Response to Editor and Reviewers

Re: egusphere-2025-5839

Title: Regulatory role of permanent gully in runoff dissolved nitrogen and phosphorus transport across rainfall types

Dear Dr Tarasova and reviewers,

We sincerely thank you for your careful evaluation and constructive guidance regarding our manuscript. Your comments, together with those of the reviewers, have greatly helped us improve it. We have carefully reviewed all comments and revised the manuscript accordingly. Based on the instructions provided in your letter, we uploaded a point-by-point response to the comments and a marked-up version of the manuscript showing the changes made. The reviewers' comments are presented in bold and labelled as Q1, Q2, etc. Our responses are shown in blue, and the revised manuscript text is highlighted in dark red or, where appropriate, presented as screenshots from the manuscript in tracked changes mode.

Sincerely,

Zhuoxin Chen, Mingming Guo

To respond to all comments in a clear and organized manner, we categorized the editor, reviewers, and community's comments based on the specific meanings and numbered them as Q1, Q2, Q3, etc. The following section outlines the main revisions made in the paper along with the corresponding responses to the comments from the editor and reviewers.

Contents

Please click the relevant entry in the table of contents above to go directly to the corresponding page.

EC (Editor Comments):

Q1. Public justification (visible to the public if the article is accepted and published):

Dear authors,

Two solicited reviewers and one community reviewer provided detailed and very useful comments for your manuscript. The second reviewer raises some rather major points that I encourage the authors to address with care, especially concerning methodological reproducibility of this study. I also share the opinion of both reviewers that the content of the Discussion needs improvement. Finally, as also recommended by both reviewers please use professional language editing services to improve the language of manuscript.

Best regards,

Larisa Tarasova

Response: We sincerely thank you for handling our manuscript and for the constructive summary of the reviewers' comments. We appreciate the detailed and valuable feedback provided by the two reviewers and the community reviewer. Following your recommendations, we have carefully addressed the major points raised by Reviewers, particularly regarding methodological clarity and reproducibility. We have also substantially revised and expanded the Discussion section to better interpret our findings in the context of existing literature. In addition, the manuscript has been carefully edited to improve the language and clarity throughout the text. We believe that these revisions have significantly improved the quality of the manuscript, and we greatly appreciate the editor's and reviewers' efforts in helping us strengthen this work.

The following is the decision letter.

Q2. We are pleased to inform you that the editor report for the following HESS manuscript is now available: egusphere-2025-5839

Title: Regulatory role of permanent gully in runoff dissolved nitrogen and phosphorus transport across rainfall types

Author(s): Zhuoxin Chen et al.

MS type: Research article

Iteration: Major revision

The editor has decided that Major revisions are necessary before the review process can be continued. Please log in using your Copernicus Office user ID 842349 to find the editor report at: https://editor.copernicus.org/HESS/ms_records/egusphere-2025-5839

We kindly ask you to revise your manuscript accordingly and to upload the revised files, a point-by-point reply to the comments, and a marked-up manuscript version showing the changes made no later than 01 Apr 2026 at: https://editor.copernicus.org/HESS/review-file-upload/egusphere-2025-5839

Response: Thank you for your decision. We have carefully checked the comments and responded to the reviewers' comments point by point. These comments are all valuable and very helpful for revising and improving our paper.

Q3. Please find all information on manuscript submission at: https://www.hydrology-and-earth-system-sciences.net/for_authors/submit_your_manuscript.html

Your revised manuscript will be reviewed again and you will be informed about the outcome by separate email.

Besides adjustments requested by the editor or referees, please check your manuscript carefully for typos, missing co-authors and their affiliations, terminology, updates of data in tables, or updates of variables in equations. All these have to be clarified with the editor and therefore have to be included before you submit your revised manuscript. Should your manuscript be finally accepted it will not be possible to include such rather substantial changes anymore when your manuscript is in final production (proofreading).

Please note that all referee and editor reports, the author's response, as well as the different manuscript versions of the peer-review completion (post-discussion review of revised submission) will be published if your paper is accepted for final publication in HESS.

You are invited to monitor the processing of your manuscript via your MS overview at: https://editor.copernicus.org/HESS/my_manuscript_overview

In case any questions arise, please do not hesitate to contact me. Thank you very much for your

cooperation.

Kind regards,

The editorial support team

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Data protection remark: emails sent from the online system CO Editor might include the email address editor@mailarchive.copernicus.org as CC. When replying to such emails and keeping this email address in CC, your replies will be archived in the online system CO Editor alongside the manuscript identified through the manuscript number in the subject line. Such archived emails are accessible for the respective handling editors, journal's chief editors, as well as Copernicus Publications' staff members.

Response: Thank you for your reminder. We have carefully checked the revised manuscript against the journal’s requirements, including author information, affiliations, terminology, tables, and equations. In addition, we would like to note that a second affiliation has been added for the first author because additional funding information has been included in the revised version, and this funding is supported by that institution. This change affects only the first author’s affiliation information. The order of affiliations remains unchanged, and the affiliations of the other authors also remain unchanged. For clarity, we have attached a screenshot showing the proposed revision and have consulted the handling editor in advance regarding this update.

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RC (Referee Comments):

RC #1:

General comment

Q1. Overall summary: This study by Chen et al. aims to understand how gullies influence nutrient transport under different rainfall conditions. This research is ethically sound, scientifically valid, and technically accurate. Additionally, the methods are clear, making this reproducible. Overall, the paper is well-written and not too long, and the authors do a good job of describing why this research is important. I recommend professional English-language editing to improve clarity and consistency, especially in the abstract. For example, the term gully is repeatedly used as a plural noun; this should be corrected to gullies throughout the manuscript. Consequently, I have restricted my language-related comments and focus on the scientific content. Minor comments are listed below.

Response: We sincerely thank you for your positive and constructive evaluation of our study. We also appreciate your suggestion regarding professional English-language editing. In the revised manuscript, we have carefully improved the language to enhance clarity and consistency, particularly in the abstract. Regarding the use of “gully” versus “gullies,” our original intention was to use the singular form when referring to an individual monitored gully and the plural form when discussing broader implications or general patterns. However, we recognize that this distinction was not always sufficiently clear in the previous version and may have caused confusion. We have therefore carefully checked and standardized the terminology throughout the manuscript to improve grammatical accuracy and consistency. We thank you again for this helpful suggestion, which has improved the clarity of the revised manuscript. The revised abstract is as follows (the rest of the manuscript has also been significantly revised. Please refer to the revised version):

Abstract. Understanding how permanent gullies regulate the transport of dissolved ammonium (NH_4^+), nitrate (NO_3^-), 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 NH_4^+, NO_3^-, 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~~y~~ in the transport of dissolved NH_4^+, NO_3^-, and P. ~~runoff and associated losses of dissolved NH_4^+, NO_3^-, 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~~y~~ 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~~y~~ exerted a pronounced dilution effect on ~~the concentrations of~~ dissolved NH_4^+, NO_3^-, and P concentrations, particularly ~~for~~on dissolved NO_3^- (dilution ratio: 0.65). Consequently, the ~~gulliesy~~ contribution of gullies~~ed~~ ~~less~~ to dissolved NH_4^+, NO_3^-, 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 NH_4^+, NO_3^-, 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 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~~y~~. These findings~~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~~.

Specific comments

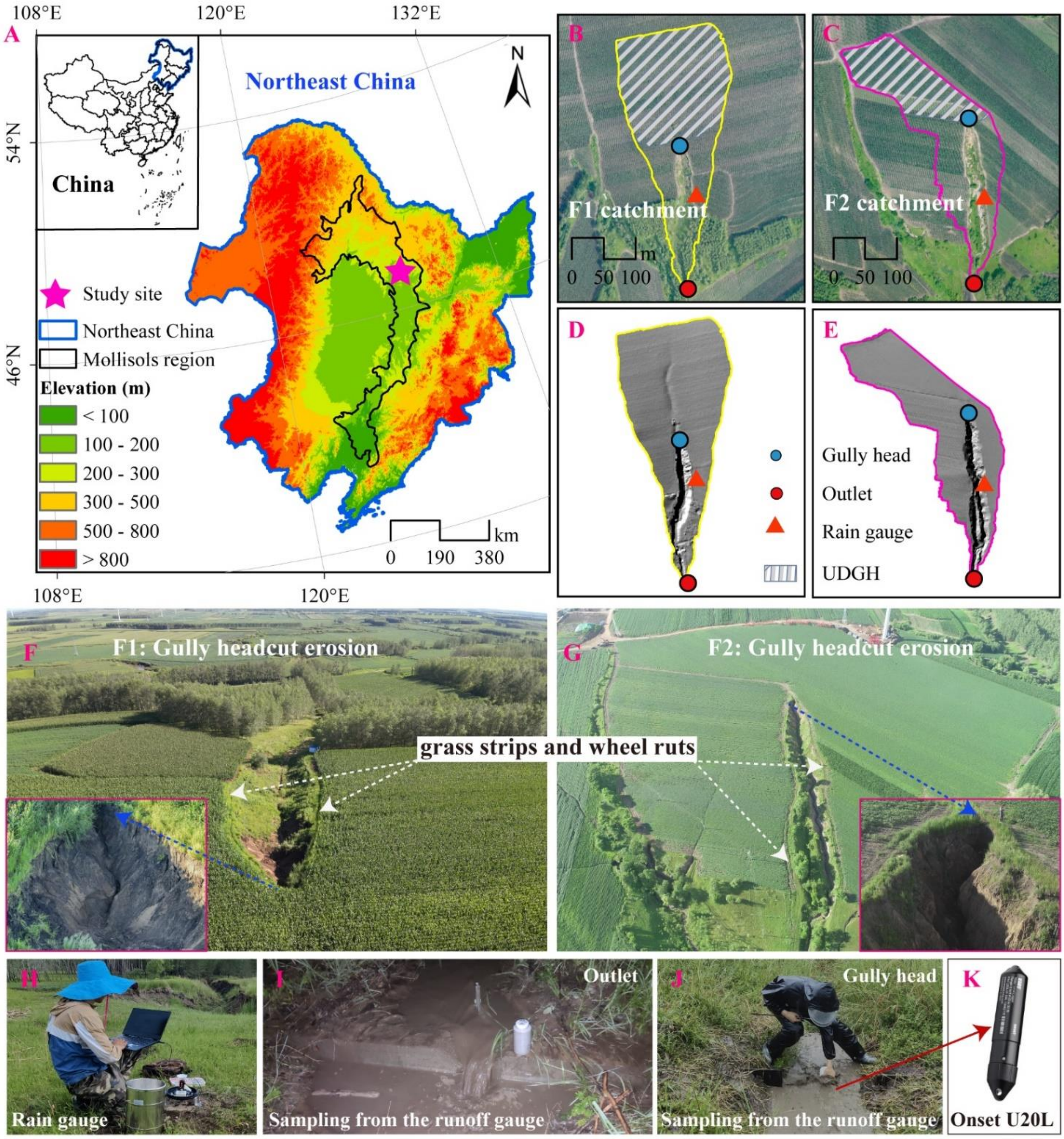
Q2. Minor Comments: L17: Define ammonium and nitrate before acronym use.

Response: We thank you for this helpful comment. We have made the necessary revisions to this and have also made corresponding adjustments in all other places in the text where abbreviations have appeared. The revised content is as follows (other revised parts, please refer to the revision and we will not repeat them):

Abstract. Understanding how permanent gullies regulate the transport of dissolved ammonium (NH_4^+), nitrate (NO_3^-), 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~~

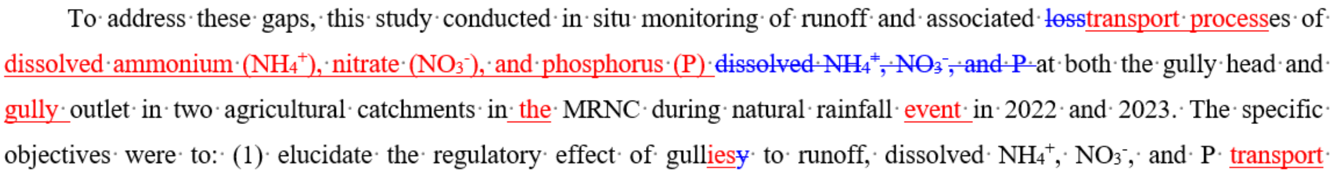
Q3. L42: Perhaps a photo (could be supplemental) of a gully could be useful here.

Response: Thank you for this constructive suggestion. We agree that field photographs can provide a more intuitive understanding of gully morphology and activity. Following your advice, we have included an unmanned aerial vehicle (UAV) image of the gully in Figure 1.



Q4. L79-80: Define ammonium and nitrate before acronym use.

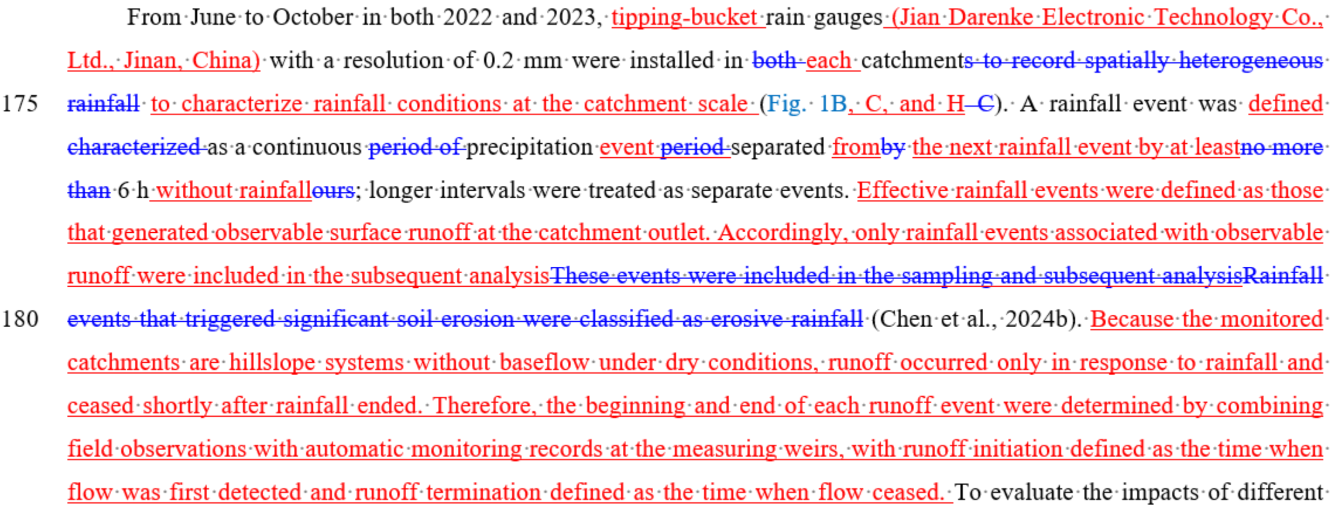
Response: We completely agree with you. We will define ammonium and nitrate at their first occurrence before introducing the corresponding acronyms in Lines 79–80. Based on this, we will check the abbreviation usage throughout the text. The revised content is as follows:



To address these gaps, this study conducted in situ monitoring of runoff and associated ~~loss~~transport processes of dissolved ammonium (NH_4^+), nitrate (NO_3^-), and phosphorus (P) ~~dissolved NH_4^+, NO_3^-, and P~~ at both the gully head and gully outlet in two agricultural catchments in the MRNC during natural rainfall event in 2022 and 2023. The specific objectives were to: (1) elucidate the regulatory effect of gullies~~y~~ to runoff, dissolved NH_4^+, NO_3^-, and P transport

Q5. L118: How did you determine how much erosion occurred? Is this using the equation below, or did you ever measure suspended sediments? And what was the threshold for "significant" here?

Response: We thank you for pointing out this issue. We intended to indicate that only rainfall events under natural conditions that generated clearly observable surface runoff at the outlet were included in the monitoring dataset. We agree that the previous wording was not sufficiently precise and will replace "significant" with a more appropriate term (such as measurable or clearly observable) to improve clarity. The revised content is as follows:



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 catchment~~s to record spatially heterogeneous rainfall~~ to characterize rainfall conditions at the catchment scale (Fig. 1B, C, and H~~–C~~). A rainfall event was defined ~~characterized~~ 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~~ours~~; 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 analysisRainfall 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

Q6. L157-163: I recommend putting the sentences that describe the types of rain (A/B/C) first, followed by the type A was dominant, followed by B and C sentence.

Response: We fully agree with your suggested revision. After comparing it with our original structure, we found that your proposed logic presents the ideas more clearly and improves the overall flow of the text. The revised content is as follows:

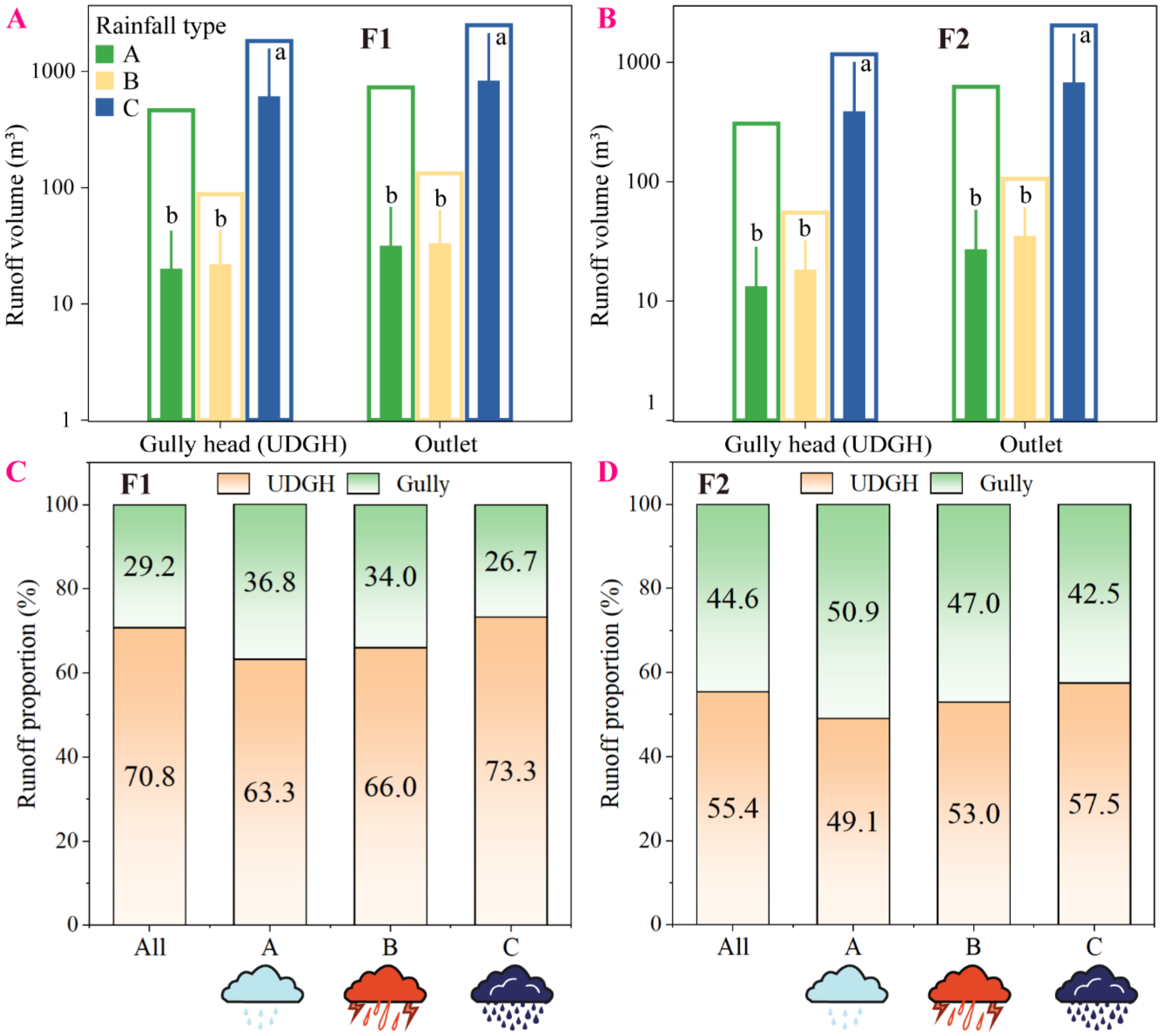
3.1 Rainfall characteristics

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 (~~491.6~~8.2 ~~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 (~~2922.4~~48.7 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~~pattern~~s identified in catchments F1 and F2.

Q7. Results (general): I am finding it difficult to remember the differences in the types of rainfall (A, B, C). Perhaps you can call them something different or redefine them in the captions of the figures?

Response: We sincerely thank you for this valuable suggestion. We agree that using simple alphabetical labels (e.g., A, B, C) may reduce clarity and make it difficult for readers to distinguish among rainfall types. Following your comment, we considered adopting more descriptive abbreviations, such as LER (Low-Erosivity Rainfall), SHI (Short-duration High-Intensity Rainfall), and LDR (Long-duration High-depth Rainfall). However, we recognize that even these abbreviations may not be sufficiently intuitive. To further enhance clarity and readability, we have revised the relevant figures by introducing distinct graphical symbols for each rainfall type. Specifically, the size and number of raindrops within the symbols will visually represent differences in rainfall intensity and erosivity. We believe this visual approach will make the classification more intuitive and improve overall readability. Take Figure 2 as an example:



Q8. Figures (general): In any figure with multiple panels, please define each letter in the caption. This is also a lot of figures, and a lot of information. Some of the figures only have a couple of sentences describing their results. I would recommend moving a couple of these to the supplemental, in order to make this an easier read and reduce redundancy.

Response: We sincerely thank you for this constructive comment. We fully agree that some subfigures lack sufficient description. In the revised manuscript, we have added clearer explanations in the figure captions to improve clarity. In addition, we agree that some figures (Fig. 8 and 9) could be moved to the Supplementary Material, as they provide supporting analyses rather than the core findings of the study. Accordingly, the manuscript structure has been adjusted. The previous Sections 3.4.1, 3.4.2, and 3.4.3 have been merged into a single Section 3.4 (Rainfall response of dissolved NH_4^+, NO_3^-, and P transport in gully-dominant catchments) to make the structure more concise and logically organized. In addition, the figures have been reorganized accordingly. The following figure captions are provided as examples:

Fig. 1 (A) Location of the study site within the MRNC;~~;~~ (B–C~~E~~) 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.

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; I_{30}, maximum 30-min rainfall intensity; and RE, rainfall erosivity.

Fig. 2 (A, F1 catchment; ~~–~~B, F2 catchment) Cumulative and event-scale runoff volumes~~Proportion of the accumulated runoff loss on~~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~~Impact of different rainfall types on runoff volume~~. 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.

Fig. 4 D~~Characterization of d~~issolved 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 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.

Fig. 6 The left y-axis represents the cumulative transport fluxes~~Characterization~~ 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.

Fig. 8~~810~~ Differences in the response of dissolved NH_4^+, NO_3^-, and P transport fluxes to ~~runoff~~ rainfall depth ~~volume~~ between the~~at~~ 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.~~

Q9. Figure 11: Type C relationships seem to be driven by a single point. Did you check if this is an outlier? Also, these all have regression lines on them. Are they all significant relationships?

Response: We thank you for this careful observation. In this study, Type C rainfall corresponds to high-erosivity events. During the two-year monitoring period, one relatively extreme rainfall event (100–200 mm) was recorded, which appears as the high-value point in Fig. 11 (The revised version refers to Fig. 9). Based on long-term local rainfall characteristics, such events occur roughly once every three years. Therefore, rather than representing a spurious outlier, this data point reflects a naturally occurring high-magnitude rainfall event and enhances the representativeness of our dataset by capturing both regular (Type A and B) and relatively extreme (Type C) conditions. In Fig. 11, the regression patterns differ substantially among rainfall types. As commonly observed, the relationship between nutrient flux and rainfall amount follows linear or power-law forms. The notably steeper slope under Type C rainfall indicates a disproportionately stronger response of nutrient loss to incremental rainfall, highlighting its enhanced erosive and transport capacity compared to the more frequent rainfall types. In addition, the number of Type B and Type C rainfall events was relatively limited. As a result, even when the coefficient of determination is high, the corresponding P-value may still exceed 0.05. However, the main objective of our analysis was to compare the slopes of the fitted lines or the associated parameters of the regression equations, in order to evaluate the regulatory role of the gully and the influence of different rainfall types. Furthermore, based on your suggestion, in Section 4.3, we also highlighted the limitations of the monitoring duration.

Q10. Discussion (general): I think the discussion could be a bit longer. There are so many results, and I think you could pull more from the literature to place this into context and provide suggestions for future research.

Response: Thank you for this helpful suggestion. We agreed that the Discussion in the previous version was too brief relative to the scope of the results. In the revised manuscript, we have expanded Sections 4.1–4.3 by adding more data-based process interpretation, incorporating additional relevant literature, and strengthening the broader implications of our findings.In particular, we further strengthened the discussion of the regulatory role of gullies in runoff generation and dissolved nutrient transport, as well as how this role differs under different rainfall types. We also added more comparison with previous studies, including relevant discussion of drainage ditches, and included a new paragraph in Section 4.3 on future research directions and study limitations. We hope these revisions have made the Discussion more informative and better contextualized. The revised discussion is as follows:

4 Discussion

4.1 Regulatory~~ing~~ effect of gull~~y~~ies on the runoff and associated ~~transport of~~ dissolved NH_4^+, NO_3^-, and P transport

Our findings indicated that, although gullies~~y,~~ ~~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, gull~~y~~ies 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 gulliesy, 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~~y~~ 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 gullyies 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~~rainstorm~~s of Type C (Fig. 4). A ~~S~~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 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 helps 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). 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).

~~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. 4Fig. 4; Fig. 6Fig. 6). This may be attributed to the distinct environmental conditions within gulliesy 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

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~~ gull~~y~~ies in agricultural catchments play~~s~~ 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. 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 (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 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 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 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 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 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 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 modeling could help disentangle the relative contributions of hydrological dilution, sediment retention, and in-channel biogeochemical transformation to dissolved nutrient dynamics.

Q11. Conclusion: Most of the conclusion is just repeated from results. I think you could cut it down to just the last couple of sentences.

Response: We fully agree with your suggestion. We thank you for this valuable suggestion. Following your comment, we have shortened the Conclusion section by removing repeated descriptions of the results and strengthening the synthesis of the main findings and their broader implications.

5 Conclusions

~~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: Gg~~Gullies~~y~~ 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 gullies~~y~~, 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, h~~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 g~~Gull~~y~~ies 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~~.

RC #2:

General comments

Q1. **This is my first review of the manuscript "Regulatory role of permanent gully in runoff dissolved nitrogen and phosphorus transport across rainfall types" by Chen et al.**

This paper investigated the influence of gullies on runoff and nutrient transport (nitrogen and phosphorous) in two small catchments in Northeast China, and how this influence changed under three different rainfall types. The authors found that gullies contributed to total runoff mostly during frequent, low-depth, low erosivity rainfall events, and they diluted dissolved NH4+, NO3-, and P concentrations. Loss of dissolved N and P were mainly caused by long duration, high erosivity rainfall events.

The topic of this manuscript is relevant and important, it is of interest for the community. A few major comments, as well as minor technical corrections are listed below.

Response: We sincerely thank you for your thoughtful review and positive evaluation of our manuscript. We appreciate your recognition of the relevance of this study. After carefully considering your comments, we realized that the manuscript could be further improved in several aspects. We have carefully addressed your suggestions in order to further improve the quality of the manuscript. We greatly appreciate your constructive comments and hope that the revised version has been substantially strengthened.

Q2. **The study presents two gullies close to each other in Northeast China. Please provide information on the generalizability of the findings.**

Response: Thank you for this very helpful comment. We agree that the generalizability of findings from two nearby gullies should be addressed more carefully. In China, about 667,000 gullies have been identified, more than 85% of which remain active, and over 70% occur in cropland. Before this study, we conducted a gully inventory survey in the study region and selected two gullies that are representative, to some extent, of the dominant active farmland gullies in the Mollisols region of Northeast China in terms of morphology, activity status, land use setting, and hydrological background. In addition, both monitored gullies are actively developing gullies. Previous studies have shown that such gullies are important sediment sources in agricultural catchments, and our earlier work published in the Journal of Hydrology also indicated that they can make a substantial contribution to sediment export. Therefore, we believe the present study provides useful field-based evidence for this common gully-development setting. At the same time, we fully acknowledge that the current study cannot represent all gullies or all agricultural catchments in the region. In particular, gullies of different sizes, development stages, and land-use settings may regulate runoff and dissolved nutrient transport differently. We have therefore clarified this limitation in the revised manuscript and further discussed it in Section 4.3, together with the need for broader monitoring across more catchments and gully types in future studies.

Q3. **The authors should identify clear research gaps in literature in the Introduction section. After listing several references and literature on gullies, the sentence in the Introduction saying "Nevertheless, the role of gullies in modulating dissolved nutrient losses under varying rainfall conditions remains insufficiently investigated." does not seem to be justified.**

Response: We thank you for this important comment. We fully agree that the research gaps were not sufficiently clear in the previous version of the manuscript. Following your suggestion, we have reorganized the second and third paragraphs of the Introduction, added further relevant literature, and revised the paragraph structure to strengthen the logical chain of the argument. The revised Introduction now progresses from the general problem of dissolved nutrient loss, to the role of gullies as hydrological pathways and regulators, to the current lack of understanding of their effects on dissolved nutrient transport under different rainfall conditions, and finally to the specific need for such research in the Mollisols region of Northeast China. This revision makes the research gap more explicit and improves the logical connection between the corresponding paragraphs. The revised content is as follows:

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 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 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 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., 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; Räty 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., 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.

~~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 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 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 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 upslope areas ~~s~~ and gullies may further amplify these effects (Miller et al., 2016). Nevertheless, the role of gullies in modulating dissolved nutrient ~~loss~~transport~~es~~ 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.~~

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., 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.

To address these gaps, this study conducted in situ monitoring of runoff and associated ~~loss~~transport processes of dissolved ammonium (NH_4^+), nitrate (NO_3^-), and phosphorus (P) ~~dissolved NH_4^+, NO_3^-, 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~~y~~ to runoff, dissolved NH_4^+, NO_3^-, and P transport ~~losses~~fluxes; (2) quantify how gullies~~y~~ contributions to these transport fluxes ~~losses~~ vary in response to different rainfall types; and (3) reveal how gull~~y~~ies regulate the response relationship between rainfall and dissolved NH_4^+, NO_3^-, and P ~~l~~transport fluxes~~osses~~. 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.~~

Q4. The results should be reproducible. The methodological description is not complete, often it is hard to understand how the results were obtained (e.g., events selection, calculation of volumes and masses, statistical analyses, etc.). The methods section should be extended.

Response: Thank you very much for this important comment. We agree that the methodological description in the previous version was not sufficiently detailed, which may have affected the reproducibility of the study. In the revised manuscript, we have carefully expanded the Methods section to provide clearer and more complete descriptions. Specifically, regarding rainfall event selection, we clarified that all rainfall events that generated observable surface runoff during the two rainy seasons were included. We also refined the terminology (e.g., replacing or clarifying terms such as “erosion rainfall”) to improve clarity and reduce potential ambiguity. For the hydrological monitoring and calculations, we have added detailed descriptions of the monitoring procedures and included the corresponding calculation methods and equations for runoff volume and dissolved nutrient transport fluxes. In addition, for the statistical analyses, we have further specified the methods used in this study, including correlation analysis and other relevant approaches. We believe that these revisions have significantly improved the transparency and reproducibility of the study, and we thank the reviewer for this valuable suggestion. The revised "Materials and Methods" section is as follows:

2.1 Study area

~~(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~~M~~ean 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 (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~~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 exhibit~~ing~~ 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~~track~~s, 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 NH_4^+, NO_3^-, and P ~~loss~~transport fluxes.

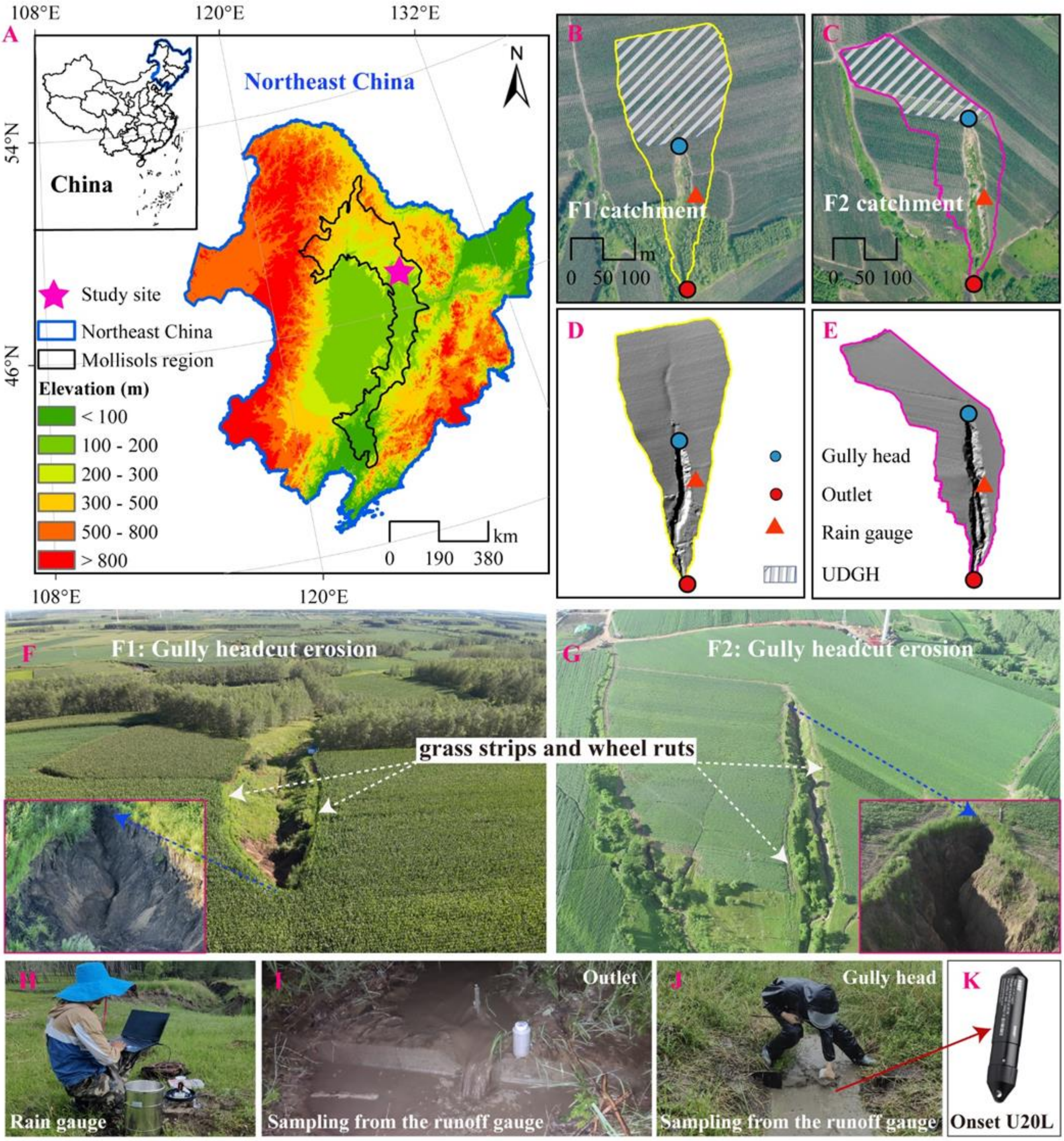


Fig. 1 (A) Location of the study site within the MRNC;~~;~~ (B–C~~E~~) overview of the two monitored gully-dominated catchments; (D–E) DEM-derived hillshade basemap; (F–G) UAV aerial images of the two gullies; (H) rainfall data acquisition; (I–J) runoff sampling at the measuring weirs; and (K) water 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 catchment~~s to record spatially heterogeneous rainfall~~ to characterize rainfall conditions at the catchment scale (Fig. 1B, C, and H~~–C~~). A rainfall event was defined ~~characterized~~ 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~~ours~~; 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 analysisRainfall 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: rainfall depth, duration, average intensity, maximum 30-~~-~~min~~ute~~ intensity, and rainfall erosivity. The calculation of rainfall erosivity (*RE*) is ~~provided~~ shown in Equations (1)–(3):

$$RE = K_e \cdot I_{30} \qquad (1)$$

$$K_e = \sum(E_r \cdot P_r \cancel{P}) \qquad (2)$$

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

In ~~the eq~~Eq.~~uation~~ (1), K_e represents the total kinetic energy of a rainfall event (MJ ~~hm~~ha^{-1}~~^{2}~~); In ~~the e~~Eq. (2), P_r represents ~~is~~ the total rainfall amount during the event (mm); and ~~I~~in E~~the e~~q. (3), *Er* denotes the unit kinetic energy during rainfall segments~~sub-event~~ *r* (MJ ha^{-1}~~m^{-2}~~ mm^{-1}). Here, ~~;~~ ~~*R*~~ *r* = 1, 2, ..., 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. 1I–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 μm 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 P~~DP~~. 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 (~~eq~~Eq. 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.

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

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 ($m^3 \cdot h^{-1}$). 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 ($mg \cdot L^{-1}$).

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).

Q5. The Discussion section should be strengthened by more data-based process understanding and interpretation of the results and referring to more and relevant studies in literature.

Response: Thank you for this helpful suggestion. We agreed that the Discussion in the previous version was too brief relative to the scope of the results. In the revised manuscript, we have expanded Sections 4.1–4.3 by adding more data-based process interpretation, incorporating additional relevant literature, and strengthening the broader implications of our findings.In particular, we further strengthened the discussion of the regulatory role of gullies in runoff generation and dissolved nutrient transport, as well as how this role differs under different rainfall types. We also added more comparison with previous studies, including relevant discussion of drainage ditches, and included a new paragraph in Section 4.3 on future research directions and study limitations. We hope these revisions have made the Discussion more informative and better contextualized. The revised discussion is as follows:

4 Discussion

4.1 Regulatory~~ing~~ effect of gull~~y~~ies on the runoff and associated ~~transport of~~ dissolved NH_4^+, NO_3^-, and P transport

Our findings indicated that, although gullies~~y, 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, gull~~y~~ies 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 gulliesy, 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~~y~~ 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 gully~~ies ~~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~~rainstorm~~s of Type C (Fig. 4). A ~~S~~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 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 helps 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). 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).

~~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. 4Fig. 4; Fig. 6Fig. 6). This may be attributed to the distinct environmental conditions within gulliesy 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

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~~ gull~~y~~ies in agricultural catchments play~~s~~ 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. 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 (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 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 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 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 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 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 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 modeling could help disentangle the relative contributions of hydrological dilution, sediment retention, and in-channel biogeochemical transformation to dissolved nutrient dynamics.

Q6. Readers should be able to understand each figure without reading the entire methods and results section, figures with their captions should be interpretable alone, without the entire manuscript. Please extend the figure captions by explaining each subfigure (a, b, c, etc.), and add legends where they are missing.

Response: We sincerely thank you for identifying these shortcomings. We agree that the figures should be understandable without requiring readers to search extensively through the main text. Accordingly, we have expanded the figure captions and added the missing legends where needed to make each figure more self-explanatory. The following figure or captions are provided as examples:

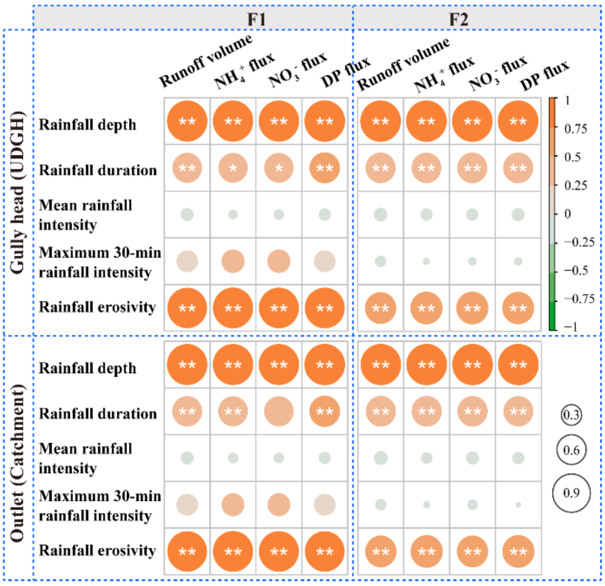


Fig. 1 (A) Location of the study site within the MRNC; ~~;~~ (B–C~~E~~) overview of the two monitored gully-dominated catchments; (D–E) DEM-derived hillshade basemap; (F–G) UAV aerial images of the two gullies; (H) rainfall data acquisition; (I–J) runoff sampling at the measuring weirs; and (K) water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

Fig. 2 (A, F1 catchment; –B, F2 catchment) Cumulative and event-scale runoff volumes~~Proportion of the accumulated runoff loss on~~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~~Impact of different rainfall types on runoff volume~~. 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.

Fig. 4 D~~Characterization of d~~issolved 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 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.

Fig. 6 The left y-axis represents the cumulative transport fluxes~~Characterization~~ 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.

Fig. 8~~810~~ Differences in the response of dissolved NH_4^+, NO_3^-, and P transport fluxes to ~~runoff~~ rainfall depth ~~volume~~ between the~~at~~ 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.~~

Q7. Can the findings (e.g., dilution effect of the gully, etc.) be attributed really to the influence of the gully or dilution could be caused by e.g., subsurface contributions? On a similar note, were the catchment characteristics (land use, subsurface, etc.) the same/similar between the upstream catchment area (until the inlet of the gully) and the rest of the catchment?

Response: Thank you very much for this valuable comment. We have now provided a more detailed description in the Materials and Methods section regarding subsurface runoff and land use. In our study, no baseflow was observed during dry periods, and during rainfall events the runoff response usually began and ended rapidly, suggesting that subsurface contributions were likely limited. In addition, land use in the catchments was dominated by cropland. Based on our field observations, there were small areas of woodland along both sides of the gullies, as well as grassed buffer strips and wheel ruts along the gully margins. During rainfall events, these grass buffers and wheel ruts tended to reduce or redirect lateral runoff entering the gullies, while runoff generation from the adjacent non-cropland areas also appeared to be limited. We therefore consider that their influence on the overall results was likely minor. At the same time, we acknowledge that these influences cannot be entirely excluded. We have therefore added a short subsection in the third part of the Discussion to further address the limitations of this study. Thank you again for this helpful suggestion.

Q8. In certain parts of the Results section, the text does not seem to be justified by the figures (please see details in technical corrections later).

Response: Thank you very much for this careful comment. We realized that some parts of the Results section were not linked clearly enough to the corresponding figures in the previous version. In the revised manuscript, we have rechecked the consistency between the text and all figures, corrected the relevant figure citations, and revised the wording where needed to make the source of each result clearer.

Q9. It is good that the Results section is compact, but using one single sentence to describe a complex plot seems to be not enough. If a figure contains the same message as another figure and not much text can be added, then such a figure should be removed or added to the Appendix.

Response: We sincerely thank you for this constructive comment. We agree that some figures (Fig. 8 and 9) could be moved to the Supplementary Material, as they provide supporting analyses rather than the core findings of the study. Accordingly, the manuscript structure has been adjusted. The previous Sections

3.4.1, 3.4.2, and 3.4.3 have been merged into a single Section 3.4 (Rainfall response of dissolved NH4+, NO3-, and P transport in gully-dominant catchments) to make the structure more concise and logically organized. In addition, the figures have been reorganized accordingly.

Q10. The authors refer to the area of the gullies (i.e., 12.4% of the catchment area; still, they contribute so much runoff to the total runoff, “36.1% of total runoff”)? Would it not be more meaningful to refer to the drainage area of the gullies in this context, i.e., the catchment area where they collect the water from? Did I understand correctly that at the “outlet” (red points in Figure 1) the catchment area contributing to runoff is the entire catchment area, i.e., 100% of the catchment? Then what do the two percentages 12.4% and 36.1% refer to? But more generally: the authors should better explain in the study area or methods section: what do “UDGH”, “Gully” and “Outlet” refer to, when (permanent/ephemeral?) and where (drainage areas?) does the water flow? On a similar note, some photos (of the gauges, gullies, etc.) might help the readers to imagine the study area and instrumentations.

Response: Thank you very much for raising these important points. We agree that the definitions of UDGH, gully, and outlet, as well as the meaning of the percentages reported in the Results, were not sufficiently clear in the previous version. In the revised manuscript, we have therefore expanded the descriptions in the study area and Methods sections to explain these terms more explicitly. In our study, 12.4% refers to the proportion of the total catchment area directly occupied by the gully itself, relative to the full catchment draining to the outlet. In contrast, 36.1% refers to the estimated contribution of the gully to total runoff at the catchment outlet, calculated as the difference between outlet runoff and runoff generated from the upslope drainage area of the gully head (UDGH). We also note that this estimate may be slightly high because a small amount of runoff from the gully banks could not be directly monitored. However, based on field observations, grassed buffer strips and wheel ruts along the gully margins greatly reduced direct lateral flow into the gully, and runoff generation from these narrow bank areas appeared to be very limited. We therefore treated this component as negligible, but now explicitly discuss it as a limitation in the revised Discussion. In addition, as noted in our earlier response, these hillslope gullies do not sustain baseflow during dry periods, and subsurface contributions during rainfall events are also likely limited. To help readers better understand the study area and instrumentation, we have also added field photographs of the gullies and monitoring equipment. Please also see our response to Q3 for the corresponding revisions.

Q11. **The manuscript would greatly benefit from thorough English language editing, please find below some technical corrections, but the list is not complete.**

Response: Thank you very much for this careful and professional comment. We fully agree that the previous version would benefit from more thorough language editing. In response, we have carefully re-examined the entire manuscript together with our co-authors and made extensive revisions to improve clarity, logical flow, and the presentation of figures and tables. In particular, we have revised unclear expressions, improved the connections between sentences and paragraphs, and corrected language issues throughout the manuscript. We sincerely appreciate this suggestion, which has helped us improve the overall quality of the revised version.

Specific comments

Q12. **title, line 14, etc.: "runoff-"dissolved nitrogen? Is this term correct/does this term exist? Or dissolved nitrogen in runoff?**

Response: Thank you for your suggestion. We have corrected it throughout the entire text to "dissolved nitrogen / phosphorus in runoff".

Q13. **Line 16: permanent gully in a catchment**

Line 16: losses or dynamics?

Line 17: please define NH4+, etc. before using the term

please also describe in 2-3 sentences which methods were used.

Line 27: by the gullies?

Line 28: improving how? Please be specific

Response: Thank you very much for your suggestions. These all address specific issues mentioned in the abstract. We incorporated the suggestions from other reviewers and the community and made the following revisions: **1)** We condensed the first two lines of the abstract into one paragraph; **2)** We defined the full names of abbreviations before using them; **3)** We refined the description in the methods section. **4)** We realized that our use of "gully" and "gullies" was not always sufficiently consistent in the previous version, which may have caused confusion. In the revised manuscript, we have carefully checked and standardized the terminology throughout. Our principle is as follows: we use the singular form (gully) when referring to a specific monitored gully or to the gully within an individual catchment, particularly in the Methods and when describing site-specific results. In contrast, we use the plural form (gullies) when discussing the broader hydrological role of this landform, generalizing the findings across the two study catchments, or referring to gullies as a geomorphic and hydrological feature in agricultural landscapes. Following this logic, we have also revised the title and related text where a broader, more general statement is intended, because the study aims to draw implications beyond a single gully and to improve understanding of the role of permanent gullies under different rainfall types. **5)** The conclusion section of the abstract was rewritten. The revised abstract is as follows:

Abstract. Understanding how permanent gullies regulate the transport of dissolved ammonium (NH_4^+), nitrate (NO_3^-), 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 NH_4^+, NO_3^-, 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~~y~~ in the transport of dissolved NH_4^+, NO_3^-, and P. ~~runoff and associated losses of dissolved NH_4^+, NO_3^-, 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~~y~~ 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~~y~~ exerted a pronounced dilution effect on ~~the concentrations of~~ dissolved NH_4^+, NO_3^-, and P concentrations, particularly ~~for~~on dissolved NO_3^- (dilution ratio: 0.65). Consequently, the ~~gulliesy~~ contribution of gullies~~ed~~ ~~less~~ to dissolved NH_4^+, NO_3^-, 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 NH_4^+, NO_3^-, and P transport fluxes in outlet, respectively. (3) Type C rainfall dominated the ~~loss~~transport of dissolved NH_4^+, NO_3^-, ~~N~~ and P. Only 10.2% of 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~~y~~. These findings~~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~~.

Q14. Lines 42-43: repetition of lines 37-38

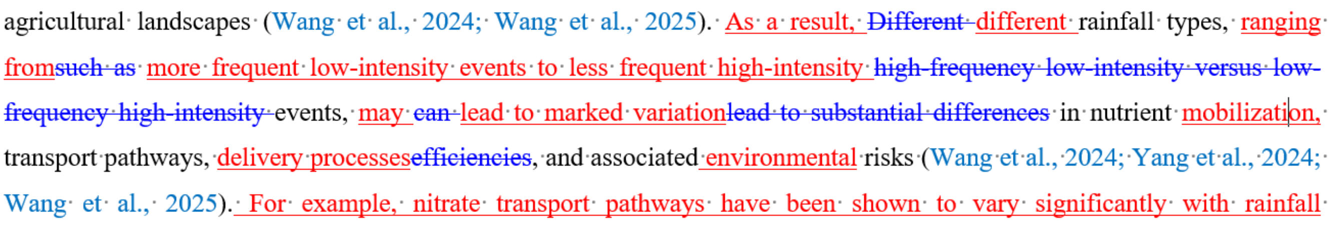
Response: Thank you very much for your detailed comments. We completely agree that these two sentences are repetitive. Therefore, we have deleted lines 42-43 from the original manuscript.

Q15. Line 49: riparian buffers? Do you mean riparian zone?

Response: Yes, we have changed it to "riparian zones".

Q16. Line 58: high frequency? Do you mean more common/events that occur more often? Please try to rephrase.

Response: Yes, exactly as you understood it. Based on your suggestion, we have rewritten this part. The revised content is as follows:



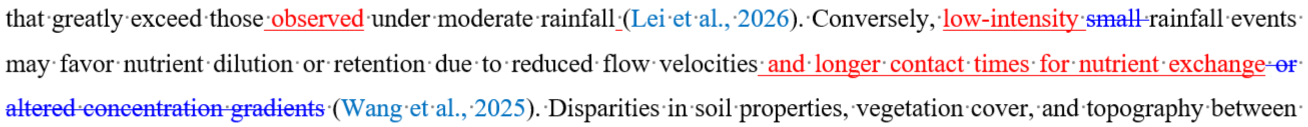
agricultural landscapes (Wang et al., 2024; Wang et al., 2025). As a result, ~~Different~~ different rainfall types, ranging from~~such as~~ more frequent low-intensity events to less frequent high-intensity ~~high-frequency low-intensity versus low-frequency high-intensity~~ events, may ~~can~~ lead 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

Q17. Line 59: efficiencies? In what?

Response: Thank you for this helpful comment. We agree that "efficiencies" was not sufficiently specific in this context. We have revised the sentence by replacing it with a more precise expression. Please refer to the revised content of Q16.

Q18. Line 63: concentration gradients? Please explain

Response: Thank you for your suggestion. We have removed this unclear expression.



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

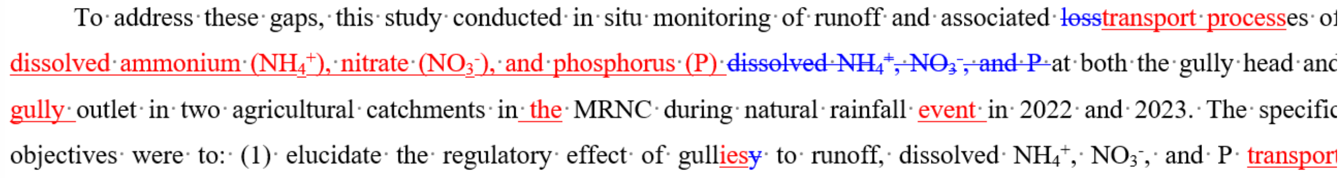
Q19. Lines 42-67: research gaps should be identified, what is missing in literature? This should be justified. Lines 68-78: how is this paragraph logically linked to the previous? Please keep a logical flow of thoughts/sentences/paragraphs – these need to be logically linked

Response: Please review the responses for Q3. We will not repeat them here as they have already been covered. Please excuse us for this.

Q20. **Line 79: please first define terms NH_4^+, etc**

Line 82: gullies?

Response: We have made the necessary revisions. The revised content is as follows:



To address these gaps, this study conducted in situ monitoring of runoff and associated ~~loss~~transport processes o
dissolved ammonium (NH_4^+), nitrate (NO_3^-), and phosphorus (P) ~~dissolved NH_4^+, NO_3^-, and P~~ at both the gully head an
gully outlet in two agricultural catchments in the MRNC during natural rainfall event in 2022 and 2023. The specifi
objectives were to: (1) elucidate the regulatory effect of gullies~~y~~ to runoff, dissolved NH_4^+, NO_3^-, and P transpor

Q21. **Introduction last sentence should be more specific**

Response: We fully agree with your suggestion. Based on your suggestion, the revised content is as follows:

The findings will support targeted mitigation of rainfall type-dependent dissolved nutrient loss in agricultural catchments.

Q22. **Line 87: (1), later (2) etc. – are these numbers necessary? Why were they added?**

Fig 1: please add some photos of the gullies.

Line 102: land use proportions? Please explain here term

Response: (1) Yes, we fully agree with your opinion. We have deleted these serial numbers and combined the two paragraphs originally numbered 2 and 3 into one paragraph to make the text more logical and readable. (2) We have added UAV photographs of the gullies to further illustrate their active conditions. In addition, the descriptions of land-use proportions and the definition of the upslope drainage area of the gully head (UDGH) have been clarified and expanded in the revised manuscript. Please also see our response to Q4 for the corresponding revisions.

Q23. **Line 104: please remove "within catchment"**

Response: We have deleted it. Please refer to the response to Q22.

Q24. Line 105: “F1 measured” please rephrase, F1 is a catchment?

Response: Thank you for pointing this out. We recognize that the previous wording was not sufficiently clear and have rewritten this part accordingly. The revised content is as follows:

~~(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 exhibit~~ing~~ 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,

Q25. Please extend all figure captions

Response: Thank you for this helpful suggestion. We have extended all figure captions in the revised manuscript to improve clarity and make the figures more self-explanatory. Please also see our response to Q6 for the corresponding revisions.

Q26. Line 114: rainfall data (please remove capture)

Response: Thank you for this careful correction. The word “capture” has been removed, and the expression has been revised to “rainfall data” in the manuscript.

Q27. Line 115: resolution of 0.2 mm? please explain which type of gauge was used

Response: We were using a tipping-type rain gauge. In Figure 1, we have provided the relevant graph and added corresponding textual descriptions. The revised content is as follows:

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 catchment~~s to record spatially heterogeneous rainfall~~ to characterize rainfall conditions at the catchment scale (Fig. 1B, C, and H~~–C~~). A rainfall event was defined

Q28. Line 116: there was one gauge within one catchment – spatially heterogenous rainfall could not be recorded in one catchment – differences between the catchments could be recorded

Response: We thank you for this important comment. We agree that, with one rain gauge installed in each catchment, spatial heterogeneity of rainfall within an individual catchment could not be resolved. The measurements were therefore used to characterize rainfall conditions at the catchment scale, whereas differences between the two catchments could be recorded. Please refer to the response to Q27 for the revised content.

Q29. section 2.2: please explain how exactly events were selected, which thresholds were used, how was the beginning and end of a rainfall event defined? And how was the beginning and end of the corresponding runoff event defined?

Response: We thank you for this important comment. We agree that the previous version did not describe the event selection procedure with sufficient clarity. In the revised manuscript, we have clarified how rainfall and runoff events were defined and selected in Section 2.2. Specifically, a rainfall event is now defined as a continuous precipitation period separated by at least 6 h without rainfall, and only events that generated clearly observable surface runoff at the catchment outlet were classified as effective rainfall events and included in the analysis. We have also clarified how the beginning and end of runoff events were defined. Because the monitored catchments do not sustain baseflow under dry conditions, runoff occurred only during rainfall events and ceased shortly after rainfall ended. Accordingly, runoff initiation and termination were determined by combining field observations with automatic monitoring records at the measuring weirs.

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 catchment~~s to record spatially heterogeneous rainfall~~ to characterize rainfall conditions at the catchment scale (Fig. 1B, C, and H~~–C~~). A rainfall event was defined ~~characterized~~ 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~~ours~~; 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 analysisRainfall 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:

Q30. **Line 118: what is significant? And how was soil erosion measured?**

Response: We thank you for this careful comment. We agree that the term "significant" was not sufficiently precise in this context and could be misleading. In the revised manuscript, we have replaced it with a clearer expression indicating that only rainfall events generating clearly observable surface runoff at the catchment outlet were included in the analysis. We also clarify that soil erosion was not directly measured in this study. The relevant text has been revised accordingly to avoid misunderstanding. Please refer to the response to Q29 for the revised content.

Q31. **Line 120: usually rainfall erosivity is EI30 in literature**

Response: We thank you for this important comment. We agree that EI_{30} is commonly used in the literature to characterize rainfall erosivity. In our study, we used maximum 30 min rainfall intensity together with rainfall kinetic energy to calculate rainfall erosivity.

Q32. **Line 125: in which equation?**

Response: We thank you for pointing this out. In the revised manuscript, we have specified the meaning of each symbol in the corresponding equations. Please refer to the response to Q27 for the revised content.

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

$$RE = K_e \cdot I_{30} \qquad \cdots\cdots(1)$$

$K_e = \sum(E_r \cdot P_r$~~P~~$)$ ……(2)

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

In ~~the eq~~Eq.~~uation~~ (1), K_e represents the total kinetic energy of a rainfall event (MJ ~~hm~~ha^{-1}~~^{2}~~); In ~~the e~~Eq. (2), P_r represents ~~is~~ the total rainfall amount during the event (mm); and ~~I~~in E~~the e~~q. (3), Er denotes the unit kinetic energy during rainfall segments~~sub-event~~ r (MJ ha^{-1}~~m^{-2}~~ mm^{-1}). Here,~~;~~ ~~R~~ r = 1, 2, ..., 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}).

Q33. is the dimension of rainfall kinetic energy correct? It is usually MJ/ha

Response: We agree with your comment. Although MJ ha^{-1} and MJ hm^{-2} are equivalent, MJ ha^{-1} is the more commonly used form in the literature. We have therefore revised the manuscript to use MJ ha^{-1} consistently throughout. Please refer to the response to Q32 for the revised content.

Q34. Line 126: what is a sub event? Please explain

Response: Here, "sub-event" does not refer to an independent rainfall event, but rather to different temporal segments within a single rainfall event. We have revised the manuscript to clarify this expression and avoid misunderstanding. Please refer to the response to Q32 for the revised content.

Q35. Line 127: what does it mean "based on rainfall intensity", how exactly?

Response: We acknowledge that the phrase "based on rainfall intensity" was too vague. Here, a rainfall event was divided into consecutive segments according to changes in the recorded rainfall intensity during the event, and the corresponding intensity was calculated for each segment. Please refer to the response to Q32 for the revised content.

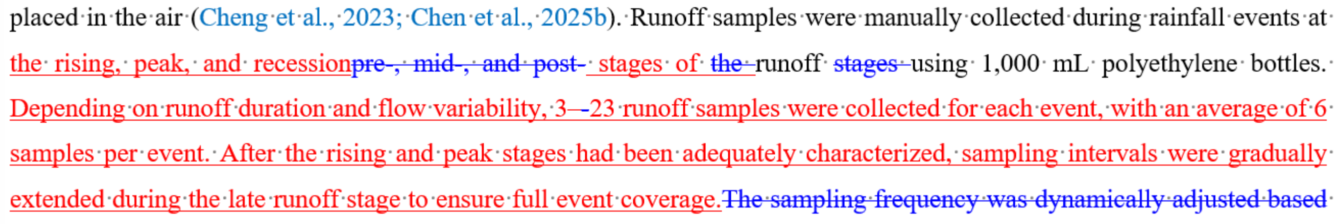
Q36. Line 129: Sample collection? Sampling strategy?

Response: We have changed "sample processing" to "Sample collection".

2.3 Runoff monitoring and sample collection~~processing~~

Q37. Line 134: "post runoff stages"? please explain or rephrase

Response: We thank you for this careful comment. We agree that the expression "post-runoff stages" was not sufficiently precise. In the revised manuscript, we have replaced it with "recession of the runoff stages" to indicate the later phase of the runoff event before flow cessation. The revised content is as follows:



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~~

Q38. Line 136: what is sufficient? How many exactly? Please provide some statistics and numbers of the samples

Response: We agree that the term "sufficient" was too vague. In the revised manuscript, we have replaced this expression with a more specific description of the sampling scheme and added the corresponding sample statistics. Specifically, 3–23 runoff samples were collected for each event, with an average of 6 samples per event, depending on runoff duration and fluctuation intensity. The text has been revised accordingly to improve transparency and reproducibility. Please refer to the response to Q37 for the revised content.

Q39. Line 145: please explain the methods from Chen et al briefly here

Response: Thank you for this helpful comment. We have revised the manuscript to briefly describe the calculation procedure of dissolved nutrient flux in the section. Specifically, we now clarify that runoff volume was derived from the calibrated depth-discharge relationship, and event-scale dissolved nutrient flux was calculated by integrating nutrient concentration with runoff volume across each sampling interval during the runoff proces. The revised content is as follows:

A subsample was filtered through a 0.45 µm 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 P~~DP~~. 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 (~~eq~~Eq. 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.

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

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 ($m^3 \cdot h^{-1}$). 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 ($mg \cdot L^{-1}$).

Q40. 2.4: please extend

Response: Thank you very much for your helpful suggestion. We have revised and expanded Section 2.4 by providing a more detailed description of the overall analytical workflow, including the tests for differences, correlation analysis, and redundancy analysis (RDA). In addition, following your suggestion, the methodological descriptions previously presented in the Results section have been moved to this section to improve the logical organization and clarity of the manuscript. The revised content is as follows:

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).

Q41. Line 156: were these the same events? Why different number of events?

Response: Although the two catchments are located relatively close to each other, rainfall during the summer can still show considerable spatial heterogeneity, especially for storm centers. As a result, the monitored runoff events were not exactly the same in the two catchments. In one rainfall event, for example, a pronounced runoff response was observed in F1, whereas no clear runoff was generated in F2. Therefore, the number of recorded runoff events differed slightly between the two catchments, which is a reasonable outcome under natural rainfall conditions.

Q42. Please extend table captions

Response: Thank you very much for this helpful suggestion. We have revised and expanded the table captions to make them more informative and self-explanatory. The updated captions now clearly describe the table content, the study catchments, the rainfall pattern classification, and the meaning of the listed rainfall variables. The revised content is as follows:

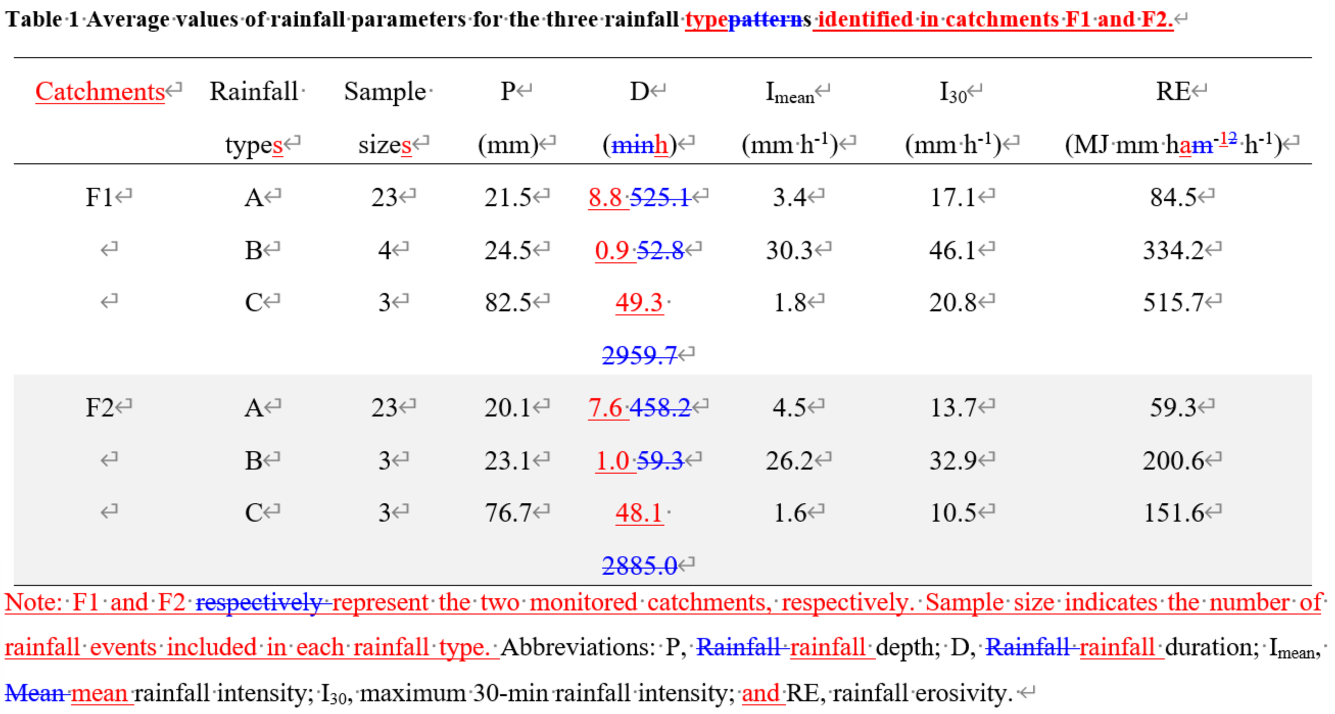


Table 1 Average values of rainfall parameters for the three rainfall type~~pattern~~s identified in catchments F1 and F2.

Catchments	Rainfall types	Sample sizes	P (mm)	D (~~min~~h)	I_{mean} (mm·h^{-1})	I_{30} (mm·h^{-1})	RE (MJ·mm·ha~~m~~$^{-1}$~~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 ~~2959.7~~	1.8	20.8	515.7
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 ~~2885.0~~	1.6	10.5	151.6

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; I_{30}, maximum 30-min rainfall intensity; and RE, rainfall erosivity.

Q43. Table 1: D might be more meaningful in hours

Response: Thank you very much for this helpful suggestion. We agree that rainfall duration is more intuitive and easier to interpret when expressed in hours rather than minutes. Accordingly, we have revised Table 1 by converting D from minutes to hours. Please refer to the response to Q42 for the revised content.

Q44. Line 169: which figure shows this? Please provide references, not just at the end of the section

Response: Thank you very much for this helpful comment. We have revised the manuscript by adding the corresponding figure citations to the relevant sentences to make the presentation clearer and easier to follow. The revised content is as follows:

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 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).

Gullies~~y~~ 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).

Q45. Line 174: these percentages should be better explained, to what exactly they refer to?

Response: Thank you for this comment. You are right that the percentages were not explained clearly enough. We have now clarified in Section 2.1 how these values were calculated and what they represent.

Q46. Figure 2: how were the volumes defined? Please add to methods

Response: Thank you for pointing this out. We have now added the method used to calculate runoff volume to the Methods section. Please also see our response to Q39 for the detailed calculation procedure.

Q47. 3.3 title is unclear, effect on what? Please rephrase, also the English

Response: We agreed that the original title was not clear enough. The revised text is given below:

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

Q48. Line 186: belongs to methods. Why downstream divided by upstream?

Response: Thank you for this comment. We agree that the definition of the dilution ratio should have been given in the Methods section. We have now added this explanation there and clarified that the outlet-to-gully head ratio was used to describe how dissolved nutrient concentrations changed after runoff passed through the gully. Ratios lower than 1 indicate dilution, whereas values greater than 1 indicate enrichment.

Q49. Lines 193-195: Fig 4 does not entirely show this – because the two catchments differ

Response: Thank you for pointing this out. We agree that the previous interpretation was too generalized and did not fully match Fig. 4C and F because the two catchments showed different patterns. We have therefore rewritten this part to better reflect the figure and the catchment-specific responses. The revised text is given below:

The effect of the gullies~~y~~ 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~~ increase~~s slight increases were~~ was observed in F1 and a slight increase in F2 catchment under Types B~~, possibly indicating episodic in-channel P release~~.

Q50. Line 202: transport fluxes: how were they estimated? Please explain in methods

Response: Thank you for pointing this out. We agree that the estimation of transport fluxes should have been explained in the Methods section. We have now added a description of the calculation procedure there and clarified how the transport fluxes of dissolved NH_4^+, NO_3^-, and P were derived. Please also see our response to Q39 for the detailed calculation procedure.

Q51. Line 205: please add reference to figure

Response: Thank you for this comment. We checked the relevant figure citations again and added the correct figure reference in the revised manuscript. The revised text is as follows:

When rainfall types were not differentiated, ~~G~~gullies~~y~~ accounted for~~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, ~~R~~rainfall 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 scale, 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 23.2% of dissolved NO_3^- transport fluxes, respectively (Fig. 6B and ~~D~~E). These results indicate that~~d~~ the gully exerted the strongest reduction ~~of~~in 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).

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).

Q52. Line 206: “similarly dominated” please rephrase

Response: Thank you for this careful comment. We found that “similarly dominated” was not sufficiently clear in this context and have rewritten this part accordingly. Please refer to our response to Q51 for the revised text.

Q53. Line 208-209: which figure shows this? Where do these values stem from?

Response: Thank you for this helpful comment. We realized that the figure reference and the origin of these values were not presented clearly enough. This part has now been revised so that the values are directly linked to the corresponding figure and the text reads more clearly. Please refer to our response to Q51 for the revised text.

Q54. Figure 5: what does “gully” refer to? To the outlet? What do “sites” refer to in the caption? What is 100%?

Response: Thank you for this very helpful comment. We realized that the meanings of “gully”, “sites”, and “100%” were not explained clearly enough in the previous version of Fig. 5 and its caption. In this figure, “gully” refers to the area covered by the gully itself, whereas UDGH represents the upslope drainage area of the gully head. The percentage contribution of the gully was calculated as the remaining proportion after subtracting the UDGH contribution from the total flux at the catchment outlet. We have revised the figure caption and the related text to make these definitions clearer. We also note that this estimate may slightly overstate the gully contribution because a small amount of runoff from the gully banks could not be directly monitored. However, based on our field observations, runoff from the gully banks was very limited because wheel tracks and dense grass cover along the gully margins acted as barriers to flow entering the channel. We therefore considered this component negligible, and we now clarify this point in the manuscript as a study limitation.

Q55. Figure 6: methods should explain how cumulative transport fluxes were obtained?

Response: Thank you for this comment. We realized that the calculation of cumulative transport fluxes needed to be described more clearly. We have now added the corresponding explanation to the Methods section so that the basis of Fig. 6 is transparent. Please also see our response to Q39 for the detailed calculation procedure.

Q56. Figure 7: methods should explain the scales (event scale? etc)

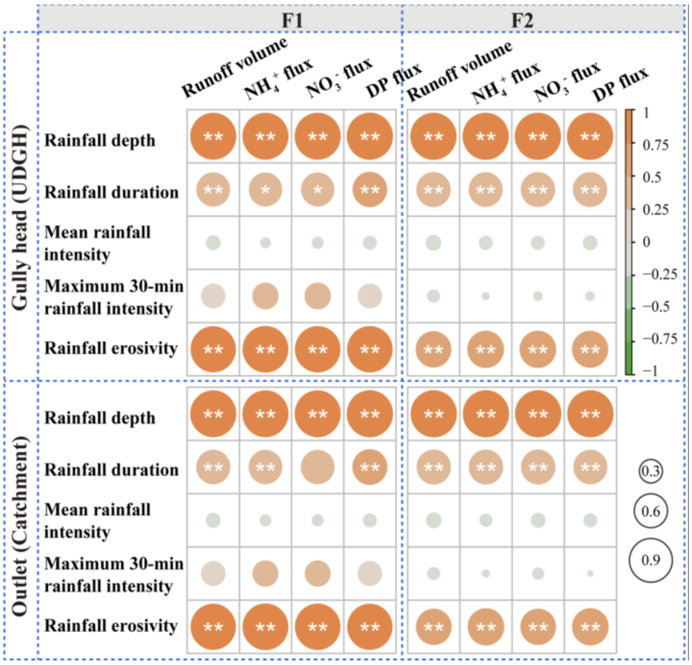
Response: We have now clarified in the Materials and Methods section that this analysis was conducted at the event scale. Please also see our response to Q40 for the detailed calculation procedure.

Q57. 3.4.1: correlation analysis should be explained in methods

Response: Thank you for this comment. We have been added the description of the correlation analysis so that the analytical procedure is clearer and easier to follow. Please also see our response to Q40 for the detailed calculation procedure.

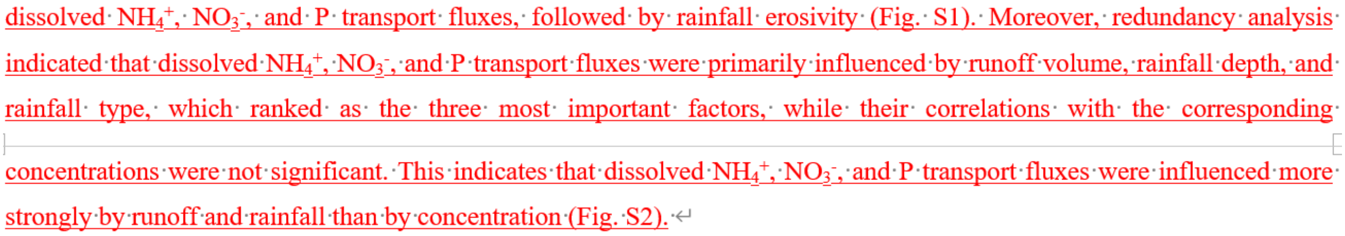
Q58. Figure 8: legend is missing

Response: We have added a legend indicating the symbol sizes. The revised content is as follows:



Q59. Lines 235-236: meaning not clear, please explain or rephrase

Response: Thank you for pointing this out. We realized that this sentence was not expressed clearly enough and have rewritten it for clarity. The revised content is as follows:


dissolved NH_4^+, NO_3^-, and P transport fluxes, followed by rainfall erosivity (Fig. S1). Moreover, redundancy analysis indicated that dissolved NH_4^+, NO_3^-, 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).

Q60. Fig 9: should be explained in methods

Response: In Section 2.4, we further elaborated on the purpose and meaning of applying RDA. The revised content is as follows:

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).

Q61. Lines 242-245: belongs to methods

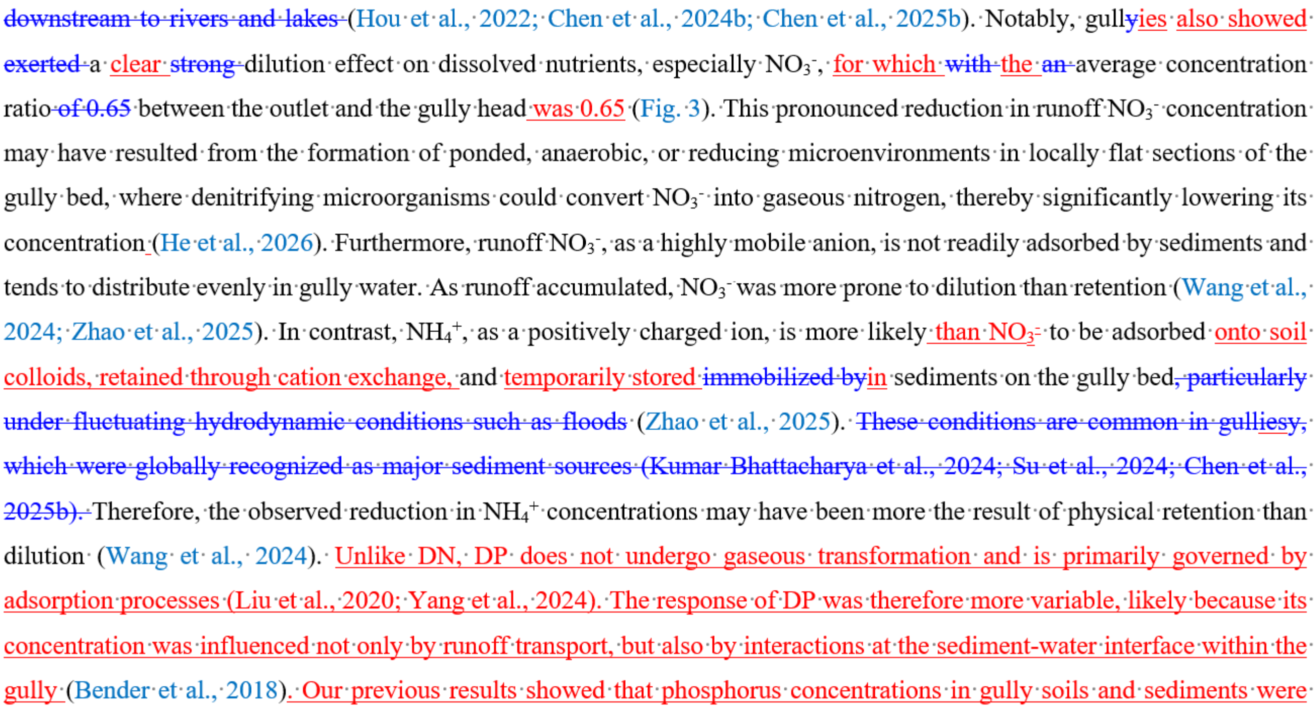
Response: Thank you very much for your suggestion. We have moved this part to Section 2.4. Please review the response to Q60.

Q62. Fig 11: to how many points were these lines fitted? C: line would be flat without that one outlying point – why is that event so different than the others? Were the measurements correct?

Response: We thank you for this careful observation. In this study, Type C rainfall corresponds to high-erosivity events. During the two-year monitoring period, one relatively extreme rainfall event (100–200 mm) was recorded, which appears as the high-value point in Fig. 11. Based on long-term local rainfall characteristics, such events occur roughly once every three years. Therefore, rather than representing a spurious outlier, this data point reflects a naturally occurring high-magnitude rainfall event and enhances the representativeness of our dataset by capturing both regular (Type A and B) and relatively extreme (Type C) conditions. In Fig. 11, the regression patterns differ substantially among rainfall types. As commonly observed, the relationship between nutrient flux and rainfall amount follows linear or power-law forms. The notably steeper slope under Type C rainfall indicates a disproportionately stronger response of nutrient loss to incremental rainfall, highlighting its enhanced erosive and transport capacity compared to the more frequent rainfall types.

Q63. Line 270: mobilized?

Response: Thank you for pointing this out. We agree that the original wording was not precise. NH_4^+ is more likely to be adsorbed onto soil colloids and retained through cation exchange rather than remain mobile in runoff. We have revised the wording in the manuscript accordingly.



~~downstream to rivers and lakes~~ (Hou et al., 2022; Chen et al., 2024b; Chen et al., 2025b). Notably, gull~~y~~ies 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 gulliesy, 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

Q64. Line 272: gullies?

Response: Thank you for pointing this out. We have checked the singular and plural use of "gully" throughout the manuscript and revised it where necessary. Please see our response to Q1 for the rationale.

Q65. Line 279: interception effects of gullies?

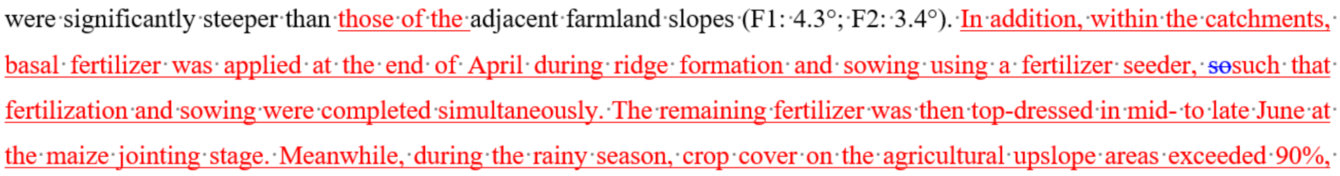
Response: Thank you for catching this. We agree that "interception" was not appropriate here and have replaced it with "retention", which better reflects the process discussed in this section.

Q66. Line 292: the methods do not mention information on land management practise? Was the timing of fertilizer application managed?

Response: Thank you for raising this point. We have added a brief description of fertilizer application practices in this region in Section 2.1. In general, fertilizer timing and management are not always well controlled, which may increase the risk of nutrient loss under rainfall conditions. We have also expanded

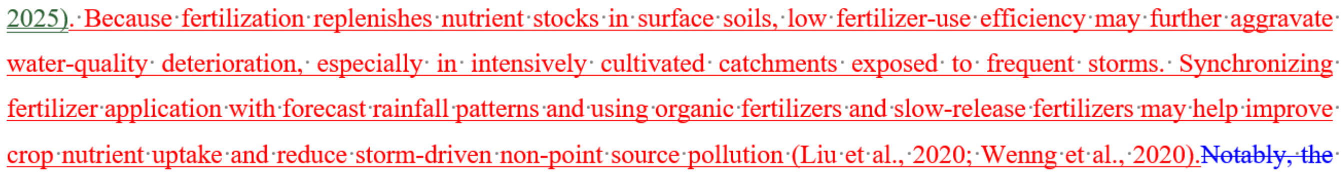
Section 4.3 to discuss possible agricultural management implications based on our results and previous studies. The revised content is as follows:

Section 2.1:



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%,

Section 4.3:



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 crop nutrient uptake and reduce storm-driven non-point source pollution (Liu et al., 2020; Wenng et al., 2020).~~Notably, the~~

Q67. Line 295: gullies

Response: We have made the necessary revisions. Please see our response to Q1 for the rationale.

Q68. Line 304: gullies in agricultural catchments play a dual role

Response: We have made the necessary revisions. Please see our response to Q1 for the rationale.

CC (Community Comments):

CC #1:

General comments

Q1. I came across the preprint of this paper on ResearchGate and found it very interesting, so I would like to share a few thoughts and comments here. Overall, this is a nice piece of work with rare field data, Most existing studies rely on large-scale remote sensing for water quality analysis, but field monitoring at the gully scale is still very limited. This is understandable, because gully flow is intermittent and hard to capture, and remote sensing basically cannot do this. So any field data at this scale are rare and valuable.

Response: We sincerely thank the commenter for the positive and encouraging remarks. We appreciate the recognition of the challenges associated with field monitoring at the gully scale, particularly given the intermittent nature of gully flow and the limitations of remote sensing approaches. We are pleased that the value of these rare field observations is acknowledged and hope that this study contributes to improving process-based understanding of gully-scale hydrological and nutrient transport dynamics.

Q2. Gully development rate, driving factors, and modeling have already been well studied. But as the authors also mention, gullies are important hydrological pathways, not only erosion features. The problem is that monitoring gullies under natural rainfall is very challenging. Because of this, studies on how gullies regulate dissolved N and P are almost absent. At least, I have not seen many papers doing this with real field data. So I think this work fits well in HESS, and it also fills a gap in current gully research.

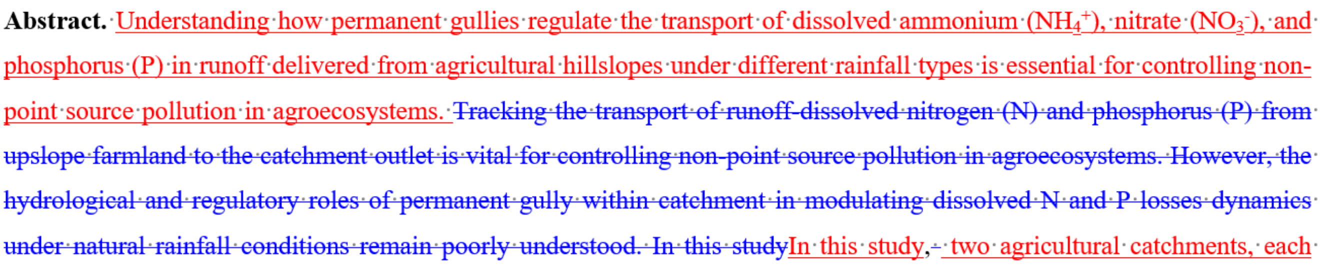
Response: We sincerely thank the commenter for the thoughtful and encouraging remarks. We fully agree that, although gully development processes and driving mechanisms have been extensively investigated, their hydrological and biogeochemical roles remain insufficiently explored, particularly under natural rainfall conditions. As noted, the intermittent nature of gully flow makes continuous field monitoring extremely challenging, which partly explains the limited availability of field-based studies on dissolved nitrogen and phosphorus transport. We appreciate the recognition that this work helps address this research gap and contributes to advancing the understanding of gullies as functional hydrological pathways rather than solely erosion features.

Specific comments

Q1. Below are some questions and suggestions that may help improve the manuscript.

1. Line 14: I think there is a small issue with the abbreviations. N is used first, but then NH_4^+ and NO_3^- appear directly later. It might be clearer to define NH_4^+ and NO_3^- directly at the beginning, to avoid confusion between abbreviations. If similar issues appear elsewhere, I suggest checking and revising them as well. In addition, I think lines 14-17 could be merged into one sentence, which may help emphasize the role of the gully more clearly.

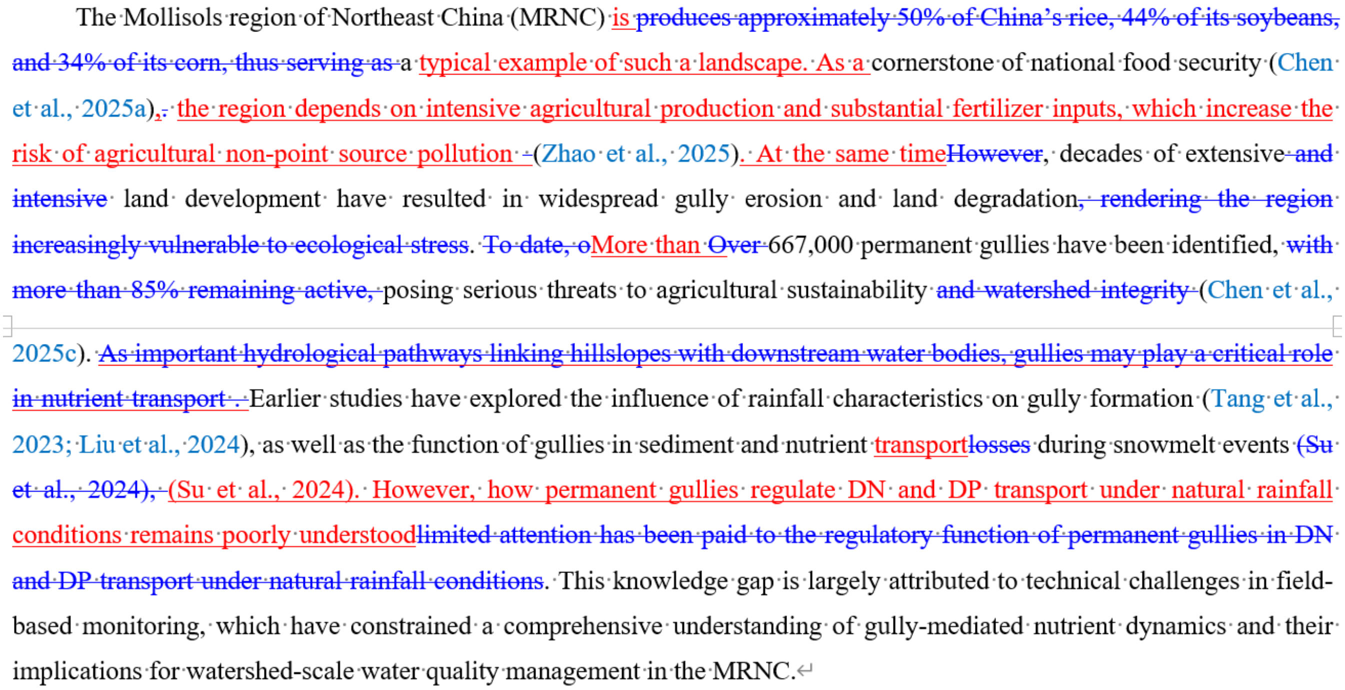
Response: We agree that defining NH_4^+ and NO_3^- at their first occurrence would improve clarity. In the revised manuscript, we introduce these terms explicitly and ensure consistent abbreviation usage throughout. We also agree that merging Lines 14–17 into one sentence will better emphasize the role of gully in regulating dissolved nitrogen and phosphorus losses, and we have revised this section accordingly. The revised content is as follows:



Abstract. Understanding how permanent gullies regulate the transport of dissolved ammonium (NH_4^+), nitrate (NO_3^-), 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

Q2. Lines 68–78: In my opinion, this part may not need too much description about the proportion of grain production, although it is important. After that, it might be better to further emphasize that more fertilizer input is needed to maintain high crop yields, which increases the risk of agricultural non-point source pollution in this region. Given that gullies act as important transport pathways but are rarely studied, this logic may make the motivation of the study clearer. Just a suggestion for the authors.

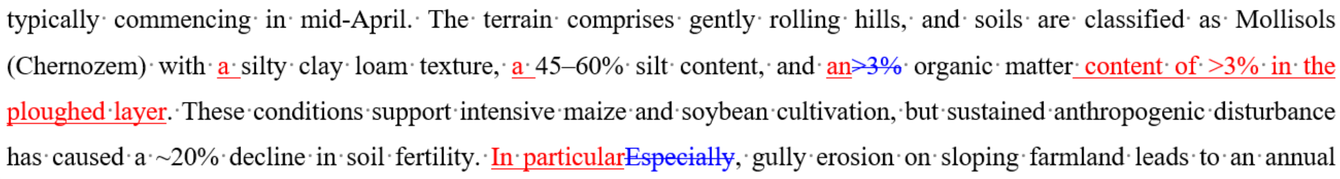
Response: We fully agree with this suggestion. Following your comment, we have reduced the description of grain production and placed greater emphasis on fertilizer inputs and the associated risk of agricultural non-point source pollution. We have also strengthened the logical connection between this regional background and the role of gullies as important yet understudied transport pathways, in order to clarify the motivation of the study. The revised content is as follows:



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., 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.↵

Q3. Lines 91–92: For the soil properties mentioned here, it would be helpful to clarify which soil layer they refer to (e.g., topsoil, ploughed layer, etc.).

Response: We appreciate your careful observation. The statement refers specifically to the plough layer. The revised content is as follows:



typically commencing in mid-April. The terrain comprises gently rolling hills, and soils are classified as Mollisols (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

Q4. Lines 95–96: I think this sentence is repetitive, as similar information has already been mentioned before. It could be simplified to make the text more concise.

Response: We thank you for this helpful comment. We recognize that there is repetition in this sentence. Therefore, in the revised version, this sentence has been removed to eliminate any unnecessary expressions.

Q5. From the survey results in lines 95–100, about 90% of the gullies are active, which explains why F1 and F2 were selected. However, in lines 101–110, the development status of these two selected gullies is not clearly described. I think the authors should add some explanation here to better justify the selection.

Response: We fully agree that the development status of the selected gullies should be more clearly described to justify their selection. In the revised manuscript, we have provided additional information on their activity and geomorphic characteristics, including photographs of active gully heads and descriptions of vegetation cover, to strengthen the rationale for selecting F1 and F2. It should be noted that we have combined the original two paragraphs into one now, which makes the text more logical and easier to read. The revised content is as follows:

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~~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 exhibit~~ing~~ 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~~track~~s, 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 NH_4^+, NO_3^-, and P ~~loss~~transport fluxes.

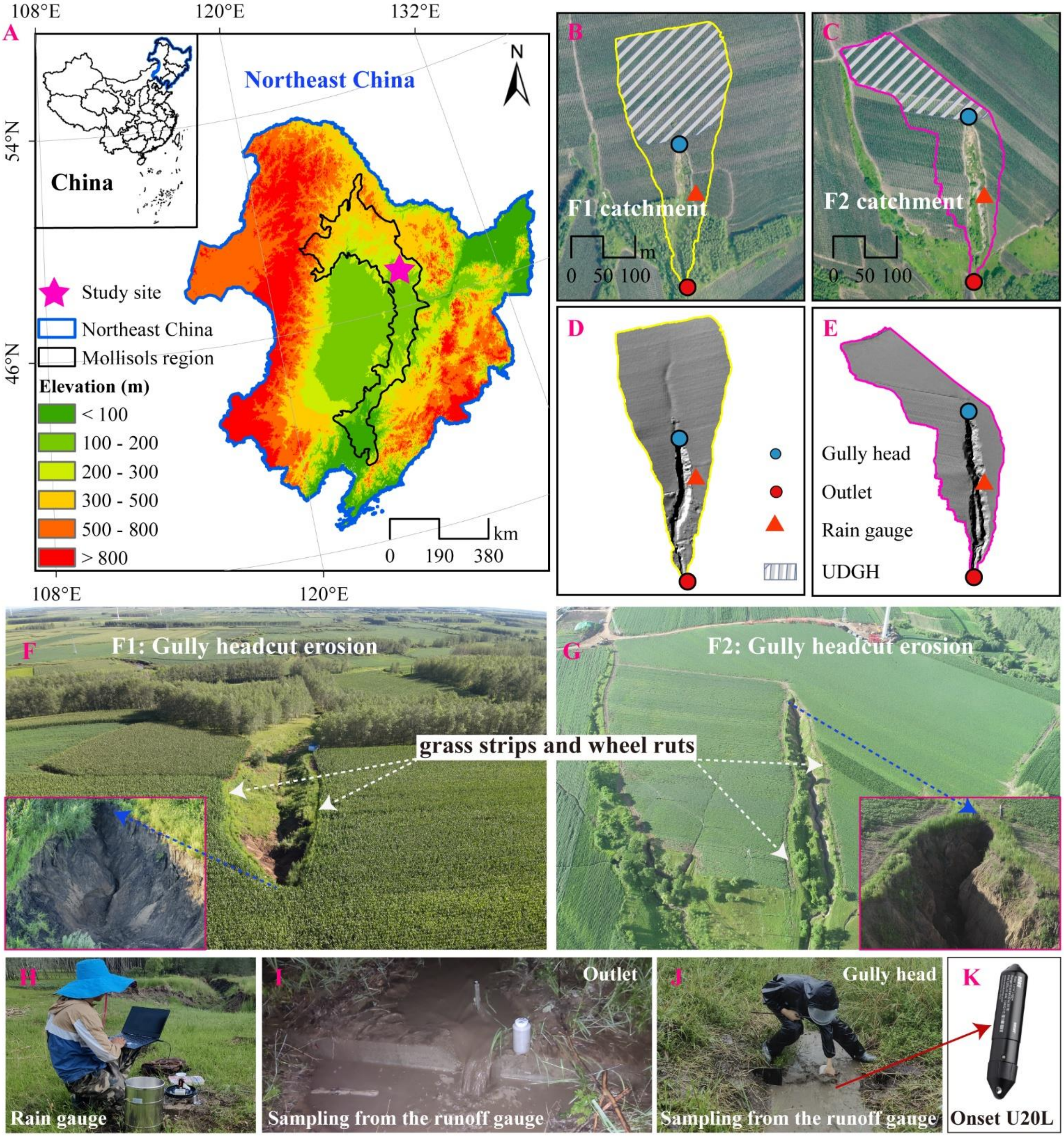
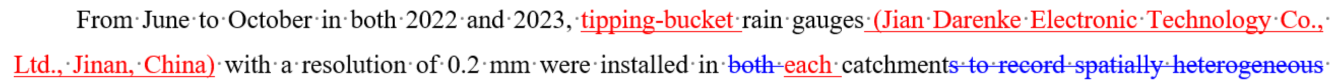


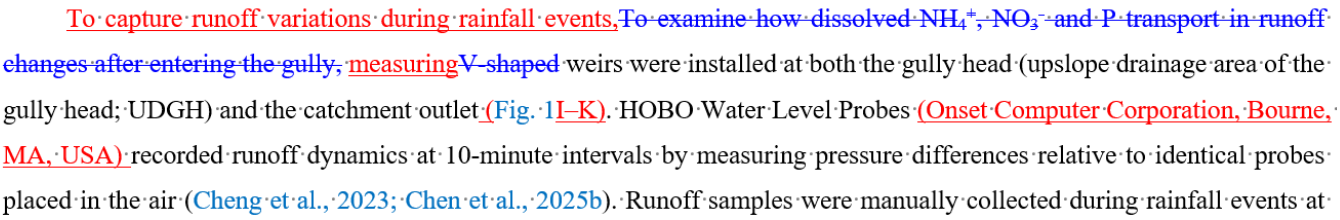
Fig. 1 (A) Location of the study site within the MRNC;~~;~~ (B–C~~E~~) overview of the two monitored gully-dominated catchments; (D–E DEM-derived hillshade basemap; (F–G) UAV aerial images of the two gullies; (H) rainfall data acquisition; (I–J) runoff sampling at the measuring weirs; and (K) water level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

Q6. Line 115: For the instruments used in the study, I suggest adding manufacturer information to improve reproducibility. For example, Specord M40 (VEB Carl Zeiss, Jena, Germany).

Response: We agree that providing manufacturer information improves reproducibility. In the revised manuscript, we have added the manufacturer details for all instruments used. The revised content is as follows:



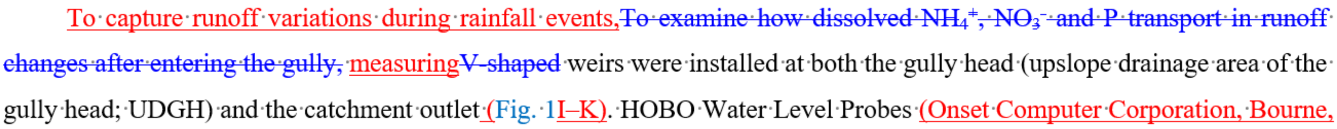
From June to October in both 2022 and 2023, tipping-bucket rain gauges (Jian Darenke Electronic Technology Co., Ltd., Jinan, China) with a resolution of 0.2 mm were installed in ~~both~~ each catchments~~ to record spatially heterogeneous~~



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. 1I–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

Q7. Line 130: Similarly, the previous sentence seems redundant and could be removed. Also, in line 131, adding instrument details would be helpful.

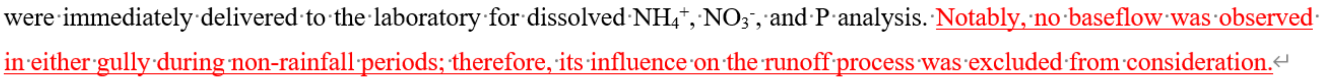
Response: We fully agree with your suggestion. We have rewritten this sentence to improve clarity and reproducibility.



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. 1I–K). HOBO Water Level Probes (Onset Computer Corporation, Bourne,

Q8. One question I have is whether the monitored gully has baseflow during non-rainfall periods. If so, should the baseflow-related nutrient flux be excluded when calculating rainfall-event N and P losses?

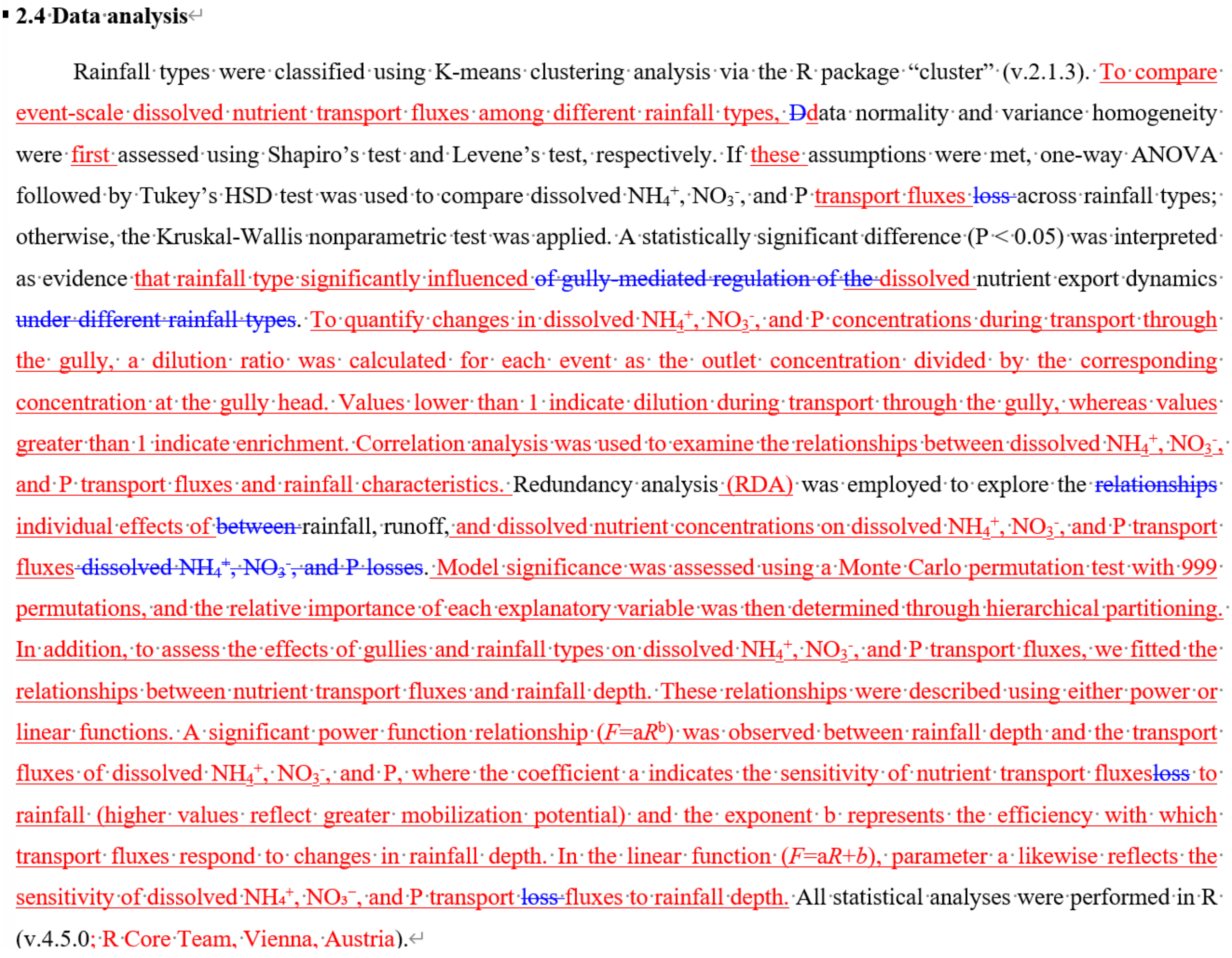
Response: We thank you for raising this important point. Gullies differ substantially from rivers in that they generally do not sustain baseflow in the absence of rainfall, particularly for hillslope gullies. Therefore, baseflow effects are not relevant for the two selected gullies in this study. To avoid potential misunderstanding, we have clarify this point explicitly in the revised manuscript.



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.

Q9. I noticed that correlation analysis and some other statistical analyses were used. Should these methods be briefly described in Section 2.4 as well?

Response: We agree that the statistical methods, including correlation analysis and related approaches, should be described in Section 2.4. Based on your suggestion, we have added the relevant method descriptions in Section 2.4.



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).

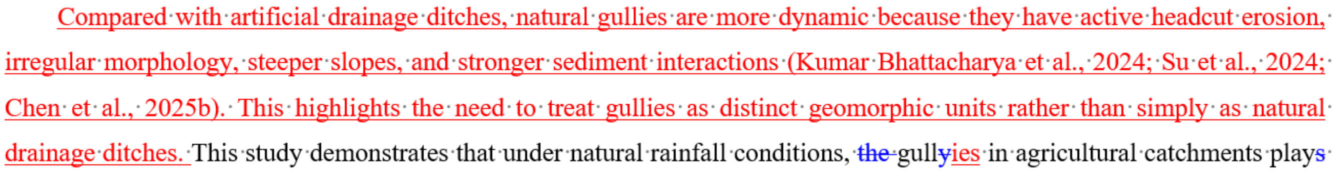
Q10. The Results and analysis section is clear and easy to follow. The key findings are well presented, and the figures are also nicely prepared.

Response: We appreciate your positive comments and are glad that the Results section and figures are clear and easy to follow.

Q11. The Discussion could possibly be strengthened by comparing the function of natural gullies with artificial drainage ditches, and by referencing relevant studies. This may help further highlight the uniqueness and importance of erosional gullies, and also better connect with the points raised

in the Introduction.

Response: We agree that comparing artificial drainage ditches with naturally formed gullies is an interesting and meaningful perspective. Following your suggestion, we will review relevant literature on drainage ditches and strengthen the comparison and discussion in the revised manuscript to better highlight the distinct characteristics of gullies and the significance of this study.



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~~ gull~~y~~ies in agricultural catchments play~~s~~

Q12. Overall, I think this is a high-quality and innovative study. After addressing the issues mentioned above, the manuscript can be considered for publication in HESS.

Response: We sincerely appreciate your positive assessment and constructive comments. We have carefully revised the manuscript to address the issues raised and to further improve its overall quality.