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To cite this article: Ruxue Gao *et al* 2020 *Environ. Res. Lett.* **15** 094085

IOP Publishing Environ. Res. Lett. 15 (2020) 094085 https://doi.org/10.1088/1748-9326/ab9d3b

Environmental Research Letters

OPEN ACCESS

RECEIVED
4 December 2019

REVISED
30 May 2020

ACCEPTED FOR PUBLICATION
16 June 2020

PUBLISHED
2 September 2020

LETTER

The mechanisms of nutrient output through water flow from sloping farmland with slight rocky desertification in a karst region

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Keywords: karst region, sloping farmland with slight rocky desertification, rainfall intensity, slope angle, nutrient output through water flow

Abstract

Nutrient loss from sloping farmland with rocky desertification in karst regions leads to low farmland productivity and non-point source pollution. The mechanisms of nutrient outputs through water flow in such contexts under different rainfall intensities and slope angles were studied by using artificial rainfall simulation. Research showed that surface water flow occurred when the rainfall intensity was between 30 $\mathrm{mm} \cdot \mathrm{h}^{-1}$ and 50 $\mathrm{mm} \cdot \mathrm{h}^{-1}$, and the nutrient (TN, TP, TK) output through water flow showed the same pattern. Nutrient output through water flow was dominated by nutrient loss from surface and subsurface water flows when the rainfall intensity was $\geq$ 50 $\mathrm{mm} \cdot \mathrm{h}^{-1}$. Rainfall intensity was found to be a dominant driver in comparison to slope angle and for limestone soil of the karst region in Southwest China, but slope angle only had a significant effect on TP output through surface water flow. The largest proportion of nutrient output was associated with surface flow, a lower proportion was associated with subsurface flow, and the lowest proportion with underground flow. The nutrient output through underground water flow directly led to groundwater pollution, although it was not large. The results of this study provide a theoretical reference for the control of nutrient output through water flow and the management of nonpoint source pollution in karst regions.

1. Introduction

The karst region in Southwest China is one of the three largest karst-concentrated areas in the world. In this region, the soil formation rate is low, the rock exposure rate is high, the surface soil layer is shallow, the soil continuity is poor, and the soil erosion is serious because of the particular topography and climatic conditions, which have led to the poor soil and low productivity of the sloping farmland in this area. Sustainable development in Southwest China is severely restricted by rocky desertification (Zhang *et al* 2016b). This process is the root cause of underdevelopment in the karst region (Chen *et al* 2011). On the other hand, the karst area forms a unique surface-underground 'dual spatial structure' owing to the karst formation process (Bloom 1989); therefore, in addition to the loss of soil and water along the surface, soil and water are also lost to underground karst pipelines (shafts, water holes and underground holes (cracks), etc) (Fu *et al* 2015b; Dai *et al* 2017), resulting in the loss of soil nutrients to karst aquifers (Mahler *et al* 2008), which may lead to further water pollution in the karst area (Hao *et al* 2019).

The loss of soil nutrients from farmland is one of the main drivers of soil barrenness and land productivity decline (Adimassu *et al* 2017). Loss of soil nutrients exacerbates land degradation and seriously threatens the sustainable development goals of the United Nations (Keesstra *et al* 2018). The loss of nutrients can further damage the ecological environment if nutrients enter and then cause eutrophication of water bodies (Ryther and Dunstan 1971, Chukalla *et al* 2018, Gao *et al* 2019b). Therefore, the loss of soil nutrients from farmland is of great concern to the academic community (Lal *et al* 2015, Karimi *et al* 2018, Zhang *et al* 2018b). The loss of soil nutrients from farmland is the most prominent and serious challenge in sloping farmland (Lin *et al* 2009; Zhang *et al* 2016a; Li *et al* 2017).

The main carriers of the lost soil nutrients in sloping farmland are water and soil (Tuo *et al* 2018);

Serious declines in soil nutrient can be observed due to soil and water losses (Lemma *et al* 2017). Major factors affecting the loss of soil nutrients are rainfall intensity (García-Díaz *et al* 2017), slope angle (Wu *et al* 2018), slope length (Xing *et al* 2016), and flow rate (Wang *et al* 2014). The main research methods have included element tracing (Kogovsek and Petric 2014) and artificial simulation of rainfall (Wang *et al* 2014). Element tracing can track the process of material movement and change, and improve the purpose and accuracy of research (Kimoto *et al* 2006). There are few disturbance factors and strong controllability of artificial simulation of rainfall.

The characteristics of nutrient loss in this karst region are different from those in other regions because of its special geological structure, and nutrients are lost due to simultaneous surface and underground water flows (Song *et al* 2017). Montiel *et al* (2017) notes that groundwater in coastal karst aquifers worldwide is the main pathway for nutrient transport to the sea. The excessive permeability of karst aquifers leads to an enhanced vulnerability to retain and spread the contamination accordingly (Kalhor *et al* 2019). Conduit and other karstic flows to aquifers are considered to be the main hydrological mechanisms that transfer phosphorus from the land surface to the groundwater body of a karstified aquifer (Mellander *et al* 2012). A study by Ma *et al* (2018) showed that the underground structure developed in karst areas leads to more nutrient loss and that nutrients are lost mainly through underground water flow under a low rainfall intensity. In particular, nutrients and water can be transported to deep soil layers through the infiltration of the soil interior and the deep migration of the rock-soil boundary and can access the groundwater system. Rainfall intensity is an important factor affecting soil nutrient loss from karst slopes, while the underground fissure degree has little effect on nutrient loss (Peng *et al* 2017). Some researchers have also noted that the fissure structure in karst regions promotes water infiltration and thus aggravates the loss of nitrogen through water flow (Wu *et al* 2017). Overall, related studies have mainly focused on nutrient loss from the surface of sloping farmland. However, some questions remain. For example, what are the mechanisms of nutrient output through water flow from sloping farmland with slight rocky desertification in karst regions? What are the percentages of TN output through surface, subsurface and underground water flows?

It is difficult to carry out experimental research in the field, and the available research methods are limited because of the multi-medium environment in karst regions; therefore, there are few systematic and comprehensive reports on nutrient loss in sloping farmland in such regions. This study simulated the 'dual-structure' microenvironment of sloping farmland with slight rocky desertification in a karst region by using a variable-slope steel trough with a perforated floor to study the mechanism of nutrient output through water flow under different rainfall intensities and slope angles by artificial rainfall simulation. The purposes of this study are as follows: (1) to reveal the characteristics of water flow and nutrient output through water flow from sloping farmland with slight rocky desertification in a karst region, (2) to explore the effect of rainfall intensity and slope angle on nutrient output through water flow from such areas, and (3) to study the percentages of nutrient output through surface, subsurface and underground water flows. This study aims to provide a theoretical reference for the control of nutrient output through water flow and the management of non-point source pollution from sloping farmland with slight rocky desertification in karst regions.

2. Test materials and methods

2.1. Soil characteristics

In this study, the representative limestone soil of the karst region in Southwest China was taken as the object of study. The experimental soil was collected from karst sloping farmland in Huaxi district, Guiyang city, Guizhou Province, China (26°19′17” N, 106°39′18” E) (figure 1). Huaxi district has a subtropical monsoon humid climate, the annual average temperature is 14.9 °C, the average frost-free period is 246 d, and the annual precipitation is 1178.3 mm. Before digging the experimental soil, five test soil samples were taken back to the laboratory to determine the basic properties (table 1). We collected soil at depths of 0–20 cm from karst sloping farmland because the soil thickness ranges from 20 to 30 cm (Yan *et al* 2018).

2.2. Experimental setup

The test instrument was composed of rainfall equipment and a steel tank (figure 2), which was similar to that described by Gao *et al* (2019a). Before the test, a rain tube was placed on each side of the steel trough to determine the rainfall intensity. The periphery of the steel groove had a subsurface water flow-collecting groove that was used to collect the subsurface water flow in each layer.

In this study, we used an experimental setup for simulated nutrient output through surface, subsurface and underground water flows in the special 'dual-structure' environment of sloping farmland with slight rocky desertification in a karst region. We set four experimental factors in this experiment, where the bedrock bareness rate (40%) and underground fissure (crack) degree (5%) were fixed. Two experimental factors were used for cross-testing, namely, slope (15°, 20°, and 25°) and rainfall intensity (30, 50, 70, and 90 $\text{mm} \cdot \text{h}^{-1}$). The bedrock bareness rate was set to that of land with slight rocky desertification (30% to 50%, based on relevant research), and the slope was set to 12°-25° (Yang *et al* 2014). The

Figure 1. Location of the study area (Huaxi district, Guiyang city, Guizhou Province, China).

Table 1. Characteristics of experimental soil.

			Particles mechanical composition (%)		
TN (g kg^{-1})	TP (g · kg^{-1})	TK (g kg^{-1})	0.02–2 mm	0.002–0.02 mm	<0.002 mm
1.72 ± 0.19	1.69 ± 0.14	8.47 ± 1.05	37.34 ± 3.33	47.53 ± 2.08	15.03 ± 1.02

bedrock bareness rate was set at 40% of the surface area of the variable-slope steel trough by adjusting the area above 30 cm of rock outcrop (Gao *et al* 2019a). Based on the survey of Fu *et al* (2015a), the slope of karst sloping farmland in Guizhou Province was between 10° and 25°, the maximum underground fissure (crack) degree was 5.98%, and the soil thickness ranged from 20 to 30 cm. The rainfall intensity was set according to the research results of (Zhang *et al* 2014). The underground fissure (crack) degree was adjusted by staggering two dozen steel plates with holes at the bottom of a variable-slope steel groove (Yan *et al* 2018).

To better simulate the actual field conditions, the soil samples were not screened, and the bulk soil samples were dispersed and treated. Plant roots, large stones and other impurities were removed at the same time. The steel tank was divided into three layers of fill, each of which was 10 cm thick. The soil compactness from top to bottom was 410, 760, and 1070 kPa. After the tank was filled with test soil, the soil surface was raked with a special plank, and edge effects were reduced by compacting the soil boundary. Before the start of the experiment, light rain induced uniform saturation and subsidence. Sample collection began when the surface flow began. Surface, subsurface and underground water flow samples were collected every 3 min into a 500 ml polyethylene bottle to determine the TN, TP and TK contents in flow-water samples. The remaining water flow was collected with

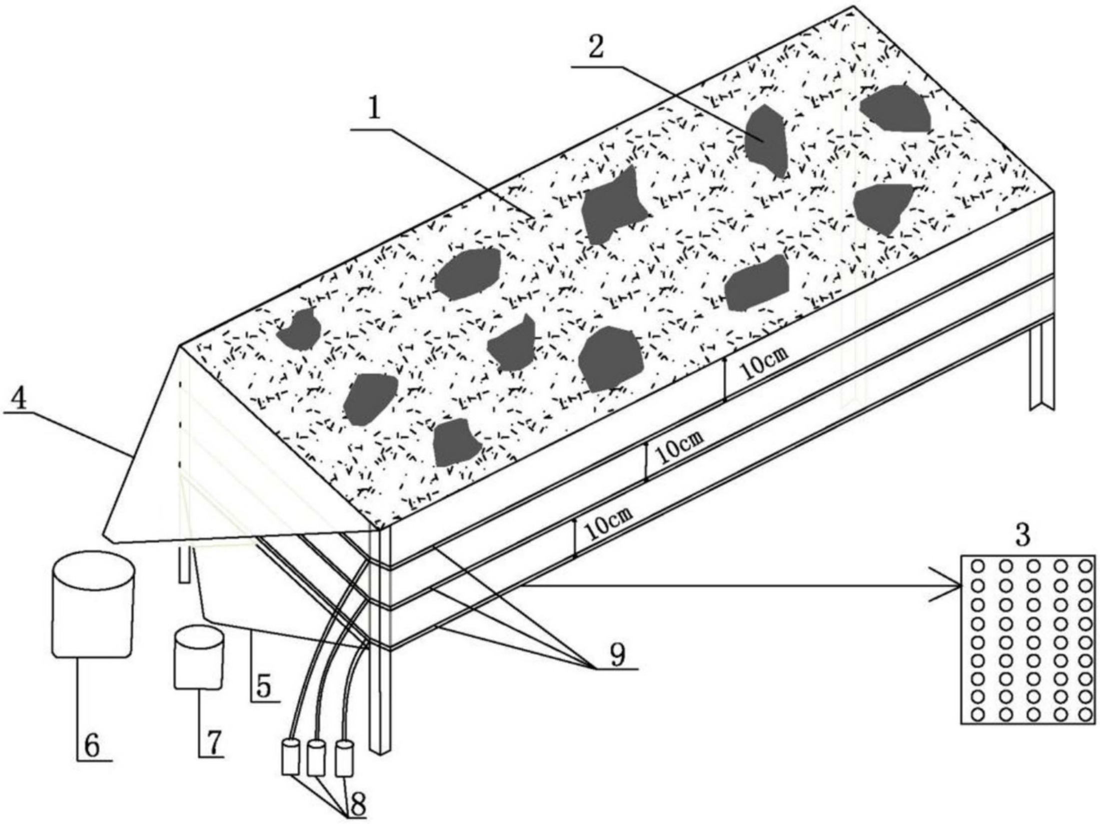

Figure 2. Schematic diagram of the experimental steel groove equipment structure.

slightly larger barrels, which was convenient for measuring runoff. After rainfall (30 min), the soil was replaced, and the design requirements for the next rainfall were met. The experiment was repeated three times, for a total of 36 simulated rainfall events. The water samples were collected in the field, preserved by adding acid (sulfuric acid) and analysed in the laboratory within 24 h.

2.3. Analytical technics

The TN in the water samples was determined by potassium persulfate oxidation-ultraviolet spectrophotometry, TP was determined by potassium persulfate molybdenum-antimony oxide anti-spectrophotometry, and TK was determined by atomic absorption spectrometry. The specific operational steps followed those of the State Environmental Protection Administration (Methods for monitoring and analysis of water and wastewater) (State Environmental Protection Administration 2002). The water nutrient content was determined by measuring the water nutrient content of a blank sample and subtracting the result from the measured water nutrient content of a water flow sample.

2.4. Data handling

(1) Flow volume

The surface and underground water flows were fed into a calibrated plastic barrel through the corresponding collecting tray, and the subsurface water flow jets in the trough layers converged through the pipe and passed into a radial flow bucket. A large number of cylinders (accuracy of 0.01 l) were used to record the surface, subsurface and underground pore (crack) water flows in each 3-min interval, and the cumulative water flow during the whole rainfall process was recorded.

(2) Water flow percentage (R_r)

$$R_r = \frac{R_O}{R_t}\%$$

In the formula, $R_P$represents the water flow percentage (%); $R_o$represents surface, subsurface, or underground water flow; and$R_t$represents total water flow under the same conditions.

(3) The modulus of nutrient output through water flow (K)

$$K = \frac{M}{T \times S}$$

In the formula, K represents the modulus of nutrient (TN, TP and TK) output through water flow (that is, the amount of the nutrient loss through water flow per unit horizontal projection area per unit time, which is an index to characterize nutrient loss intensity); M represents the nutrient loss through water flow; T represents the rainfall duration (30 min);

Table 2. Characteristics of flow yield of sloping farmland.

Slope angle (°)	Rainfall intensity ($mm \cdot h^{-1}$)	Surface flow yield (L)	Surface The ratio of flow (%)	Subsurface flow flow yield (L)	Subsurface flow The ratio of flow (%)	Underground flow yield (L)	Underground The ratio of flow (%)
15	30	0.00	0.00	32.51 Ca	66.51 Aa	16.37 Ba	33.49 Ac
	50	87.79 Cb	45.21 Cc	78.32 Ba	40.34 Ba	28.04 Ba	14.45 Ca
	70	118.06 Bc	51.14 Aa	83.54 AB	36.20 Ca	29.22 Bc	12.66 Db
	90	159.30 Aa	49.97 Bb	88.16 Aa	27.66 Db	71.31 Aa	22.37 Ba
20	30	0.0	0.00	30.22 Da	62.10 Ac	18.44 Ba	37.90 Aa
	50	105.77 Ca	53.35 Aa	70.73 Ca	35.67 Bb	21.76 Cb	10.98 Dc
	70	137.60 Bb	53.01 Bb	79.73 Ba	30.71 Cc	42.27 Ba	16.28 Ca
	90	164.62 Aa	49.80 Cc	96.33 Aa	29.14 Da	69.62 Aa	21.06 Bb
25	30	0.00	0.00	33.41 Da	63.12 Ab	19.52 Ba	36.88 Ab
	50	114.83 Ca	52.42 Bb	76.43 Ca	34.89 Bc	27.82 Ca	12.70 Cb
	70	155.08 Ba	55.85 Ca	88.53 Ba	31.88 Cb	34.07 Bb	12.27 Db
	90	234.42 Aa	59.75 Aa	99.55 Aa	25.37 Dc	58.39 Ab	14.88 Bc

Note: In the same column (slope angle of 15°, 20°, or 25°), there was a significant difference between groups with different capital letters ($P < 0.05$), but there was no significant difference between groups marked with the same capital letter ($P > 0.05$). Different lowercase letters show significant differences between different slopes at the same rainfall intensity ($P < 0.05$). The same lowercase letter indicates that there was no significant difference between different slopes at the same rainfall intensity ($P > 0.05$); the same is true below.

and S represents the horizontal projected area of the grooved steel floor for different slopes (m^2).

(4) Percentage of nutrient output through water flow (T_P)

$$T_P = \frac{T_O}{T_t}\%$$

In the formula, T_P represents the percentage of nutrient output through water flow (%); T_o represents the nutrient output through surface, subsurface, or underground water flow; and T_t represents the total nutrient output through water flow under the same conditions.

A standard statistical technique was used to analyse the experimental data. Excel 2007 was used to calculate the standard deviation and produce graphs, and SPSS 17.0 was used to analyse the differences, correlations and regressions among the treatments.

3. Results

3.1. Characteristics of water flow

The analysis of water flow characteristics in sloping farmland with slight rocky desertification (table 2) was the basis for understanding soil nutrient loss. Water began to flow on the surface when the rainfall intensity reached 50 $mm \cdot h^{-1}$, which indicated that there was mainly subsurface water flow and underground pore (crack) water flow under the light rainfall intensity. The critical rainfall intensity for water flow production on the slope was between 30 and 50 $mm \cdot h^{-1}$. The influence of rainfall intensity on water flow from sloping farmland was obvious. The slope angle had little effect on the underground pore (crack) water flow. On the same slope, the difference in surface water flow among rainfall intensities was significant. The difference in subsurface water flow between slopes of 20° and 25° was significant, but there was no significant difference in underground water flow. Under the conditions of surface water flow production, the proportion of total water flow accounted for by surface water flow was between 45.21% and 59.75%, by subsurface water flow was between 25.37% and 40.34%, and by underground water flow was between 10.98% and 22.37%.

3.2. The mechanism of nutrient output through water flow

3.2.1. The characteristics of nutrient output through water flow.

As shown in table 3, when water began to flow on the surface, the average concentration of TN lost through water flow fluctuated between 1.86 $mg \cdot l^{-1}$ and 3.30 $mg \cdot l^{-1}$, the TP was between 0.15 $mg \cdot l^{-1}$ and 0.34 $mg \cdot l^{-1}$, and the TK was between 0.40 $mg \cdot l^{-1}$ and 1.07 $mg \cdot l^{-1}$. The nutrient loss modulus of TN lost through water flow fluctuated between 11.91 $mg \cdot h^{-1} \cdot m^{-2}$ and 195.71 $mg \cdot h^{-1} \cdot m^{-2}$, the TP was between 0.99 $mg \cdot h^{-1} \cdot m^{-2}$ and 17.81 $mg \cdot h^{-1} \cdot m^{-2}$, and the TK was between 3.21 $mg \cdot h^{-1} \cdot m^{-2}$ and 41.15 $mg \cdot h^{-1} \cdot m^{-2}$. The average concentration of TP lost through underground water flow was the highest. The average concentration of TN lost through underground water flow was higher than that lost through surface and subsurface water flows overall. On the same slope, the modulus of TN and TP output through water flow all increased with increasing rainfall intensity. Under the same rainfall intensity, the modulus of TP output through water flow increased with increasing slope angle. The average concentration of TK lost through surface and water subsurface flows was not significantly affected by rainfall intensity. The modulus of TK output through surface and underground water flows increased with the increase in rainfall

Table 3. Characteristics of nutrient output through water flow.

		TN						TP		
	Rainfall intensity/ $(mm \cdot h^{-1})$	Average loss concentration/$(mg \cdot l^{-1})$			Nutrient loss modulus/$(mg \cdot h^{-1} \cdot m^{-2})$			Average loss concentration/$(mg \cdot l^{-1})$		
Slope angle (°)		Surface	Subsurface flow	Underground	Surface	Subsurface flow	Underground	Surface	Subsurface flow	Underground
15	30	0.00	2.08 Bb	2.10 Ba	0.00	23.43 Ca	11.91 Db	0.00	0.15 Ab	0.17 Bb
	50	2.32 Bab	1.88 Bb	2.13 Ba	70.38 Bb	50.96 Ba	20.67 Cab	0.18 Ab	0.16 Bb	0.20 Bb
	70	2.82 Aa	2.82 Aa	3.30 Aa	115.01 Aa	57.04 Aa	33.31 Bab	0.18 Ab	0.15 Cb	0.19 Bc
	90	2.32 Ba	1.98 Ba	2.17 Ba	127.93 Ab	85.96 Ba	53.40 Aa	0.18 Ab	0.16 Db	0.25 Ab
20	30	0.00	2.35 Aab	2.35 ABa	0.00	25.27 Ca	15.40 Ca	0.00	0.18 Aa	
	50	2.58 Aa	2.21 ABa	2.15 ABa	97.103 Ba	55.62 Ba	16.64 Cb	0.21 Aa	0.17 ABab	0.20 Bb
	70	2.15 Bb	2.07 Bb	2.40 Ab	105.05 Ba	58.64 ABb	35.98 Ba	0.19 Ab	0.16 BCb	0.26 Ab
	90	2.24 Ba	1.86 Ba	2.09 Ba	130.82 Ab	76.71 Aa	51.78 Aa	0.19 Aab	0.15 Cb	0.25 Ab
25	30	0.00	2.57 Aa	2.33 Aa	0.00	31.60 Ba	16.79 Ca	0.00	0.16 Cb	
	50	2.18 Ab	2.31 ABa	2.22 Aa	92.36 Ca	65.09 Aa	22.78 BCa	0.22 Aa	0.19 Ba	0.33 ABa
	70	2.27 Ab	2.10 Bb	2.09 Ac	129.80 Ba	68.46 Ab	26.24 Bb	0.22 Aa	0.18 BCa	0.34 Aa
	90	2.26 Aa	2.12 Ba	2.15 Aa	195.71 Aa	77.82 Aa	46.38 Aa	0.21 Aa	0.22 Aa	0.30 Ba

Table 3. (*Continued*)

TK								
Nutrient loss modulus/(mg · h $^{-1}$ · m^{-2})			Average loss concentration/(mg · l^{-1})			Nutrient loss modulus/(mg · h^{-1} · m^{-2})		
Surface	Subsurface flow	Underground	Surface	Subsurface flow	Underground	Surface	Subsurface flow	Underground
0.00	1.73 Ba	0.99 Cb	0.00	0.71 Aa	0.65 Bb	0.00	8.02 Ba	3.69 Cb
5.37 Cb	4.43 Aa	1.92 Bb	0.69 Aa	0.74 Aa	0.69 Bb	20.84 Ca	20.00 Aa	6.65 Cb
7.23 Bc	4.28 Ab	1.96 Bb	0.65 Aa	0.69 Aa	1.04 Aa	26.58 Ba	19.92 Aa	10.50 Bb
9.67 Ab	4.88 Ab	6.24 Aa	0.68 Aa	0.68 Aa	1.07 Aa	37.27 Aa	20.69 Aa	26.46 Aa
0.00	1.66 Ba	1.26 Cab	0.00	0.63 Ab	0.50 Bab	0.00	6.76 Cab	3.25 Dab
7.76 Ba	4.32 Aa	1.55 Cb	0.57 Ab	0.64 Ab	0.94 Ab	21.44 Ba	16.02 ABb	7.28 Cb
9.19 Bb	4.46 Ab	4.00 Ba	0.42 Cb	0.57 Ab	0.87 Ab	20.31 Bb	16.30 Aa	13.05 Ba
11.07 Ab	5.27 Ab	6.19 Aa	0.46 Bb	0.38 Bb	0.86 Ab	27.09 Ab	13.03 Bb	21.21 Ab
0.00	1.94 Ca	1.44 Ca	0.00	0.49 Ac	0.51 Ba	0.00	6.05 Cb	3.67 Da
9.40 Ca	5.23 Ba	3.34 Ba	0.48 Ac	0.40 Bc	0.69 Aa	20.47 Ca	11.22 Bc	7.06 Ca
12.31 Ba	5.83 Ba	4.21 Ba	0.45 Bb	0.52 Ab	0.75 Ab	25.86 Ba	17.01 Aa	9.42 Ba
17.81 Aa	6.73 Aa	6.41 Aa	0.48 Ab	0.43 Bb	0.75 Ab	41.15 Aa	15.65 Ab	16.25 Aa

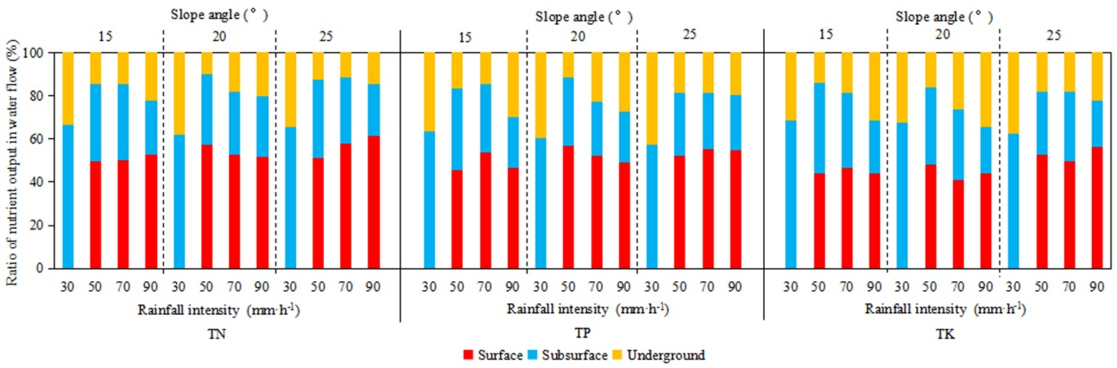

Figure 3. Ratio of nutrient output in water flow.

intensity, but the modulus of TK output through subsurface water flow was not significantly affected by rainfall intensity. The modulus of TK output through water flow was not significantly affected by slope angle.

3.2.2. The ratio of nutrient output through water flow. Figure 3 shows the nutrient (TN, TP and TK) output through subsurface and underground water flows under low rainfall intensity (30 mm $\cdot$ h^{-1}). When water began to flow on the soil surface, the nutrients were mainly lost through surface and subsurface water flows. The nutrient output accounted for by surface water flow was the largest, TN was between 49.54% and 61.18%, TP was between 45.82% and 56.93%, and TK was between 40.95% and 56.39%. The percentage of TN output accounted for by subsurface water flow was between 24.32% and 66.30%, TP was between 23.45% and 37.80%, and TK was between 21.21% and 42.08%. The percentage of TN accounted for by underground water flow was between 9.83% and 22.21%, TP was between 11.40% and 30.03%, and TK was between 13.99% and 34.56%. The percentage of TN and TP in the subsurface water flow decreased with increasing rainfall intensity overall. The percentage of TP output accounted for by surface water flow decreased with an increase in rainfall intensity when the slope angle was 25°, but underground water flow showed the opposite result. The percentage of TK output through underground water flow increased with increasing rainfall intensity, but the percentage of TK output through subsurface and underground water flows was not affected by rainfall intensity.

3.2.3. The process of nutrient output through water flow.

As shown in figure 4, on the whole, the process of nutrient (TN, TP and TK) output through water flow showed a fluctuating trend, among which the nutrient output through surface water flow fluctuation was the most obvious. At the same time, as the slope angle increased, the nutrient output through surface water flow increased obviously, and the fluctuation range was also obvious. The TN output through surface water flow first appeared to increase and then tended to fluctuate slightly, while the subsurface and underground water flows first appeared to increase and then tended to stabilize. The TP output through water flow was mainly the result of surface water loss, followed by subsurface water flow, but the TP output through underground water flow was significantly greater than that through subsurface water flow when the rainfall intensity was 90 mm $\cdot$ h^{-1}. The trend of change in TP output with a change in water flow duration first appeared to increase and then tended to fluctuate slightly. The TK output through surface and subsurface water flows fluctuated unsteadily with rainfall duration. The trend of change in TK lost through underground water flow with the change in rainfall duration was also unstable under the high rainfall intensity (90 mm $\cdot$ h^{-1}). The TK loss first increased and then stabilized under the low rainfall intensity (30 mm $\cdot$ h^{-1}) and moderate rainfall intensity (50 or 70 mm $\cdot$ h^{-1}).

3.3. Correlation analysis of nutrient output through water flow with rainfall intensity, flow, and slope angle

Correlation analysis of nutrient output through water flow with rainfall intensity, water flow, and slope angle (table 4) showed that rainfall intensity was positively correlated with water flow, TN output was positively correlated with water flow, TP output was positively correlated with water flow and TK output was positively correlated with surface and underground water flows ($P < 0.01$); the correlation coefficients were all above 0.90. Rainfall intensity was positively correlated with subsurface water flow and TP output through subsurface water flow ($P < 0.01$) and positively correlated with TN and TK outputs through subsurface water flow ($P < 0.05$). Rainfall intensity and surface and underground water flows were positively correlated with TN, TP and TK outputs ($P < 0.01$), and the correlation coefficients

Table 4. Correlation analysis of rainfall intensity and slope angle with nutrient indexes.

Index	Total surface flow	Total nitrogen loss in surface flow	Total phosphorus loss in surface flow	Total potassium loss in surface flow	Total Subsurface flow	Total nitrogen loss in Subsurface flow	Total phosphorus loss in Subsurface flow	Total potassium loss in Subsurface flow	Total underground flow	Total nitrogen loss in underground flow	Total phosphorus loss in underground flow	Total potassium loss in underground flow
Rainfall intensity	0.953**	0.941**	0.931**	0.926**	0.917**	0.846*	0.877**	0.740*	0.916**	0.946**	0.933**	0.918**
Total surface flow	1	0.993**	0.997**	0.974**	-	-	-	-	-	-	-	-
Total Subsurface flow	-	-	-	-	1	0.935**	0.929**	0.761**	-	-	-	-
Total underground flow	-	-	-	-	-	-	-	-	1	0.975**	0.986**	0.979**
Slope angle	0.558	0.393	0.660*	−0.056	0.162	0.124	0.523	−0.594	−0.069	−0.306	0.447	−0.444

Note: **. Significant correlation at the 0.01 level (bilateral); *. Significant correlation at the 0.05 level (bilateral).

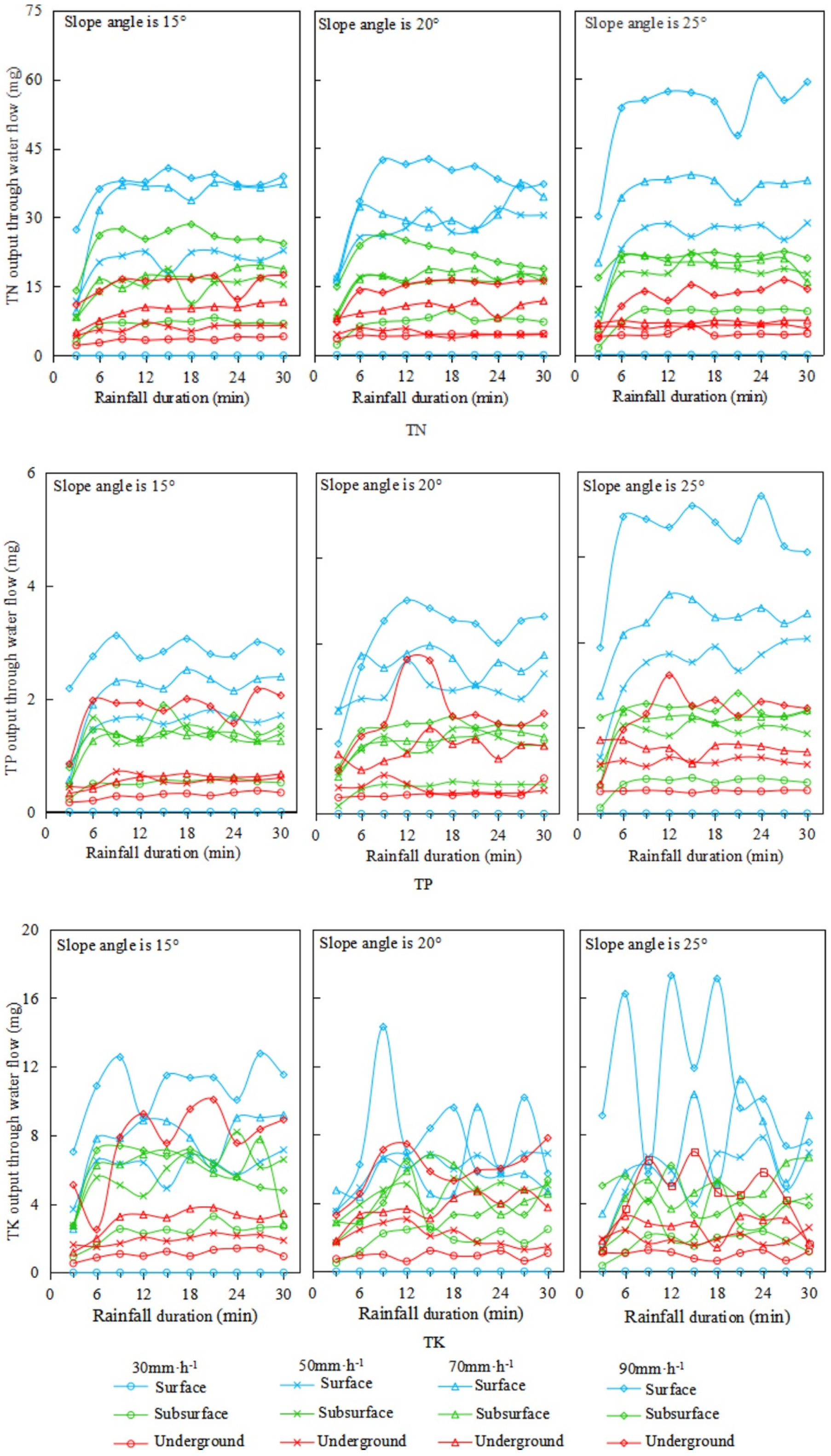

Figure 4. Process of nutrient (TN, TP and TK) output through water flow.

were all above 0.90. Rainfall intensity and subsurface water flow were positively correlated with TN, TP and TK outputs through water flow ($P < 0.01$), and the minimum correlation coefficient was 0.761. There was a significant positive correlation between slope angle and TP output through surface water flow ($P < 0.05$), and the correlation coefficient was 0.660. There was no significant correlation between slope angle or flow and the other types of nutrient outputs through water flow. There was a negative correlation between slope angle and TK output through surface water flow, TK output through subsurface water flow and underground water flow, TN output through underground water flow, and TK output through underground water flow.

4. Discussion

4.1. Effects of rainfall intensity and slope angle on water flow

Water flow on slopes is the main agent of soil nutrient loss from sloping farmland, and rainfall intensity is the main determinant of water flow on slopes; therefore, rainfall intensity is the driver of soil nutrient loss from sloping farmland (Ramos *et al*, 2006). Water flow can also cause water pollution and further damage to the ecological environment if the nutrients in the flowing water enter surrounding water bodies or groundwater systems. Therefore, studying the characteristics of water flow in sloping farmland with slight rocky desertification in karst regions will shed light on the mechanism of soil nutrient loss. This study showed that the water flow in sloping farmland with slight rocky desertification in a karst region was positively related to rainfall intensity, which was consistent with the results of (Yan *et al* 2018). The water flow on the slopes was obviously influenced by slope angle under a given rainfall intensity, which was the same as the conclusion reached by (Wu *et al* 2018), mainly because the downward tangential force of the slope increased with increasing slope angle; as a result, the loss of flowing water along the slope also increased. However, underground water flow was not obviously affected by slope angle, probably because soil particles clog soil macropores after being washed by rain (Wang *et al* 1996), which hinders rainwater infiltration.

On the other hand, the study showed that there was subsurface water flow and underground water flow, but not surface water flow, under a low rainfall intensity (30 mm $\cdot$ h^{-1}) and that water began to flow on the surface when the rainfall intensity reached 50 mm $\cdot$ h^{-1}. Therefore, the water flow from sloping farmland with slight rocky desertification in this karst region progressed from underground water flow to surface water flow, and the critical rainfall intensity was between 30 and 50 mm $\cdot$ h^{-1}. (Wei *et al* 2011), through field monitoring, showed that the surface runoff coefficient of karst areas is very low; not every rainfall surface will produce runoff, and mainly heavy rainfall (25 mm-50 mm), especially very heavy rainfall ($\geq$50 mm), will produce runoff. The conclusion of this study is roughly similar to that of previous studies. This progression was mainly caused by the special ‘dual structure’ of the karst soils; most of the rainfall enters the underground system through the underground fissure (crack) of karst (Peng *et al* 2017). There are a number of reasons for this, most likely related to the particular structure of the karst region. In the future, we can further explore the problem of identifying the critical rainfall intensity for surface water flow in sloping farmland with slight rocky desertification in karst regions.

4.2. Response of nutrient output through water flow to rainfall intensity and slope angle

As the three major nutrient elements in soil, nitrogen, phosphorus and potassium support crop growth. The nutrient loss of sloping farmland with runoff and soil particle migration (Xing *et al* 2016), (Peng *et al* 2017) studies have shown that, overall, the TN and TP of karst sloping farmland are mainly runoff loss, while the TK is mainly sediment loss. (Wang *et al* 2014) also pointed out that runoff-associated available nitrogen and phosphorus losses were mainly controlled by runoff rate and were weakly affected by soil erodibility. Rainfall intensity and slope angle are two main natural factors affecting nutrient loss from sloping farmland in karst regions. Rain intensity produces runoff, and one of the main carriers of nutrient loss is runoff. The slope angle determines runoff erosion and migration ability to some extent (Shen *et al* 2016). Related studies showed that the amount of nitrogen lost increased with increasing rainfall intensity (Liu *et al* 2014, Wu *et al* 2018). TP output through water flow also increases with increasing rainfall intensity (Kleinman *et al* 2006, Shigaki *et al* 2007, Gao *et al* 2010), and rainfall intensity is the decisive factor affecting potassium loss (Alfaro *et al* 2013). (Mellander *et al* 2012) notes that there is a positive correlation between the soil nutrient concentrations and the rainfall intensity. The results of this study also revealed a significant positive correlation between nutrient output through water flow from sloping farmland with slight rocky desertification in a karst region and rainfall intensity, including the nutrient outputs through surface, subsurface and underground water flows.

The results of (Wang *et al* 2014) showed that soil nutrient loss increased with increasing rainfall intensity and slope angle but not significantly. Zhang *et al* (2018a) also showed that TP output through water flow increased significantly with increasing rainfall intensity and slope angle, and the effect of rainfall intensity on TP output through water flow was greater than the effect of slope angle. The results of this study also showed that rainfall intensity was positively correlated with TN, TP and TK outputs through water flow ($P < 0.01$), and the correlation coefficients were above 0.9. Slope angle exhibited a significant positive correlation with TP output through surface water flow ($P < 0.05$) but had no significant effect on the output of other nutrients through water flow, even though there were negative correlations between slope angle and TK output through surface water flow, TK output through subsurface water flow, TN and TK output through underground water flow. Simard *et al* (1995) pointed out that the increase in slope angle reduced the time of contact between surface runoff and soil and reduced the soluble nutrients lost with runoff to some extent, which was similar to the results of our studies. However, the content of the soil nutrient form type directly affects the transfer of nutrients with runoff, phosphorus output through surface water flow contains two forms, granular state and soluble state, and it is possible that phosphorus output through subsurface water flow and underground water flow is mainly soluble state. On the other hand, the surface water flow increases with increasing slope angle, which may remove more phosphorus, together with the gradual dissolution and release of phosphorus carried by sediment in surface water flow. In addition, the available phosphorus content also affects the characteristics of phosphorus loss, which may be the reason why the slope has a significant effect on the amount of TP output through surface water flow. Research at this point could be strengthened in the future.

TN in soil contains organic nitrogen and inorganic nitrogen; among them, plants absorb inorganic nitrogen in soil, the proportion of inorganic nitrogen in soil is small, and it is easy to dissolve in water and lose with runoff. Therefore, for sloping farmland in karst areas, nitrogen loss control and nitrogen fertilizer supplementation should be considered. However, the proportion of nitrogen and phosphorus in each morphological type and the solubility of the nutrient in water need further investigation. In addition, it might also be due to the particular underground structure of the sloping farmland. On the other hand, the nutrient output through water flow was affected by many factors, especially nutrient output through underground water flow, which was mainly influenced by the permeability of the soil and the size and connectivity of the underground pores (cracks). Therefore, the nutrient output through water flow was special and complex for sloping farmland with slight rocky desertification in this karst region. However, there are many factors affecting soil nutrient loss in sloping farmland, and the effects of soil characteristics (Walton *et al* 2000), tillage and fertilization methods (Lin *et al* 2009), surface cover (Kooch *et al* 2020) and management control measures (Martínez-Mena *et al* 2020) should be considered in future research. The basic characteristics of soil include soil texture, permeability, structure condition, water condition, etc.

Sloping farmland with slight rocky desertification is a common farmland type in the karst region of Southwest China, and its special underground 'dual structure' leads to nutrient loss from underground water flow, which is different from the loss in other regions. The nutrient output through underground water flow is easily ignored because the flow is hidden underground, which makes it easy to store nutrients in karst aquifers and difficult for surface vegetation to use these nutrients. In addition, the loss of nutrients into the underground river will cause ecological environmental pollution. Therefore, we should further strengthen the prevention and control of nutrient loss from sloping farmland in karst regions to reduce the impact on the environment. The internal structure of sloping farmland with slight rocky desertification in karst regions is complicated, which will cause some differences between the results obtained with a variable-slope steel trough with floor perforations and the actual dynamics in the field. In the future, fixed-point field research should be carried out to correct the results of laboratory simulation tests. Moreover, the influences of morphological characteristics and the connectivity of underground fissures (cracks) on nutrient loss should be considered. On the other hand, studies have shown that vegetation restoration can alleviate soil erosion and improve soil quality in karst areas (Zhang *et al* 2019) and that vegetation can reduce the strike force of raindrops, helping alleviate the erosion of sloping farmland; therefore, we can reduce the loss of nutrients in sloping farmland by planting crops or vegetation with high coverage.

5. Conclusions

The rainfall intensity was between 30 mm $\cdot$ h^{-1} and 50 mm $\cdot$ h^{-1} when surface water flow occurred in sloping farmland with slight rocky desertification in the karst region. TN, TP and TK losses through water flow showed the same pattern. Nutrient output through water flow was dominated by nutrient loss from surface and subsurface water flows when the rainfall intensity was ≥ 50 mm $\cdot$ h^{-1}. The largest proportion of nutrient output was associated with surface flow, a lower proportion was associated with subsurface flow, and the lowest proportion with underground flow. The nutrient output through underground water flow directly led to groundwater pollution, although it was not large. Rainfall intensity was found to be a dominant driver in comparison to slope angle and for limestone soil of the karst region in Southwest China, but slope angle only had a significant effect on TP output through surface water flow. In addition, due to the special geological background of sloping farmland with slight rocky desertification in karst regions, field research in the field with the help of advanced research technology, such as ground-penetrating radar and short pulses, should be further considered.

Acknowledgments

This work was funded by grants from the First-class Discipline Construction Project of Guizhou Province (GNYL [2017]007), the National Natural Science Foundation of China [No. 41671275] and the National Key Research and Development Plan [No. 2016YFC0502604]. In addition, we appreciate the project support provided by the High-level Innovative Talents in Guizhou Province of Guizhou Province [Qian Ke He Platform Talents [2018]5641], the Major Project of Guizhou Province [Qian Ke He Major Project [2016]3022], and the Science and Technology Projects of Guizhou Province [Qian Ke He Platform Talents [2017]5788].

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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