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Hydrological and Pollutant Export Responses to Rainfall Intensity in Paddy Fields

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Abstract

Agricultural non-point-source pollution poses a significant threat to water quality and sustainable water resource management, a challenge intensified by climate change-induced increases in rainfall intensity. In this study, we quantified how rainfall intensity controls runoff and the export of key pollutants (COD, TN, and TP) from paddy fields. Controlled simulation experiments with two rainfall intensities (40 mm/h, S40; 120 mm/h, S120) were conducted in the Yangtze River Basin. The results showed that high-intensity rainfall (S120) nearly doubled the surface runoff volume and coefficient compared to S40. A notable finding was the observed asymmetric response between pollutant concentration and export load. Despite a marked dilution effect under high-intensity rainfall that sometimes led to lower concentrations of COD and TP, the total export loads of all pollutants increased sharply due to the overwhelming increase in runoff volume. Specifically, COD export rose from 2.21 kg/ha (S40) to 4.90 kg/ha (S120), and TN export increased from 211.71 to 585.16 g/ha. In May, TP export under S120 was 2.5 times greater than that under S40. These results provide critical evidence and a mechanistic basis for developing climate-adaptive, sustainable nutrient management strategies aimed at mitigating water pollution and enhancing the environmental sustainability of rice production systems in the Yangtze River Basin and similar monsoon-affected regions.

Keywords: agricultural pollution; rainfall intensity; sustainable agriculture; Yangtze river basin; controlled rainfall simulation; paddy field; non-point-source pollution

Academic Editor: Giovanni De Feo

Received: 17 December 2025

Revised: 17 January 2026

Accepted: 2 February 2026

Published: 4 February 2026

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1. Introduction

The expansion and intensification of global agriculture are essential to meet the food demands of a growing population. However, excessive fertilizer application has also led to widespread water pollution [1–3]. Unlike industrial discharges and other point-source pollutants, agricultural non-point-source pollution is diffuse in nature, originating from widespread sources and primarily driven by rainfall or irrigation activities [4]. These nutrients subsequently flow into adjacent rivers, lakes, and groundwater, triggering ecological issues that threaten aquatic biodiversity and compromise drinking water safety [5,6]. This challenge is particularly pronounced in intensive agricultural regions such as the middle and lower reaches of China's Yangtze River Basin [7]. There, decades of high-input farming have resulted in widespread nutrient surplus, making agricultural runoff a key

driver of severe eutrophication and water quality degradation observed in the region's intricate network of waterways, including the Yangtze River and its connected lakes [8]. This situation is not unique; similar pressures are observed in other major monsoon-affected, rice-dominated agricultural regions globally, such as the Mekong Delta in South-east Asia and the Ganges River Basin in South Asia, where intensive cultivation and seasonal rainfall pulses synergistically elevate the risk of non-point-source pollution [9,10].

The translocation of agricultural nutrients, particularly total nitrogen (TN) and total phosphorus (TP), into the environment profoundly alters natural biogeochemical cycles [11,12]. These nutrients not only directly contribute to eutrophication but also accumulate continuously in soils and sediments, forming long-term internal pollution sources. As a major reservoir, soil mediates complex N transformation processes—such as nitrification and denitrification—that influence greenhouse gas emissions [13,14]. Meanwhile, P can undergo adsorption and desorption in response to changing environmental conditions. Sediments act as both a sink and a potential secondary source of nutrients, continuously releasing them into water bodies, thereby promoting algal growth and disrupting the balance of aquatic ecosystems [15,16]. Such disturbances not only affect local water bodies but also alter regional nutrient budgets, impairing the health of downstream ecosystems, including estuaries and coastal areas [17]. Therefore, quantifying the initial export flux of pollutants from agricultural fields represents a critical first step in managing their impacts on surrounding ecosystems.

The transport of nutrients from agricultural soils to adjacent water bodies is predominantly driven by hydrological processes, with rainfall being the most dynamic and influential factor [18,19]. The intensity and distribution patterns of rainfall events directly determine the generation of surface runoff, which serves as the primary pathway for transporting pollutants such as soil organic matter, N, and P [20,21]. Under low-intensity rainfall, water may infiltrate into the soil, thereby minimizing surface runoff [22]. In contrast, high-intensity rainfall often exceeds soil infiltration capacity, resulting in substantial runoff that carries particulate nutrients, dissolved fertilizers, and organic matter [23,24]. Although the general connection between rainfall and non-point-source pollution is well established, quantitative studies under controlled field conditions—specifically those able to isolate the effect of rainfall intensity on the simultaneous transport of multiple pollutants such as chemical oxygen demand (COD), TN, and TP—remain scarce [25,26].

Global climate change is intensifying the challenges of agricultural nutrient management by altering the hydrological cycle, particularly through changes in the intensity and frequency of rainfall events [27]. Many climate models project a significant increase in extreme precipitation across major agricultural regions, including the Yangtze River Basin [28,29]. This shift toward more intense rainfall patterns is likely to further elevate the risks of non-point source pollution [30,31]. Consequently, historical data and models calibrated under past climate conditions may not accurately predict future pollution loads. In this context, controlled rainfall simulation experiments become particularly valuable, serving as an essential tool for proactively exploring “what-if” scenarios under future climatic conditions.

Previous studies on rainfall-driven pollutant export have primarily relied on long-term monitoring or laboratory experiments, which often cannot isolate the effect of rainfall intensity from other field variables or fail to replicate the complex hydrology and biogeochemistry of actual field environments [32,33]. More importantly, many field simulations have focused on individual nutrients (e.g., N or P) [34,35]. A critical gap exists in simultaneously quantifying and comparing the export of co-occurring pollutants—COD, TN, and TP—under controlled rainfall intensities in real field settings. This simultaneous assessment is essential for understanding integrated pollution risks but remains notably scarce.

To effectively address the challenges outlined above—particularly the need to predict outcomes under intensified rainfall regimes—a critical gap remains in quantifying pollutant export responses under controlled, variable rainfall scenarios [19]. Existing studies largely rely on long-term monitoring or natural rainfall events, which are subject to uncertainties due to the unpredictable nature of weather and the difficulty of isolating the effects of rainfall intensity from other influencing factors [36]. Therefore, this study aimed at addressing the following research questions: (1) How do surface runoff generation and the runoff coefficient respond nonlinearly to increases in rainfall intensity? (2) How do the concentration and, crucially, the export load (the mass of pollutant exported per unit area) of key pollutants (COD, TN, and TP) differ under low versus high rainfall intensity? Based on these questions, we hypothesized that extreme rainfall intensity triggers a nonlinear increase in surface runoff, which in turn drives a disproportionate (more than linear) rise in the export load of pollutants (COD, TN, and TP) from paddy fields, regardless of concurrent changes in pollutant concentration. To address this, we conducted controlled rainfall simulation experiments in Jingzhou, Hubei Province—a representative area of intensive agriculture in the middle and lower reaches of the Yangtze River Basin. The experiments employed two rainfall intensities (40 mm/h and 120 mm/h) to quantify the responses of surface runoff and associated pollutants. The findings are expected to offer critical predictive insights and a mechanistic foundation for developing climate-adaptive nutrient management strategies in the Yangtze River Basin and other monsoon-influenced agricultural regions.

2. Materials and Methods

2.1. Study Area

The Yangtze River Basin, particularly its middle and lower reaches, represents a critical region for studying agricultural non-point-source pollution [37,38]. As Asia's largest river and one of China's most important grain production bases, the area epitomizes the dual pressures of intensive agricultural production and environmental sustainability [39,40]. The basin contains more than 24.6 million hectares of cultivated land, accounting for about one-quarter of the nation's total farmland and contributing approximately 40% of the country's grain output. Characterized by a subtropical monsoon climate, the region receives abundant but unevenly distributed rainfall, creating a high-risk environment for nutrient runoff. Intensive farming practices, including high inputs of chemical fertilizers and manure, are widely adopted to maintain high crop yields. Consequently, nutrient loss from vast agricultural areas has become a major driver of water quality degradation in the Yangtze River system and its connected water bodies, such as Dongting Lake and Poyang Lake [41,42]. Thus, the region serves as a representative case for investigating pollutant export mechanisms under variable rainfall conditions.

2.2. Experimental Design

The rainfall control experiment was conducted at the Drainage and Irrigation Experimental Station of the Sihui Project Administration Bureau, located in the middle and lower reaches of the Yangtze River (Figure 1; Jingzhou City, Hubei Province; 30°21' N, 112°31' E). The representativeness of this experimental site for the region was evaluated. Spatial statistical analysis indicates that the site is situated within the dominant land use and soil matrix of the Four Lakes Basin. According to the IUSS Working Group WRB (2006) [43], the local soil is classified as Hydragric Anthrosol with a clay content of 19.8%. Background soil samples (0–20 cm) collected from the plots showed consistent physico-chemical properties, which align closely with regional average values derived from the Second National Soil Census (Table S1 and Figure S1), confirming the site's

representativeness. Moreover, spatial analysis confirms that paddy fields are the dominant land use type in the basin, covering 48.64% of the total area (Figure S1). Therefore, the site embodies the typical agricultural environment of the region, supporting the generalizability of the experimental results.

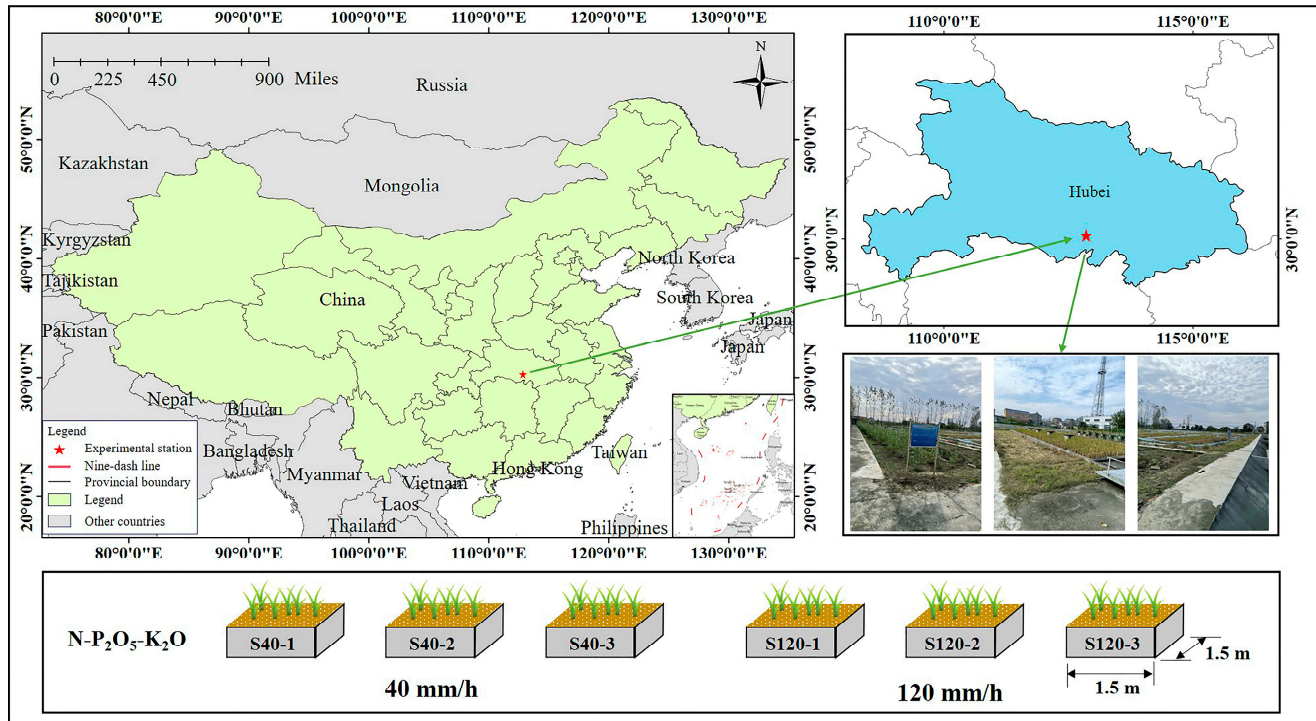


Figure 1. Study area and experimental design. Map lines define the study area and do not necessarily represent recognized state boundaries.

To couple field-representative agronomic conditions with precise hydrologic isolation, an in situ nested design was employed. Six square experimental plots, each measuring $1.5 \text{ m} \times 1.5 \text{ m}$, were established. The boundaries of each plot were constructed with cement and bricks to prevent runoff inflow and outflow. Rice (variety: Chuliu Jingsi) was transplanted at the end of April 2024. Crop management followed the standardized cultivation techniques for this variety. The fertilizer regime was designed with a target $\text{N/P}_2\text{O}_5/\text{K}_2\text{O}$ ratio of 1:0.5:0.5. TN was applied at a rate of 180 kg ha^{-1} , with P (P_2O_5) and potassium (K_2O) each applied at 90 kg ha^{-1} . N was applied in split doses: 50% as basal fertilizer (mechanically incorporated into the top 0–10 cm soil), 30% at the tillering stage, and 20% at the panicle stage.

Within the center of each field plot, a PVC soil column (30 cm diameter; 50 cm height) was inserted to a depth of 20 cm prior to simulated rainfall initiation to serve as the isolated hydrologic response unit. This design minimized disturbance to the soil structure and rice root system while the PVC wall prevented lateral water exchange, ensuring that all measured runoff was generated solely from the simulated rainfall applied to the column surface.

To reflect both current conditions and the projected increase in rainfall intensity in the middle and lower Yangtze River Basin, two rainfall intensities were applied, 40 mm/h and 120 mm/h, each with a total rainfall amount of 80 mm. These intensities were selected based on a hydrological frequency analysis (Pearson Type III distribution) of local historical data (1981–2019), where 40 mm/h represents a typical heavy rainfall event with a 2–3

year return period, and 120 mm/h represents an extreme scenario with a return period exceeding 100 years (Figure S2).

Simulations were conducted daily from 1 May to 31 August 2024, encompassing the key rice growth stages. Each intensity treatment was applied to three replicate columns ($n = 3$), totaling six experimental units. A portable split-type rainfall simulator (Aozuo ecology instrumentation ltd, Beijing, China) was positioned directly above each column for the event duration. The simulator, equipped with manufacturer-calibrated sieve meshes specific to each target intensity, ensured consistent and uniform rainfall application over the small column area (0.07 m^2). To achieve the 80 mm total rainfall, the simulation duration was 120 minutes for S40 and 40 minutes for S120. All experiments were conducted at prevailing ambient field temperatures.

Soil moisture in the columns was managed to reflect standard paddy field water regimes. Tillage and Tillering Stage: Columns were maintained at saturated conditions with a standing water layer. Mid-Season Drainage ('Sun-drying') Period: Water was drained, and moisture was maintained at approximately field capacity.

2.3. Sample Collection and Analysis

2.3.1. Runoff Sampling Protocol

Surface runoff generated during each simulated rainfall event was collected via the side port at the soil surface level of each PVC column. The runoff was channeled through tubing into a pre-cleaned, graduated container. For each event, the start and end times of both rainfall application and runoff initiation/cessation were recorded to calculate precise event duration and lag times. The total runoff volume was measured directly from the container.

A single, well-mixed composite sample was collected from the total runoff of each column per event immediately upon cessation of runoff flow. This sampling strategy was chosen to obtain an event-mean concentration, which is standard for calculating pollutant export loads. Samples were collected in 500 mL polyethylene bottles that had been pre-acid-washed and rinsed with deionized water. To minimize biological alteration, samples were immediately placed on ice in a dark cooler in the field, transported to the laboratory within 2 h, and stored at 4°C in the dark. All chemical analyses were initiated within 24 h of collection and completed within 7 days, a storage duration within the stability period recommended for the analyzed parameters by standard methods.

2.3.2. Laboratory Analytical Methods

The TN concentration was determined using the alkaline potassium persulfate digestion–UV spectrophotometric method [44]. Briefly, a 10 mL aliquot was placed in a 25 mL glass-stoppered colorimetric tube, mixed with 5.00 mL of alkaline potassium persulfate solution, and digested in an autoclave (Shanghai Boxun, Shanghai, China) at $120\text{--}124^\circ\text{C}$ for 30 min. After cooling, 1.0 mL of hydrochloric acid was added, and the volume was adjusted to 25 mL with water. The absorbance was measured at 220 nm and 275 nm using a UV spectrophotometer (SGLC, Shanghai, China) with water as a reference.

The TP was analyzed via the ammonium molybdate spectrophotometric method [45]. A 25 mL sample was digested with 4 mL of potassium persulfate in an autoclave (1.1 kg/cm^2 , 120°C) for 30 min. After cooling, 1 mL of ascorbic acid solution was added to the digestate, followed by 2 mL of molybdate solution 30 s later. The mixture was allowed to stand for 15 min at room temperature before measuring the absorbance at 700 nm.

The COD was measured according to the dichromate method [46]. A 10 mL sample was added to a conical flask with 5 mL of mercury sulfate and potassium dichromate solution. The mixture was digested under reflux for 2 h. After cooling, the remaining

dichromate was titrated with ferrous ammonium sulfate solution, and the COD concentration was calculated.

2.3.3. Quality Control, Data Processing, and Potential Biases

Replication and Statistical Descriptors: The experiment employed three independent biological replicates per rainfall intensity treatment ($n = 3$). All results for runoff volume, concentration, and export load are presented as the mean $\pm$ standard deviation (SD) of these replicates.

Data Processing: The pollutant export load for each event was calculated as the product of the event-mean concentration and the total runoff volume, expressed per unit area (kg/ha).

Discussion of Potential Biases: The use of short-term storage at 4 °C is a standard preservation technique for nutrients and COD, effectively slowing microbial activity. The chosen maximum holding time of 7 days for analysis is within the stability periods specified in the referenced standard methods. While minimal adsorption or transformation cannot be entirely ruled out, the consistent handling of all samples across treatments means that any such effects are systematic and unlikely to alter the comparative conclusions between rainfall intensity treatments, which is the central focus of this study. The flowchart for this study is shown in Figure S3.

2.4. Statistical Analyses

A heatmap was used to illustrate daily temperature variations during the experimental period. Violin plots were applied to compare the differences in surface runoff under varying rainfall conditions from May to August. Changes in runoff coefficient and COD concentration across the experimental period (May–August) were presented using bar charts and line graphs, respectively. A cloud chart was employed to visualize monthly differences in COD. The variations in TN and TP in surface runoff under different rainfall intensities and months were displayed using ring bar charts and box plots. Finally, Pearson correlation analysis was conducted to assess relationships among variables, with results visualized through correlation heatmaps and network diagrams.

One-way analysis of variance (ANOVA) followed by the least significant difference (LSD) test (SPSS 26.0, IBM, Chicago, IL, USA) was used to evaluate differences among treatments, with the significance level set at $\alpha = 0.05$. Canonical correlation analysis between temperature, runoff, and concentrations of COD, TN, and TP was performed using SPSS (version 26.0, IBM, Chicago, IL, USA).

3. Results

3.1. Response of Surface Runoff to Rainfall Intensity

Variations in daily air temperature during the experimental period (May to August) in the study area are shown in Figure 2A. The region experiences a subtropical monsoon climate, with monthly mean temperatures increasing progressively from May to August, ranging between 28 °C and 35 °C. The lowest daily temperature recorded was 17 °C (in May), while the highest reached 39 °C (in August).

The surface runoff volume and runoff coefficient under different rainfall intensity treatments (S40 and S120) across the experimental months are presented in Figure 2B,C. Overall, the higher rainfall intensity (S120) consistently resulted in greater runoff volumes and higher runoff coefficients. Specifically, in the S40 treatment group, daily surface runoff ranged from 3.63 to 9.70 mm, with corresponding daily runoff coefficients varying between 4.55% and 12.13%; the peak values occurred on 15 July. In contrast, the S120 treatment group exhibited significantly higher daily runoff, ranging from 7.55 to 16.76 mm,

and runoff coefficients between 9.44% and 20.95%, with the maximum observed on 2 July. Statistical analysis further confirmed that, throughout the observation period (May–August), both the runoff volume and runoff coefficient in the S120 treatment were significantly higher than those in the S40 treatment ($p < 0.001$), clearly demonstrating the decisive influence of rainfall intensity on surface runoff generation.

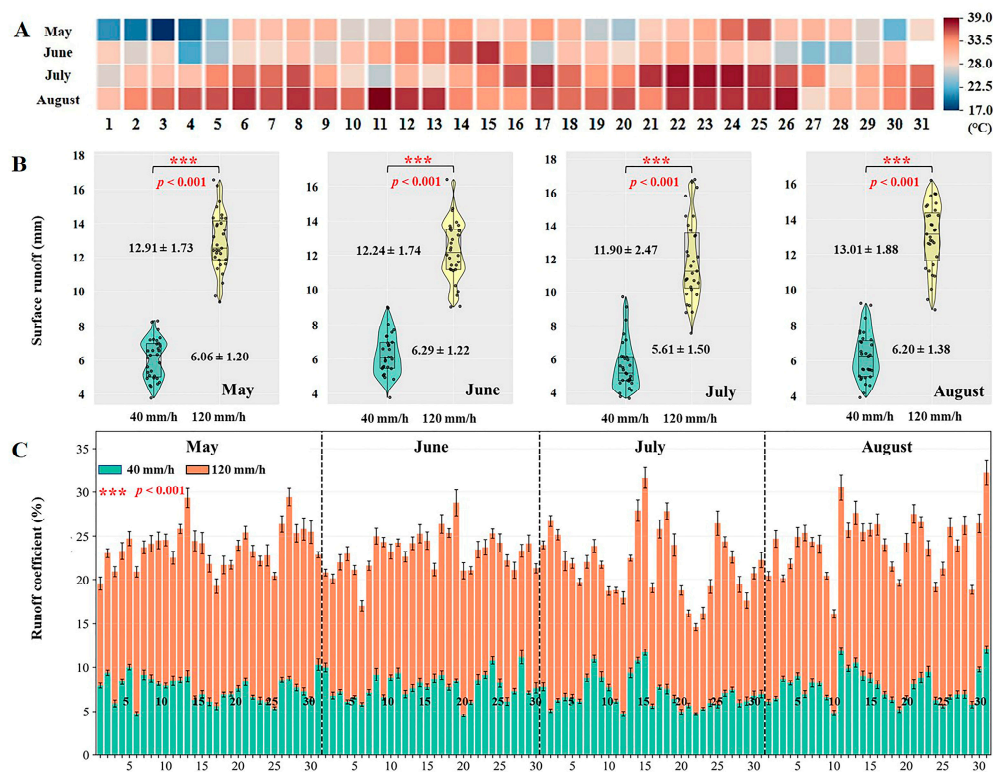


Figure 2. (A) Daily temperature variation at the experimental station from May to August. (B) Changes in surface runoff volume under different rainfall intensities from May to August. (C) Variations in rainfall runoff coefficient in farmland under different rainfall intensities from May to August. *** Significant at the 0.001 level. The horizontal axis of (A,C) represents dates, with the full format being: 1 May 2024–31 August 2024. Error bars are based on the standard deviation of the means ($n = 3$). The black dots represent the observed values.

3.2. Response of COD Export Characteristics in Surface Runoff to Rainfall Intensity and Month

Figure 3 illustrates the effects of rainfall intensity and month on COD concentration and export load in surface runoff. The results indicate that COD concentration dynamics were jointly influenced by both factors and exhibited distinct temporal variations. Under the S40 treatment (40 mm/h), COD concentration showed significant monthly fluctuations ($p < 0.001$; Figure 3A). The highest concentration was observed in May (32.06 mg/L), followed by a significant decrease to the lowest value in June (31.15 mg/L), with a slight rebound in July and August to 31.40 mg/L and 31.50 mg/L, respectively; however, no significant difference was detected between these two latter months (Figure 3A). In contrast, under the S120 treatment (120 mm/h), the COD concentration displayed an overall declining trend from May to August. The concentration in May was significantly the highest (33.35 mg/L) and gradually decreased from June to August, with no significant differences observed among these three months (Figure 3B).

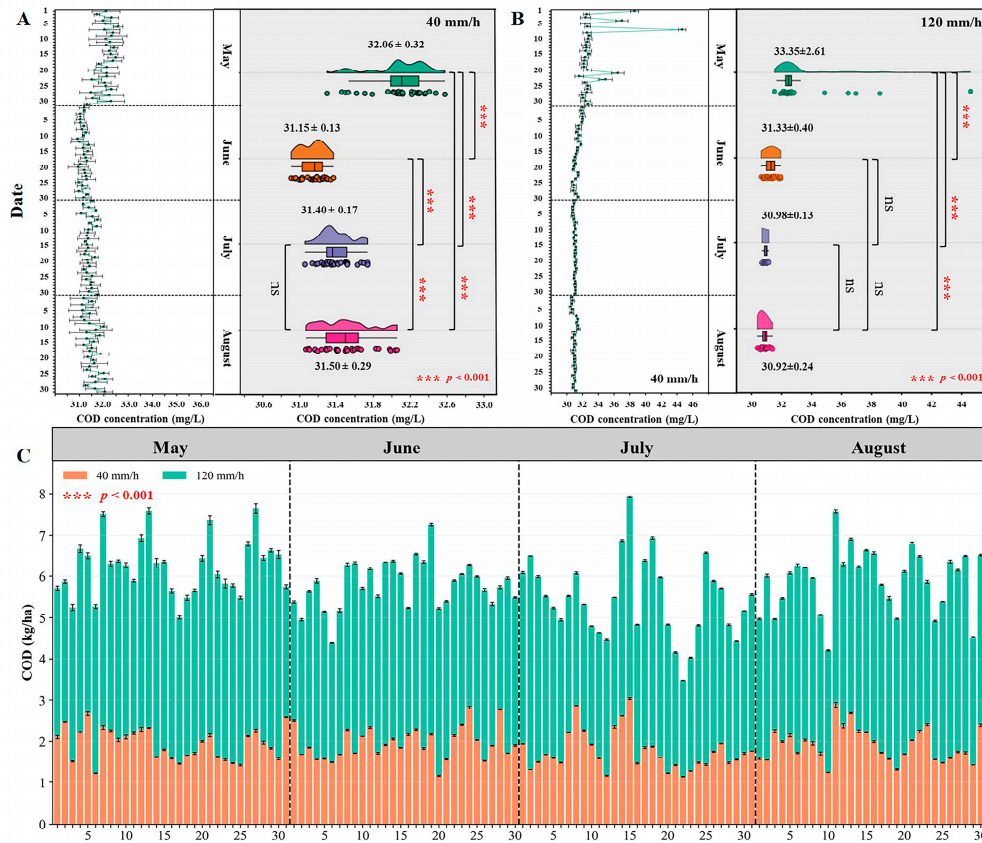


Figure 3. (A) Variation in COD concentration in farmland runoff under 40 mm/h rainfall; (B) Variation in COD concentration in farmland runoff under 120 mm/h rainfall; (C) Variation in COD export load in farmland runoff under 40 mm/h and 120 mm/h rainfall. *** Significant at the 0.001 level. The complete format for the date coordinates in the figure is: 1 April 2024–31 August 2024. Error bars are based on the standard deviation of the means ($n = 3$). The cloud charts of (A,B) are color-coded by month: green (May), orange (June), purple (July), and red (August). The abbreviation “ns” indicates no statistically significant difference.

Notably, the effect of rainfall intensity on COD concentration varied monthly (Figure 3 and Table S2). In May, the mean COD concentration under high-intensity rainfall (S120) was 33.35 mg/L, which was 4.02% higher ($p < 0.01$) than that under low-intensity rainfall (S40, 32.06 mg/L). In contrast, during July and August, this pattern reversed: the mean COD concentration under S120 became lower than under S40 ($p < 0.001$). Overall, the variation in COD concentration was greater under the S120 treatment than under the S40 treatment. Among all 123 rainfall events observed, the COD concentration in surface runoff exceeded 30 mg/L (the Class IV limit of China’s “Environmental Quality Standards for Surface Water”), resulting in a 100% exceedance rate.

In terms of export load, the effect of rainfall intensity was more direct and pronounced (Figure 3C). The average COD export load under the S120 treatment reached 4.90 kg/ha, which was significantly higher than the 2.21 kg/ha under the S40 treatment ($p < 0.001$), indicating that increased rainfall intensity substantially enhanced the absolute export of COD.

3.3. Response of N and P Concentrations and Export Loads in Surface Runoff to Rainfall Intensity and Month

Figure 4 illustrates the dynamic changes in concentrations and export loads of TN and TP in surface runoff under different rainfall intensities from May to August. Throughout the observation period, both TN and TP concentrations showed significant fluctuations, with concentration ranges of 0.71–7.57 mg/L and 0.57–3.20 mg/L, respectively. Among all 123 runoff events, 109 (88.6%) exceeded the Chinese surface water environmental quality standards (TN: 2.0 mg/L; TP: 0.4 mg/L).

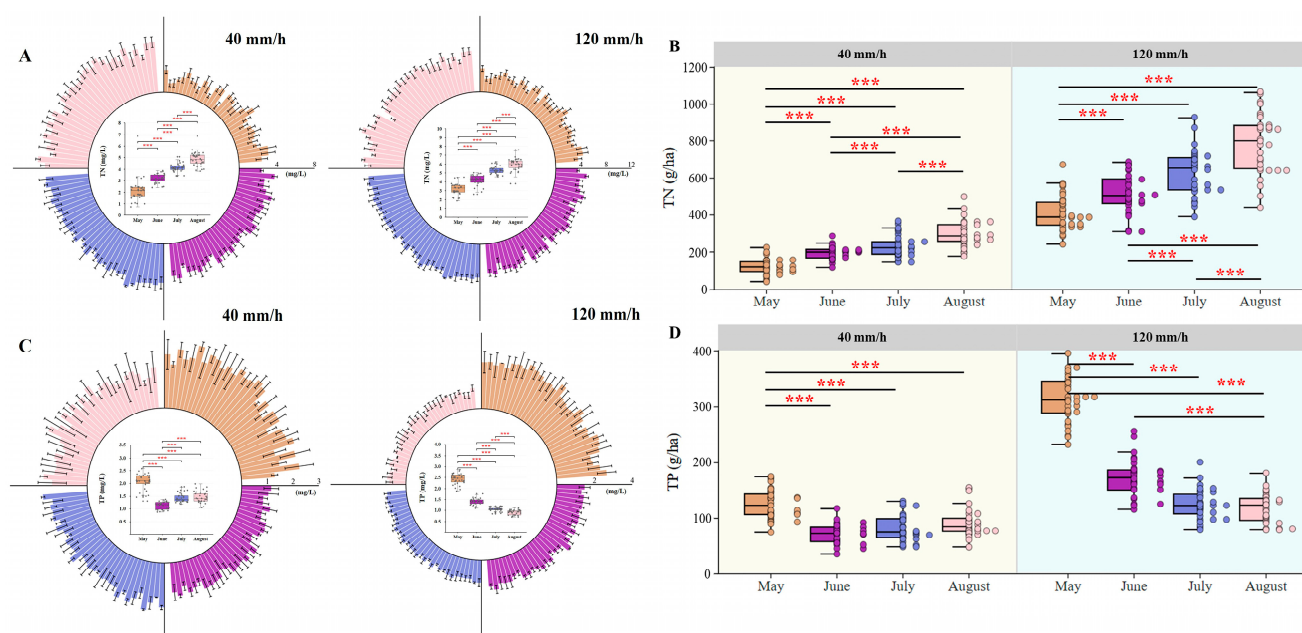


Figure 4. Variations in (A) TN concentration, (B) TN export load, (C) TP concentration, and (D) TP export load in farmland runoff under rainfall intensities of 40 and 120 mm/h. *** Significant at the 0.001 level. Error bars are based on the standard deviation of the means ($n = 3$). The box plots are color-coded by month: yellow (May), purple-red (June), blue (July), and pink (August). The dots represent the observed values.

For TN concentration (Figure 4A), an increasing trend over time was observed under both the S40 and S120 treatments, with significant differences among months ($p < 0.001$). Overall, the TN concentration under the S120 treatment (4.66 mg/L) was significantly higher than that under the S40 treatment (3.53 mg/L) (Table S2; $p < 0.001$). In contrast, the temporal pattern of TP concentration varied with rainfall intensity (Figure 4C). Under the S40 treatment, the TP concentration first decreased and then increased, with the highest value in May (2.06 mg/L) and the lowest in June (1.13 mg/L). Under the S120 treatment, however, the TP concentration decreased month by month, also showing significant differences among months ($p < 0.001$). Notably, the TP concentration under S120 was lower than that under S40 during July and August (Table S2; $p < 0.001$).

Compared with concentration changes, the differences in nutrient export loads between treatments were more pronounced (Figure 4B,D). TN export increased over the months under both treatments, with a significant month effect ($p < 0.001$), and the export under S120 (585.16 g/ha) was significantly higher than that under S40 (211.71 g/ha). The temporal dynamics of TP export also resembled its concentration pattern, showing rainfall intensity-dependent characteristics (Figure 4D): under S40, it first decreased and then increased, peaking in May (123.83 g/ha) and reaching the lowest point in June (71.32 g/ha);

under S120, TP export decreased progressively each month, with May (311.52 g/ha) being significantly higher than the subsequent months ($p < 0.001$).

3.4. Interactions Between Environmental Factors and Pollutant Concentrations

Correlation analysis was conducted to elucidate the relationships between temperature, surface runoff, and the concentrations of each pollutant (COD, TN, and TP). In the S40 treatment group (Figure 5A), temperature showed a highly significant positive correlation with TN concentration ($r = 0.565$; $p < 0.001$). Among the pollutants, COD and TP concentrations also exhibited a highly significant positive correlation ($r = 0.513$; $p < 0.001$). In contrast, TN concentration was significantly negatively correlated with COD concentration ($r = -0.385$; $p < 0.001$) and significantly positively correlated with TP concentration ($r = 0.231$; $p < 0.05$). Monthly analysis indicated that the variation patterns of TP concentration in May, June, and July were significantly correlated, suggesting a degree of similarity in their intra-monthly trends (Figure 5B).

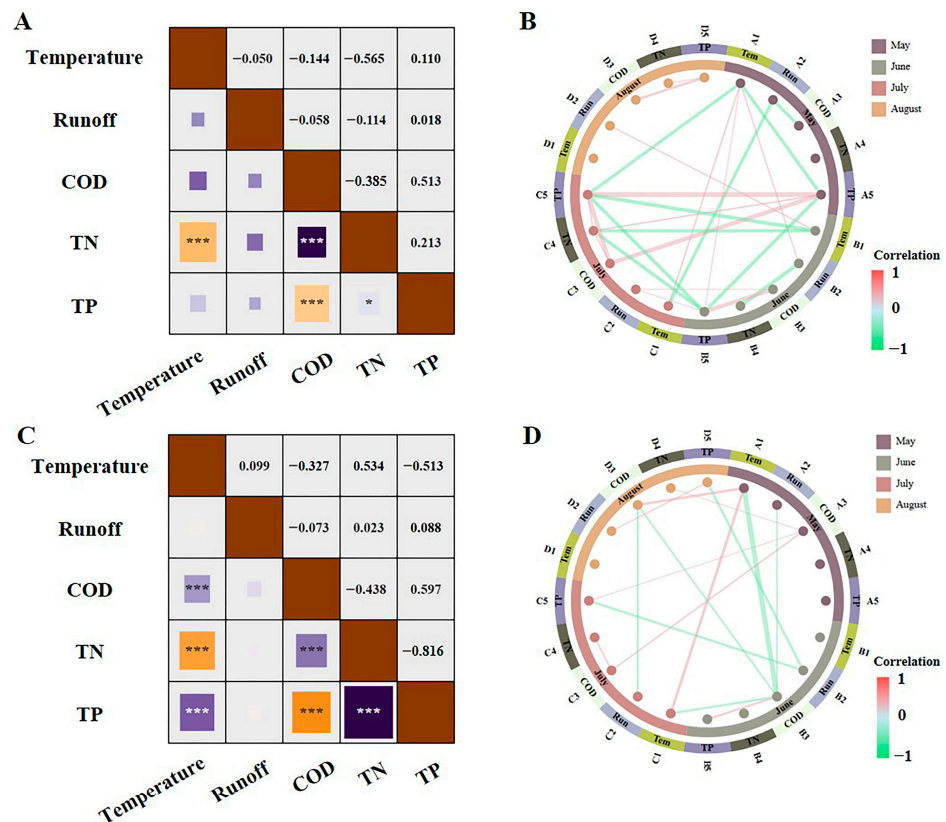


Figure 5. Correlation analysis between temperature, runoff, COD, TN, and TP concentrations under (A,B) 40 mm/h and (C,D) 120 mm/h rainfall conditions. Panels (A) and (C) depict the overall correlation analysis, while (B) and (D) illustrate the monthly dynamics of the correlations from May to August. The connections in the ring network diagrams represent significant correlations ($p < 0.05$). * Significant at the 0.05 level. *** Significant at the 0.001 level. Yellow boxes of (A,C) indicate positive correlations, while purple boxes represent negative correlations.

In the S120 treatment group (Figure 5C), temperature maintained a highly significant positive correlation with TN concentration ($r = 0.534$; $p < 0.001$) but shifted to significant negative correlations with both the COD ($r = -0.327$; $p < 0.001$) and TP ($r = -0.513$; $p < 0.001$) concentrations. Similarly to the S40 treatment, a strong positive correlation remained

between COD and TP concentrations ($r = 0.579$; $p < 0.001$). However, the TN concentration was significantly negatively correlated with both the COD ($r = -0.438$; $p < 0.001$) and TP ($r = -0.816$; $p < 0.001$) concentrations, with the negative correlation between TN and TP being particularly pronounced. Monthly similarity analysis revealed a significant correlation in the variation patterns of the COD concentration between May and July (Figure 5D).

4. Discussion

4.1. Impact of Rainfall Intensity on Farmland Runoff

Rainfall intensity plays a critical role in determining the dynamics of farmland runoff generation and associated nutrient transport [47,48]. However, ongoing climate change, characterized by an increased frequency and intensity of rainfall events, poses significant challenges to agricultural management [49,50]. Through controlled rainfall simulation experiments, this study clearly demonstrates the significant effect of rainfall intensity on surface runoff volume and runoff coefficient. Specifically, as shown in Figure 2, the daily surface runoff volume and runoff coefficient under the high-intensity treatment (S120) were significantly higher—approximately double—than those under the low-intensity treatment (S40) across all months. This result clearly indicates a direct positive correlation between increased rainfall intensity and significantly enhanced surface runoff generation [51]. The runoff coefficients observed in high-intensity simulations (often > 0.20 for S120) align with the range of field-measured coefficients (typically 0.15–0.65) reported for rice paddies during rainfall events in the Yangtze River Basin [52,53].

This finding aligns with numerous previous studies, which report that higher rainfall intensities exceed soil infiltration capacity, leading to more rapid ponding and runoff formation [54]. For example, Hou et al. [55] also highlighted the dominant role of rainfall intensity in surface runoff generation in the Taihang Mountain region. Our study further reveals that this response was particularly pronounced from May to August, with differences between the S120 and S40 treatments reaching a highly significant level ($p < 0.001$). This inter-month prominence may be linked to vigorous crop growth and antecedent soil moisture during this period [56,57]. Moreover, the peak runoff occurred on 15 July for S40 and 2 July for S120, suggesting that summer high-intensity rainfall events pose the greatest risk for surface runoff generation in agricultural watersheds.

The underlying mechanism driving this phenomenon can be attributed to the fact that high-intensity rainfall delivers more water per unit time to the soil surface. This rapidly leads to surface saturation, as the infiltration rate fails to match the rainfall rate, resulting in substantial infiltration-excess runoff [58]. Concurrently, raindrop impact aggravates surface crusting, further reducing soil infiltration and promoting runoff concentration [59]. The observed inter-month differences may be associated with the dynamics of crop canopy cover, soil water content, and field management practices, all of which influence the rainfall–runoff conversion efficiency [60–62]. Therefore, rainfall intensity is not only a key variable triggering runoff events, but its interaction with inter-month factors also significantly modulates the actual runoff yield.

4.2. Influence of Rainfall Intensity on COD Export Behavior in Runoff

Rainfall is a key environmental driver of non-point-source pollution in watersheds, with precipitation events, particularly during flood seasons, often significantly increasing pollutant fluxes in receiving waters [63,64]. Among these pollutants, chemical oxygen demand (COD), a crucial indicator of organic pollution, is strongly influenced by rainfall characteristics during its export process [65,66]. During the monitoring period from May to August 2024, the COD concentration in all surface runoff samples exceeded 30 mg/L (the Class IV limit of China's "Environmental Quality Standards for Surface Water"),

ranging from 30.28 to 45.12 mg/L. This indicates a persistent risk of organic pollutant export from the study area during the crop growing season.

Rainfall intensity is a critical variable modulating the form and flux of COD export. Notably, our results indicate a clear inter-month divergence in the effect of rainfall intensity on COD concentration: in May, the COD concentration under the S120 treatment was significantly higher than that under S40 ($p < 0.01$). However, this relationship reversed in July and August, with S120 showing lower COD concentrations than S40 ($p < 0.001$). The underlying mechanisms are likely linked to differences in prior soil nutrients, crop cover, and pollutant transport pathways. During the early growth stage (May), when soil nutrients are relatively abundant, high-intensity rainfall can rapidly generate surface runoff, effectively scouring and transporting substantial amounts of residual surface organic matter, leading to higher COD concentrations in runoff [64]. In contrast, low-intensity rainfall promotes greater infiltration and yields a weaker scouring effect. As crops enter the vigorous growth stage (July–August), increased vegetation cover enhances surface organic matter accumulation and microbial activity. Under these conditions, low-intensity rainfall, characterized by slower flow velocity and longer soil–water contact time, favors the continuous leaching of soluble organic matter, resulting in relatively higher COD concentrations [67–69]. Conversely, high-intensity rainfall during the same period, while generating larger runoff volumes, exhibits a significant dilution effect. Furthermore, the strong turbulent flow primarily mobilizes particulate organic matter, leading to relatively lower concentrations of dissolved COD [70,71]. This finding aligns with observations by Fukushima et al. [72], who reported decreased COD concentrations in water bodies following heavy rainfall, and further elucidates the moderating role of inter-month variation in this process. Similar results have also been reported in South Africa, and research indicates that heavy rainfall can dilute pollutants such as COD within a watershed [73].

Although the COD concentration under the S120 treatment was sometimes lower, its COD export load (4.90 kg/ha) was significantly higher than that under the S40 treatment (2.21 kg/ha). This result highlights the asymmetric response of pollutant concentration and export load to rainfall intensity. This asymmetry stems from a shift in transport regime: high-intensity rainfall, while diluting dissolved fractions, dramatically increases runoff energy and volume, thereby enhancing the erosion and transport of particulate organic matter. The resulting surge in runoff volume outweighs the dilution effect on concentration, leading to a net increase in total mass export. While high-intensity rainfall may reduce pollutant concentration via dilution, the substantially greater total runoff volume it generates leads to a significant increase in the absolute mass of pollutants exported (i.e., the export load) [74]. This is consistent with the finding of Yang et al. [64] that extreme rainfall events can contribute a major portion (41.9%) of the annual COD export within a short period. Therefore, when assessing agricultural non-point-source pollution risks, reliance solely on concentration metrics is insufficient; greater attention must be paid to pollutant export fluxes, which are directly regulated by rainfall intensity.

In summary, rainfall intensity, by governing water movement, determines the dominant transport form (dissolved or particulate) and total export of COD. Under high-intensity rainfall, despite a potential decrease in concentration due to dilution, the sharply increased runoff volume leads to a significantly higher COD export load, posing a greater threat to regional water environment security.

4.3. Influence of Rainfall Intensity on TN and TP in Farmland Runoff

Rainfall is a key environmental driver regulating N and P loads in watersheds [8]. Numerous studies indicate that increased rainfall is typically accompanied by elevated TN and TP loads [75–77]. The combination of human activities and extreme precipitation events further exacerbates the transfer of nutrients from land to water bodies, leading to

water quality degradation [78–80]. In this study, the TN and TP concentrations in surface runoff exhibited significant fluctuations, ranging from 0.71 to 7.57 mg/L and 0.57 to 3.20 mg/L, respectively. Both concentrations fall within the broad concentration range observed in agricultural runoff from the middle and lower reaches of the Yangtze River [81,82]. It is noteworthy that pollutant concentrations in the vast majority of runoff events exceeded water quality standards (Section 3.3), indicating a pronounced risk of non-point-source pollutant export from the agricultural watershed during the growing season. Moreover, the TP concentrations peaked in May across all treatment groups, potentially due to the application of high-dose basal fertilizer creating a high-concentration nutrient source [83].

Regarding concentration, the effects of different rainfall intensities on TN and TP showed distinct patterns. The average TN concentration under the high-intensity treatment (S120, 4.66 mg/L) was significantly higher than that under the low-intensity treatment (S40, 3.53 mg/L), with both showing an increasing trend over the months. This aligns with the common observation that high-intensity rainfall enhances the leaching and transport capacity for soluble N species (e.g., NH_4^+ and NO_3^-) from soil [31,84], thereby increasing the TN concentration in runoff. In contrast, the response of the TP concentration to rainfall intensity was more complex, displaying two different patterns: “first decreasing then increasing” for S40 and “progressively decreasing month by month” for S120. The monthly decline in TP concentration under high-intensity rainfall may be related to the adsorption–desorption dynamics of soil P. As the growing season progresses, the readily mobile P pool in the surface soil is continuously depleted by successive rainfall events, while adsorption sites on soil particles gradually become saturated, reducing the extraction efficiency of dissolved P in later events. The rebound in TP concentration during July–August following a mid-season (June) decrease under low-intensity rainfall may reflect a priming effect on P release, driven by combined factors such as mid-to-late season fertilization and changes in soil moisture conditions.

The influence of rainfall intensity on export loads was even more pronounced. The TN export load under the S120 treatment (585.16 g/ha) was significantly higher than that under S40 (211.71 g/ha). TP export load showed a similar trend, with the value under S120 in May (311.5 g/ha) being 2.5 times that under S40 (123.8 g/ha) in the same month. This result is highly consistent with the modeling conclusion of Li et al. [8] that high rainfall intensity significantly increases pollutant flux. Notably, although high rainfall intensity had a diluting effect on TP concentration during some periods, it still led to a significant rise in TP export load by substantially increasing the total runoff volume. This echoes observations by Wang et al. in a subtropical river, where extreme rainfall could contribute over 30% of the annual N and P export load within a very short period [31]. This demonstrates that the response of export load to rainfall intensity is more sensitive and direct than that of concentration, highlighting the dominant role of extreme rainfall events in regional nutrient export. For P, this is because high-intensity rainfall rapidly detaches and transports soil particles (the primary carriers of particulate P), whereas the short contact time limits dissolved P release, often manifesting as concentration dilution [85]. The massive runoff volume ensures that the total particulate P export load increases substantially. Pollution export load projections for the Jialing River Basin also indicate that increased runoff during future rainy seasons will significantly amplify N and P pollution loads discharged from agricultural areas [86].

In summary, rainfall intensity comprehensively regulates the output concentration and export flux of TN and TP by influencing runoff generation mechanisms and soil nutrient release pathways. High-intensity rainfall not only enhances the dissolution and transport of N but also significantly increases the absolute export of both nutrients by elevating the total runoff volume.

4.4. Implications, Limitations, and Future Perspectives

This study demonstrates that rainfall intensity is a critical climatic driver controlling nutrient loss from farmland. These findings underscore the urgent need for climate-adaptive agricultural practices that prioritize reducing runoff generation and optimizing nutrient application timing ahead of forecasted intense rainfall in similar intensive paddy systems. Given that a limited number of extreme rainfall events can contribute a major portion of the annual pollutant load, traditional fertilization recommendations based on seasonal average rainfall may be insufficient to ensure environmental safety [87]. A key finding with direct implications for environmental risk assessment and policy is the asymmetric response of pollutant concentration versus export load to rainfall intensity. This decoupling means that water quality monitoring programs and regulations based solely on pollutant concentration may significantly underestimate the actual ecological threat posed by extreme rainfall events. For policymakers and land managers, this underscores the necessity to prioritize export load as a primary metric for non-point-source pollution risk assessment and mitigation target-setting, particularly in the context of increasing rainfall extremes. Furthermore, differences in pollutant transport mechanisms (e.g., dissolved N or particle-associated P) necessitate targeted best management practices (BMPs). The correlation analysis in this study further suggests that the relationship between temperature and nutrient export is modulated by rainfall intensity. Therefore, developing management strategies requires a comprehensive consideration of the synergistic effects of temperature and rainfall [88].

However, this study has certain limitations. First, while controlled rainfall experiments can precisely isolate the effect of rainfall intensity, they differ from complex and variable natural rainfall conditions [89,90]. Second, although the four-month observation period covered the main growing season, it cannot capture the long-term impacts of interannual variability on nutrient export [91,92]. Third, our experiment was conducted within a single field to maximize control over soil and management variables. While this design effectively isolates the rainfall intensity effect, it does not account for spatial heterogeneity (e.g., in soil permeability or micro-topography) across different fields. Similarly, in this study we employed a deterministic framework; the inherent variability of field conditions (e.g., initial soil moisture and nutrient residue) and their associated uncertainties were not quantified through probabilistic sensitivity analysis. Finally, while we focused on the total export loads of key pollutants (COD, TN and TP) to assess integrated water quality risks, we did not analyze the specific fractions or speciation of these pollutants (e.g., dissolved versus particulate forms of COD and TP, or ammonium versus nitrate for TN).

Additionally, the recommendations derived from this study are bounded by its specific experimental conditions. The findings are based on a single rice-growing season within small, controlled plots under a specific water management regime (alternating saturated and field capacity conditions). Therefore, the quantitative relationships between rainfall intensity and pollutant export observed here may not be directly transferable to all agricultural systems. Their application is most relevant to intensively managed paddy fields in monsoon-affected regions with similar soil types and farming practices. Caution should be exercised when extending these findings to systems with significantly different management, such as continuously flooded or actively drained paddies, or to other crop types and climatic regions, as the underlying hydrological and biogeochemical processes may differ.

Future research could be advanced in the following aspects: (1) conducting multi-site, long-term observations that combine natural rainfall events with controlled experiments across diverse fields to verify and refine the quantitative relationships established here and assess their spatial transferability; (2) integrating key parameters obtained from

this experiment into watershed-scale models (e.g., SWAT and HSPF) to simulate non-point source pollution risks under future climate scenarios at larger spatial scales [93,94]; (3) incorporating probabilistic approaches, such as Monte Carlo simulation, to quantify the uncertainty in runoff and export estimates stemming from the variability of key input parameters (e.g., soil properties and antecedent moisture), thereby providing a more robust scientific basis for risk assessment and regional water quality management.

5. Conclusions

In this study, through controlled rainfall simulation experiments, we elucidated the decisive role of rainfall intensity in regulating surface runoff and pollutant export from intensively managed paddy fields in the Yangtze River Basin. The main conclusions are as follows.

Rainfall intensity is the primary control on runoff generation and pollutant export load. High-intensity rainfall (120 mm/h) approximately doubled the surface runoff volume and runoff coefficient compared to low-intensity rainfall (40 mm/h). This resultant increase in runoff volume was the key driver leading to significantly higher export loads of COD, TN, and TP, despite more complex concentration dynamics. These nonlinear relationships underscore the heightened risk of pollutant loss under future climate scenarios characterized by more frequent high-intensity rainfall events.

A critical finding is that the responses of pollutant concentration and export load to rainfall intensity are asymmetric. For COD and TP, concentration frequently decreased under high intensity due to a pronounced dilution effect, yet the total export load increased substantially due to the greater runoff volume. This asymmetry underscores that pollution risk assessment must prioritize export flux over concentration alone, as reliance on concentration data would severely underestimate the actual ecological threat posed by extreme rainfall events. This necessitates a paradigm shift towards load-based, rather than solely concentration-based, water quality monitoring and regulation in agricultural watersheds.

Extreme rainfall events contribute disproportionately to seasonal nutrient loads. The high runoff coefficients (>0.20) observed under intense rainfall, coupled with the magnitude of export loads, suggest that a small number of extreme events can account for a major portion of the total pollutant export during the growing season, posing a peak risk to receiving waters. Consequently, effective mitigation strategies must prioritize forecasting and managing these discrete, high-export-load events, in addition to managing baseline nutrient applications.

These findings underscore the urgent need for climate-adaptive agricultural practices that prioritize reducing runoff generation and optimizing nutrient application timing ahead of forecasted intense rainfall to mitigate water quality risks in the Yangtze River Basin and similar intensive agricultural regions under a changing climate.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18031589/s1>, Table S1. Comparison of soil properties between the experimental site and the regional background values. Table S2. One-way analysis of variance for the effect of different rainfall intensities on COD, TP, TN concentration. Figure S1. (A) Spatial distribution of the 20 random sampling points selected within the Four Lakes Basin for regional soil background analysis. Data source: The Second National Soil Census of China. (B) Land Use Types in the Four Lakes Basin. Figure S2. Hydrological frequency analysis of precipitation intensity at two local observation stations (Pearson Type III Distribution (P-III)). Figure S3. Flowchart of the research methodology.

Author Contributions: Conceptualization: Z.L.; Data curation: J.G.; Formal analysis: Z.C.; Funding acquisition: Z.L.; Investigation: Y.W.; Methodology: Z.C.; Project administration: Y.W.; Resources: Z.L.; Validation: J.L.; Visualization: J.G.; Writing—original draft: Z.C., J.L.; Writing—review & editing: Z.C. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Key Research and Development Program of China (No. 2022YFC3201902), and the National Natural Science Foundation of China (No.52109078).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: We would like to thank Yang Chenchen and Zhan Jiankang for their assistance in sample collection and data analysis.

Conflicts of Interest: The authors have no relevant financial or non-financial interests to disclose.

Abbreviations

The following abbreviations are used in this manuscript:

TN	Total Nitrogen
TP	Total Phosphorus
COD	Chemical Oxygen Demand

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