, G., Knapen, A., 2006. Effects of grass roots on the erodibility of topsoils during concentrated flow. Geomorphology 76, 54–67.

De Lima, J.L.M.P., Singh, V.P., 2002. The influence of the pattern of moving rainstorms on overland flow. Advances in Water Resources 25, 817–828.

Drew, D.P., 1983. Accelerated soil erosion in a karst area: the Burren, Western Ireland. Journal of Hydrology 61, 113–124.

Feng, Z.G., Wang, S.J., Liu, X.M., 2009. Impact of acid-insoluble residua of carbonate rocks on developing intensities of their weathering crusts. Acta Geologica Sinica 83 (6), 885–893 in Chinese.

Ford, D.C., Williams, P.W., 2007. Karst Hydrogeology and Geomorphology. Wiley, Chichester.

Francis, C.F., Thornes, J.B., 1990. Runoff hydrofraphs from three Mediterranean vegetation cover types. Vegetation and erosion: Processes and environments, pp. 363–384.

Fu, B.J., Wang, Y.F., Lu, Y.H., He, C.S., Chen, L.D., Song, C.J., 2009. The effects of land-use combinations on soil erosion: a case study in the Loess Plateau of China. Progress in Physical Geography 33, 793–804.

Gan, L., Wan, G.J., Liang, X.B., 2002. Causes of karst desertification in Guizhou and its controlling countermeasures. Journal of Desert Research 22 (1), 69–74 in Chinese.

Garcia-Ruiz, J.M., Valero-Garces, B.L., 1998. Historical geomorphic processes and human activities in the Central Spanish Pyrenees. Mountain Research and Development 18, 309–320.

Gyssels, G., Poesen, J., Bochet, E., Li, Y., 2005. Impact of plant roots on the resistance of soils to erosion by water: a review. Progress in Physical Geography 29, 189–217.

Higgitt, D.L., 1991. Soil-erosion and soil problems. Progress in Physical Geography 15, 91–100.

Higgitt, D.L., 1993. Soil-erosion and soil problems. Progress in Physical Geography 17, 461–472.

Imeson, A.C., Lavee, H., Calvo, A., Cerdà, A., 1998. The erosional response of calcareous soils along a climatological gradient in Southeast Spain. Geomorphology 24, 3–16.

Jiang, Z.C., Wang, R.J., Fei, J.G., 2001. Epikarst zone in south China and its regulation function to karst water. Carsologica Sinica 30, 106–110 in Chinese.

Kasai, M., Brierley, G.J., Page, M.J., Marutani, T., Trustrum, N.A., 2005. Impacts of land use change on patterns of sediment flux in Weraamaia catchment, New Zealand. Catena 64, 27–60.

Kheir, R.B., Abdallah, C., Khawlie, A., 2008. Assessing soil erosion in Mediterranean karst landscapes of Lebanon using remote sensing and GIS. Engineering Geology 99, 239–254.

Kinnell, P.I.A., 2005. Raindrop-impact-induced erosion processes and prediction: a review. Hydrological Processes 19, 2815–2844.

Kosmas, C., Danalatos, N., Cammeraat, L.H., Chabart, M., Diamantopoulos, J., Farand, R., Gutierrez, L., Jacob, A., Marques, H., MartinezFernandez, J., Mizara, A., Moustakas, N., Nicolau, J.M., Oliveros, C., Pinna, G., Puddy, R., Puigdefabregas, J., Roxo, M., Simao, A., Stamou, G., Tomasi, N., Usai, D., Vacca, A., 1997. The effect of land use on runoff and soil erosion rates under Mediterranean conditions. Catena 29, 45–59.

Kosmas, C., Gerontidis, S., Marathianou, M., 2000. The effect of land use change on soils and vegetation over various lithological formations on Lesvos (Greece). Catena 40, 51–68.

Li, R.L., Wang, S.J., Zhou, D.Q., 2003. The correlation between rock desertification and lithology in karst area of Guizhou. Acta Geographica Sinica 58, 314–320 in Chinese.

Li, Y.B., Wang, S.J., Wei, Z.F., 2006. The spatial distribution of soil loss tolerance in carbonate area in Guizhou province. Earth and Environment 34, 36–40 in Chinese.

Lin, C.H., Zhu, A.G., 1999. A study on soil erosion and prevention in karst mountainous region of Guizhou. Research of Soil and Water Conservation 6 (2), 109–113 in Chinese.

Moody, J.A., Martin, D.A., 2009. Synthesis of sediment yields after wildland fire in different rainfall regimes in the western United States. International Journal of Wildland Fire 18, 96–115.

Morgan, R.P.C., 1995. Soil Erosion and Conservation. Longman, London.

Mwendera, E.J., Saleem, M.A.M., 1997. Infiltration rates, surface runoff, and soil loss as influenced by grazing pressure in the Ethiopian highlands. Soil Use and Management 13, 29–35.

Nearing, M.A., Bradford, J.M., 1985. Single waterdrop splash detachment and mechanical-properties of soils. Soil Science Society of America Journal 49, 547–552.

Nearing, M.A., Bradford, J.M., Parker, S.C., 1991. Soil detachment by shallow flow at low slopes. Soil Science Society of America Journal 55, 339–344.

Oldeman, L.R., 1994. The global extent of soil degradation. Soil Resilience and Sustainable Land Use, pp. 99–118.

Perruchet, C., 1983. Constrained agglomerative hierarchical classification. Pattern Recongnition 16, 213–217.

Rogers, R.D., Schumm, S.A., 1991. The effect of sparse vegetative cover on erosion and sediment yield. Journal of Hydrology 123, 19–24.

Symeonakis, E., Calvo-Cases, A., Arnau-Rosalen, E., 2007. Land use change and land degradation in southeastern Mediterranean Spain. Environmental Management 40, 80–94.

Vandaele, K., Poesen, J., 1995. Spatial and temporal patterns of soil-erosion rates in an agricultural catchment, Central Belgium. Catena 25, 213–226.

Wang, S.J., 2003. The most serious eco-geologically environmental problem in southwestern China — karst rocky desertification. Bulletin of Mineralogy, Petrology and Geochemist, 22(3), pp. 120–126. in Chinese.

Wang, S.J., Liu, Q.M., Zhang, D.F., 2004. Karst rocky desertification in southwestern China: geomorphology, landuse, impact and rehabilitation. Land Degradation & Development 15, 115–121.

Wei, Q.F., 1995. Soil erosion in karst region of south China and its control. Research of Soil and Water Conservation 3 (4), 72–75 in Chinese.

Wei, W., Chen, L.D., Fu, B.J., Huang, Z.L., Wu, D.P., Gui, L.D., 2007. The effect of land uses and rainfall regimes on runoff and soil erosion in the semi-arid loess hilly area, China. Journal of Hydrology 335, 247–258.

Wei, H., Nearing, M.A., Stone, J.J., Guertin, D.P., Spaeth, K.E., Pierson, F.B., Nichols, M.H., Moffett, C.A., 2009. A new splash and sheet erosion equation for rangelands. Soil Science Society of America Journal 73, 1386–1392.

Williams, P.W., 2004. The epikarst: evolution of understanding. In: Jones, W.K., Culver, D.C., Herman, J.S. (Eds.), Epikarst. Karst Waters Institute, Charles Town, WV, pp. 8–15. Special Publication 9.

Williams, P.W., 2008. The role of the epikarst in karst and cave hydrogeology: a review. International Journal of Speleology 37 (1), 1–10.

Xu, Y.Q., Shao, X.M., Kong, X.B., Peng, J., Cai, Y.L., 2008. Adapting the RUSLE and GIS to model soil erosion risk in a mountains karst watershed, Guizhou Province, China. Environmental Monitoring and Assessment 141, 275–286.

Yair, A., 1996. Spatial variablility in runoff in semiarid and arid areas. In: Rubio, J.L., Calvo, A. (Eds.), Soil Degradation and Desertification in Mediterranean Environments. Geoforma, Logrono, pp. 71–90.

Zhang, B., Yang, Y.S., Zepp, H., 2004. Effect of vegetation restoration on soil and water erosion and nutrient losses of a severely eroded clayey Plinthudult in southeastern China. Catena 57, 77–90.

Zhang, Z.C., Chen, X., Wang, W., Shi, P., 2007. Analysis of rainfall trend and extreme events in Guizhou. Earth and Environment 35 (4), 351–356.

Zhang, Q.A., Xu, C.Y., Zhang, Z.X., Chen, X., Han, Z.Q., 2010. Precipitation extremes in a karst region: a case study in the Guizhou province, southwest China. Theoretical and Applied Climatology 101, 53–65.

Zhang, X.B., Bai, X.Y., Liu, X.M., 2011a. Application of a $^{137}$Cs fingerprinting technique for interpreting responses of sediment deposition of a karst depression to deforestation in the Guizhou Plateau, China. Science China Earth Science 54, 431–437.

Zhang, Z.C., Chen, X., Chen, Q.B., 2011b. Hydrogeology of epikarst in karst mountains — a case study of the Chenqi catchment. Earth and Environment 39 (1), 19–25.

Zhou, Z.C., Gan, Z.T., Shangguan, Z.P., Dong, Z.B., 2010. Effects of grazing on soil physical properties and soil erodibility in semiarid grassland of the Northern Loess Plateau (China). Catena 82, 87–91.

Zhu, A.G., Lin, C.H., 1995. The synthetical study on elements of loss of water and soil in mountain area. Guizhou Scientific and Technological Pressing, Guiyang, pp. 48–59. in Chinese.