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Factors on Particulate Phosphorus Loss in Surface Runoff under Simulated Rainfalls

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Particulate phosphorus loss in surface runoff had special significance compared with total phosphorus loss. We designed 12 stochastic simulated rainfall events with different conditions to find out the key contributing factors on particulate phosphorus loss in surface runoff. There were 6 indices relating to particulate phosphorus loss process were considered, including particulate phosphorus percentage in total phosphorus, particulate phosphorus loss modulus, sediment yield, sediment concentration, runoff coefficient and runoff occurrence time. Four contributing factors were studied, including rainfall intensity, slope, coverage ratio and gravimetric soil moisture content. The studied reveal that runoff occurrence time and runoff coefficient are the key indices to describe the phosphorus loss process. The contributing factors impacted the runoff occurrence time and runoff coefficient to impact the phosphorus loss characteristics. Slope is the most important contributing factor to sediment yield. The gravimetric soil moisture content is the second key contributing factor. Coverage ratio impacted runoff coefficient, while rainfall intensity impacted runoff occurrence time.

Key Words: Particulate phosphorus loss, Surface runoff, Rainfall event, Contributing factors.

INTRODUCTION

Phosphorus was considered to be the limiting element to the eutrophication of water[1-3]. The production and export of phosphorus focused on the upper 0-5 cm of surface soil. Phosphorus loss mainly occurred in the surface runoff[4] and it was a complicated process, which was influenced by the rainfall process (rainfall intensity and duration) and the surface situations (landforms, physiognomy, chemical and physical characters of soil, vegetation characteristics and agricultural practical managements)[5-7].

Many studies have reported the speed of the water eutrophication brought by phosphorus in runoff had a close relationship to the forms of phosphorus in runoff[8-10]. Most of total phosphorus stored within ecosystems is found associated with particulate phosphorus because of its strong affinity for the solid phase. In addition, the predominant mode of transport of phosphorus is limited to runoff. Particulate phosphorus is the dominant form of phosphorus loss in surface runoff. It contained phosphorus in phosphorite and organic matters and phosphorus absorbed by soil particulates. Particulate phosphorus would become the potential source of dissolved phosphorus when there were dissolutions or dissociation adsorptions under in some certain instances[8]. Dissolved phosphorus released from the soils, plants and fertilizers. It existed as the form of tribasic phosphate which could be absorbed by the algae directly.

Differentiating phosphorus forms in runoff could find their validities to the algae in the water bodies the runoff flowed into and also could ensure the major source of phosphorus in runoff to adopt the related fathering measures[11,12].

Phosphorus in surface runoff came from water and sediment in runoff. Phosphorus in water was more important than that in sediments to water pollution because phosphorus in water was the direct source for algae. So the study considered phosphorus in water, not phosphorus bond to sediments.

Phosphorus loss in the agricultural non-point source pollution is a complicated process. It relates to 6 indices, which could describe the characteristics of particulate phosphorus loss in surface runoff, including particulate phosphorus percentage in total phosphorus, particulate phosphorus loss modulus, sediment yield, sediment concentration, runoff coefficients and runoff occurrence time. The contributing factors were considered adequately, such as the rainfall intensity, slope, vegetation coverage ratio and the gravimetric soil moisture content.

The objective of this study is to find out the importance of each factor step by step, according to the data processing system (DPS), a software to process data in Chinese which was used widely in China and then, confirm the key contributing factor on particulate phosphorus loss in surface runoff.

EXPERIMENTAL

Simulated rainfall experiments were designed and conducted in a glasshouse in Zhejiang University, China. The temperature in the glasshouse was maintained at 25 ºC all the time.

There were two 2 m^2 experimental wooden troughs (A and B), with length, width and height measuring 2.0, 1.0 and 0.5 m, respectively, with 2 replicates. The troughs were sealed at the four sides to avoid runoff leak. Troughs A and B were designed at two slopes of 11º and 25º, respectively, which were chosen based on the landforms of local vegetable lands. Troughs were filled with yellow red soil taken from a typical hilly area in Qingshan Lake watershed of Zhejiang Province. We selected same plots with length and width measuring 2 and 1 m at local fields. Five layers of soils, with 10 cm depth in each layer, were dug and kept separately. Then they were put into the troughs layer by layer in original order. The physical and chemical characteristics of soils at 5 layers were measured, respectively (Table-1).

In each set of rainfall, the period from rainfall beginning to runoff occurrence was recorded as runoff occurrence time. Each set of rainfall lasted for approximately 20 min, including runoff occurrence time (they were different among 12 rainfall events) and runoff duration (15 each in all the 12 rainfall events). The rainfall intensities of simulated rainfalls were designed based on the local meteorological data in Qingshan Lake watershed.

The waterworks were assembled with two 4 m long stand-up steel tubes and supported by two tripods. Steel tubes stood on the two sides of the troughs. Two sprinklers were fixed on the top of tubes. One sheet metal with one pore was used in one sprinkler and various size pores made various rainfall intensities. Pressure gauges and valves were placed on the tubes near the water source. We adjusted the valves to stabilize the water flowing speed from water source according to pressure gauges. Hence the size of pore was the only various contributing factor to simulated rainfall intensity. There were six barrels surrounding each wooden trough to calculate CU (coefficient of uniform) of each set of rainfall. Coefficient of uniform (CU) (Christiansen, 1941) was adopted to describe the distributing uniform of spout quantity and it could be calculated by the following formula:

$$\text{Coefficient of uniform} = 100 \times \left(1 - \frac{\sum_{i=1}^{N} |x_i - \bar{x}|}{N\bar{x}} \right) \quad (1)$$

In the formula (1), x_i = depth of the rainfall in the barrel located I; $\bar{x}$ = average depth of all barrels $\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$; N = number of barrels.

The vegetation coverage ratio changed with the growth of the cabbages planted in the troughs. The values were obtained by eyeballing. The gravimetric soil moisture contents in 6 symmetrical spots of the troughs were measured and the average value of them was calculated. The period was recorded from the rainfall beginning to the runoff occurrence.

Samples collection: In each set of rainfall event, 15 runoff samples were collected separately every minute in order as soon as the runoff occurred. Following on, the 15 runoff samples were taken back to the laboratory. The concentrations of total phosphorus and dissolved phosphorus in runoffs were measured in 24 h, respectively. The volumes of runoff samples and the sediment yields in each sample were also measured, respectively.

Samples analysis: The concentrations of total phosphorus and dissolved phosphorus were measured immediately. Total phosphorus was measured according to the ascorbic acid-molybdenum blue method (USEPA method 365.2)[13]. After being filtered using 0.45 μm filters, dissolved phosphorus was obtained using molybdenum colorimetry after isobutanol extraction[14]. The difference between total phosphorus and dissolved phosphorus concentrations yielded the particulate phosphorus concentration.

The sediments were filtered out from runoff samples and then dried at 105 ºC for 8 h. The weights of the dry sediments in each runoff sample were measured, respectively.

Definitions: The runoff coefficient was calculated by the formula (2):

$$C_R = \frac{V_R}{P} \quad (2)$$

In the formula 2, C_R = runoff coefficient; V_R = runoff volume in each set of rainfall (L); P = precipitation in each set of rainfall (L). The particulate phosphorus loss modulus was obtained from the formula 3:

$$M_{PP} = \frac{C}{(S \times T)} \quad (3)$$

In the formula 3, M_{PP} is particulate phosphorus loss modulus (mg/m^2 h); C= particulate phosphorus content (mg); S = area of experimental field (m^2); T = rainfall time (h).

RESULTS AND DISCUSSION

The values of contributing factors, particulate phosphorus loss modulus and particulate phosphorus percentages were given in Table-2. On the basis of the experimental data in Table-2, the significance levels of factors were calculated by data processing system (DPS).

Particulate phosphorus percentage: The significance levels of factors about particulate phosphorus percentage were given in Table-3. In Table-3, x_1 was slope, x_2 was rainfall intensity, x_3 was coverage ratio, x_4 was gravimetric soil moisture content, x_5 was sediment yield, x_6 was sediment concentration,

TABLE-1
DENSITIES OF EXPERIMENTAL SOIL

Soil depth (cm)	0-10	10-20	20-30	30-40	40-50
Soil density (g/cm^3)	1.13	1.14	1.15	1.16	1.19
Total P (TP) content (g/kg)	0.56	0.50	0.48	0.46	0.45
Olsen-P content (mg/kg)	20.43	16.44	14.34	13.26	12.80

TABLE-2
CONTRIBUTING FACTORS DESIGNED AND THE RESULTS INCLUDING PARTICULATE PHOSPHORUS LOSS MODULUS AND PARTICULATE PHOSPHORUS PERCENTAGES IN TOTAL PHOSPHORUS

Rainfall measurement	1	2	3	4	5	6	7	8	9	10	11	12
Slope (º)	11	11	11	11	11	11	25	25	25	25	25	25
Rainfall intensity (mm/min)	1.1	1.1	1.3	1.6	2.2	2.4	1	1	1	1.6	1.7	1.7
Coverage ratio	0.3	0.4	0.1	0.2	0.3	0.4	0.4	0.6	0.7	0.9	0.3	0.8
Gravimetric soil moisture content	14.86	21.98	14.24	16.39	9.78	22.96	30.3	20.07	15.3	20.6	14.91	19.34
Sediment (g)	14.01	82.81	86.03	98.24	477.6	119.01	830.03	1175.14	340.58	1782.58	1677.42	1422.1
Sediment concentration (g/L)	2.49	2.59	4.2	4.37	21.6	4.94	31.97	49.56	23	45.46	57.31	39.97
Runoff coefficient	0.089	0.491	0.508	0.482	0.335	0.337	0.873	0.758	0.491	0.83	0.574	0.682
Runoff occurrence time (min)	9.12	5.87	3.83	5.92	4.93	2.07	1.83	1.05	1.73	5	1.17	1.58
Particulate phosphorus loss modulus ($mg/m^2 \cdot h$)	0.01	0.297	0.192	0.062	0.389	0.541	0.508	0.291	0.053	0.75	0.513	0.782
Particulate phosphorus (%)	0.674	0.774	0.578	0.362	0.706	0.771	0.757	0.643	0.418	0.768	0.672	0.749

TABLE-3
SIGNIFICANCE LEVELS OF FACTORS ABOUT PP PERCENTAGE

Factors and their combinations	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	$x_2 \times x_9$	$x_4 \times x_9$	$x_7 \times x_9$	y
Significance level	0.7827	0.4420	0.4382	0.1544	0.2660	0.4689	0.5825	0.8645	0.0094	0.0232	0.0097	0.0394	1.0000

x_1 was slope, x_2 was rainfall intensity, x_3 was coverage ratio, x_4 was gravimetric soil moisture content, x_5 was sediment yield, x_6 was sediment concentration, x_7 was runoff coefficient, x_8 was runoff occurrence time, x_9 was PP loss modulus, y was PP percentage.

x_7 was runoff coefficient, x_8 was runoff occurrence time, x_9 was particulate phosphorus loss modulus.

Table-3 showed particulate phosphorus loss modulus (x_9) had the significant effects on particulate phosphorus percentage which had the extremely significance level $0.0094 < 0.01$. The combination of gravimetric soil moisture content (x_4) and particulate phosphorus loss modulus (x_9) had the extremely significance level $0.0097 < 0.01$. The combination of particulate phosphorus loss modulus (x_9) with rainfall intensity (x_2) had the significance level less than 0.05.

The results showed the contributing factors including gravimetric soil moisture content and rainfall intensity could enhance the relationships between particulate phosphorus loss modulus and particulate phosphorus percentage. Changing the contributing factors singly could not change particulate phosphorus percentage obviously.

Particulate phosphorus loss modulus: The significance levels of factors about particulate phosphorus loss modulus were given in Table-4. In Table-4, x_1 was slope, x_2 was rainfall intensity, x_3 was coverage ratio, x_4 was gravimetric soil moisture content, x_5 was sediment yield, x_6 was sediment concentration, x_7 was runoff coefficient, x_8 was runoff occurrence time.

Table-4 showed sediment yield (x_5) and sediment concentration (x_6) both had the significant effects on particulate phosphorus loss modulus, but no contributing factor had. The combinations which only related to the contributing factors were rainfall intensity (x_2) and slope (x_1), rainfall intensity (x_2) and coverage ratio (x_3), rainfall intensity (x_2) and gravimetric soil moisture content (x_4), coverage ratio (x_3) and gravimetric soil moisture content (x_4). Rainfall intensity participated in the most combinations.

Rainfall intensity impacted the runoff according to the diameter and the kinetic energy of rainfall drops. In the process of rainfall, the striking of rainfall drops led to the compactness of soil surface. The aggregate breakdown in general results in soil surface sealing and after drying, surface seals will form crusts[15-17]. Other researchers investigated the mechanisms of aggregate breakdown and crust formation by raindrop impact[18-21]. The crust reduced the surface roughness of soil and enhanced the runoff volume. The crust also reduced the infiltration volume in the ways of increasing runoff speed and decreasing the settling time of runoff on the surface[22]. It was obvious that stronger rainfall intensity could lead to less dissolution of phosphorus.

TABLE-4
SIGNIFICANCE LEVELS OF FACTORS ABOUT PP LOSS MODULUS

Factors and their combinations	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	$x_1 \times x_2$	$x_1 \times x_5$	$x_1 \times x_7$	$x_2 \times x_3$	$x_2 \times x_4$	$x_2 \times x_5$
Significance level	0.1247	0.1386	0.0715	0.1925	0.0064	0.0454	0.0538	0.1461	0.0017	0.0093	0.0500	0.0034	0.0271	0.0030
Factors and their combinations	$x_2 \times x_6$	$x_2 \times x_7$	$x_3 \times x_4$	$x_3 \times x_5$	$x_3 \times x_6$	$x_3 \times x_7$	$x_4 \times x_5$	$x_4 \times x_6$	$x_5 \times x_6$	$x_5 \times x_7$	$x_5 \times x_8$	$x_6 \times x_7$	$x_6 \times x_8$	y
Significance level	0.0132	0.0003	0.0248	0.0066	0.0258	0.0241	0.0043	0.0310	0.0221	0.0064	0.0270	0.0317	0.0482	1.0000

x_1 was slope, x_2 was rainfall intensity, x_3 was coverage ratio, x_4 was gravimetric soil moisture content, x_5 was sediment yield, x_6 was sediment concentration, x_7 was runoff coefficient, x_8 was runoff occurrence time, y was PP modulus.

TABLE-5
SIGNIFICANCE LEVELS OF FACTORS ABOUT SEDIMENT YIELD

Factors and their combinations	x_1	x_2	x_3	x_4	x_5	x_6	x_7	$x_1 \times x_2$	$x_1 \times x_3$	$x_1 \times x_4$	$x_1 \times x_5$
Significance level	0.0011	0.8454	0.0323	0.6182	0.0001	0.0111	0.1047	0.0001	0.0075	0.0225	0.0001
Factors and their combinations	$x_1 \times x_6$	$x_2 \times x_3$	$x_2 \times x_5$	$x_2 \times x_6$	$x_3 \times x_4$	$x_3 \times x_5$	$x_3 \times x_6$	$x_4 \times x_5$	$x_5 \times x_6$	$x_5 \times x_7$	y
Significance level	0.0011	0.0357	0.0001	0.0025	0.0366	0.0001	0.0041	0.0001	0.0001	0.0108	1.0000

x_1 was slope, x_2 was rainfall intensity, x_3 was coverage ratio, x_4 was gravimetric soil moisture content, x_5 was sediment concentration, x_6 was runoff coefficient, x_7 was runoff occurrence time, y was sediment yield.

Sediment yield: The significance levels of factors about sediment yield are given in Table-5. In Table-5, x_1 was slope, x_2 was rainfall intensity, x_3 was coverage ratio, x_4 was gravimetric soil moisture content, x_5 was sediment concentration, x_6 was runoff coefficient, x_7 was runoff occurrence time.

Table-5 showed slope (x_1) and sediment concentration (x_6) both had the significant effects on sediment yield which had the extremely significance level less than 0.01. Coverage ratio (x_3) had the significance level less than 0.05. The contributing factors affected the sediment yield included slope and coverage ratio.

Slopes had effects on runoff in two ways. One was fastening the runoff speed by the component forces of rainwater gravity at the direction of slope. The other way was reducing the vertical component force of rainwater gravity with increasing gradient, weakening the striking of rainfall drops to soil surface, slowing down the forming of crust and increasing the speed of runoff. Based on this theory, it was obvious that particulate phosphorus percentage in total phosphorus became more at the steeper slope while dissolved phosphorus became less. Slower speed of runoff was advantage to the dissolution of phosphorus.

Many studies had proved increasing coverage ratio is an important measure to control water erosion and improve soil environments[23-27]. Coverage ratio affected runoff by the ways of reducing the kinetic energy of rainfall drop, holding up rainwater and changing the soil surface. Less kinetic energy of rainfall drop smashed less soil particulates and dissolved less phosphorus into the surface runoff.

Sediment concentration: The significance levels of factors about sediment concentration were given in Table-6. In Table-6, x_1 was slope, x_2 was rainfall intensity, x_3 was coverage ratio, x_4 was gravimetric soil moisture content, x_5 was runoff coefficient, x_6 was runoff occurrence time.

Table-6 showed slope (x_1) had the significant effects on sediment concentration which had the extremely significance level 0.0002 < 0.01. Runoff coefficient (x_5) and runoff occurrence time (x_6) both had the significant effects with the significance levels less than 0.05.

Based on the results of Tables 5 and 6, slope had a closer relationship with sediments than with other contributing factors. Compared with sediment yield, runoff coefficient and runoff occurrence time influenced sediment concentration more by influencing runoff volume. These two indices were both variables, so we need the analysis on them sequentially.

Runoff coefficient: The significance levels of factors about runoff coefficient are given in Table-7. In Table-7, x_1 was slope, x_2 was rainfall intensity, x_3 was coverage ratio, x_4 was gravimetric soil moisture content.

Table-7 showed slope (x_1) had the significant effects on runoff coefficient which had the extremely significance level 0.0042 < 0.01. Gravimetric soil moisture content (x_4) had the significant effects with the significance levels less than 0.05. Coverage ratio (x_3) also had effects by combining with slope and gravimetric soil moisture content, respectively.

Runoff occurrence time: The significance levels of factors about runoff occurrence time are given in Table-8. In Table-8, x_1 was slope, x_2 was rainfall intensity, x_3 was coverage ratio, x_4 was gravimetric soil moisture content.

Table-8 showed slope (x_1) had the significant effects on runoff occurrence time which had the significance level 0.0176 < 0.05. Rainfall intensity (x_2) and gravimetric soil moisture content (x_4) had effects on runoff occurrence time by combining with the slope. We could obtain the contributing factors which

TABLE-6
SIGNIFICANCE LEVELS OF FACTORS ABOUT SEDIMENT CONCENTRATION

Factors and their combinations	x_1	x_2	x_3	x_4	x_5	x_6	$x_1 \times x_2$	$x_1 \times x_3$	$x_1 \times x_4$	$x_1 \times x_5$	$x_2 \times x_5$	$x_3 \times x_5$	$x_4 \times x_6$	y
Significance level	0.0002	0.9098	0.0607	0.7154	0.0140	0.0319	0.0008	0.0125	0.0166	0.0007	0.0216	0.0150	0.0500	1.0000

x_1 was slope, x_2 was rainfall intensity, x_3 was coverage ratio, x_4 was gravimetric soil moisture content, x_5 was runoff coefficient, x_6 was runoff occurrence time, y was sediment concentration.

TABLE-7
SIGNIFICANCE LEVELS OF FACTORS ABOUT RUNOFF COEFFICIENT

Runoff coefficient	Factors and their combinations	x_1	x_2	x_3	x_4	$x_1 \times x_3$	$x_1 \times x_4$	$x_3 \times x_4$	y
	Significance level	0.0042	0.4059	0.0863	0.0496	0.0221	0.0005	0.0172	1.0000

x_1 was slope, x_2 was rainfall intensity, x_3 was coverage ratio, x_4 was gravimetric soil moisture content, y was runoff coefficient.

TABLE-8
SIGNIFICANCE LEVELS OF FACTORS ABOUT RUNOFF OCCURRENCE TIME

Runoff occurrence time	Factors and their combinations	x_1	x_2	x_3	x_4	$x_1 \times x_2$	$x_1 \times x_4$	y
	Significance level	0.0176	0.8142	0.3095	0.3342	0.0436	0.0472	1.0000

x_1 was slope, x_2 was rainfall intensity, x_3 was coverage ratio, x_4 was gravimetric soil moisture content, y was runoff occurrence time.

affected the runoff obviously include slope and gravimetric soil moisture content according to Tables 7 and 8.

Based on all the above results and discussions, we could obtain: The order of the indices being affected by factors was particulate phosphorus percentage → particulate phosphorus loss modulus → sediment yield → sediment concentration → runoff coefficient/runoff occurrence time. Slope was the most important contributing factor to sediment yield. Runoff occurrence time and runoff coefficient were the key indices to describe phosphorus loss process. The contributing factors affected runoff occurrence time and runoff coefficient to affect phosphorus loss characteristics. The order of factors affected runoff coefficient was slope > gravimetric soil moisture content > rainfall intensity = coverage ratio. The order of factors affected runoff occurrence time was slope > gravimetric soil moisture content = rainfall intensity = coverage ratio. Gravimetric soil moisture content was the second key contributing factor. Coverage ratio affected runoff coefficient, while rainfall intensity effected runoff occurrence time.

Conclusion

Different rainfall events with different conditions were designed to find out the key contributing factors on particulate phosphorus loss in surface runoff. Based on the discussions, the conclusions were obtained. Runoff occurrence time and runoff coefficient were the key indices to describe phosphorus loss process. The contributing factors affected runoff occurrence time and runoff coefficient to affect phosphorus loss characteristics. Slope was the most important contributing factor to sediment yield. Gravimetric soil moisture content was the second key contributing factor. Coverage ratio affected runoff coefficient, while rainfall intensity affected runoff occurrence time.

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