RC1: Anonymous Referee 1#

Dear reviewer,

Thank you for your valuable and constructive comments on our manuscript. Following your suggestions, we have extensively discussed the heterogeneity involved in this study and conducted additional simulations to address this aspect. We have also added more background on runoff processes in thin soil hillslopes to clarify the mechanisms underlying our findings, and we further extended the discussion on the conceptualization and methodology concerning preferential flow paths. Please find below your comments in blue and our response in black.

With regards,

The authors.

[Comment 1] The manuscript deals with the role of the vegetation, and its potential prevalent impact, on subsurface flow pathways. The structure and goals are clear, and the results offering is well-suited. This paper can for sure be published after some adjustments, listed below. I think that these itemized improvements would make the work more scientifically sound and robust. These considerations come from my expertise as a hydrogeologist, so they will pertain to this sphere of competency.

Response: We sincerely appreciated your positive comments and insightful suggestions that help us improve the quality of manuscript. We addressed the specific points suggested to strengthen the scientific rigor and robustness of this work.

[Comment 2] It is interesting to notice that the root structures are highly spatially heterogeneous, while the soil layers that have been taken are (if I understood correctly) homogeneous. This setup is highly debatable and should be sustained somehow. We know that the first dozen of centimeters below ground are highly randomly formed and have a lot (a lot!) of strongly non-homogeneous features (see e.g. Li et al., 2022), like mole-holes, worm-holes, cracks and fissures, small drainage pipes occurring for example, when some roots dry and die. Please comment extensively and adequately within the Introduction and highlight where these points may (or may not) impact the methodology.

Reply: Thanks for the constructive and insightful comments. We fully agree with the view of the inherent heterogeneity of shallow soil layer that arise from physical and biological processes. However, our focus was on heterogeneity from the perspective of pore perspective rather than soil phases. This is because soil structure is defined by the internal spatial arrangement of pore features alongside solid constituents (i.e., mineral and aggregates) (Romero-Ruiz et al., 2018). The pore system itself is composed of a collection of macropores, fissures, cracks, pipes, and other void features (Beven and

Germann, 2013; Nimmo, 2021), directly governs soil heterogeneity through its spatial distribution and geometry.

Perspectives on soil structure depend on the perception of what is actively shaped (Rabot et al., 2018). We emphasized the pore perspective because field evidence from our previous studies showed that the soils along mountain elevation are sandy resulting from similar geological settings and frequent rainfall, thereby resulting in similar sand, silt, and clay contents (Wang et al., 2022). Thus, pore perspective best captures soil heterogeneity here than solid constituents. We therefore treated void features as heterogenous variable to effectively represent spatial variation in soil.

We addressed these points in the Discussion section, specifically the section 4.3, to clarify the pros and cons of adopting a pore-perspective in generating preferential flow paths (hereafter abbreviated as PFPs), which also addressed the scale and site dependence of PFPs in [Comment 3]. The revised contents are shown below:

[Line 400-411] *"More importantly, we explicitly represented the hillslope using pore-scale PFPs, as this pore system was identified dominant at this scale and was deemed appropriate for better representing soil heterogeneity given the relatively uniform soil phases in this study. Despite the fact that pore system fundamentally determines the structure of porous media and governs the water flow (Vogel, 2019), it remains necessary to account for the formation processes of the pore system with respect to the studied medium to enable accurate representation of PFPs in physically based models. For example, PFPs in the form of wormholes (common in gypsum or limestone karst) created by flow and dissolution have lengths following a power-law distribution (Li et al., 2022), and PFPs are dynamic through reaction–transport coupling in calcite (Shavelzon et al., 2025). However, extending pore-scale representations to larger spatial scales entails prohibitive computational demands. Nevertheless, most flow processes forget about small-scale perturbations when going to larger scales, reducing the necessity to keep fine-scale complexity. For example, representing PFPs as the most permeable alluvial facies, delineated by gridded cells, achieved satisfactory results in a glaciofluvial sedimentary basin (Schiavo, 2022, 2023). These points emphasize the importance of representing heterogeneity with respect to site-specific processes and the scale of investigation."*

[Comment 3] On the other side, I do agree that the roots are (some of the) preferentially heterogeneous features at THIS spatial scale. I would introduce that there may be various scales of inspection, each of them dealing with various features that rule preferential pathways spatial distribution (at the micro-scale, pores irregularity and chemical weathering, as in Shavelzon et al., 2025; at the root scale, roots, mole-holes, etc, as in Li et al., 2022; permeable sediments organized as preferential pathways, as in

Schiavo, 2023).

Reply: Thanks for your valuable comment regarding distinct PFPs across different study areas and spatial scales.

At the hillslope scale, numerous field studies have demonstrated that main flow paths (or high soil hydraulic conductivity areas) are primarily associated with macropores (Nimmo, 2021). A review of 190 studies found that 57% recognized macropores as dominant flow paths (Guo and Lin, 2018), and macropore flow is often treated as synonymous with preferential flow (Nimmo, 2021). In particular, on forested hillslopes with thin soil and steep slopes, preferential flow has been observed to extend to a depth of about 55 cm, coinciding with the maximum depth reached by roots; thin soil promotes vertical channels through loose soil structures created by animal burrowing, fissures, and cracks caused by pronounced hydrothermal conditions and fluctuations (Buttle and Mcdonald, 2002; Alaoui et al., 2011; Laine-Kaulio et al., 2015).

Of course, there are distinct types of PFPs that are characteristic of particular porous media and scales, such as dissolution-precipitation of calcite driven by chemical weathering at the core scale (Shavelzon et al., 2025); wormholes formed by fluid flow and chemical reactions in processes of gypsum or limestone karst formations at the soil column (Li et al., 2022); and preferential groundwater pathways in form of permeable alluvial at regional scale (Schiavo, 2023).These examples underscore two key points in identifying and representing PFPs: (1) the necessity to determine the predominant PFPs for the studied medium; and (2) the critical importance of spatial scale. Physically based models must represent PFPs accurately and effectively to from a "bottom-up" perspective to capture spatial heterogeneity, while balancing computational costs with scale.

The revised content has been incorporated at the end of our response to [Comment 2].

[Comment 3]: Were parameters in tables 1 and 2 calibrated?

Response: The parameters were not calibrated. Instead, we integrated field evidence of PFPs with using uncalibrated parameters to predict subsurface flow. This approach is valuable for conceptualizing numerical models and predicting flow in data-scarce regions, especially where flow (e.g., subsurface flow) is difficult to measure directly, or where field monitoring is limited due to harsh environment conditions. Moreover, calibrated or optimized parameters may obscure the underlying physical processes due to the issue of equifinality. In this study, simulations have revealed that multiple hillslope configurations achieved satisfactory results at the event scale, indicating equifinality across hillslope set-ups. Adding calibrated parameters of soil would further reduce the physical interpretability of the modeled hydrological processes. Meanwhile, given the persistent challenge for quantifying and parameterizing preferential flow (Beven and Germann, 2013), integrating field evidence with uncalibrated parameters provides a practical way to conceptualize and simulate hydrological processes involving PFPs, thereby facilitating the exploration of its feasibility across different environmental and geographic contexts.

[Comment 4]: Please add R2 coefficients to the fitted data in Figure 4.

Response: Thanks for the kind reminder. We have added the R^2 coefficients to the revised Figure 4. We also acknowledge that the slopes of the fitting equations were incorrectly adopted in the previous version of figure 4 owing to an inadvertent oversight on our part. The revised graph is as follows:

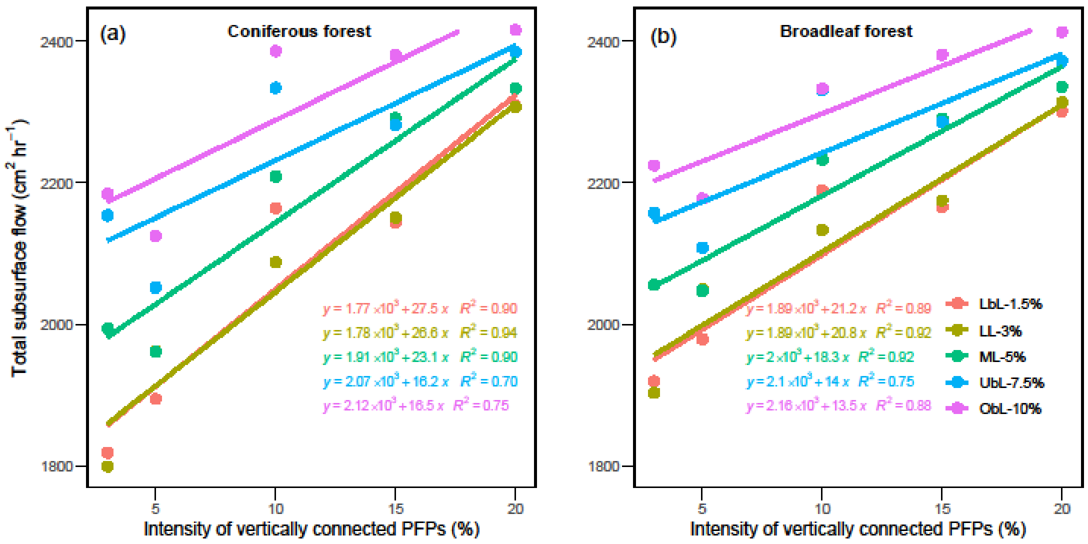

Figure 4: Relationships between total subsurface flow and intensity of vertically connected PFPs in the coniferous (a) and broadleaf (b) forest.

[Comment 6]: I think that more should be said about preferential pathways at the planar (not vertical) scale. Even if the root apparatus is mainly vertical, its horizontal component, due to the angle of the setup, makes the horizontal highly permeable zone not negligible. This would play as a planar preferential pathway, such as those recognized at the microscale (Shavelzon et al., 2025) and at the catchment scale (Schiavo, 2023). I think that commenting more and relating these works would serve to somehow 'close the circle' among different perspectives and spatial scales in hydrology.

Response: We deeply appreciate your insightful comment. On the one hand, we focused primarily on vertically connected PFPs rather than lateral ones, because field evidence consistently showed that vertical preferential flow often extends throughout the entire root zone in forested areas (Alaoui et al., 2011), with connected PFPs acting as the principal conduits for substantial water transport (Anderson et al., 2009; Koestel and Larsbo, 2014). In addition, organic-rich forest soil often restricts lateral flow due to the relatively impermeable organic coatings, limiting the connectivity of lateral PFPs (Jarvis, 2007). Moreover, the lateral PFPs typically intersect with vertically connected PFPs that extend through the entire profile, channeling water into them. On the other hand, the sustaining vertically preferential flow facilitates rapid water movement to the soil-bedrock interface, where water fills bedrock depressions before spilling into adjacent depressions, connecting saturated zones and triggering lateral downslope flow (Mcdonnell et al., 2021). The "fill-spill" theory suggests that vertical preferential flow in forested hillslopes with thin soil is the main controlling factor in subsurface flow generation, followed by soil-bedrock lateral flow (Buttle and Mcdonald, 2002; Tromp-Van Meerveld and Mcdonnell, 2006; Zhang et al., 2025). Thus, lateral PFPs in soil play a relatively minor role.

We introduced detailed backgrounds on the dominant subsurface flow generation mechanisms within thin soil, steep hillslopes, with the aim of directing attention to vertically connected PFPs. The revised content is as follows:

[Line328-335] "*This is especially true on forested hillslopes with thin soil, preferential flow usually develops vertically through the entire soil profile via a connected flow network of soil-root interfaces, decayed root channels, animal burrows, fissures, and cracks, allowing for fast movement of infiltrated rainfall to the soil-bedrock interface. Subsequently, lateral flow at the soil-bedrock interface transmits water downslope and generates subsurface flow (Tromp-Van Meerveld and Mcdonnell, 2006; Mcdonnell et al., 2021; Zhang et al., 2025). Meanwhile, flow in the lateral PFPs within the forest soil is restricted by the relatively impermeable organic coatings, which limits lateral connectivity, and the flow usually converges into vertically connected PFPs that extend through the entire soil profile (Jarvis, 2007), supporting the dominant role of vertically connected PFPs in subsurface flow.*"

[Comment 7]: In Figure 5, every time you have a more intense rainfall event, the model somehow slightly fails in predicting the flow. Can you comment on this? Which fixings and adjustments could be implemented?

Reply: We attribute the pronounced phenomenon to the following factors: a simplified conceptualization of PFPs, the assumption of static PFPs during rainfall, and the neglect of other flow regimes. We have addressed this issue in the Discussion, as it represents a potential avenue for future improvement in simulation performance. The revised content is as follows:

[Line423-436] *Specifically, there are noticeable deviations between simulated and* *observed subsurface flow under heavy rainfall conditions (Fig. 5). Although these deviations may appear rather small given the complexity and heterogeneity of natural hillslopes, we nevertheless delve into them in light of the aforementioned uncertainties, aiming to provide insights for improving model conceptualization and predictive accuracy. First, we defined macropores as pores with diameter or aperture over 30 μm; however, it is evident that fracture apertures ≤ 30 μm can still transmit preferential flow in the form of film or rivulet flow (Tokunaga and Wan, 2001; Lange et al., 2009); Secondly, although the model reproduced acceptable results using a fixed and below-average number of PFPs, increased soil wetness during continuous rainfall promotes the self-organization of PFPs into larger flow networks, thereby engaging more PFPs in subsurface flow (Sidle et al., 2001; Nieber and Sidle, 2010; Zehe et al., 2013). Finally, the potential initiation of other preferential flow types, such as finger flow and funnel flow induced by heterogeneity in soil moisture, soil hydraulic conductivity, or water flux, was not considered (Hartmann et al., 2020; Nimmo, 2021). In summary, the simplified conception of PFPs, the assumption of their static nature during rainfall, and the omission of other preferential flow regimes collectively contribute to the underestimation of subsurface flow under heavy rainfall conditions. Addressing these limitations in numerical models would help improve simulation accuracy, particularly for flood prediction under extreme rainfall events.*

[Comment 8]: My ending feeling is, to be honest, that the absence of flow heterogeneity plays a crucial role in letting the root apparatus play a major role in the subsurface flow. I think more work should be implemented to convince the reader of this point. How to implement heterogeneity? What about the vast literature implementing Monte Carlo-based models to deal with the inherent groundwater heterogeneity, which is due to geological heterogeneity?

Reply: Thanks for your thoughtful and valuable suggestions. We constructed the two-dimension hillslope from the perspective of pore system, which is assumed as a collection of soil-root interfaces, decayed root channels, fissures, and cracks derived from CT-imaged photographs rather than sole root apparatus. Since soil structure, which governs water flow, is shaped and influenced by both pore features and solid constituents, and the latter tend to be similar under comparable hydraulic conditions, the differences in soil structure are mainly attributed to the pore system, with vegetation roots playing a dominant role in its formation.

As for the heterogeneity, given the dominant role of pore system in shaping soil structure in this study, we applied a random placement of PFPs to represent the pore system, also the soil heterogeneity. This issue has been covered in our reply to [Comment 2]. While, we did not account for lateral heterogeneity, which is reflected as ridges and depressions in impermeable or relatively impermeable layers in hillslopes, specifically the bedrock and restrictive soil horizons. Nevertheless, the developed preferential flow results in the absence of subsurface flow within soil horizons, thus establishing bedrock as a key controlling factor, subordinate to preferential flow on forested hillslopes with thin soil (Buttle and Mcdonald, 2002; Tromp-Van Meerveld and Mcdonnell, 2006; Guo et al., 2019). We configured the numerical model to match the artificial physical configurations where bedrock was initially idealized as straight layer parallel to the hillslope to isolate the influence of forest soils and avoid excessive variables.

Regarding the inherent groundwater heterogeneity arising from geological heterogeneity, this suggests that, if we understand correctly, even with a fixed combination of lateral and vertical PFPs intensities, the spatial configuration of PFPs, which is the specific pore system representing soil heterogeneity, can vary and may lead to different simulation outcomes. We fully agree with the referee's comment on this point. Therefore, we selected the set-ups (i.e., LV-SLL, LV-LL, and LV-ML) that successfully reproduced the event-scale outflow dynamics and additionally included a set-up of MV-LL. For each set-up, the combination of lateral and vertical PFP intensities was fixed, while 10 simulations were performed with randomly generated pore systems following the specific intensity combination. Differences within and between set-ups were assessed using PERMANOVA (Permutational Multivariate Analysis of Variance), implemented via "vegan" package in R. The results showed significant differences between set-ups ($p < 0.01$), but no significant differences within set-ups except for the ML-LL set-up in the coniferous forest (Fig. 1 below). This indicates that the set-ups, which successfully reproduced the event-scale outflow dynamics, were generally robust against spatial heterogeneity in PFPs, thereby validating their reliability in representing the underlying hydrological processes. It is worth noting that the simulations of the ML-LL in the coniferous forest exhibited significant differences, not only indicating a higher sensitivity of the coniferous forest to variations in PFPs than the broadleaf forest, but also suggesting a certain predictive capability of these set-ups in conjunction with the modelling approach.

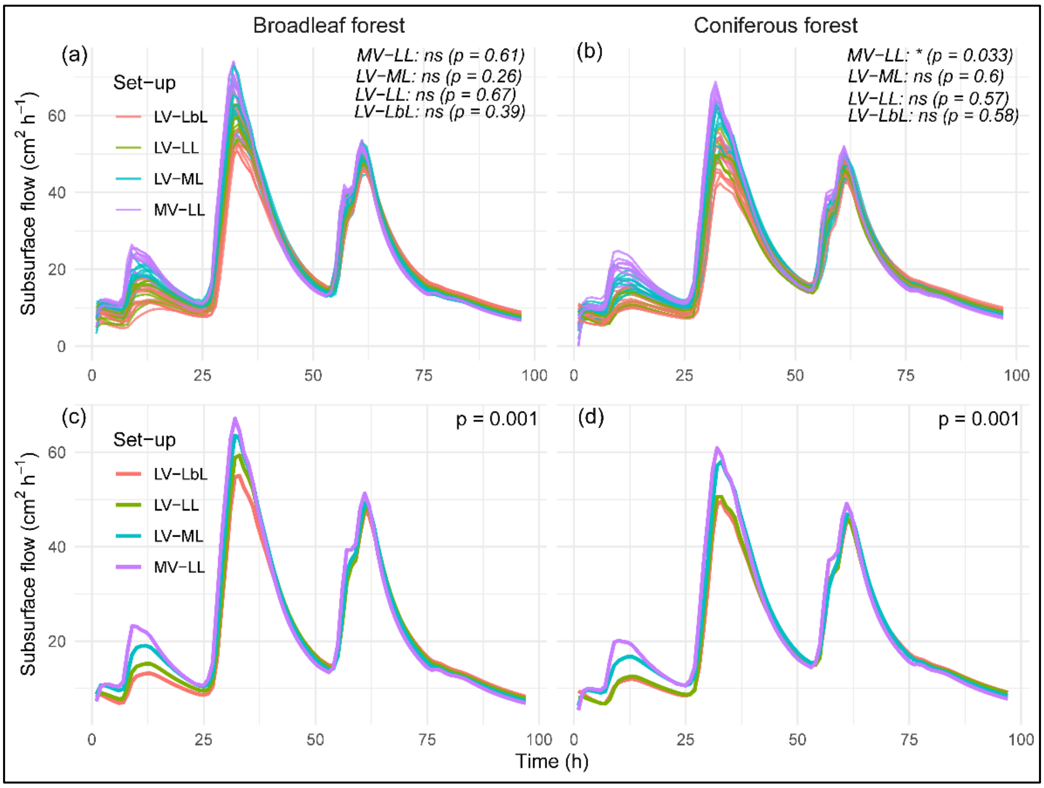

Figure 1: Multiple simulations under each set-up and within-group differences (a, b), as well as between-group differences among different set-ups (c, d) in the broadleaf and coniferous forests (ns denotes not significant; * denotes significance at the 0.05 level).

We incorporated this point into the Results and added the graph in the Supplementary material. The revised content is as follows:

[Line239-245] *"Furthermore, to assess the robustness of the approach under consistent PFP intensity but varying spatial distribution, multiple runs were conducted for each acceptable set-up with an additional ML-LL set-up. The results revealed significant differences between set-ups ($p < 0.01$), but no significant differences within set-ups, except for the ML-LL set-up in the coniferous forest (Fig. S3). These findings suggest that the set-ups were generally robust against spatial heterogeneity in PFPs, thereby supporting their reliability in representing the underlying hydrological processes. Particularly, the ML-LL set-up in the coniferous forest was the first to exhibit differences within replicates of the same set-up (Fig. S3), further supporting its greater sensitivity to changes in PFPs."*

RC2: Anonymous Referee 2#

Dear reviewer,

Thank you for your valuable comments and suggestions on our manuscript. Following your suggestions, we have carefully revised the manuscript to ensure clarity and improve the overall linguistic quality, particularly those unclear statements and inappropriate word usage. We have also have added supporting material to provide more details about the study area, and modified figures and tables (and captions) for clearer presentation. Please find below your comments in blue and our response in black.

With regards,

The authors.

[Comment 1]: This work is interesting and could bring a valuable contribution to the scientific discussion about hillslope hydrology. In my opinion it could be published after some adjustments. I suggest you double check the writing of the entire manuscript one more time, as some sentences make little sense and I am not sure some words are used properly.

Reply: We thank the referee for the positive comments and thoughtful language suggestions. Accordingly, we took specific actions in response to the comments. (1) For specific modification suggestions, we implemented the changes directly as suggested; (2) For unclear statements, we either adopted the referee's suggested phrasing when provided or rephrase the text to improve clarity and precision; (3) For the statements that are inappropriate or doubtful, we rephased them based on relevant literature and expert advice; (4) Finally, we engaged a professional English editing service to ensure the overall language quality, including grammar, style, punctuation, and syntax, as well as content clarity, such as reconstruction of sentences for better interpretation of the intended meaning.

[Comment 2 (grouped)]: Provide the coordinate range of the study area along with a picture of the real experimental apparatus for additional information. Some figures and tables require improvement due to insufficient information, inaccurate citations, and inadequate explanations.

Reply: Thanks for the suggestions. We took the following principles to address the referee's comments: (1) Specific suggestions on figures and tables provided by the referee were implemented directly (e.g., adding R^2 value to graphs and including dates in Fig. 5 to clearly indicate the growing season referenced in this study, and the revised figures can be found in the manuscript). (2) The coordinate of the study area (Hailuo Valley) and a picture of the experimental apparatus is presented and included in the

"Supplementary" materials (see Fig. 1 below). (3) We carefully checked all figures and tables to assert that the information they present is adequately and correctly explained in the text, thereby reducing potential uncertainties in interpretation.

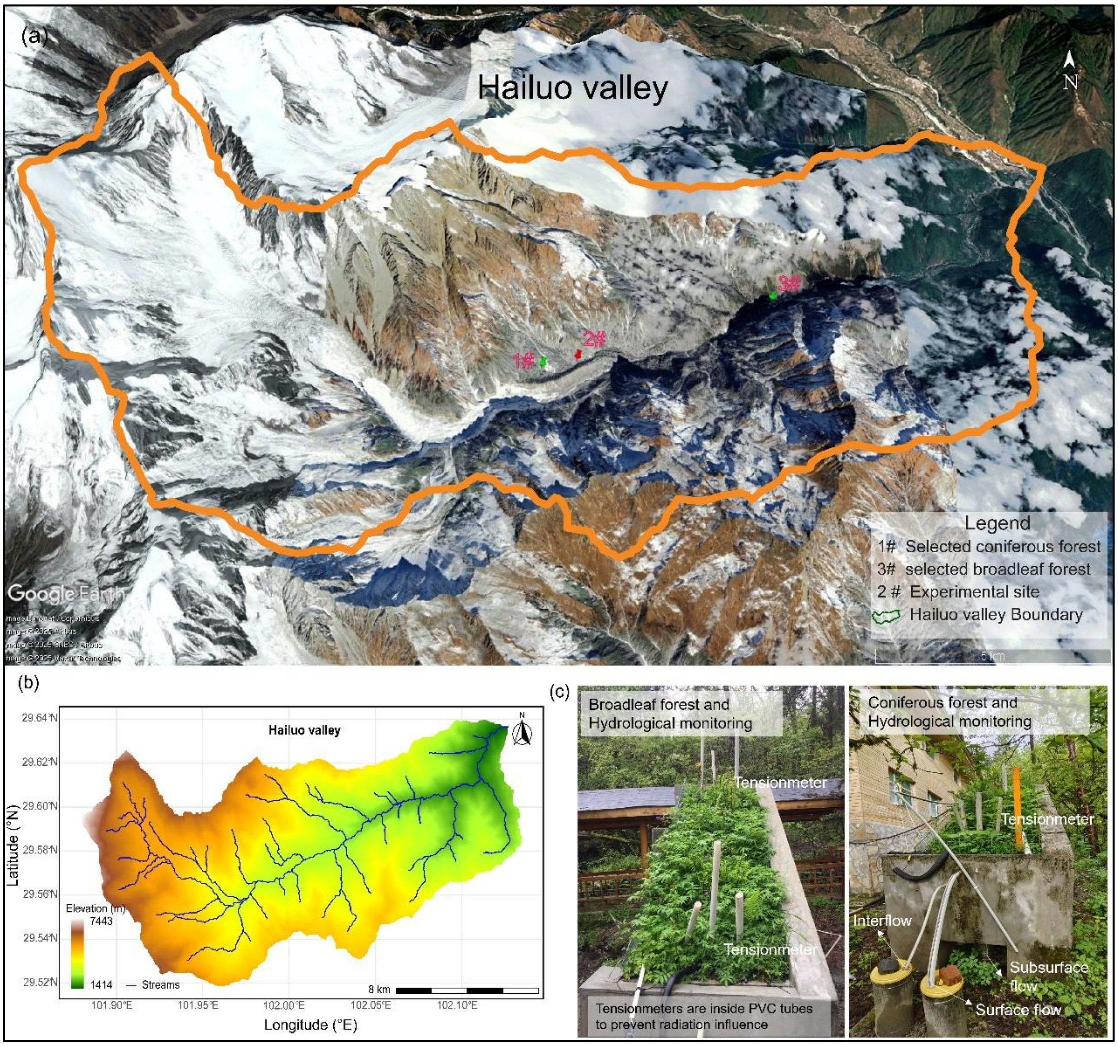

Figure 1: Overview of (a) the selected forests (1# and 3#) and the experiment site (2#) at Hailuo valley (image retrieved from Google Earth; note that the blue areas represent shadows in the satellite view), (b) digital elevation model of Hailuo valley, and (c) a photograph of the experimental apparatus at 2#.

[Comment 3]: What possible hypotheses may account for the mismatch between simulated and observed outflow under heavy rainfall conditions?

Reply: We did discuss this phenomenon in Section 4.3 (Uncertainties and future outlooks) of the manuscript, specifically at lines 390-393 and 400-405. We reorganized and expand the discussion to better address the discrepancy between simulated and observed outflow, thereby benefiting future improvements in model conceptualization and predictive accuracy. The revised content is as follows:

[Line423-436] *Specifically, there are noticeable deviations between simulated and observed subsurface flow under heavy rainfall conditions (Fig. 5). Although these deviations may appear rather small given the complexity and heterogeneity of natural hillslopes, we nevertheless delve into them in light of the aforementioned uncertainties, aiming to provide insights for improving model conceptualization and predictive accuracy. First, we defined macropores as pores with diameter or aperture over 30 μm; however, it is evident that fracture apertures ≤ 30 μm can still transmit preferential flow in the form of film or rivulet flow (Tokunaga and Wan, 2001; Lange et al., 2009); Secondly, although the model reproduced acceptable results using a fixed and below-average number of PFPs, increased soil wetness during continuous rainfall promotes the self-organization of PFPs into larger flow networks, thereby engaging more PFPs in subsurface flow (Sidle et al., 2001; Nieber and Sidle, 2010; Zehe et al., 2013). Finally, the potential initiation of other preferential flow types, such as finger flow and funnel flow induced by heterogeneity in soil moisture, soil hydraulic conductivity, or water flux, was not considered (Hartmann et al., 2020; Nimmo, 2021). In summary, the simplified conception of PFPs, the assumption of their static nature during rainfall, and the omission of other preferential flow regimes collectively contribute to the underestimation of subsurface flow under heavy rainfall conditions. Addressing these limitations in numerical models would help improve simulation accuracy, particularly for flood prediction under extreme rainfall events.*

Additional minor revisions:

(1) The y-axis range of the broadleaf forest in Figure 3 (right panels) was not properly set due to auto-alignment setting, which lead to incomplete data display. The Figure 3 has been updated accordingly.

(2) The data used to plot soil water retention curve of coniferous forest at 30-50 depth in Figure S6 was not appropriately reference. We have corrected it.

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