Regulatory mechanisms of runoff separation and sediment transport rates on sloping agricultural land via a combined planting method of Prunella vulgaris with earthworms in the soil

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Research Article

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Abstract

The combination of prunella vulgaris and earthworm cultivation can effectively improve the economic benefits and utilization rate of small-scale sloping farmland, while also improving soil organically and preventing agricultural pollution and soil erosion. In this study, field-simulated rainfall experiments were conducted to investigate the regulatory mechanisms of runoff separation and sediment transport rates by planting *Prunella vulgaris* with earthworms. The runoff separation and sediment transport rates and bare slope significantly increased with a higher rainfall intensity or slope angle except for at a rainfall intensity of 1.2–1.6 mm/min and slope angle of 5°–10°. This relationship can be described using a binary linear or exponential equation with correlation coefficients > 0.6 or 0.9. Additionally, the regulatory effect of this study's combined planting method on the runoff separation rate was positively correlated with rainfall intensity and negatively correlated with slope angle. A binary logarithmic function can describe this correlation, with rainfall intensity having a greater influence than the slope angle. Furthermore, the regulatory effect on the runoff separation rate was mainly due to the sediment transport rate, contributing 94.73% of the effect. The runoff separation rate primarily influenced the regulatory effect on the sediment transport rate, contributing to 70.81% of the effect.

1. Introduction

Prunella vulgaris and earthworm are both medicinal herbs and soil animals with high medicinal value. Prunella vulgaris has good medicinal value and is easy to cultivate and manage. Earthworms can improve soil properties and soil environment. The combination of prunella vulgaris and earthworm cultivation can effectively improve the economic benefits and utilization rate of small-scale sloping farmland, while also improving soil organically and preventing agricultural pollution and soil erosion.

Rainfall leads to complex soil detachment and transport patterns. However, conducting studies in this area has been challenging; thus, the lack of studies results in contentious debates (Wang et al. 2021). The slope angle, flow rate, or rainfall intensity are applied in erosion simulations and frequently used to describe erosion (Wang et al. (2016). Scholars agree that runoff separation and sand transport rates increase with slope angle, flow rate, or rainfall intensity and can be described using linear or power functions (Zhang et al. 2008; Xiao 2017; Lei et al. 2006; Qingwei et al. 2018). The power function relating slope angle to flow rate can be applied in the ANSWERS model (Beasley et al. 1980). However, viewpoints on the extent to which slope angle, flow rate, or rainfall intensity affects the runoff separation or sediment transport rate differs, possibly due to variations in experimental design.

Even before eliminating the effects of raindrop splash, splash detachment and soil erosion contribute to runoff depth. Current research acknowledges that soil migration differs under the combined effects of raindrops and runoff; however, most studies focus on splash detachment and neglect the transport effect of raindrops. In addition, existing erosion concepts do not adequately define the relationship between splash detachment and runoff separation in sediment transport. This gap has led to a debate in calculating runoff separation and sand transport rates (Wang et al. 2021). This study aimed to overcome the limitation in studying sediment separation and transport by runoff under rainfall by improving the experimental design and the understanding of erosion mechanisms. Regarding the field experimental design, the plot length was

120 cm, and erosion collection was conducted in four directions (upward, downward, leftward, and rightward) to achieve more accurate measurements of erosion indicators. Concerning erosion concepts, the study employed a detailed analysis of splash erosion in four directions to assess the relationship between splash detachment and sediment transport across different erosion stages, thereby improving the accuracy of erosion indicator calculations. In this study, we characterised the changes in runoff separation and sediment transport rates on the slope by planting *Prunella vulgaris* with earthworms in the soil and the regulatory effects in the secondary precipitation. In addition, the regulatory mechanisms of runoff separation and sediment transport rates were also assessed.

2. Research methodology

2.1 Overview of the research area

The study was conducted at the Soil and Water Conservation Science and Technology Park in Wuhua County, Guangdong Province (Fig. 1). The park is located between 23°23' and 24°12' N latitude and 115°18' and 116°02' E longitude. Wuhua has a humid southern subtropical monsoon climate at the low-to-mid latitudes. The annual average temperature of the county between 1979 and 2000 was 21.2°C. The annual average precipitation, thunderstorm days, and frost-free period were 1519.7 mm, 77 days, and 330 days, respectively. Wuhua has a complex geological composition, primarily consisting of five major types of rocks: intrusive rocks, extrusive rocks, sandy rocks, limestone, and granite. These geological formations give rise to three major landforms: mountains, hills, and basins.

2.2 Preparation of test materials

The field test and soil sample measurement were conducted at the Soil and Water Conservation Technology Demonstration Park in Wuhua County, Guangdong Province and the Guangdong Environmental Science and Technology Public Laboratory, respectively. The study equipment comprised a portable rainfall system (Fig. 2), a laser disdrometer, a digital camera (ORDRO), and consumables such as buckets, sample boxes, sample bags, and testing reagents. The study also used *P. vulgaris* of the same year (planted 15 cm between plants × 20 cm between rows) and the redworm *Eisenia foetida* (5 g/pc; 400 g/m^2 density). The red soil is predominant in South China; soil properties are presented in Table 1.

2.3 Experimental sample site establishment and survey

One-year-old *P. vulgaris*, a perennial herbaceous plant of the *Lamiaceae* family, was planted in the experimental plots. Standard planting practices were followed for propagation, seedling establishment, water and fertiliser management, cultivation, weeding, harvesting, and processing of the plant. The earthworms selected for the study were the “Taiping II” redworm—*E. foetida.* These earthworms were chosen based on specific criteria, including ≥ 90 mm body length, ≥ 3 mm body width, and ≥ 5 g weight (200 g/m^2 density). We performed a sample plot survey before and after planting *P. vulgaris* to determine the soil’s physicochemical and biological properties. All the indicators were determined according to the standard practices. The simulated rainfall experimental sample site had dimensions of 1.2 × 1.0 m. Four erosion collectors were installed along contour lines in all four directions, each measuring 5 × 5 × 20 cm. The investigation plots had dimensions of 5.0 × 1.2 m to assess the soil properties and characteristics of *P.*

vulgaris. The sample plots were ploughed and transplanted with *P. vulgaris*, and earthworms were introduced without further cultivation.

2.4 Design of field simulated rainfall experiments

Five slope angles (2°, 5°, 10°, 15°, and 20°) were chosen for the experiment, with five plots of earthworm treatment and bare ground plots for each slope angle. One rainfall test at five rain intensities (0.7, 1.0, 1.6, 2.2, and 2.6 mm/min) was conducted on the 10° slope with earthworm treatment and the bare ground sample plots. Furthermore, one rainfall test was conducted at 1.6 mm/min on the other four slopes (2°, 5°, 15°, and 20°), with 36 rainfall tests in total. Experimental treatments and sessions are presented in Table 2.

2.5 Measurement of soil and grass cover indicators

Soil bulk density was determined using the ring knife sampling method. Soil density was determined using the specific gravity determination method. Additionally, soil organic matter content was determined using the potassium dichromate-sulfuric acid digestion method. Soil mechanical composition was determined using a laser particle size analyser—MasterSizer 2000 (Malvern, UK). Soil porosity was determined via soil bulk density and density calculations. Plant root system characteristics (including root length, surface area, diameter, and volume) were determined using the WinRHIZO root system analyser. The dry weight of the root was obtained by rinsing the live roots, drying them in an oven at 80°C to a constant mass, and weighing them. Before the rainfall test, a digital camera was used to take portrait photos of the plot, which were subsequently analysed and processed in the laboratory. The method was to select the vegetation part of the photos as the area of interest (AOI) in the imageJ environment. Unsupervised classification was conducted using the minimum distance method. The classification results were visually interpreted and grouped into two major categories: vegetation cover and no vegetation cover. The number of image elements was counted to accurately determine the vegetation cover.

2.6 Field simulated rainfall experiments

Field simulated rainfall was conducted after the growth of *P. vulgaris* was stabilised. Before rainfall, the rain intensity was adjusted according to the experimental protocol. The sampling process commenced immediately with the onset of rainfall and continued at 3-min intervals until the rainfall ended, which lasted 40 min. Before sampling, the flow velocity within the velocity measurement zone (2 cm from the bottom and 2 cm from the edges of the erosion monitoring area) was measured using a dye tracer method. Measurements were taken on both sides of the velocity measurement zone, covering 50 cm. The average value represented the stream velocity for the sampling period. A thermometer was used to determine the temperature of the muddy water during rainfall, and a laser rain spectrometer was used to measure the size and terminal velocity of raindrops. A runoff bucket was set at the bottom of each sample plot to receive water and sediment samples. Four erosion collectors placed along the contour lines around the plot, with two in each direction, were flushed with 10 mL of water during sampling. After drying the sediment from the sheet and splash erosion, a small bucket was used to collect all the water and sediment from the designated time. The total volume of the muddy water was measured using a graduated cylinder. The collected water was then allowed to settle, and the clear water was separated and discarded. The remaining sediment was dried and weighed.

Similarly, water and sand samples were collected during rainfall to determine their physicochemical properties. The observed rainfall parameters include flow rate, sediment content, flow velocity, muddy water temperature, splash detachment (spattering), and raindrop size composition. The other research parameters were derived from calculations based on the observed data.

2.7 Estimating indicators

Based on relevant literature, hydraulic, rainfall, and basic erosion parameters were calculated(Dongdong et al.,2018;Feng et al.,2019). The regulatory effect was estimated by dividing the difference between the runoff separation and sediment transport rates with the bare soil and planting method by the rates with the bare soil, expressed as a percentage. Soil migration indicators were calculated using the sediment transport and erosion balance principles and raindrop runoff separation and sediment transport balance. The splash detachment rate was the total amount of the upward, downward, left, and right splash per unit time and area of the splash collection area (Eq. 1). The raindrop sediment transport rate was the difference in sediment separation between the upward and downward directions per unit time and area of the splash collection area in the upward and downward directions (Eq. 2). The runoff sediment transport rate (runoff sediment transport capacity) was equal to the difference between the erosion and the raindrop sediment transport rates (Eq. 3). The runoff separation rate was the difference between the erosion rate and the splash detachment capacity (Eq. 4). The formula for calculating the runoff sediment transport rate remained unchanged.

$$D_1 = (S_{upwards} + S_{downwards} + S_{left} + S_{right}) / (A_S \times t) \quad (1)$$

$$T_1 = (S_{downwards} - S_{upwards}) / (A_o \times t) \quad (2)$$

$$T_2 = SE - T_1 \quad (3)$$

$$D_2 = SE - D_1 \quad (4)$$

Where D_1, T_1, SE, T_2, and D_2 represent the splash detachment rate, raindrop sediment transport rate, erosion rate, runoff sediment transport rate, and runoff separation rate, respectively, with units in kg m^{-2} s^{-1}. $S_{upwards}$, $S_{downwards}$, S_{left}, and S_{right} represent the upward, downward, left, and right splash volumes, respectively, with units in kg. A_S and A_O represent the projected splash collection areas in the upward and downward directions, respectively, with units in m^2. Finally, t represents the rainfall duration in s (seconds).

2.8 Data processing

The data analysis and charting software used were SPSS 19.0, EXCEL 2003, and Auto CAD 2014. The data analysis methods include correlation analysis, least significant difference (LSD) multiple comparisons, analysis of variance (ANOVA), regression analysis, time series analysis, and interval estimation F-test. The optimal multivariate equation was established by incorporating the independent factors with the dependent variables, and the multiple regression squared was determined using the contribution formula (Eq. 5).

$$P_i = \frac{R^2}{\sum_{i=1}^{n} \beta_i^2} \beta_i^2 \times 100\% \quad (5)$$

Where O_i represents the contribution of the i^{th} factor, R^2 represents the coefficient of determination,

$$\beta_i^2 = b_i \frac{\sigma_i}{\sigma_y}$$

b_i represents the regression coefficient of the ith factor, σ_i represents the mean square deviation of the i^{th} factor, and σ_y represents the mean square deviation of the dependent variable.

3. Results

3.1 Characteristics of changes in the runoff separation and sediment transport rates on slopes due to planting P. vulgaris with earthworms in the soil in secondary precipitation

The bare slope and planting of *P. vulgaris* with earthworms in the soil had the same trend in runoff separation and sediment transport rates with rainfall intensity and slope (Table 3). The runoff separation and sediment transport rates increase with rising rainfall intensity and slope, with values of 1×10^{-5}–7×10^{-5} kg/m^2·s or 1×10^{-5}–9×10^{-5} kg/m^2·s, and 0–3×10^{-5} kg/m^2·s or 0–4×10^{-5} kg/m^2·s, respectively. Under 0.7 mm/min rainfall intensity, the runoff separation and sediment transport rates of the bare ground slope were significantly lesser than those under 1.6–2.6 mm/min rainfall intensity. The 2°–5° slope angles had significantly smaller runoff separation and sediment transport rates than slopes with < 20° angle. Except for the rainfall intensity of 1.2–1.6 mm/min, the runoff separation and sediment transport rates on the slope with combined planting of *P. vulgaris* with earthworms in the soil increased significantly with increased rainfall intensity. The bare slope's runoff separation and sediment transport rates increased with higher rainfall intensity or slope angle, which can be described using a binary linear equation with a correlation coefficient > 0.6 (Table 4). The runoff separation and sediment transport rates of combining *P. vulgaris* with earthworms in the soil increased with higher rainfall intensity or slope angle (except for the slope at 5°–10° angles), which can be described using a binary linear or exponential equation with correlation coefficients > 0.9.

3.2 Changes in the regulatory effects of planting P. vulgaris with earthworms in the soil on runoff separation and sediment transport rates

The regulatory effect of planting *P. vulgaris* with earthworms in the soil on runoff separation rate increases with increased rainfall intensity (10–40%) (Table 5). Rainfall intensity increased from 1.6 to 2.6 mm/min. This regulatory effect on runoff separation rate varies with the slope angle, initially decreasing before increasing (4–40%). A comprehensive analysis of this regulatory effect of the combined method on runoff separation rate with rain intensity and slope degree was conducted to establish the correlation equation (Eq. 4 – 2).

RDB = 0.571–0.186Ln (S) + 0.378Ln(I) R^2 = 0.6903 (6)

Where RDB-regulatory effect of combining *P. vulgaris* with earthworms in the soil on separation rate (%); S-slope angle ( ); I-rainfall intensity (mm/min). From Eq. 6, the regulatory effect of runoff separation rate using the combined method was positively correlated with rainfall intensity and negatively correlated with slope angle. Additionally, the effect of rainfall intensity was greater than that of slope angle. This can be described using a binary logarithmic function with a 0.6903 correlation coefficient.

A comprehensive analysis of the regulatory effect of the combined planting method on runoff sediment transport rate with rain intensity and slope angle was conducted to establish the related equation (Eq. 7).The regulatory effect of the combined method on runoff sediment transport rate decreased with increasing rainfall intensity (0–70%) (Table 5). This regulatory effect on runoff sediment transport rate decreased with increasing slope (10–80%).

RTB = 2.799 $e^{-0.09S-0.273I}$ R^2 = 0.7276 (7)

Where RDB-regulatory effect of the combined method of planting *P. vulgaris* with earthworms in the soil on sediment transport rate (%); S-slope angle ( ); I-rainfall intensity (mm/min). The regulatory effect of sediment transport rate using the combined method was negatively correlated with rainfall intensity and slope (Eq. 7). This correlation can be described using the binary exponential function with a 0.7276 correlation coefficient. In addition, the effect of rainfall intensity was greater than that of slope angle.

3.3 Regulatory mechanisms of the runoff separation and sediment transport rates by planting P. vulgaris with earthworms in the soil

With the combined planting method, high correlations existed between organic matter, soil particle density, stream power, runoff sediment yield, and runoff separation rate control effects (Tables 6 and 7). The main influence arose from the runoff sediment yield, contributing 94.73%. High correlations were observed between organic matter, soil particle density, stream power, runoff separation rate, and runoff sediment yield control effects. The main influence arose from the runoff separation rate, contributing 70.81%.

The regulatory effect rate of the combined planting method on the runoff separation mainly resulted from the runoff sediment transport rate. In addition, the regulatory effect on the runoff sediment transport rate mainly originated from the runoff separation rate.

4. Discussion

The greater the rainfall intensity, the higher the kinetic energy of raindrops, resulting in larger surface runoff. Consequently, the runoff separation and sediment yield rates also increase. Slope angle alone cannot provide erosion energy; however, a steeper slope results in a smaller unit area of erosion energy on the hillslope and a higher energy conversion rate. Thus, the overall erosion energy remains constant and increases. This increases runoff separation and sediment yield rates with increasing slope angle. Under the combined influence of rainfall intensity and slope, rainfall intensity has over ten times more impact than slope angle. Rainfall intensity primarily controls the overall variations in runoff separation and sediment yield rates. Due to the high sand and gravel content in the soil of South China, as rainfall intensity and infiltration increase, the control effect on sediment yield rate varies greatly. In contrast, the regulation effect on the separation rate varies minimally. With a steeper slope, the vegetation density may be higher; nonetheless, the erosion energy on the slope surface is smaller. Therefore, the regulation effect on the separation and runoff sediment yield rates will be smaller.

The contribution of the combined planting method to controlling runoff separation or sediment yield rate originates primarily from the sediment yield or separation rate. As the runoff volume stabilises in the later stages, the ability of runoff separation and sediment transport becomes limited, stabilising the separation and sediment yield rates. In addition, organic matter and soil particle density contributed to 16.71% of the regulation of runoff sediment transport. This revealed that the runoff sediment transport rate was the determinant of regulating the runoff separation rate using the combined method of planting *P. vulgaris* with earthworms in the soil. The runoff separation rate is essential in regulating runoff transport via the combined planting method. However, the influence of soil property changes should not be neglected.

5. Conclusion

The runoff separation and sediment transport rates of the bare slope and combining *P. vulgaris* with earthworms in the soil had trends consistent with changes in rainfall intensity and slope angle. The runoff separation and sediment transport rates increased with higher rainfall intensity and slope angle, except rainfall intensity at 1.2–1.6 mm/min and slope degree 5°–10°.

The regulatory effect of the combined planting method on runoff separation rate increased with higher rainfall intensity and decreased higher slope angles. In contrast, the regulatory effect of the combined planting method on sediment yield rate decreased with increasing rainfall intensity or slope angle, with rainfall intensity having a greater impact than slope angle.

The runoff sediment transport rate is crucial to regulating the runoff separation rate by planting *P. vulgaris* with earthworms in the soil. The runoff separation rate is essential in regulating runoff transport using the combined method. Nevertheless, the influence of soil properties changes should not be neglected.

Declarations

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Author Contributions Statement

Data analysis, chart production, and paper writing were done by Wang Dongdong, and revisions were done by other authors.

Declaration of Interest Statement

This manuscript has not been published or presented elsewhere in part or in entirety and is not under consideration by another journal. We have read and understood your journal's policies, and we believe that neither the manuscript nor the study violates any of these. There are no conflicts of interest to declare.

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Tables

Table 1. Indicators of soil physicochemical properties of the sample site

Test item	pH	Organic matter	Density of soil particles	Electrical conductivity	Total water-soluble salts	Bulk density	Microbial carbon
Unit of measurement	No dimension	g/kg	g/cm^3	ds/m	g/kg	g/cm^3	mg/kg
-	5.84	7.80	2.60	0.13	0.9	1.12	7.80

Table 2. Design and sessions of the field simulated rainfall experiment

Treatment	Bare ground	Planting method of combining *Prunella vulgaris* with earthworms in the soil
Level	18 fields at 0.7, 1.2, 1.6, 2.2, and 2.6 mm/min at 10° slope angle or at 1.6 mm/min rain intensity at 2°, 5°, 15°, 20° slope angles with earthworm treatment and bare ground sample plots	
Repeats	1	
Total	36	

Table 3. Runoff separation and sediment transport rates on the slopes using both treatments

Index	S ° / I mm/min		Two treatment	
			O	B
D_2 10^{-5}	1.6	2	1.12a	0.56a
		5	1.15ab	0.53a
		10	2.22ab	0.88a
		15	3.28ab	1.15a
		20	3.48b	2.62b
	10	0.6	4.33a	1.98a
		1.2	5.60ab	3.48b
		1.6	7.79b	4.59b
		2.2	8.77b	6.05c
		2.6	9.64b	7.80d
T_2 10^{-5}	1.6	2	6.39a	3.10a
		5	6.29a	3.85ab
		10	7.79ab	4.59b
		15	8.15ab	5.90c
		20	9.43b	7.61d
	10	0.6	4.37a	1.99a
		1.2	5.61ab	3.50b
		1.6	7.81b	4.60b
		2.2	8.80b	6.07c
		2.6	9.67b	7.81d
	1.6	2	6.40a	3.11a
		5	6.33a	3.87ab
		10	7.81ab	4.60b
		15	8.16ab	5.93c
		20	9.48b	7.64d

Note: a, b, c, and d compare LSD variability under various rainfall intensities or slopes; O: bare ground, B: combining *P. vulgaris* with earthworms in the soil; A: Planting *P. vulgaris* alone. S is the slope, and I is the rain intensity. D_2 Is runoff separation rate, T_2 is runoff sediment transport rate

Table 4. Association of runoff separation and sediment transport rates with rainfall intensity and slope degree under both treatments

Equations	
O	B
D_1=-7.8×10^{-9}+2.59×10^{-8}S+1.31×10^{-7}I R^2=0.6839,	D_1=-1.2×10^{-7}+2.72×10^{-8}S+8.07×10^{-7}I R^2=0.8311
T_1=-1.1×10^{-7}+1.52×10^{-8}S+9.88×10^{-7}I R^2=0.8854	T_1=7.73×10-9e^(0.09S+0.83I) R^2=0.7755
D_2=9.43×10^{-6}+1.77×10^{-6}S+2.83×10^{-5}I R^2=0.9473	D_2=-9.43×10^{-6}+1.77×10^{-6}S+2.83×10^{-5}I R^2=0.9473
T_2=9.54×10^{-6}+1.79×10^{-6}S+2.83×10^{-5}I R^2=0.9473	T_2=-9.54×10^{-6}+1.79×10^{-6}S+2.83×10^{-5}I R^2=0.9473

Note: S is the slope, and I is the rain intensity. D_2 Is runoff separation rate, T_2 is runoff sediment transport rate

Table 5. Moderating the effects of the combined *Prunella vulgaris* planting method on runoff separation and sediment transport rates

Reduction %										
Index	Slope º / Rain intensity mm/min									
	10					1.6				
	0.6	1.2	1.6	2.2	2.6	2	5	10	15	20
Runoff separation rate	54.32	37.72	41.14	31.06	19.14	51.45	38.76	41.14	27.65	19.33
Runoff sediment transport rate	54.49	37.49	41.06	31.07	19.23	51.47	38.83	41.06	27.39	19.39

Note: D_2 Is runoff separation rate, T_2 is runoff sediment transport rate

Table 6. Correlation analysis of the regulatory effects of sediment yield rate or runoff separation rate on the main factors

	T_2	D_2
BD	0.64	0.64
pH	0.27	0.27
OM	0.64	0.64
SD	-0.66	-0.66
CD	-0.32	-0.32
WS	0.08	0.08
MC	0.62	0.62
P_1	-0.64	-0.64
P_2	0.49	0.50
τ	-0.13	-0.13
ω	-0.86	-0.86
U	-0.71	-0.71
E	0.33	0.32
T_1	-0.83	-0.83
D_1	-0.76	-0.76
T_2	1	-0.96
D_2	-0.96	1

Note: Significance was set at 0.05. BD is soil bulk density, PH is soil pH, OM is organic matter, SD is soil particle density, CD is electrical conductivity, WS is water-soluble salt content, MC is microbial carbon, P1 is >2 soil particle content, P2 is <0.002 soil Particle content, τ is shear stress, ω is stream power, U is unit stream power, E is unit energy, RD is raindrop diameter, RE is raindrop kinetic energy, D_1 is raindrop separation rate, T_1 is raindrop sediment transport rate, D_2 Is runoff separation rate, T_2 is runoff sediment transport rate

Table 7. Contribution rates of the main control factors to the regulatory effects of the planting method of combining *Prunella vulgaris* with earthworms in the soil on runoff separation and sediment yield rates

	Equation	Contribute
D_2	$RD_2=298.917e\text{^}(-2.41OM-131.505SD+5.572\omega-17658.9T_2)$ $R^2=0.9473$	OM: 0.00%, SD:0.00%, ω:0.00%. T_2:94.73%
T_2	$RT_2=223.044e\text{^}\ 0.01OM-2.275SD+3.64\omega-17183.7D_2$ $R^2=0.9579$	OM:6.66%, SD:9.75%, ω:7.40%, D_2:70.81%

Figures

Figure 1

Plan of Soil and Water Conservation Science and Technology Park in Wuhua County, Guangdong Province

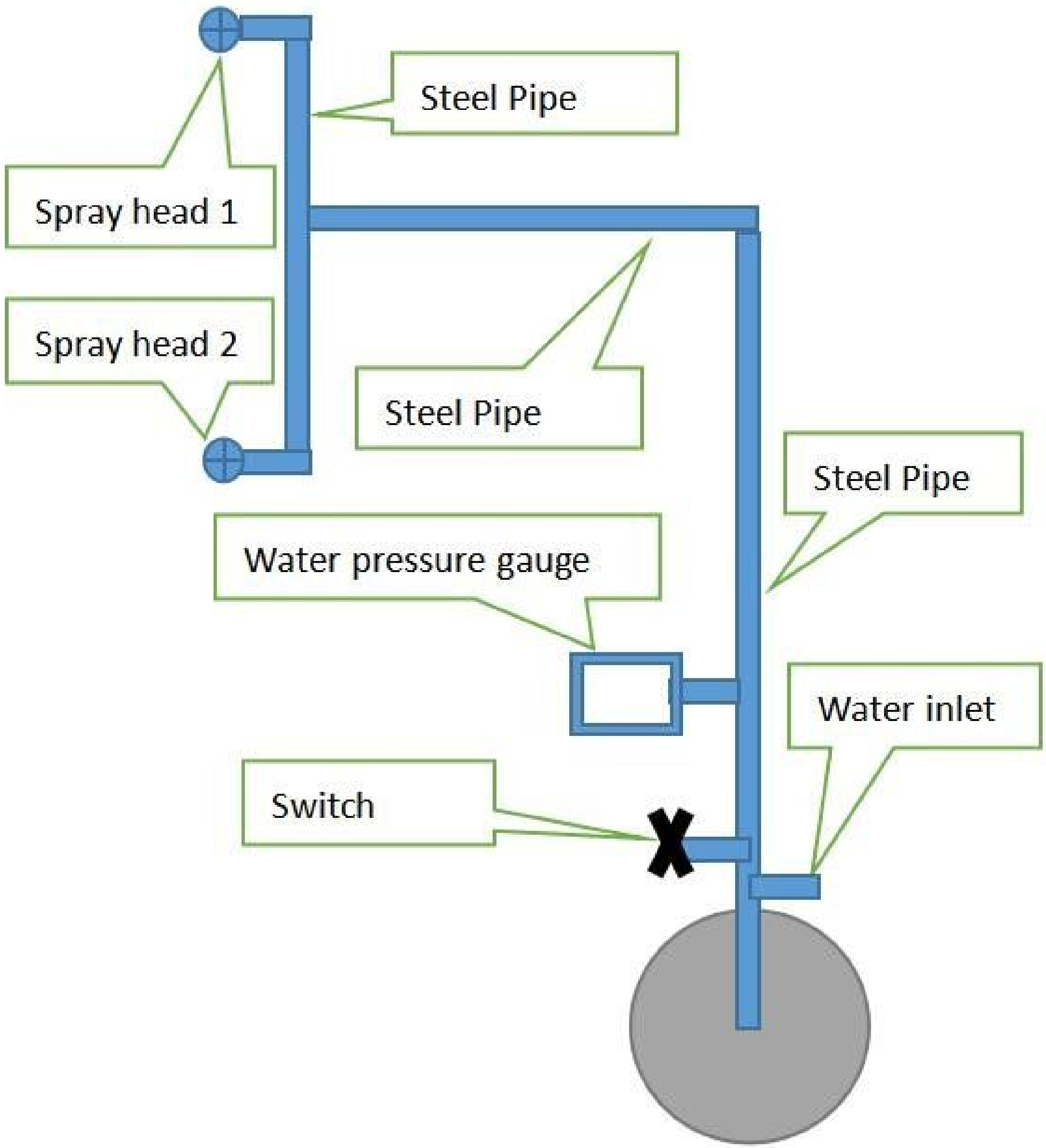

Figure 2

Elevation drawing of the rainfall device