

Regulatory role of permanent gullies in runoff-dissolved nitrogen and phosphorus transport under across-different rainfall types

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Abstract. Understanding how permanent gullies regulate the transport of dissolved ammonium (NH₄⁺), nitrate (NO₃⁻), and phosphorus (P) in runoff delivered from agricultural hillslopes under different rainfall types is essential for controlling non-point source pollution in agroecosystems. ~~Tracking the transport of runoff dissolved nitrogen (N) and phosphorus (P) from upslope farmland to the catchment outlet is vital for controlling non-point source pollution in agroecosystems. However, the hydrological and regulatory roles of permanent gully within catchment in modulating dissolved N and P losses dynamics under natural rainfall conditions remain poorly understood. In this study~~ In this study, two agricultural catchments, each containing a single permanent gully, were selected, and the runoff was monitored processes at the gully head and gully outlet during the rainy seasons of 2022 and 2023. Runoff samples were filtered through 0.45 μm membrane filters and analyzed for dissolved NH₄⁺, NO₃⁻, and P concentrations, and the corresponding nutrient transport fluxes were then calculated. Based on event-scale rainfall characteristics, including rainfall depth, duration, average intensity, maximum 30-min intensity, and erosivity, rainfall events were classified using the k-means method to examine how different rainfall types influenced the role of gullies in the transport of dissolved NH₄⁺, NO₃⁻, and P. runoff and associated losses of dissolved NH₄⁺, NO₃⁻, and P were measured at both the gully head and the outlet from 2022 to 2023. The results ~~are as follows~~ showed that: (1) Gullies significantly enhanced runoff generation, contributing 36.1% of total runoff despite occupying only 12.4% of the catchment area. This contribution varied across rainfall types (Type A: frequent, low-depth, low-erosivity; Type B: short-duration, high-intensity; Type C: long-duration, high-erosivity) and was highest under Type A (43.2%) and lowest under Type C (33.8%). (2) Gullies exerted a pronounced dilution effect on ~~the concentrations of~~ dissolved NH₄⁺, NO₃⁻, and P concentrations, particularly ~~for on~~ dissolved NO₃⁻ (dilution ratio: 0.65). Consequently, ~~the gullies contribution of gulliesed less to dissolved~~ NH₄⁺, NO₃⁻, and P nitrogen and phosphorus transport fluxes was lower than relative to their that its contribution to runoff volume, accounting for 31.4%, 22.4%, and 31.1% of dissolved NH₄⁺, NO₃⁻, and P transport fluxes in

the outlet, respectively. (3) Type C rainfall dominated the ~~loss~~transport of dissolved NH_4^+ , NO_3^- , N and P. Only 10.2% of
35 events contributed over 68% of dissolved NH_4^+ , NO_3^- , N, and P ~~transport~~ fluxes at the catchment scale and markedly
increased their ~~loss~~transport sensitivity to rainfall compared to Type A and Type B. These sensitivities were also intensified
by gullies. ~~The study highlight the importance of prioritizing permanent gullies and high-erosivity rainfall
events in strategies to reduce dissolved nutrient losses from agricultural catchments, provides new insights into runoff
dissolved nutrient interactions within gully systems and offers a foundation for improving nutrient management in gully-
dominated agricultural landscapes.~~

1 Introduction

The ~~loss~~transport of nitrogen (N) and phosphorus (P) via agricultural surface runoff poses a major challenge to
watershed management, as these nutrients are key contributors to downstream eutrophication (Berretta & Sansalone, 2011;
McDowell & Haygarth, 2024; Huo et al., 2025). Dissolved nitrogen (DN) and dissolved phosphorus (DP), ~~being~~which are
45 the most mobile and bioavailable forms, are rapidly transported to aquatic systems during rainfall events, where they can
trigger algal blooms due to their high ecological reactivity (Wang et al., 2024; Xiao et al., 2024). Compared to particulate
forms, DN and DP respond more quickly to storm-driven hydrological processes and are more easily mobilized along
surface flow paths (Berretta & Sansalone, 2011). In agricultural landscapes, these flow paths are often shaped by permanent
gullies that act as hydrological conduits linking farmland ~~with~~to downstream water bodies. Gullies are widespread in
50 farmland across China, the United States, and various regions of Europe and Australia (Dube et al., 2020; Shi et al., 2022;
Walker et al., 2024; Chen et al., 2025c). However, their role in regulating ~~hydrological processes~~the hydrological and
dissolved nutrient dynamics ~~of dissolved nutrient transport~~ under natural rainfall remains insufficiently quantified.

~~Permanent gullies are geomorphic features formed through prolonged water erosion, serving as critical pathways that
connect upslope farmland with downstream aquatic systems.~~ Unlike engineered drainage ditches, these gullies typically lack
55 vegetation cover, experience minimal human intervention, and are often subject to severe erosion (Wang et al., 2019; Kumar
Bhattacharya et al., 2024). Such characteristics suggest that gullies function not only as efficient hydrological pathways but
~~may~~also ~~play~~exhibit multifaceted roles in nutrient dynamics, ~~serving~~ (as sources, sinks, or regulators) depending on
prevailing hydrological conditions (Miller et al., 2016; He et al., 2024). DN and DP, owing to their higher mobility and
bioavailability, are more responsive to hydrological processes and land use changes than their particulate forms (Lee et al.,
60 2013). Land use exerts a critical influence on nutrient fluxes: forests, grasslands, and riparian ~~zones~~ buffers often act as
nutrient sinks (Miller et al., 2016; Rätty et al., 2020), whereas intensively managed croplands, frequently subject to fertilizer
misapplication, represent major nutrient sources (Liu et al., 2020; Risal et al., 2020; Wang et al., 2025). In agricultural
catchments, gullies predominantly receive runoff from upslope cultivated fields (Zhang et al., 2011), and their sparse
vegetation and limited internal nutrient inputs ~~may further~~inevitably modulate nutrient transport processes (Ezzati et al.,
65 2020). Steep gully gradients ~~further~~intensify runoff energy and hydrological connectivity, accelerating sediment transport

(Kumar Bhattacharya et al., 2024). Studies have shown that deposited sediments within gullies may be re-mobilized during rainfall events, releasing dissolved nutrients and thereby posing a potential risk of secondary pollution (Miller et al., 2016; Ezzati et al., 2020; Xu et al., 2022). However, existing studies have mainly focused either on the regulatory role of gullies under snowmelt conditions or on the effects of gullies on total nitrogen and phosphorus loss(Chen et al., 2025b). Their influence on dissolved nutrient loss under rainfall conditions remains poorly understood. However, existing previous studies have mainly focused on the effects of gullies on nutrient spatial distribution (Sun et al., 2022; Wang et al., 2026), the regulatory role of gullies in nutrient transport under snowmelt conditions (Chen et al., 2024c), and their influence on total nitrogen and phosphorus transport (Chen et al., 2025b). In contrast, studies on how gullies affect dissolved nutrient transport under different rainfall conditions remain limited, which hinders effective nutrient management at the catchment scale.

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75 During rainfall events, deposited sediments within gullies may re-mobilize nutrients, presenting a potential risk of secondary pollution (Miller et al., 2016; Ezzati et al., 2020; Xu et al., 2022). Moreover, the strength and direction of this regulatory effect Notably, such regulatory mechanisms are likely to depend on vary with rainfall type. Rainfall characteristics, including depth, intensity, duration, and erosivity, are key drivers of runoff generation, erosion, and nutrient mobility in agricultural landscapes (Wang et al., 2024; Wang et al., 2025). As a result, Different different rainfall types, ranging

80 from such as more frequent low-intensity events to less frequent high-intensity high-frequency low-intensity versus low-frequency high-intensity events, may can lead to marked variation lead to substantial differences in nutrient mobilization, transport pathways, delivery processes efficiencies, and associated environmental risks (Wang et al., 2024; Yang et al., 2024; Wang et al., 2025). For example, nitrate transport pathways have been shown to vary significantly with rainfall characteristics. Under low-intensity rainfall, transport is mainly restricted to near-stream contributing areas, whereas

85 increasing rainfall intensity progressively expands these pathways from riparian zones to hillslopes, leading to complex dynamic changes in the sources and concentrations of nitrate in runoff-(Wang et al., 2024). Likewise, both the number of critical source areas for phosphorus transport and the intensity of phosphorus export increase significantly with rainfall intensity (Zhao et al., 2026). Against the backdrop of With the ongoing growing intensification intensity of extreme weather events under global climate change, the influence of heavy storms on nutrient export from agricultural catchments is

90 expected to become even more pronounced (Zhang & Zhang, 2025; Bian et al., 2026). heavy storms In general, heavy storms are increasingly associated with intense erosion and elevated nutrient loads, often resulting in dissolved-DN and DP exports that greatly exceed those observed under moderate rainfall_(Lei et al., 2026). Conversely, low-intensity small-rainfall events may favor nutrient dilution or retention due to reduced flow velocities and longer contact times for nutrient exchange-or altered concentration gradients (Wang et al., 2025). Disparities in soil properties, vegetation cover, and topography between

95 upslope areas s-and gullies may further amplify these effects_(Miller et al., 2016). Nevertheless, the role of gullies in modulating dissolved nutrient losstransportes under varying rainfall conditions remains insufficiently investigated. This limitation is especially critical in gully-dominated agricultural regions, where rainfall-driven hydrological connectivity may strongly influence nutrient delivery from fertilized hillslopes to downstream waters.A comprehensive understanding of their regulatory function is thus crucial for environmental sustainability at the agriculture dominated watershed scale.

100 The Mollisols region of Northeast China (MRNC) ~~is produces approximately 50% of China's rice, 44% of its soybeans, and 34% of its corn, thus serving as a typical example of such a landscape. As a~~ cornerstone of national food security (Chen et al., 2025a), ~~the region depends on intensive agricultural production and substantial fertilizer inputs, which increase the risk of agricultural non-point source pollution~~ (Zhao et al., 2025). ~~At the same time~~ However, decades of extensive ~~and intensive~~ land development have resulted in widespread gully erosion and land degradation, ~~rendering the region increasingly vulnerable to ecological stress. To date, o~~ More than Over 667,000 permanent gullies have been identified, ~~with more than 85% remaining active,~~ posing serious threats to agricultural sustainability ~~and watershed integrity~~ (Chen et al., 105 2025c). ~~As important hydrological pathways linking hillslopes with downstream water bodies, gullies may play a critical role in nutrient transport~~. Earlier studies have explored the influence of rainfall characteristics on gully formation (Tang et al., 2023; Liu et al., 2024), as well as the function of gullies in sediment and nutrient ~~transport losses~~ during snowmelt events (Su et al., 2024), (Su et al., 2024). ~~However, how permanent gullies regulate DN and DP transport under natural rainfall conditions remains poorly understood~~ limited attention has been paid to the regulatory function of permanent gullies in DN and DP transport under natural rainfall conditions. This knowledge gap is largely attributed to technical challenges in field-based monitoring, which have constrained a comprehensive understanding of gully-mediated nutrient dynamics and their implications for watershed-scale water quality management in the MRNC.

115 To address these gaps, this study conducted in situ monitoring of runoff and associated ~~los~~ transport processes of ~~dissolved ammonium (NH₄⁺), nitrate (NO₃⁻), and phosphorus (P)~~ dissolved NH₄⁺, NO₃⁻, and P at both the gully head and ~~gully~~ outlet in two agricultural catchments in ~~the~~ MRNC during natural rainfall ~~events~~ in 2022 and 2023. The specific objectives were to: (1) elucidate the regulatory effect of gullies to runoff, dissolved NH₄⁺, NO₃⁻, and P ~~transport losses~~ fluxes; (2) quantify how gullies contributions to these ~~transport fluxes losses~~ vary in response to different rainfall 120 types; and (3) reveal how gullies regulate the response relationship between rainfall and dissolved NH₄⁺, NO₃⁻, and P ~~transport fluxes losses~~. ~~The findings will support targeted mitigation of rainfall-type-type-dependent dissolved nutrient loss in agricultural catchments. The findings provide a scientific basis for non-point source pollution mitigation and control.~~

2 Materials and methods

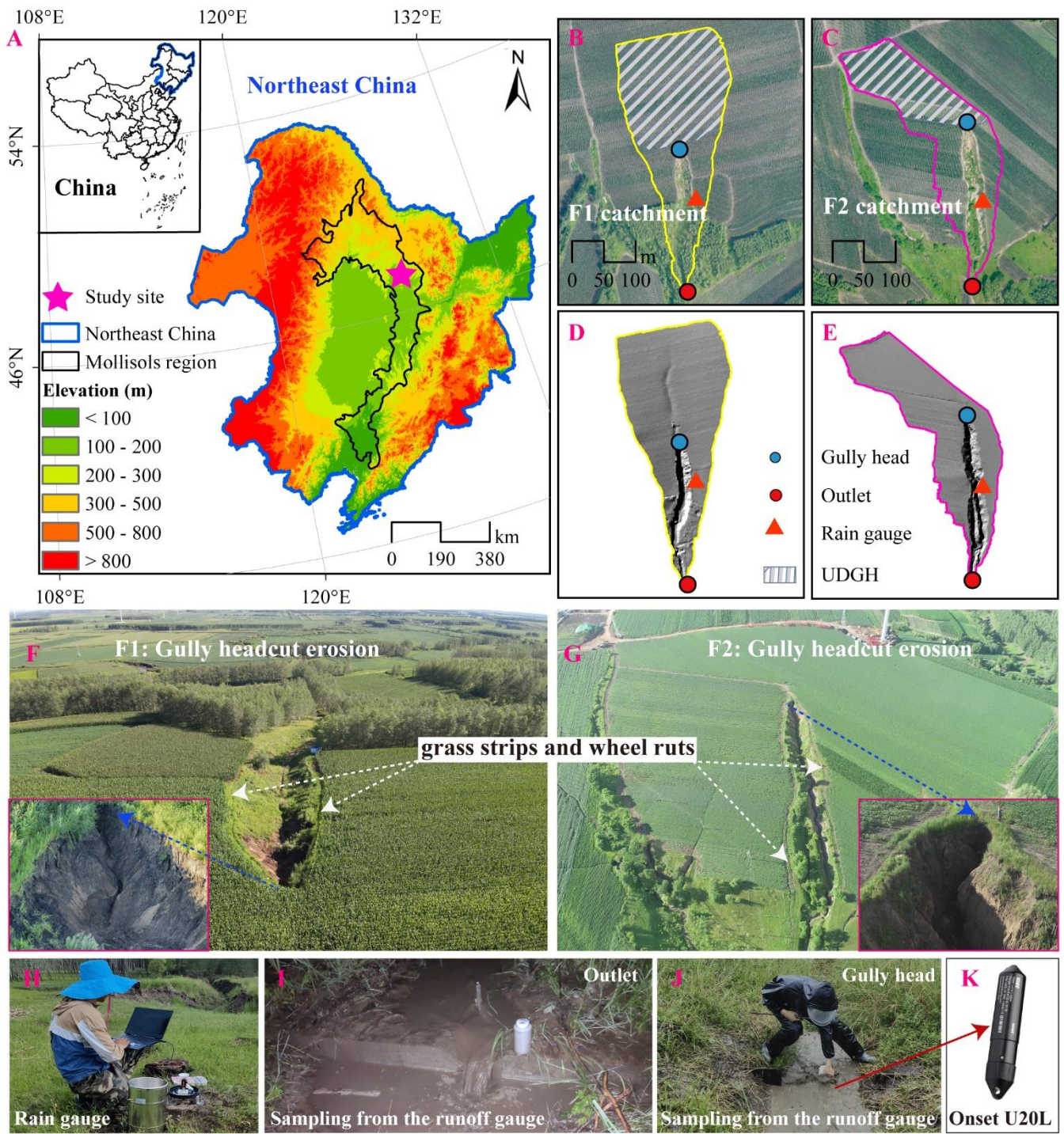
2.1 Study area

125 (1) The study area is located in Guangrong Village (N 47°34'–47°38', E 126°81'–126°88'), Hailun City, Heilongjiang Province, within the central MRNC (Fig. 1A). The region experiences a continental monsoon climate, with annual precipitation of 300–900 mm ~~during (2000–2022), of which approximately ~80.7% of which~~ falls between June and October, coinciding with peak ~~period of~~ soil erosion. ~~The m~~ Mean annual temperature is ~1.5°C (-25.6°C to 26.6°C), with crop sowing typically commencing in mid-April. The terrain comprises gently rolling hills, and soils are classified as Mollisols 130 (Chernozem) with ~~a~~ silty clay loam texture, ~~a~~ 45–60% silt content, and ~~an~~ >3% organic matter ~~content of >3% in the ploughed layer~~. These conditions support intensive maize and soybean cultivation, but sustained anthropogenic disturbance

has caused a ~20% decline in soil fertility. In particular~~Especially~~, gully erosion on sloping farmland leads to an annual arable land loss of ~0.097%, with gully density reaching 1.5 km km⁻² (Chen et al., 2025c).

To assess the morphological characteristics and activity status of the gullies in the region, ~~(2) During rainfall events, these gullies serve as efficient conduits for runoff generated from upslope farmlands. To elucidate the role that gullies play in mediating the transport of dissolved nitrogen and phosphorus within this runoff, a~~ comprehensive gully survey was conducted in May 2021 prior to hydrological monitoring. ~~This survey aimed to assess the morphological characteristics and activity status of the gullies in the region, thereby enabling the selection of representative gullies for detailed investigation.~~ The results revealed that over 90% of farmland gullies were ~~found to be~~ highly active, with average widths and depths of 13.3 m and 3.4 m, respectively.

~~(3) On this basis, two permanent gullies in representative and actively eroding farmland catchments gullies (the F1 and F2 catchments; the two catchments are 1.1 km apart)~~ were selected (Fig. 1B–E), as they ~~exhibiting~~ similar catchment areas, land use proportions, and typical morphological and topographic features. It should be noted that only one permanent gully was present in each of the two catchments, and both gullies exhibited clear signs of active development. The gully heads were highly susceptible to headward erosion under rainfall-driven runoff. In addition, vegetation cover on the gully slopes was relatively sparse, particularly in the upstream sections of the gullies (Fig. 1F–G). The characteristics of the two catchments and their gullies are described as follows. The F1 and F2 catchments cover 4.3 ha and 3.4 ha, respectively. Farmland is the dominant land use, comprising 83.4% of F1 and 85.5% of F2. ~~Both gullies within catchment showed pronounced erosion, including active headcuts and exposed sidewalls. The area directly occupied by the gully accounts for 9.6% and 15.2% of the total catchment area in F1 and F2, respectively, with a mean value of 12.4%. In contrast, the upslope drainage area of the gully head (UDGH) accounted for~~ represents 64.8% and 43.9% of the catchment area in F1 and F2, respectively ~~(with a mean: 54.3%), and is entirely covered by farmland. Moreover, G~~ gully dimensions were consistent with the survey averages: the gully in F1 measured 0.38 ha in (area), 242.3 m in (length), 17.7 m in (width), and 3.8 m in (depth); and the gully in F2 measured 0.54 ha, 293.7 m, 18.4 m, and 4.8 m, respectively. Gully slope gradients (F1: 36.2°; F2: 39.5°) were significantly steeper than those of the adjacent farmland slopes (F1: 4.3°; F2: 3.4°). In addition, within the catchments, basal fertilizer was applied at the end of April during ridge formation and sowing using a fertilizer seeder, so such that fertilization and sowing were completed simultaneously. The remaining fertilizer was then top-dressed in mid- to late June at the maize jointing stage. Meanwhile, during the rainy season, crop cover on the agricultural upslope areas exceeded 90%, while vegetation cover within the gullies exceeded 70%. It should also be noted that A a 2 m wide unplanted buffer along the gully bank zone, maintained ~~along gully banks~~ for machinery access, was colonized by natural grass cover (Fig. 1F–G). Field monitoring during intense rainfall indicated that these grass strips, together with wheel rut tracks, effectively diverted lateral runoff downslope along their margins, reducing direct flow into the gullies (Chen et al., 2025b). Therefore, this minor component was excluded when estimating the contribution of the gully to runoff and dissolved NH₄⁺, NO₃⁻, and P loss transport fluxes.



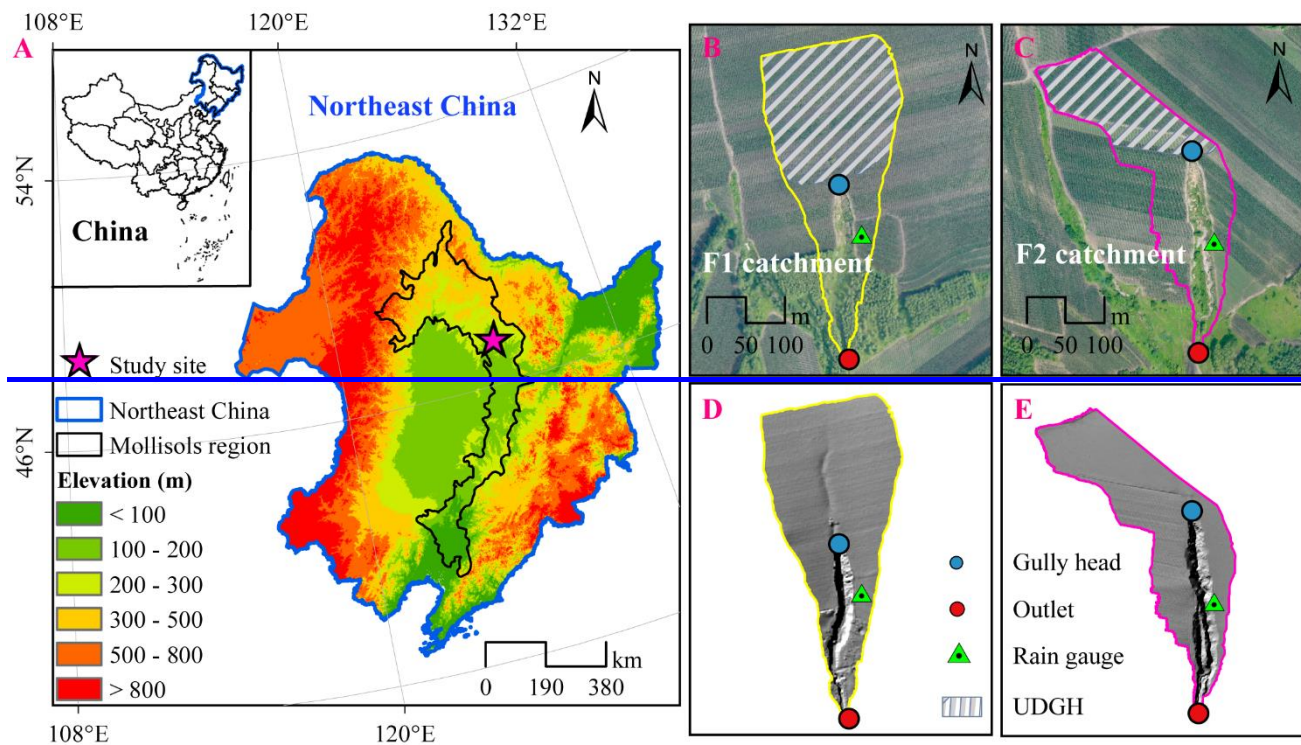


Fig. 1 (A) Location of the study site within the MRNC; (B–C) overview of the two monitored gully-dominated catchments; (D–E) DEM-derived hillshade basemap; (F–G) UAV aerial images of the two gullies; (H) rainfall data acquisition; (I–J) runoff sampling at the measuring weirs; and (K) water level monitoring using pressure sensors. UDGH represents the upslope drainage area of the gully head.

2.2 Rainfall data capture

From June to October in both 2022 and 2023, tipping-bucket rain gauges (Jian Darenke Electronic Technology Co., Ltd., Jinan, China) with a resolution of 0.2 mm were installed in both each catchments to record spatially heterogeneous rainfall to characterize rainfall conditions at the catchment scale (Fig. 1B, C, and H–I). A rainfall event was defined as a continuous period of precipitation event period separated from by the next rainfall event by at least no more than 6 h without rainfall hours; longer intervals were treated as separate events. Effective rainfall events were defined as those that generated observable surface runoff at the catchment outlet. Accordingly, only rainfall events associated with observable runoff were included in the subsequent analysis. These events were included in the sampling and subsequent analysis. Rainfall events that triggered significant soil erosion were classified as erosive rainfall (Chen et al., 2024b). Because the monitored catchments are hillslope systems without baseflow under dry conditions, runoff occurred only in response to rainfall and ceased shortly after rainfall ended. Therefore, the beginning and end of each runoff event were determined by combining field observations with automatic monitoring records at the measuring weirs, with runoff initiation defined as the time when flow was first detected and runoff termination defined as the time when flow ceased. To evaluate the impacts of different rainfall types on dissolved NH_4^+ , NO_3^- , and P transport fluxes losses, five parameters were selected for cluster analysis:

185 rainfall depth, duration, average intensity, maximum 30-minute intensity, and rainfall erosivity. The calculation of rainfall erosivity (RE) is provided shown in Equations (1)–(3):

$$RE = K_e \cdot I_{30} \quad \text{_____ (1)}$$

$$K_e = \sum(E_r \cdot P_r P) \quad \text{_____ (2)}$$

$$E_r = 0.29[1 - 0.72e^{-0.082i_r t}] \quad \text{_____ (3)}$$

190 In the eq. Equation (1), K_e represents the total kinetic energy of a rainfall event ($\text{MJ hm}^{-1}\text{h}^{-2}$); In the eEq. (2), P_r represents is the total rainfall amount during the event (mm); and in Ethe eq. (3), E_r denotes the unit kinetic energy during rainfall segments sub-event r ($\text{MJ ha}^{-1}\text{m}^{-2} \text{mm}^{-1}$). Here, $r = 1, 2, \dots, n$ refers to the consecutive rainfall segments sub-events into which within a single rainfall event, which were defined according to the temporal variation in recorded rainfall intensity is divided based on rainfall intensity; and i_r is the rainfall intensity during the consecutive rainfall segments sub-event r (mm h^{-1}).

2.3 Runoff monitoring and sample collection processing

To capture runoff variations during rainfall events, To examine how dissolved NH_4^+ , NO_3^- and P transport in runoff changes after entering the gully, measuring V-shaped weirs were installed at both the gully head (upslope drainage area of the gully head; UDGH) and the catchment outlet (Fig. 11–K). HOBO Water Level Probes (Onset Computer Corporation, Bourne, MA, USA) recorded runoff dynamics at 10-minute intervals by measuring pressure differences relative to identical probes placed in the air (Cheng et al., 2023; Chen et al., 2025b). Runoff samples were manually collected during rainfall events at the rising, peak, and recession pre-, mid-, and post- stages of the runoff stages using 1,000 mL polyethylene bottles. Depending on runoff duration and flow variability, 3–23 runoff samples were collected for each event, with an average of 6 samples per event. After the rising and peak stages had been adequately characterized, sampling intervals were gradually extended during the late runoff stage to ensure full event coverage. The sampling frequency was dynamically adjusted based on runoff fluctuations to capture peak flow dynamics. During rapid discharge changes, intervals were shortened to as little as 2 min. As flow subsided, the sampling frequency was reduced accordingly. Once sufficient samples had been obtained to characterize the runoff process, intervals were further extended to ensure full coverage of the event. All collected samples were immediately delivered to the laboratory for dissolved NH_4^+ , NO_3^- , and P analysis. Notably, no baseflow was observed in either gully during non-rainfall periods; therefore, its influence on the runoff process was excluded from consideration.

A subsample was filtered through a $0.45 \mu\text{m}$ Millipore membrane to obtain the filtrate for nutrient analysis. Concentrations of dissolved NH_4^+ , NO_3^- , and P were determined using standard spectrophotometric methods: Nessler's reagent spectrophotometry for NH_4^+ , ultraviolet spectrophotometry for NO_3^- , and ammonium molybdate spectrophotometry for dissolved PDP. The runoff volume for each rainfall event was calculated using the calibrated flume-weir depth-discharge runoff curve and an empirical formula. By integrating high-frequency runoff sampling and dissolved nutrient concentrations, the dissolved nutrient transport flux load induced by for each rainfall event was determined (eqEq. 4). Specifically, nutrient concentrations measured from discrete runoff samples were assigned to their corresponding sampling

intervals, and the event-scale dissolved nutrient transport flux was calculated by summing the products of runoff volume and nutrient concentration across the entire runoff process (Bender et al., 2018). A detailed description of the calculation process can be found in our previous study research (Chen et al., 2025b). In addition, after rainfall events were classified, dissolved nutrient transport fluxes were further aggregated within each rainfall type to compare differences in cumulative nutrient transport fluxes among rainfall types.

$$F = \int_{t_1}^{t_2} \frac{Q_t \cdot C}{1000} dt \quad (4)$$

Where F is the dissolved NH_4^+ , NO_3^- , and P transport flux of dissolved NH_4^+ , NO_3^- , and P (kg). Q_t refers to the runoff discharge at time t ($\text{m}^3 \text{h}^{-1}$). t_1 and t_2 correspond to the times when runoff begins and ends, respectively (h). C represents the concentrations of dissolved NH_4^+ , NO_3^- , and P (mg L^{-1}).

2.4 Data analysis

Rainfall types were classified using K-means clustering analysis via the R package “cluster” (v.2.1.3). To compare event-scale dissolved nutrient transport fluxes among different rainfall types, D data normality and variance homogeneity were first assessed using Shapiro’s test and Levene’s test, respectively. If these assumptions were met, one-way ANOVA followed by Tukey’s HSD test was used to compare dissolved NH_4^+ , NO_3^- , and P transport fluxes loss across rainfall types; otherwise, the Kruskal-Wallis nonparametric test was applied. A statistically significant difference ($P < 0.05$) was interpreted as evidence that rainfall type significantly influenced of gully-mediated regulation of the dissolved nutrient export dynamics under different rainfall types. To quantify changes in dissolved NH_4^+ , NO_3^- , and P concentrations during transport through the gully, a dilution ratio was calculated for each event as the outlet concentration divided by the corresponding concentration at the gully head. Values lower than 1 indicate dilution during transport through the gully, whereas values greater than 1 indicate enrichment. Correlation analysis was used to examine the relationships between dissolved NH_4^+ , NO_3^- , and P transport fluxes and rainfall characteristics. Redundancy analysis (RDA) was employed to explore the relationships individual effects of between-rainfall, runoff, and dissolved nutrient concentrations on dissolved NH_4^+ , NO_3^- , and P transport fluxes dissolved NH_4^+ , NO_3^- , and P losses. Model significance was assessed using a Monte Carlo permutation test with 999 permutations, and the relative importance of each explanatory variable was then determined through hierarchical partitioning. In addition, to assess the effects of gullies and rainfall types on dissolved NH_4^+ , NO_3^- , and P transport fluxes, we fitted the relationships between nutrient transport fluxes and rainfall depth. These relationships were described using either power or linear functions. A significant power function relationship ($F=aR^b$) was observed between rainfall depth and the transport fluxes of dissolved NH_4^+ , NO_3^- , and P, where the coefficient a indicates the sensitivity of nutrient transport fluxes loss to rainfall (higher values reflect greater mobilization potential) and the exponent b represents the efficiency with which transport fluxes respond to changes in rainfall depth. In the linear function ($F=aR+b$), parameter a likewise reflects the sensitivity of dissolved NH_4^+ , NO_3^- , and P transport loss fluxes to rainfall depth. All statistical analyses were performed in R (v.4.5.0; R Core Team, Vienna, Austria).

3.1 Rainfall characteristics

From June to October of 2022 and 2023, 30 and 29 rainfall events were recorded in F1 and F2, respectively. K-means clustering classified these events into three distinct rainfall types (Table 1). ~~Type A was dominant, occurring 23 times in both catchments, while Types B and C were less frequent (F1: 4 and 3; F2: 3 and 3, respectively).~~ Type A was characterized by low rainfall depth (20.8 mm), moderate duration (491.68.2 min h), moderate intensity (3.9 mm h⁻¹), and low erosivity (71.9 MJ mm ha⁻¹ h⁻¹). Type B featured moderate rainfall depth (23.8 mm), short duration (56.1 min 0.9 h), high intensity (28.3 mm h⁻¹), and moderate erosivity (267.4 MJ mm ha⁻¹ h⁻¹). Type C exhibited high rainfall depth (79.6 mm), long duration (2922.448.7 h min), low intensity (1.7 mm h⁻¹), and the highest erosivity (333.7 MJ mm ha⁻¹ h⁻¹). Among these rainfall types, Type A was dominant, occurring 23 events times in both catchments, while Types B and C were less frequent (F1: 4 and 3; F2: 3 and 3, respectively). ~~However~~ Despite their lower frequency, the erosivity of Types B and C was 3.6 and 4.3 times higher than that of Type A, respectively (Table 1).

Table 1 Average values of rainfall parameters for the three rainfall ~~type patterns~~ identified in catchments F1 and F2.

| <u>Catchments</u> | <u>Rainfall types</u> | <u>Sample sizes</u> | <u>P</u> (mm) | <u>D</u> (min h) | <u>I_{mean}</u> (mm h ⁻¹) | <u>I₃₀</u> (mm h ⁻¹) | <u>RE</u> (MJ mm ha ^{-1.2} h ⁻¹) |
|-------------------|-----------------------|---------------------|------------------|----------------------------------|--|--|--|
| F1 | A | 23 | 21.5 | 8.8 525.1 | 3.4 | 17.1 | 84.5 |
| | B | 4 | 24.5 | 0.9 52.8 | 30.3 | 46.1 | 334.2 |
| | C | 3 | 82.5 | 49.3 | 1.8 | 20.8 | 515.7 |
| | | | | 2959.7 | | | |
| F2 | A | 23 | 20.1 | 7.6 458.2 | 4.5 | 13.7 | 59.3 |
| | B | 3 | 23.1 | 1.0 59.3 | 26.2 | 32.9 | 200.6 |
| | C | 3 | 76.7 | 48.1 | 1.6 | 10.5 | 151.6 |
| | | | | 2885.0 | | | |

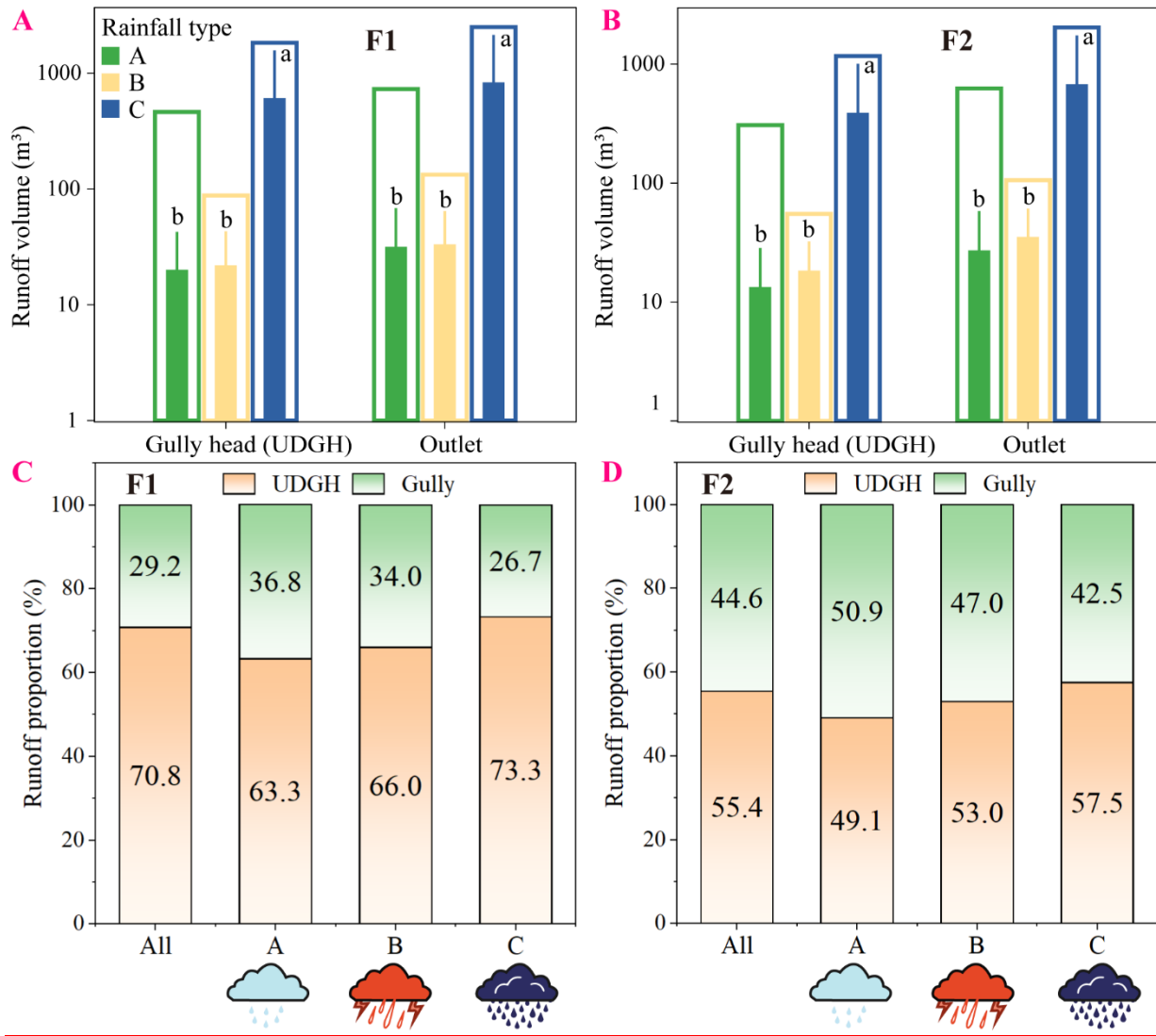
Note: F1 and F2 respectively represent the two monitored catchments, respectively. Sample size indicates the number of rainfall events included in each rainfall type. Abbreviations: P, Rainfall-rainfall depth; D, Rainfall-rainfall duration; I_{mean}, Mean-mean rainfall intensity; I₃₀, maximum 30-min rainfall intensity; and RE, rainfall erosivity.

3.2 The role of gullies in regulating runoff

During Type C rainfall, cumulative runoff volume in the UDGH was 3.9 and 21.0 times ~~(based on the mean values of the F1 and F2 catchments)~~ greater higher than that under Types A and B, respectively, based on the mean values of the F1 and F2 catchments (Fig. 2A–B). At the outlet, cumulative runoff under Type C was 3.3 times higher than that under Type A

270 and 19.0 times higher than that under Type B. On average, Type C rainfall generated significantly more runoff than Types A and B at both locations ($P < 0.05$) (Fig. 2A–B). Specifically, the average runoff volume in the UDGH during Type C was 29.8 and 24.5 times greater than that under Types A and B, respectively, while at the outlet, it was 25.6 and 22.1 times higher than that under Types A and B, respectively (Fig. 2A–B). Although Type B produced more runoff than Type A, the difference was not statistically significant ($P > 0.05$) (Fig. 2A–B).

275 Gulliesy accounted for only 12.4% of the catchment area but contributed an average of 36.1% of total runoff (calculated from based on the mean value of the catchments F1 and F2 catchments) (Fig. 2C–D). This contribution varied with rainfall type, with the highest value observed under Type A (43.2%), followed by Type B (40.1%), and the lowest under Type C (33.8%) (Fig. 2C–D).



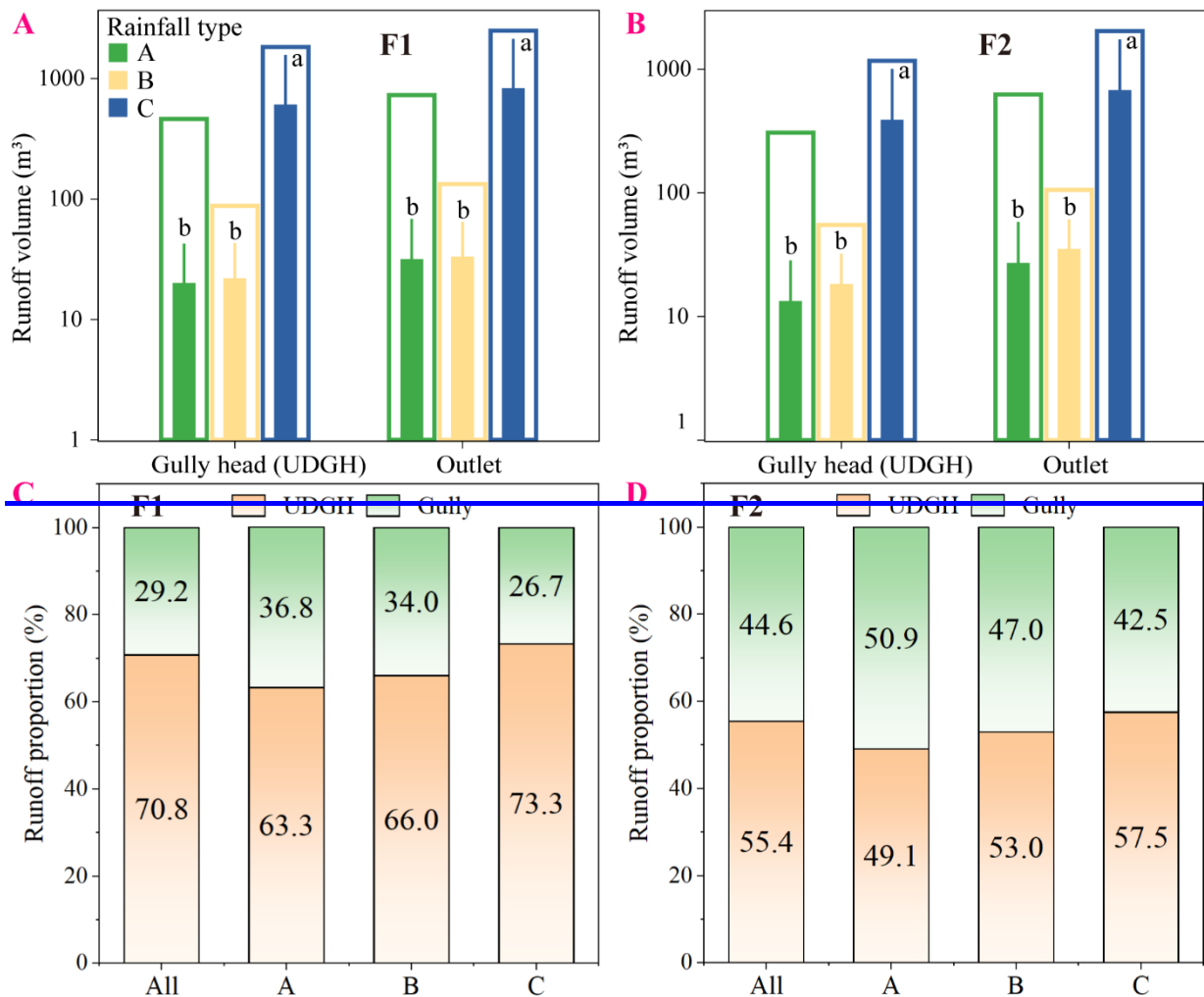


Fig. 2 (A, F1 catchment; -B, F2 catchment) Cumulative and event-scale runoff volumes from the UDGH and the gully under different rainfall types. (C, F1 catchment; -D, F2 catchment) Contribution of the UDGH and the gully to total runoff under different rainfall types. Note: Bars without filled colors represent cumulative runoff volume under different rainfall types, embedded bars with filled colors represent the average runoff volume for individual rainfall events, and different lowercase letters represent significant differences in runoff volume between different rainfall types (A-B). Abbreviation: UDGH represents the upslope drainage area of the gully head.

3.3 Transport The transport effect of dissolved NH_4^+ , NO_3^- and P mediated by gullies by gully

3.3.1 Concentrations of dissolved NH_4^+ , NO_3^- and P concentration

Dissolved NH_4^+ , NO_3^- and P concentrations measured at the outlet were consistently lower than those observed at the gully head (Fig. 3). On average, the dilution ratios (outlet concentration divided by gully head concentration) were 0.77 for dissolved NH_4^+ , 0.65 for NO_3^- , and 0.87 for P. These values indicated that the gullies exerted a stronger dilution effect on NO_3^- than on NH_4^+ or P (Fig. 3).

The effect of the gullies on dissolved NH_4^+ , NO_3^- , and P concentrations also varied with rainfall type (Fig. 4). On average, the dissolved NH_4^+ concentrations at the gully head were 1.33, 1.24, and 1.21 times higher than those at the outlet under rainfall Types A, B, and C, respectively (Fig. 4A and D). For dissolved NO_3^- , the corresponding ratios were 1.61, 1.58, and 1.21 (Fig. 4B and E). For DP, the ratios were 1.19, 0.94, and 1.21 (Fig. 4C and F). These results suggested that, under rainfall Types A and B, the gully intensified the concentration gradient of NH_4^+ and NO_3^- between the gully head and the outlet. In contrast, the pattern for DP appeared more variable: strong dilution occurred under Types A (particularly in catchment F1) and C (particularly in catchment F2), whereas an marked increases slight increases were was observed in F1 and a slight increase in F2 catchment under Types B, possibly indicating episodic in channel P release.

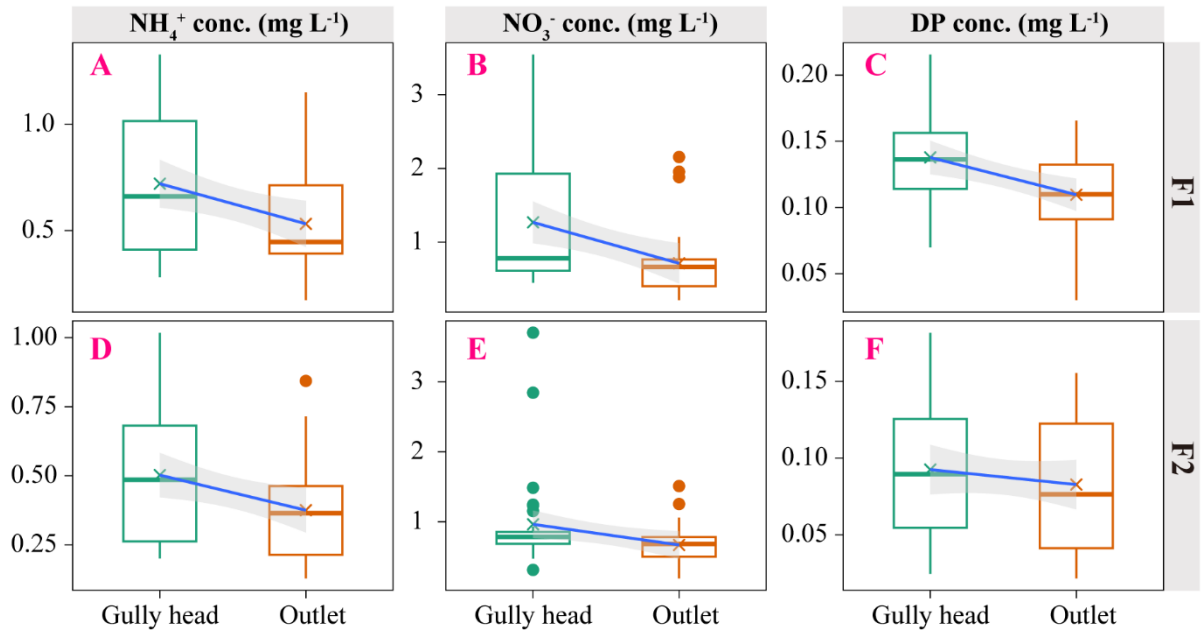


Fig. 3 Comparison of dissolved NH_4^+ , NO_3^- , and P concentrations between the at-gully head and the outlet. (A–C) F1 catchment; (D–F) F2 catchment.

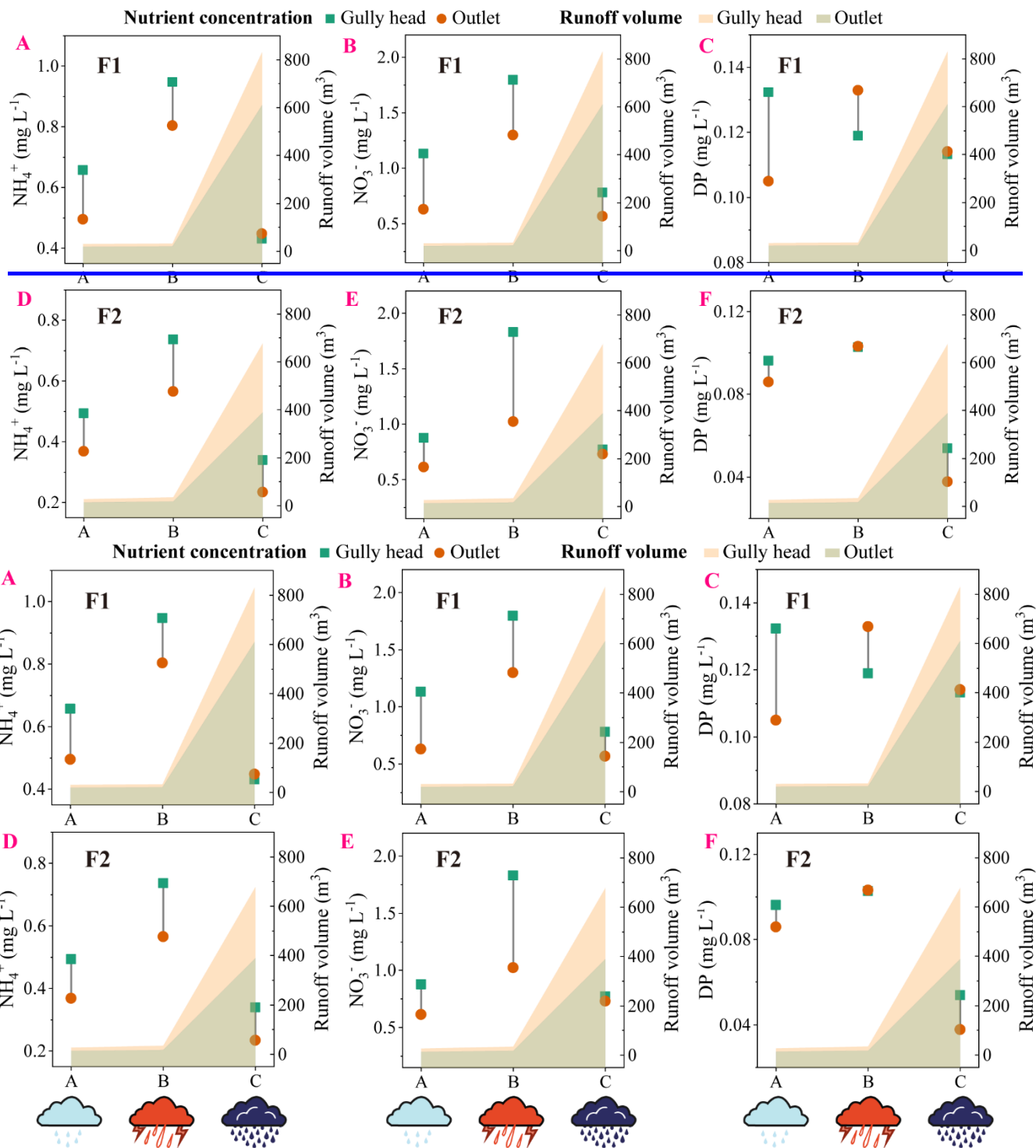


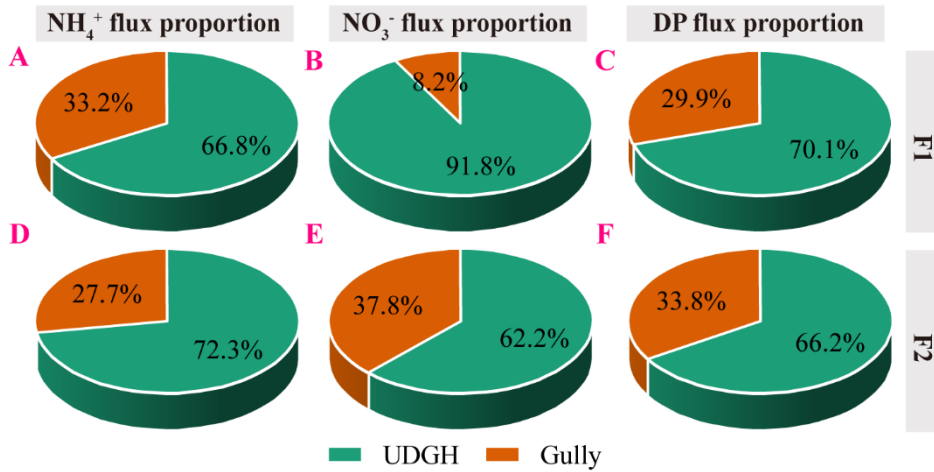
Fig. 4 ~~D~~Characterization of dissolved NH_4^+ , NO_3^- , and P concentrations under different rainfall types. (A–C) F1 catchment; (D–F) F2 catchment. Note: The length of the lines connecting different points represents the concentration difference between the gully

310 head and the outlet; longer lines indicate larger differences. The colored shaded areas represent the variation in mean runoff volume under different rainfall types at the gully head and the outlet.

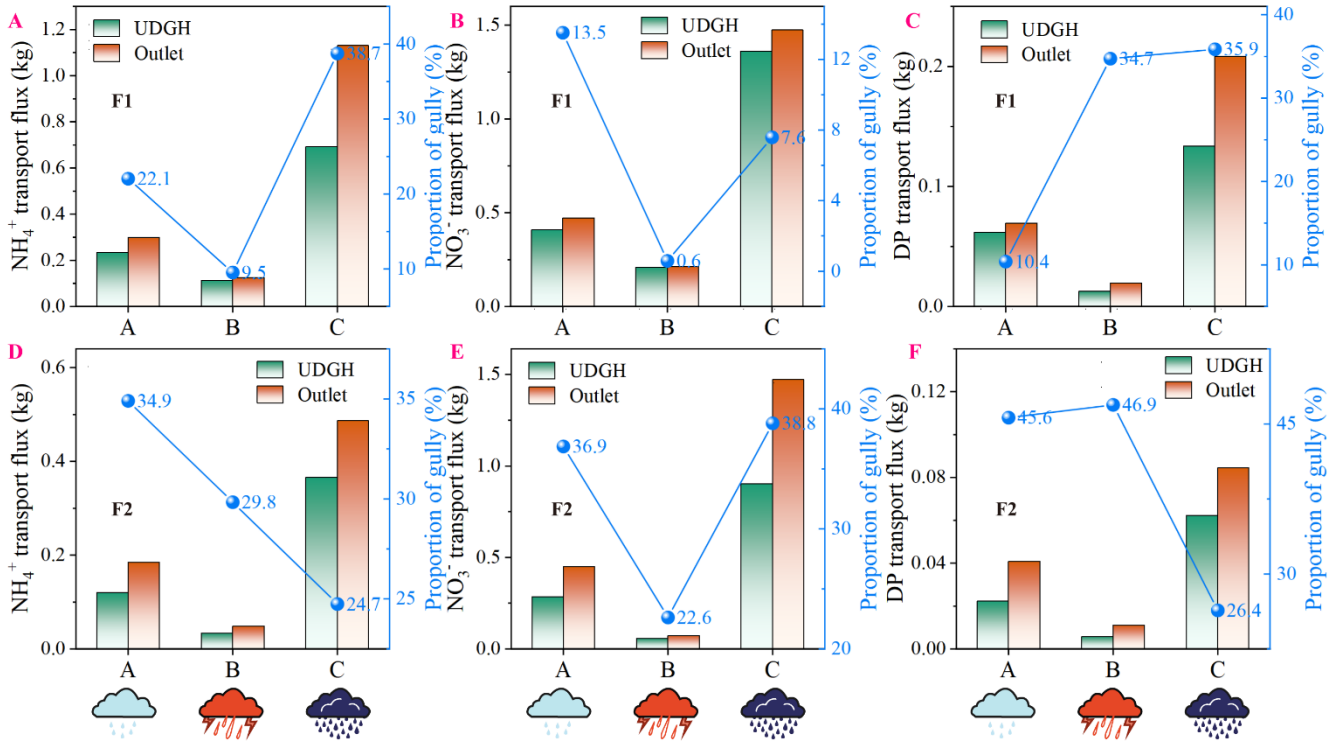
3.3.2 Transport fluxes of dissolved NH_4^+ , NO_3^- and P

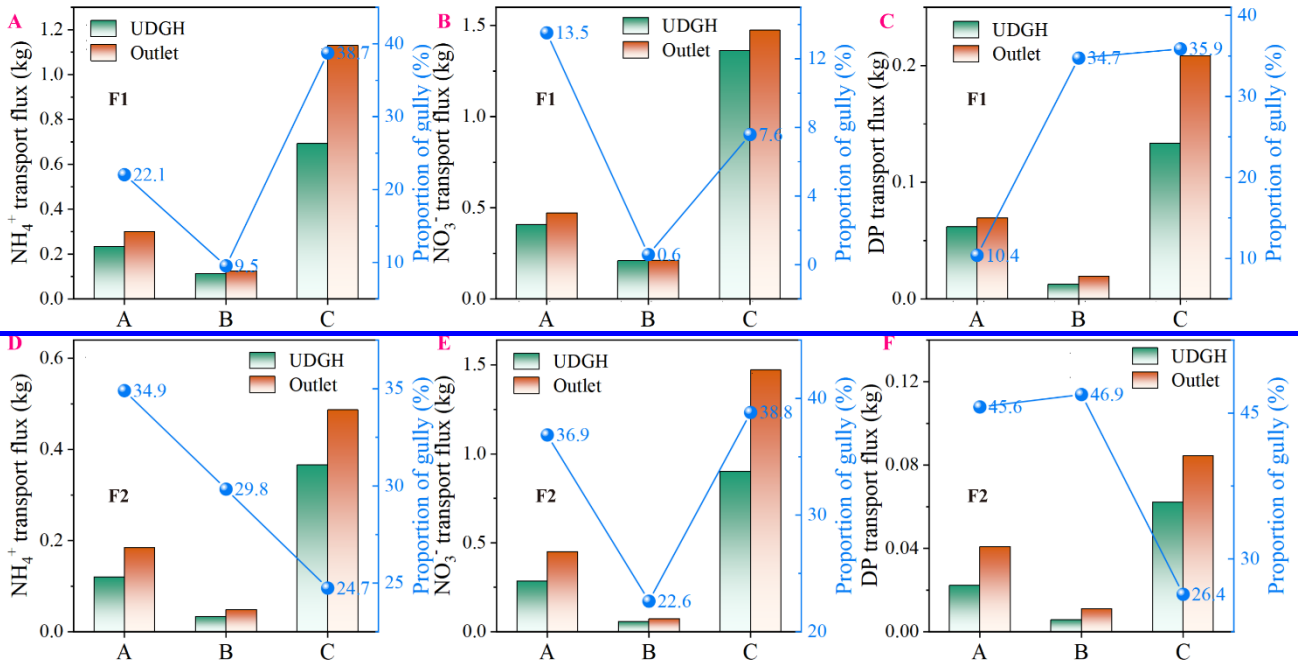
315 When rainfall types were not differentiated, Gulliesy accounted fore contributed 31.4%, 22.4%, and 31.1% of the total dissolved NH_4^+ , NO_3^- , and P transport fluxes at the catchment scale, respectively (Fig. 5). Moreover, Rrainfall type had a significant impact on dissolved nutrient transport. Although Type C rainfall accounted for only 10.2% of all events, it contributed ~~78.1%, 73.4%, and 71.9% of the gully transport fluxes of NH_4^+ , NO_3^- , and P, respectively. At the catchment seale, Type C events similarly dominated, contributing~~ 68.2%, 73.8%, and 71.8% of the total dissolved NH_4^+ , NO_3^- , and P transport fluxes at the outlet, respectively (Fig. 6). Meanwhile, the influence of the gully on the transport fluxes of dissolved NH_4^+ , NO_3^- , and P in the catchment also depended on rainfall type. On average, the gully accounted for 27.1%, 15.3%, and 34.5% of dissolved NH_4^+ transport fluxes under Types A, B, and C (Fig. 6A and D), respectively, and for 24.8%, 8.0%, and 320 23.2% of dissolved NO_3^- transport fluxes, respectively (Fig. 6B and DE). These results indicate that the gully exerted the strongest reduction of NH_4^+ and NO_3^- fluxes under Type B rainfall and the weakest under Type C. In contrast, gully contributions to DP transport were 22.7%, 40.9%, and 33.1% under Types A, B, and C, respectively, suggesting a reduced regulatory effect during Type B events and an enhanced effect during Type A (Fig. 6C and F).

325 At the event scale, transport fluxes of dissolved NH_4^+ , NO_3^- , and P were significantly higher than under Type C rainfall compared to Types A and B ($P < 0.05$). Although the fluxes under Type B exceeded those of Type A, the differences were not statistically significant ($P > 0.05$) (Fig. 7). Specifically, at the gully head (UDGH), NH_4^+ transport fluxes under Type C rainfall were 3.1 and 7.6 times higher than those under Types A and B, respectively; NO_3^- transport fluxes were 3.3 and 9.7 times higher than those under ~~those~~ under Types A and B, respectively; and DP transport fluxes were 2.5 and 10.1 times higher than those under Types A and B, respectively. ~~Although Type B fluxes exceeded those of Type A, the differences were not statistically significant ($P > 0.05$) (Fig. 7).~~ At the outlet, NH_4^+ transport fluxes under Type C rainfall were 4.3-fold higher than those under Type A and 22.2-fold higher than those under Type B. The corresponding multiples were 2.7 and 57.0 for NO_3^- and 5.8 and 7.2 for DP (Fig. 7).

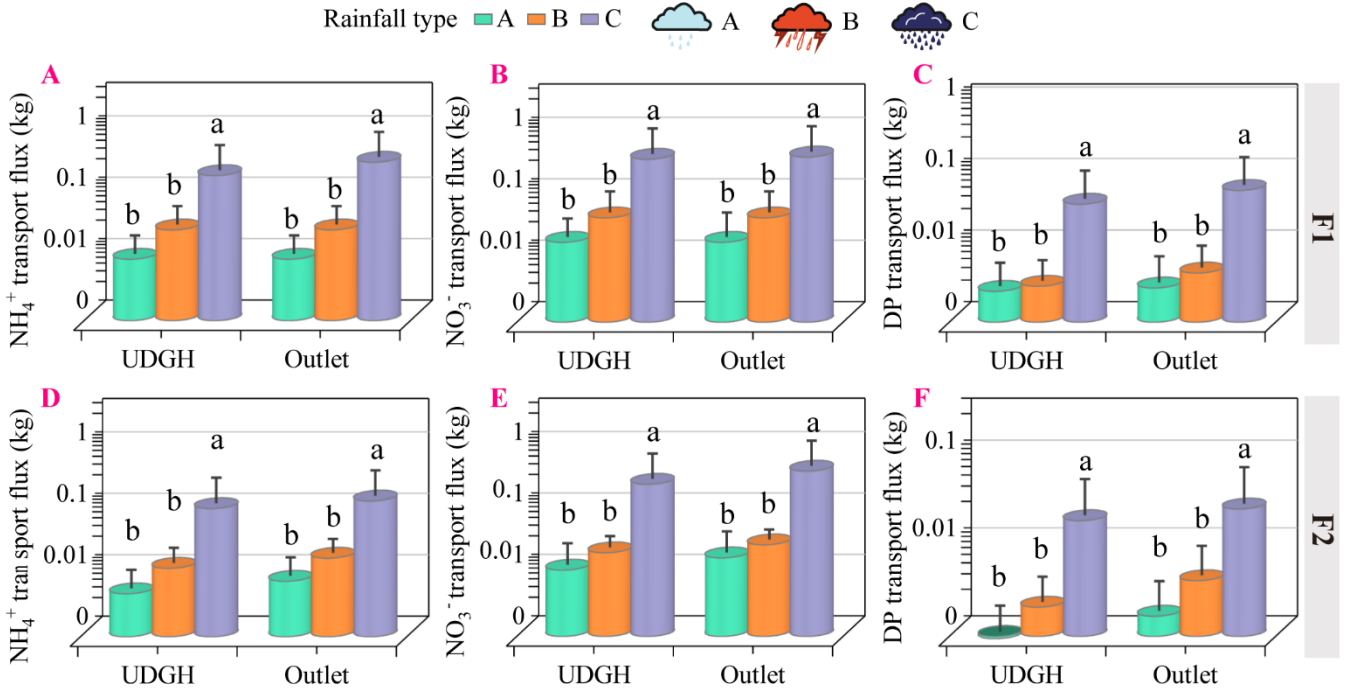


335 **Fig. 5 Contributions of the UDGH and the gully different sites to dissolved NH₄⁺, NO₃⁻ and P transport loss fluxes in agricultural catchments. (A–C) F1 catchment; (D–F) F2 catchment. Abbreviation: UDGH represents the upslope drainage area of the gully head.**





340 **Fig. 6** The left y-axis represents the cumulative transport fluxes of dissolved NH_4^+ , NO_3^- , and P cumulative transport flux under different rainfall types, presented as bar charts. The right y-axis represents the corresponding gully contribution, illustrated by a dotted line. (A-C) F1 catchment; (D-F) F2 catchment. Abbreviation: UDGH represents the upslope drainage area of the gully head.



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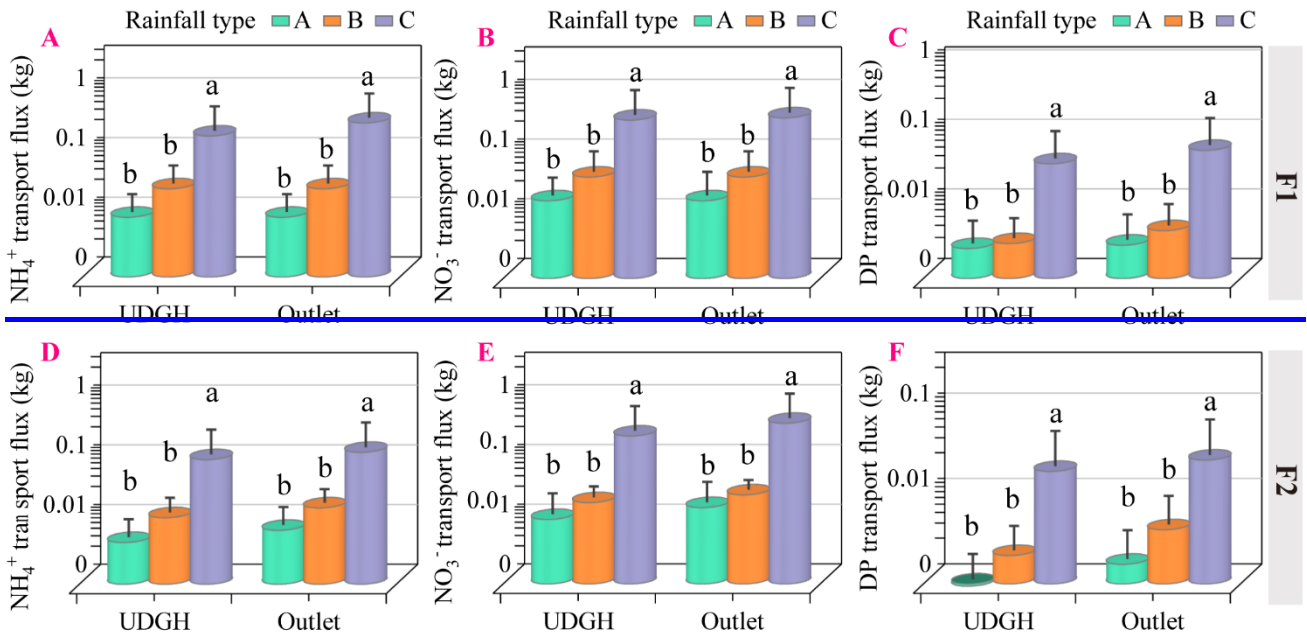


Fig. 7 Effects of different rainfall types on the average mean event-scale transport fluxes of dissolved NH₄⁺, NO₃⁻, and P at event scale. (A-C) F1 catchment; (D-F) F2 catchment. Abbreviation: UDGH represents the upslope drainage area of the gully head.

3.4 Gully regulates response relationships among runoff and dissolved NH₄⁺, NO₃⁻ and P fluxes

350 3.4.1 Correlation analysis of rainfall factors with runoff and dissolved NH₄⁺, NO₃⁻ and P fluxes

At both the gully head and outlet, rainfall depth was the factor with the greatest correlation with runoff volume and dissolved NH₄⁺, NO₃⁻, and P fluxes, followed by rainfall erosivity. Relative to the gully head (UDGH), the presence of the gully led to only a slight enhancement in the correlation between runoff volume, dissolved NH₄⁺, NO₃⁻, and P fluxes and rainfall depth at the outlet (Fig. 8).

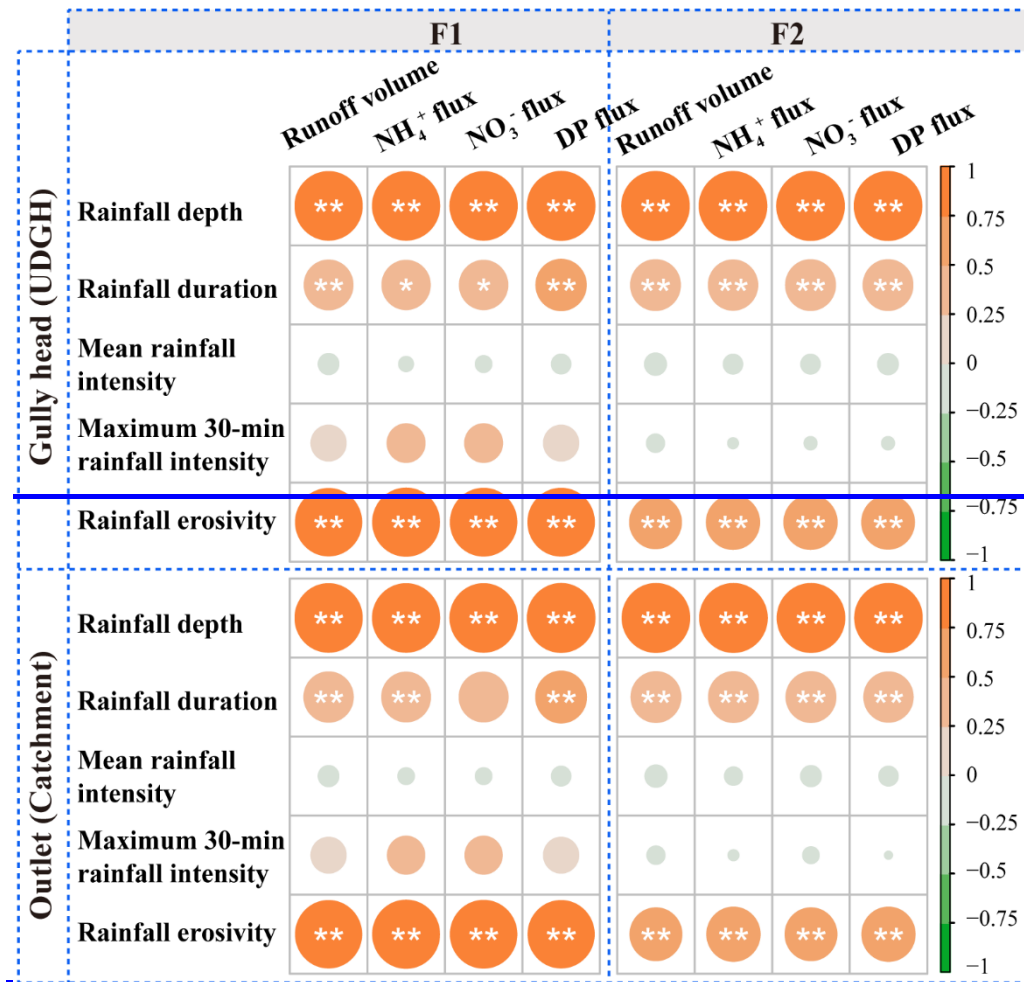
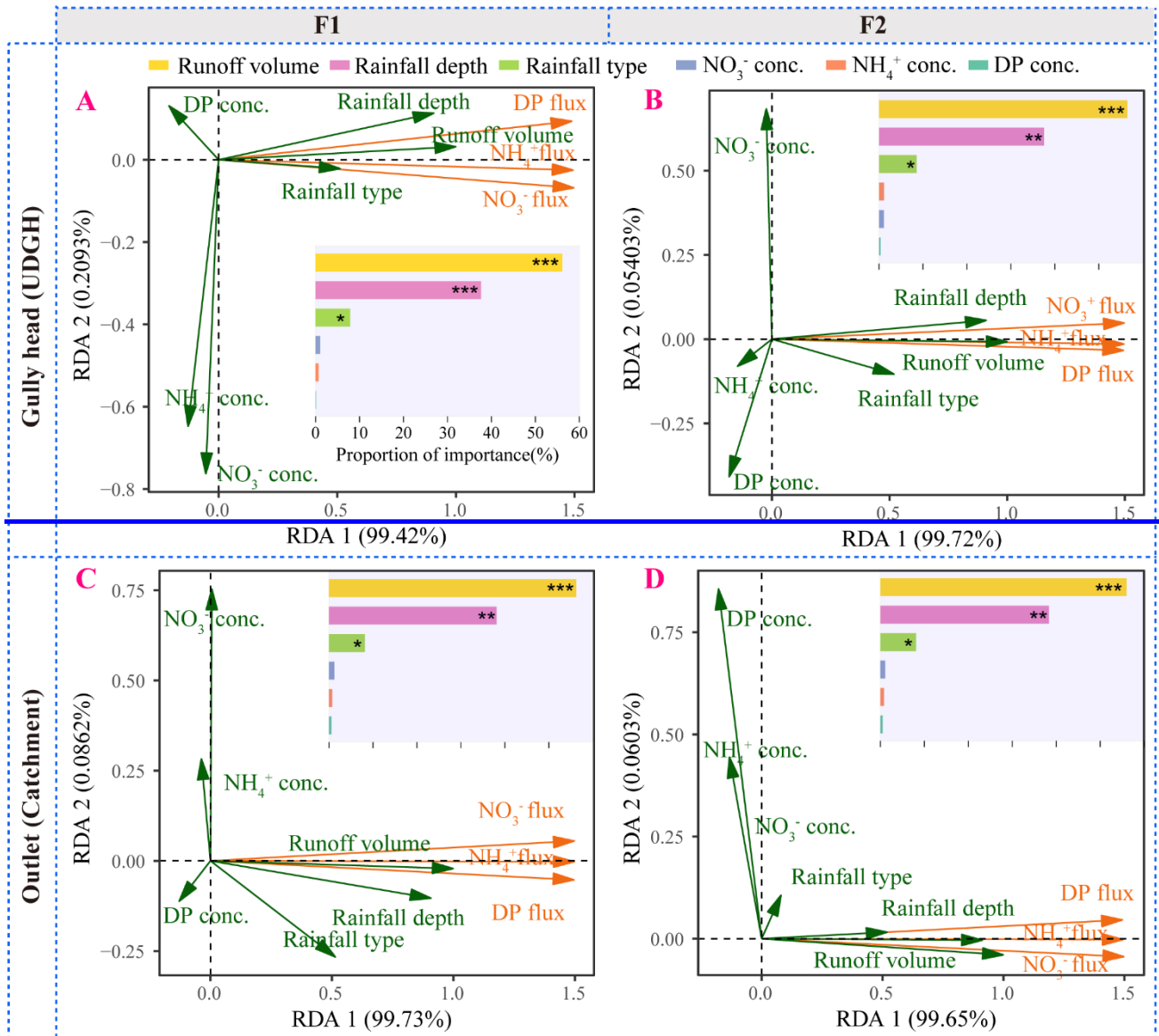


Fig. 8 Correlation analysis of rainfall characteristics with runoff and dissolved NH_4^+ , NO_3^- and P fluxes.

3.4.2 Response of dissolved NH_4^+ , NO_3^- and P transport flux to rainfall, runoff, and concentration

Redundancy analysis was used to reveal dominant factors of dissolved nutrient fluxes, and the results indicated that the transport fluxes of dissolved NH_4^+ , NO_3^- , and P fluxes were primarily influenced by runoff volume, rainfall depth, and rainfall type, while their correlations with corresponding concentrations were not significant. This indicated that the transport of dissolved NH_4^+ , NO_3^- , and P was mainly controlled by runoff rather than concentration (Fig. 9).



365 **Fig. 9** Ordination plots of redundancy analysis for the dissolved NH₄⁺, NO₃⁻ and P transport flux response. Variation partitioning analysis of rainfall, runoff, and dissolved nutrient concentration to variation in dissolved nutrient transport flux and individual effects of explanatory variables based on hierarchical partitioning.

370 **3.4.3** Rainfall Gully modulated the response of relationship between rainfall, dissolved NH₄⁺, NO₃⁻, and P transport in gully-dominant catchments fluxes

At both the gully head and the outlet, rainfall depth was the factor most strongly correlated with runoff volume and dissolved NH₄⁺, NO₃⁻, and P transport fluxes, followed by rainfall erosivity (Fig. S1). Moreover, redundancy analysis indicated that dissolved NH₄⁺, NO₃⁻, and P transport fluxes were primarily influenced by runoff volume, rainfall depth, and rainfall type, which ranked as the three most important factors, while their correlations with the corresponding

concentrations were not significant. This indicates that dissolved NH_4^+ , NO_3^- , and P transport fluxes were influenced more strongly by runoff and rainfall than by concentration (Fig. S2).

The power-law relationships between dissolved NH_4^+ , NO_3^- , and P transport fluxes and rainfall depth revealed the regulatory role of gullies in modulating transport sensitivity (Fig. 8). A significant power function relationship ($F=aI^b$) was observed between rainfall depth and the transport fluxes of dissolved NH_4^+ , NO_3^- , and P, where the coefficient a indicates the sensitivity of nutrient loss to rainfall (higher values reflect greater mobilization potential) and the exponent b represents the transport efficiency at which fluxes respond to changes in rainfall depth ($P < 0.01$; Fig. 10). The results revealed that the gully significantly increased the sensitivity coefficient (a) for the dissolved NH_4^+ , NO_3^- , and P transport fluxes, with increases of 3.04, 1.71, and 2.84 times, respectively. However, the gully also reduced the overall transport efficiency (parameter b), by 4.8%, 2.0%, and 19.5% for dissolved NH_4^+ , NO_3^- , and P, respectively (Fig. 8 Fig. 10). Among the different rainfall types, Type C rainfall markedly enhanced the sensitivity of dissolved NH_4^+ , NO_3^- , and P fluxes compared to Types A and B (Fig. 9). Furthermore, within the same rainfall category, a comparison of the slopes values of the linear relationships equation between the gully head and the outlet showed that the presence of the gully amplified the rainfall sensitivity of dissolved NH_4^+ , NO_3^- , and P transport at the catchment outlet (Fig. 9 Fig. 11).

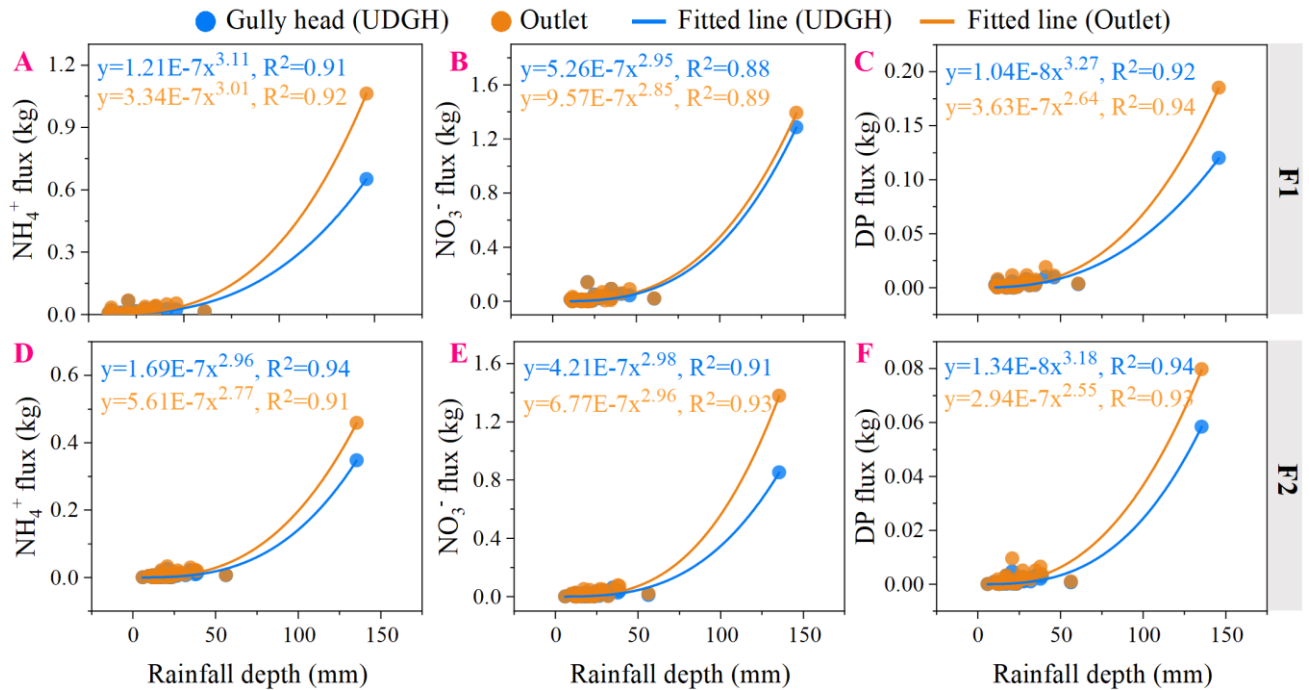
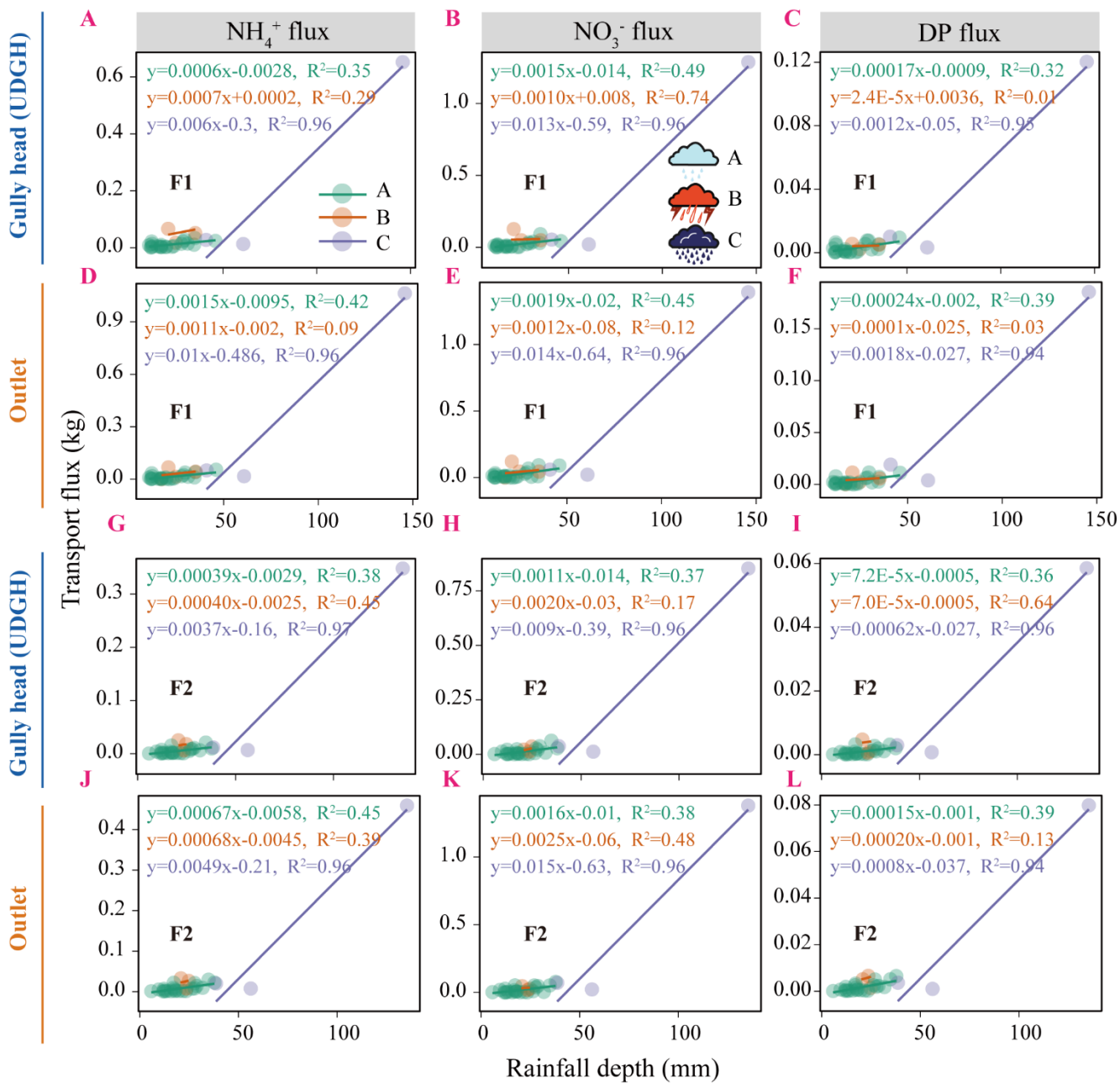


Fig. 8 Differences in the response of dissolved NH_4^+ , NO_3^- , and P transport fluxes to runoff rainfall depth volume between the gully head and the outlet. Solid lines indicate the fitted standard major axis (SMA) regression lines. (A-C) F1 catchment; (D-F) F2 catchment. Abbreviation: UDGH represents the upslope drainage area of the gully head. $P < 0.05$ indicates a significant difference between the slopes of the regression lines at the gully head and outlet.



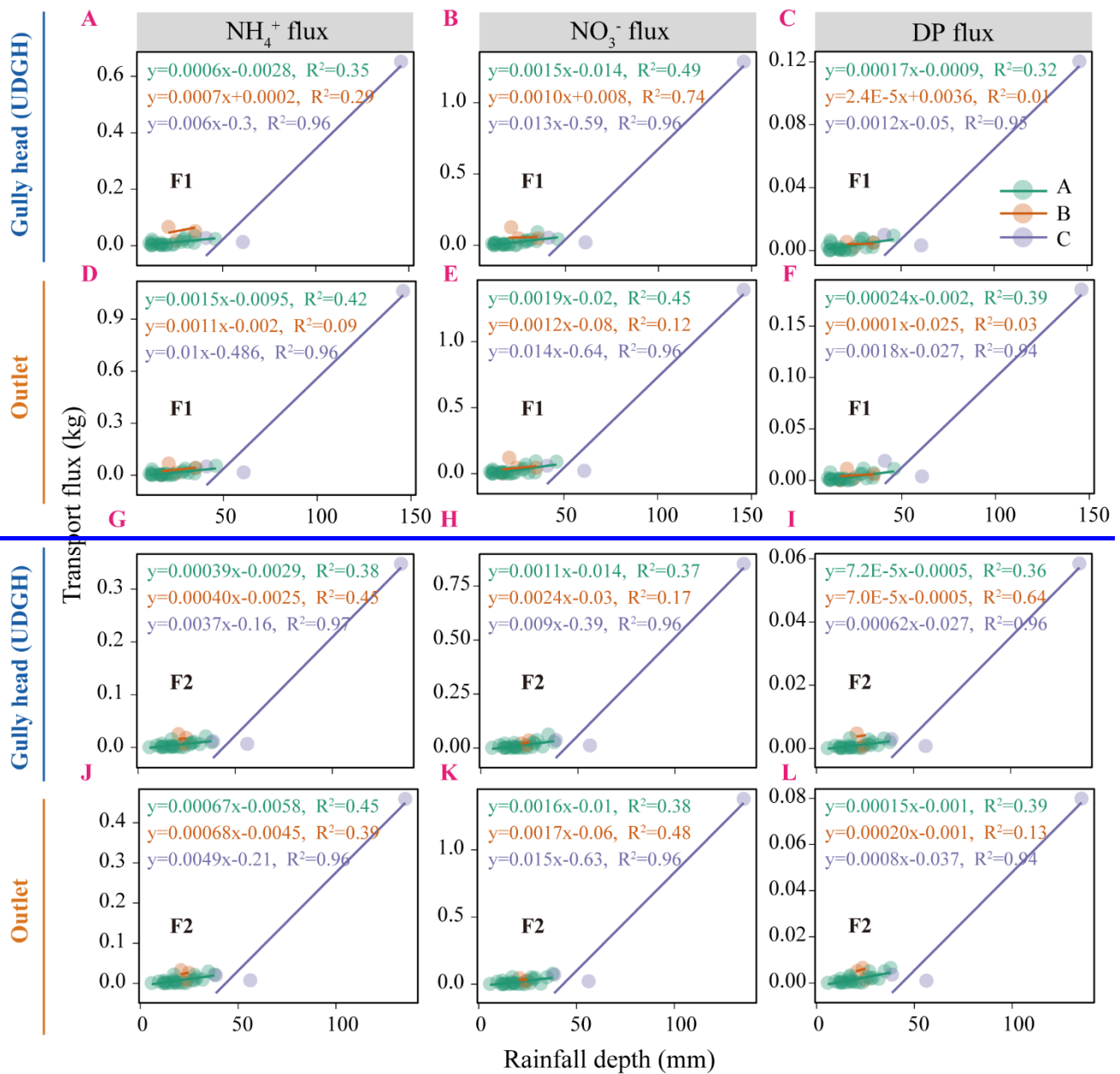


Fig. 9914 Differences in the response of dissolved NH₄⁺, NO₃⁻, and P transport fluxes to rainfall depth under different rainfall types. **Solid lines indicate the fitted regression lines.**

395

4 Discussion

4.1 Regulatory effect of gullies on the runoff and associated transport of dissolved NH_4^+ , NO_3^- , and P transport

Our findings indicated that, ~~although~~ gullies, ~~despite~~ occupying only 12.4% of the catchment area, ~~they~~ contributed 36.1% of the total runoff, ~~highlighting their promotive effect on runoff generation~~ (Fig. 2). Compared with the gently sloping farmland covered by dense crops ~~during the rainy season (Section 2.1)~~, the steep topography and ~~relatively~~ sparse vegetation of ~~the~~ gully provided favorable conditions for the generation and concentration of runoff, ~~which is consistent with previous studies~~ (Chen et al., 2025a; Zhang & Zhang, 2025). ~~These studies showed that, compared with bare land, crop -covered slopes can reduce runoff by 55.8%–92.2% (Chen et al., 2025a), and that the runoff coefficient under vegetation cover is only about 10% of that on bare land (Zhang & Zhang, 2025). This effect is mainly related to rainfall interception by vegetation~~ (Zhang et al., 2025), ~~while steeper gully slopes further promote flow concentration~~ (Zhang & Zhang, 2025; Xu et al., 2026). ~~Together, these results suggest that gullies act as efficient hydrological connectors, rapidly transferring water from upslope farmland to the catchment outlet, which agrees with previous studies which subsequently transported dissolved nutrients downstream to rivers and lakes~~ (Hou et al., 2022; Chen et al., 2024b; Chen et al., 2025b). Notably, gullies ~~also showed exerted a clear strong~~ dilution effect on dissolved nutrients, especially NO_3^- , ~~for which with the an~~ average concentration ratio ~~of 0.65~~ between the outlet and the gully head ~~was 0.65~~ (Fig. 3). This pronounced reduction in runoff NO_3^- concentration may have resulted from the formation of ponded, anaerobic, or reducing microenvironments in locally flat sections of the gully bed, where denitrifying microorganisms could convert NO_3^- into gaseous nitrogen, thereby significantly lowering its concentration (He et al., 2026). Furthermore, runoff NO_3^- , as a highly mobile anion, is not readily adsorbed by sediments and tends to distribute evenly in gully water. As runoff accumulated, NO_3^- was more prone to dilution than retention (Wang et al., 2024; Zhao et al., 2025). In contrast, NH_4^+ , as a positively charged ion, is more likely ~~than NO_3^-~~ to be adsorbed ~~onto soil colloids, retained through cation exchange, and temporarily stored immobilized by in~~ sediments on the gully bed, ~~particularly under fluctuating hydrodynamic conditions such as floods (Zhao et al., 2025). These conditions are common in gullies, which were globally recognized as major sediment sources (Kumar Bhattacharya et al., 2024; Su et al., 2024; Chen et al., 2025b)~~. Therefore, the observed reduction in NH_4^+ concentrations may have been more the result of physical retention than dilution (Wang et al., 2024). ~~Unlike DN, DP does not undergo gaseous transformation and is primarily governed by adsorption processes (Liu et al., 2020; Yang et al., 2024). The response of DP was therefore more variable, likely because its concentration was influenced not only by runoff transport, but also by interactions at the sediment-water interface within the gully (Bender et al., 2018). Our previous results showed that phosphorus concentrations in gully soils and sediments were significantly lower than those on adjacent farmland slopes (Chen et al., 2024c; Chen et al., 2025b; Wang et al., 2026). This pattern suggests that the equilibrium phosphorus concentration in gully sediments was lower than that in runoff water, which may favor phosphate release from sediments, especially under anoxic conditions (Bender et al., 2018). P, unlike N, does not undergo gaseous transformation and is primarily governed by precipitation and adsorption processes, making its dilution response less straightforward (Liu et al., 2020; Yang et al., 2024)~~. Interestingly, while gullies generally reduced the

concentrations of dissolved NH_4^+ , NO_3^- , and P from upslope runoff, they also amplified the sensitivity of transport fluxes to runoff (Fig. 8 Fig. 10). In other words, This indicates that the transport of dissolved NH_4^+ , NO_3^- , and P transport was primarily governed by runoff volume rather than concentration (Fig. S2). Once runoff connectivity was established, the increase in water volume outweighed the decrease in concentration. Therefore, managing runoff pathways within catchments may be important for reducing dissolved nutrient transport fluxes.

4.2 Rainfall type-dependent gully effects on the transport of Regulation-effect-of runoff and associated dissolved NH_4^+ , NO_3^- , and P the gullies was influenced by rainfall types

This study classified rainfall events using five rainfall parameters to examine how rainfall type affects runoff and dissolved N and P transport fluxes in gully-dominated catchments. This leads to the first key question: how do the hillslope and gully differ in their hydrological responses under different rainfall types? Our results showed that the runoff contribution of gullies was highest under Type A rainfall (43.2%), followed by Type B (40.1%), and lowest under Type C (33.8%) (Fig. 2C–D). This pattern indicates clear differences in flow-path connectivity between hillslopes and gullies among rainfall types. Previous studies have shown that intense rainfall can activate surface hydrological connectivity through saturation-excess runoff and near-surface lateral flow, thereby connecting more distant potential runoff pathways and allowing runoff from remote hillslopes to participate in the hydrological process (Winter et al., 2022; Bian et al., 2026; Lei et al., 2026). This may explain why hillslope runoff contributed more, whereas gully runoff contributed less, under Type B rainfall with higher intensity and Type C rainfall with greater erosivity (extreme rainfall event). Different hydrological response patterns are likely to create different conditions for nutrient transport (Winter et al., 2022). In this study, concentrations of dissolved NH_4^+ , NO_3^- , and P were significantly higher during the relatively light rainfall events of Type A and B events than during the compared to extreme rainfall event rainstorms of Type C (Fig. 4). A similar pattern trends have been observed in Southwest China, where nutrient concentrations in runoff decreased with increasing rainfall following straw return practices on sloping farmland (Zhang et al., 2024; Feng et al., 2025). In contrast, monitoring in micro-catchments comprising paddy fields and drylands found that peak concentrations of dissolved NH_4^+ and NO_3^- followed the order: heavy rainstorm event > rainstorm > moderate rain (Zhang et al., 2011). In the Jinglin River watershed of the Three Gorges Reservoir area, rainfall intensity was also found to enhance DP concentrations (Chen et al., 2024a), which differs from our results, where DP concentrations were lowest during extreme rainfall events (Fig. 4). These contrasting patterns may reflect differences in runoff volume and land use. Rainstorms can generate large runoff volumes that dilute nutrient concentrations (Wenng et al., 2020; Winter et al., 2022). As discussed earlier in (Section 4.1), the mechanisms driving DN and DP transport losses differ. Under varying rainfall conditions, the heterogeneity in gully soil, topography, and vegetation may intensify these differences (Wenng et al., 2020; Winter et al., 2022), leading to inconsistent patterns of nutrient concentrations across rainfall types (Feng et al., 2025). In contrast to concentration, nutrient transport fluxes showed a more consistent pattern (Zhao et al., 2026). Extreme storms produced much greater dissolved nutrient fluxes than Types A and B. These findings emphasize the need for rainfall-specific management strategies in agricultural catchments. (Fig. 6; Fig. 7), indicating that nutrient export under these events was

465 driven mainly by hydrological forcing rather than by concentration alone (Zhang & Zhang, 2025). At the plot scale in a potato-maize-sweet potato rotation system, dissolved NH_4^+ , NO_3^- , and P transport fluxes during intense storm events were 613.8%, 220.5%, and 268.0% higher, respectively, than those during moderate rainfall events (Feng et al., 2025). At the catchment scale, monitoring of 11 agricultural catchments in Canada showed that only three extreme storm events per year contributed 14%–44% of annual dissolved P flux (Ross et al., 2022). These findings help highlight why a small proportion of rainfall events accounted for most dissolved nutrient transport fluxes at the catchment scale (Chen et al., 2018). In addition, the sensitivity of dissolved nutrient fluxes clearly differed among rainfall types. The power-law coefficient a and the slope of the linear relationship with rainfall depth reflected the vulnerability of dissolved nutrient transport to rainfall forcing (Fig. 8).
470 Our results showed that this sensitivity increased markedly under extreme rainfall and was further amplified by the presence of gullies (Fig. 8; Fig. 9). From a practical perspective, nutrient management in gully-dominated catchments should pay particular attention to low-frequency but high-impact storm events, because a single extreme storm may generate dissolved nutrient transport fluxes comparable to those from several ordinary rainfall events combined (Bian et al., 2026).

475 Meanwhile, our results also indicated that the regulatory effect of the gully on dissolved NH_4^+ and NO_3^- concentrations weakens under extreme rainfall, while its influence on DP concentrations increases (Fig. 4; Fig. 6). This may be attributed to the distinct environmental conditions within gullies compared to upslope farmland. Gully soils are typically less fertile and less responsive to nutrient mobilization by rainfall. In addition, steep gully slopes promote rapid runoff from upslope farmland, especially during extreme events, when high rainfall intensity and long duration accelerate soil saturation and shorten hydrological response times, thereby enhancing the gully's regulating role (Wenng et al., 2020; Wang et al., 2025).

4.3 Implications for agricultural catchment management, study limitations, and future research

485 Compared with artificial drainage ditches, natural gullies are more dynamic because they have active headcut erosion, irregular morphology, steeper slopes, and stronger sediment interactions (Kumar Bhattacharya et al., 2024; Su et al., 2024; Chen et al., 2025b). This highlights the need to treat gullies as distinct geomorphic units rather than simply as natural drainage ditches. This study demonstrates that under natural rainfall conditions, the gullies in agricultural catchments play a dual role. They can reduce dissolved nutrient concentrations through dilution or retention, but they can also enhance dissolved nutrient export by increasing runoff connectivity and transport efficiency. These findings provide important guidance for developing best management practices (BMPs) in gully-dominated catchments. The runoff-amplifying function of the gully makes it a major contributor to total catchment runoff, especially during frequent, low-intensity rainfall events.
490 At the same time, its dilution effect on dissolved nutrient concentrations partially offsets the increased nutrient fluxes associated with enhanced runoff. The sharp increase in dissolved N and P fluxes during extreme rainfall events was mainly associated with enhanced surface hydrological connectivity. Therefore, a key management priority is to disrupt rapid flow connectivity during heavy storms and improve water and nutrient retention within the catchment. On agricultural upslopes, conservation tillage has been shown to increase water storage, improve surface roughness, and lengthen runoff pathways

495 (Bayad et al., 2022; Chen et al., 2025a; Cui et al., 2025; Feng et al., 2025). In addition, microtopographic modifications such as terracing can effectively intercept runoff and slow surface flow connectivity on hillslopes (Wang et al., 2023; Wu et al., 2025). Because fertilization replenishes nutrient stocks in surface soils, low fertilizer-use efficiency may further aggravate water-quality deterioration, especially in intensively cultivated catchments exposed to frequent storms. Synchronizing fertilizer application with forecast rainfall patterns and using organic fertilizers and slow-release fertilizers may help improve
500 crop nutrient uptake and reduce storm-driven non-point source pollution (Liu et al., 2020; Wenng et al., 2020). ~~Notably, the regulatory effect on dissolved nutrients suggested that the gully may, under certain conditions, function as a buffer mitigating soluble nutrient losses (Krzeminska et al., 2023). These findings challenge the conventional view of the gully as a passive conduit of non-point source pollution. Instead, its response and regulatory capacity vary significantly with the rainfall type. Effective management should therefore account for the gully's developmental stage, spatial position, and~~
505 hydrological biogeochemical behavior. Measures such as vegetation restoration and landscape optimization may enhance gully function (Wang et al., 2023; Wu et al., 2025). For example, in regions with frequent small rainfall events, maintaining certain hydrological functions of the gully may be beneficial, whereas in areas prone to intense storms, enhancing its retention and interception capacity becomes essential. Simultaneously, controlling nutrient sources remains critical. Practices such as straw return, balanced fertilization, and accurate field management can reduce nutrient concentrations and loss risk
510 from upslope farmlands. Within gullies, increasing vegetation cover on gully slopes and establishing buffer strips along gully margins may be especially important for slowing and weakening rapid surface runoff connectivity during major storms (Krzeminska et al., 2023). In addition, planting nutrient-intercepting vegetation or constructing small wetlands in the middle and lower parts of gullies can reduce pollutant loads and improve surface water quality (Krzeminska et al., 2023). Although these measures provide a practical basis for promoting sustainable agriculture and protecting water quality in the Mollisols
515 region, their implementation still needs to be adjusted to local topography, land use, and rainfall conditions (Wenng et al., 2020).

This study also has several limitations. First, although the catchments were small, rainfall in each catchment was characterized using only one rain gauge, and thus spatial heterogeneity in rainfall within the catchment could not be resolved. Second, although extreme rainfall events were captured during the two-year monitoring period, climate change is expected to
520 alter the frequency and intensity of such events. Longer-term monitoring is therefore needed to test whether the observed patterns remain valid across broader temporal scales and under future climate conditions. Third, a small amount of runoff from the gully banks could not be directly quantified. Although field observations suggested that this component was minor because grass cover and wheel ruts along the gully margins reduced direct flow into the gully, its contribution may still have led to a slight overestimation of the gully effect. These limitations should be considered when interpreting the results and
525 planning future studies. Future research should further examine how gully morphology, vegetation recovery, and sediment deposition interact with rainfall extremes to regulate dissolved nutrient export. Long-term monitoring across more catchments is also needed to determine whether the patterns observed here are consistent across different gully sizes, developmental stages, and land-use settings. In addition, combining field monitoring with tracer techniques or process-based

530 modeling could help disentangle the relative contributions of hydrological dilution, sediment retention, and in-channel biogeochemical transformation to dissolved nutrient dynamics.

5 Conclusions

535 ~~the~~ In this study, two gully-dominated small agricultural catchments in the Mollisols region of Northeast China were monitored under natural rainfall conditions from 2022 to 2023 to assess runoff and dissolved NH_4^+ , NO_3^- , and P losses at both the upslope inflow (gully head) and the outlet. The key findings are as follows: Gullyies markedly significantly amplified catchment runoff generation, but this effect decreased as the rainfall gradient increased. ~~Although it~~ Despite occupied ~~occupying~~ only 12.4% of the total catchment area, it contributed 36.1% of total runoff, rising to 43.2% under Type A rainfall ~~(frequent, low intensity, and low erosivity rainfall events)~~. After runoff entered the gullyies, notable dilution of ~~the~~ dissolved NH_4^+ , NO_3^- , and P concentrations occurred, with the strongest effect observed for NO_3^- . ~~Due to dilution, the gully's contributions to dissolved~~ NH_4^+ , NO_3^- , and P fluxes were all lower than its runoff contribution. Low frequency, High-erosivity rainfall events (10.2% of total events, Type C rainfall) dominated dissolved nutrient transport, accounting for 68.2%, 73.8%, and 71.8% of total NH_4^+ , NO_3^- , and P fluxes, respectively. The gullyies enhanced the sensitivity of the dissolved NH_4^+ , NO_3^- , and P transport to rainfall, with the strongest effect occurring under Type C events. ~~Dissolved nutrient fluxes were more strongly influenced by runoff volume than by changes in concentration, leading to increased sensitivity of dissolved nutrient transport to rainfall within the gully system.~~ In summary, the developing gully functions not only as a hydrological conduit linking upslope farmland with downstream water bodies but also plays a regulatory role in dissolved N and P transport under variable rainfall types. These findings enhance understanding of non-point source pollution processes under different rainfall types and provide a basis ~~and provide a scientific foundation~~ for targeted gully management in the agricultural landscapes ~~the Mollisols region~~.

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Data availability

550 Data will be made available upon request (guomingming@iga.ac.cn).

Author contributions

Z.C., M.G., and X.Z. conceived and designed the study. Z.C. prepared the initial manuscript, and M.G. and J.J. contributed to manuscript revision. Z.C., M.G., L.W., X.L., and Q.C. were deeply involved in data collection and discussions on experimental design. Z.C., M.G., and X.Z. provided financial support for the research.

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560 Competing interests

The authors declare that they have no conflict of interest.

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