Preferential flow patterns in forested hillslopes of the east Tibetan Plateau revealed by dye tracing and soil moisture network

Fei Wang[1 2], Genxu Wang[3] ✉, Junfang Cui[1] ✉, Li Guo[3], Carlos R. Mello[4], Elizabeth W. Boyer[5], Xiangyu Tang[1], Yi Yang[1 2]

[1] Institute of Mountain Hazards and Environment, Chengdu 610041, China
[2] University of Chinese Academy of Science, Beijing 100049, China
[3] State Key Laboratory of Hydraulics and Mountain River Engineering, College of Water Resource and Hydropower, Sichuan University, Chengdu 610065, China
[4] Water Resources Department, Universidade Federal de Lavras, CP 3037, Lavras MG 37200-900, Brazil
[5] Department of Ecosystem Science and Management, The Pennsylvania State University, University Park, PA 16802, USA
✉ corresponding authors: Genxu Wang, wanggx@scu.edu.cn; Junfang Cui, jfcui@imde.ac.cn

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Abstract

Preferential flow (PF) through soil and regolith results in a rapid vertical and lateral water movement within the profile. This study focused on quantifying PF in contrasting forested hillslopes of the Hailuo Valley, located on China's east Tibetan Plateau. Quantifying PF in this region is challenging since the underlying matrix is complex – with shallow soils, thick underlying saprolite, and the combined effect of moraines, weathered residual material, and debris flows. We developed new methods that integrated dye tracing with high-frequency soil moisture monitoring to characterize PF pathways and quantity PF frequency on contrasting forested hillslopes (broadleaf and coniferous). Dye tracing experiments showed that soil-root interfaces in the upper soil layer (10-50 cm) and the deeper soil layer (50-100 cm) were the primary PF pathways, and that large rocks strongly influence the percolation depth of water. The high-frequency soil moisture network revealed that the mean PF frequency was 67.8% and 71.7% in the coniferous and broadleaf forests, respectively. The frequency of PF in the deeper soil layer increases from upslope to downslope locations on both forested hillslopes, highlighting the tendency for PF to occur downslope. In addition to matrix conditions (e.g., stony saprolite soil), the total amount and maximum intensity of precipitation (as throughfall in these forests) were identified as factors that control PF occurrence. In contrast, the initial soil water conditions (at 10, 50, and 100 cm depths) were insignificant in predicting PF occurrence. Results of this field-based study highlight that PF is a ubiquitous and critical subsurface flow mechanism that regulates rainfall-runoff relationships in forests of the Tibetan Plateau, underscoring the need to consider PF in hillslope hydrological modeling.

Keywords: Preferential flow, flow paths, hillslope hydrology, hydropedology, subsurface flow, subsurface structure, glacial till, throughfall, Tibetan Plateau

1. Introduction

Preferential flow (PF) in soils refers to the process by which infiltrating water bypasses most of the soil matrix, resulting in a rapid vertical and lateral movement of water within the soil profile, typically delivering water to deeper horizons (Beven 1982, Jarvis et al., 2016; Guo and Lin, 2018; Nimmo, 2021). Hydrologically, PF affects the water balance of the critical zone – influencing the rate and pathways of infiltration, runoff, subsurface stormflow, and groundwater recharge (Buttle and McDonald, 2002; Green and Erskine, 2011; Jost et al., 2012; Beven and Germann, 2013; Dusek and Vogel, 2016; Guo et al., 2020). Ecologically, PF influences mass transport of water and associated loadings of solutes, sediments, and nutrients (Clothier et al., 2008; Wilson et al., 2008; Weill et al., 2011; Larsbo et al., 2014; Fishkis et al., 2020; Liu and She, 2020). Given the strong influence of macropores on the flow paths and residence times of water in the soils, PF could play an essential role in the dynamic feedback between water and vegetation (Guswa et al., 2020). Understanding PF and its variability over space and time will advance fundamental knowledge of coupled hydrological and ecological processes (Mcdonnell and Beven, 2014; Nimmo, 2021).

Forest soils commonly have high infiltration capacities that favor PF, given extensive macropore systems consisting of decayed root channels and animal burrows in shallow soils (Beven, 1982; Alaoui et al., 2011; Laine-Kaulio et al., 2015; Wiekenkamp et al., 2016; Demand et al., 2019). Forested hillslopes often have a variably weathered and deposited zone between the soil surface and the intact bedrock (Salve et al., 2012). Rainwater can infiltrate into the weathered and deposited zone through PF pathways before reaching the bedrock, and the presence of macropore networks is known to influence the transport of water (Salve et al., 2012; Guo et al., 2019). Conceptual understanding of PF in the weathered and deposited zone continues to evolve. In steep hillslopes with shallow soils and thick saprolite, PF-induced subsurface flow through macropore systems is a potential link to rapid runoff response. The shallow soil promotes lateral development of root networks and channels, delivering the water at a high velocity downward (Sidle et al., 2001). Thick saprolite may promote rapid water transport through structural macropores or cracks, strongly affecting the water residence time in soils (McGlynn et al., 2002). Saprolite underlying hillslope areas are typically stonier and coarser-textured than the toe-slope colluvium (Laine-Kaulio et al., 2015; Hartmann et al., 2020). Coarse-textured soils typically have no prominent structural channels and have high saturated hydraulic conductivity along the soil profile, favoring PF occurrence (Hendrickx and Flury, 2001; Hardie et al., 2011; Laine-Kaulio et al., 2015). Stony soils alter water flow by dispersion, lead to an unstable wetting front due to the impermeability of rock, and are markedly associated with the PF process (Cerdà, 2001; Jarvis, 2007; Bogner et al., 2014; Liu and She, 2020). The ubiquity of PF occurrence in forests is of great importance to hillslope hydrology, as PF flow pathways can be a significant factor in predicting subsurface flow characteristics on hillslopes (Wienhöfer and Zehe, 2014). Thus, PF and its controlling factors should be carefully examined (Beven and Germann, 2013; Li et al., 2018).

Numerous methods have been developed to visualize and quantify PF at different spatial and temporal scales (Allaire et al., 2009; Jarvis et al., 2016). There have been great advances in X-ray and MRI methods for imaging macropore structures at soil core or soil column scales (Jarvis et al., 2017; Feng et al., 2020). Dye tracing experiments reveal PF patterns in soil profiles (Weiler and Flühler, 2004; Laine-Kaulio et al., 2015; Filipović et al., 2020). Moreover, the increasing availability of geophysical techniques (e.g., ground-penetrating radar and electrical resistivity tomography) offered new opportunities to quantify PF with minimal disturbance at plot to hillslope scales (Koestel et al., 2009; Gormally et al., 2011; Haarder et al., 2011; Guo et al., 2014; Guo et al., 2020). At catchment and regional scales, reliable measurement and quantification of PF by the methods mentioned above remain arduous, with a need for bridging gaps across scales (Nimmo, 2012; Jarvis et al., 2016; Guo and Lin, 2018; Nimmo, 2021). An alternative method utilizing a high-frequency soil moisture monitoring network was developed, which has advanced in-situ detection of PF across spatial and temporal scales (Graham and Lin, 2011; Wiekenkamp et al., 2016). Using this method, researchers have gained new understanding of PF relationships with watershed characteristics, such as rainfall events (Jost et al., 2012; Lozano-Parra et al., 2015; Tian et al., 2019), soil depth and hillslope topography (Graham and Lin, 2011; Liu and Lin, 2015; Wiekenkamp et al., 2016); and initial soil water conditions and landforms (Holden, 2009; Liu and Lin, 2015; Demand et al., 2019; Tang et al., 2020). However, using a data-intensive network-based approach alone cannot resolve individual PF pathways or establish the continuity and possible soil depths of the PF processes. Here, we propose that integrating dye tracing experiments with a high-frequency soil moisture monitoring network is a promising way forward to quantify PF characteristics and its contribution to hillslope water cycling in forests. We use the combined approaches to illuminate multiscale PF processes and their controlling factors under the natural conditions at field sites.

This study aims to advance the understanding of PF in steep mountain forests of the Hailuo Valley, located on China's east Tibetan Plateau. Quantifying PF and its contribution to hillslope water cycling in this region is challenging since the underlying porous media matrix is complex. The forested hillslopes have shallow soils, thick underlying saprolite, and the combined effect of moraines, weathered residual material, and debris flows. Our specific objectives were to (i) Quantify PF occurrence over space and time, using state-of-the-art methods that integrate intensive measurements from soil moisture monitoring networks with field-scale dye tracing experiments, (ii) Identify PF pathways and frequency in soil profiles of contrasting forest woodland habitats (broadleaf and coniferous), and (iii) explore factors that potentially regulate PF patterns. Our results provide insights into PF mechanisms on the Tibetan Plateau.

2. Materials and Methods

2.1 Site description

Our field sites are located in the Hailuo Valley on the eastern slope of Gongga Mountain on the east edge of the Tibetan Plateau (Fig. 1). Elevation along the east slope of Gongga mountain rises by 6400 m along just 29 km of horizontal distance, resulting in distinct vertical zones of climate and a rich natural vegetation diversity along the elevation gradient. The climate is dominated by the southeast Pacific monsoon, with annual precipitation concentrated during the wet period from May to October (Zhong, 2002). Two hillslopes were selected for explorations of PF, in contrasting forest types typical along the vertical vegetation gradient of the Hailuo Valley. One is in the evergreen coniferous forest (*Abies fabri, Picea brachytyla*) at 3000m asl, and the other is the deciduous broadleaf forest (*Lithocarpus cleistocarpus, Salix babylonica*) at 2260m asl. On these hillslopes, soils are characterized by thin O and A horizons, a thick B horizon, and rich rock fragments (Fig. 2) with the occasional size of a single rock fragment up to meters in diameter (He et al., 2004).

2.2 Soil measurements

Soil characteristic measurements. To quantity soil properties of hillslopes, soil samples at three slope positions (upslope, middle, and downslope) were collected near in summer 2020, at locations within 2 m of the installation positions of the soil moisture sensor arrays. Sampling included undisturbed soil core samples (n=3 for each depth, cutting ring 100 cm^3 in volume) and disturbed soil (n=3 for each depth). Root biomass was collected from a 50 cm × 50 cm quadrat (n=2 for each slope position) at the upper (10-50 cm) and deeper layers (50-100 cm). Soil core samples were oven-dried at 105°C for 24 hours to determine soil bulk density, and soil porosity was calculated from the dry bulk density with a particle density of 2.65 g/cm^3 (Shao et al., 2006). Oven-dried soil core samples were later passed through a 2-mm sieve to separate rock fragments (> 2 mm), and rock fragment content (cm^3/cm^3) was determined by the volume replacement method. Disturbed soil was divided into two sub-samples after being air-dried and passed through a 2-mm sieve, with one for soil particle size composition analysis by laser particle size analyzer (Mastersizer 3000, Malvern Instruments Ltd, UK) and the other for soil organic carbon (SOC) by dry combustion method after passing through 0.01 mm sieve (Vario Macro Cube, Elementar Analysensysteme, Germany). Soil organic matter (SOM) was estimated as SOC multiplied by 1.72 (after Pribyl, 2010). Collected roots were gently washed to remove attached soil and oven-dried at 60°C for 72 hours to constant weight. Soil saturated hydraulic conductivity (K_s) was measured using a Guelph Permeameter (Soil Moisture Equipment Corp, USA) with at least three depths (3 replications at each depth) at the upper (10-50 cm) and deeper soil layer (50-100 cm). Detailed processes of measurement refer to Guelph manual (Guelph Manual, Soil Moisture Equipment Corp, USA).

Soil moisture monitoring. A soil moisture monitoring network was deployed at three slope positions (up, middle and down slopes) in the forested hillslopes (Fig. 3). Soil water potential (T4e, UMS Corp, Germany. Measurement ranges from -85 kPa to 100 kPa with 0.03kPa precision) was used to replace generally used soil water content, and soil water potential is the force that governs the transport of in soils (Novick et al., 2022). Installment of sensors was processed as follows: a nearly 60 cm-wide and 120 cm-deep soil profile was firstly excavated, and then holes were drilled at 10, 50, and 100 cm depth with an inclination between 15°-20° at the soil profile. Next, a total of 18 sensors (3 depths × 3 slope positions × 2 forest types) were carefully installed. Finally, soil was backfilled with the original soils layer by layer to maintain the original soil setting and minimum disturbance. The installation was finished at the end of October 2019.

2.3 Dye tracing experiments and image analysis

Dye tracing experiments. At the two study hillslopes, dye tracing experiments were conducted at downslope locations during summer 2020 using a double ring method (Fig. 4). A dye tracer solution (using Brilliant Blue FCF, 4g/L) was continually added to reach a constant head of 2 cm, and a total of 16 L solution was added for each experiment (Fig. 4). After four hours, the tracer completely infiltrated into the soil, and the soil profile was ready for excavation. The dye-stained area was separated into two sub-areas along the diameter of the outer ring (Fig. 4). Half of the dye area was excavated from 45 cm away from the diameter center to the double ring center for vertical dye photographs. The other half of the dye area was excavated from surface soil to deeper soil layer for horizontal dye photographs until there was no clear dye bule color in the soils. The excavation interval of soil profile was set to 5 cm. Dye photographs of soil profiles were photographed by a D700 camera (Nikon Corp, Japan).

Preferential flow imaging. Image processing was conducted based on the theory established by Flury (1994). First, a geometric correction was applied to eliminate geometric distortion caused by photographing. Second, color adjustment was applied to simplify image information and highlight the stained area. Third, RGB images were converted to grayscale images, and a threshold of the color scale was set to turn images into binary images with the stained area as black and unstained area as white, and the threshold was cross-validated. The following parameters derived from the dye tracing experiments were chosen for detection and quantification of PF patterns (van Schaik, 2009): (i) dye coverage (stained area divided by 30 cm×70 cm for horizontal photographs, 100 cm × 100 cm for vertical photographs), the best guess of total infiltration into the profile, where a higher infiltration capacity will result in a larger stained area; and (ii) the maximum depth of blue stains (MDS), the maximum penetration depth of water in the PF pathways. Here we took the total depth of the last stained soil layer visualized in the vertical soil profile as MDS.

2.3 Preferential flow occurrence

Throughfall measurements. Rainfall on the forested hillslopes was designated as throughfall, i.e., the effective throughfall reaching land surface after canopy interception. Five throughfall collection trenches (300 cm × 25 cm ×30 cm) were placed 1 m above the ground with slight inclination (less than 2°) to eliminate the non-uniform distribution of throughfall (Li et al., 2010). The outlet of the trench was connected to tipping buckets for throughfall amount measurement by pipes. T4e sensors and tipping buckets were all connected to CR1000 (Campbell Scientific Ltd, USA) for data collection, and data logger was programmed to record data every 15 mins to capture the dynamics of soil water potential. Recorded data during the growing season (May-September) in 2020 was used in our study, that was 6 months after the installment of sensors, and excluded possible disturbance and freezing damage during cold season (November-April).

Preferential flow quantification. The throughfall and soil moisture data at the 15-min time interval were used in PF analysis. Based on the response time series of sensors through the soil profile to a throughfall event, PF has been divided into two ways: (1) a non-sequential response to a throughfall event, where a deeper soil layer responds before shallow soil layers (Lin and Zhou, 2008), and this indicates rainwater bypassed the shallow soil layers and percolated into the deeper soils, (2) a rapid rainwater flux through the monitoring soil profile, characterized by a sequential response of sensors with depth at a velocity greater than measured K_s of adjacent soil layer (Beven and Germann, 1982; Flühler et al., 1996). A throughfall event was defined with a minimum depth amount of 1 mm. The end was defined as the last monitored response of a tipping bucket followed by 6 h with throughfall amount less than 0.2 mm of throughfall. Once the throughfall events were determined, if the soil water potential increased above the threshold (0.3 hPa), the response time of each sensor was recorded. Sequential and non-sequential responses were determined as follows (Fig. 5). Non-sequential responses (NSR) were defined when sensors responded *out of sequence;* where any deeper sensor responded earlier than the upper sensors (e.g., the 50 cm sensor showed a response before the 10 cm sensor). Sequential responses (SR) were defined when sensors responded *in sequence,* with the surface sensor responding first, then the next deeper sensor probe, and so on through all sensors in the soil profile. According to the PF definition, all NSR events and part of SR events were PF events. Further, the sum of PF events and SR events is referred to as total response events. The PF frequency was calculated by the following equation:

$$\text{PF frequency}=\frac{\text{PF events}}{\text{PF events+SR events}}*100\%$$

Factors controlling preferential flow. To explore potential factors that control PF occurrence, temporally varying factors including throughfall characteristics (total throughfall amount, throughfall duration, throughfall intensity, maximum throughfall intensity, throughfall skewness, kurtosis, and standard deviation) and initial soil water condition, and spatially varying factors including soil bulk density, soil porosity, SOM, clay content, rock fragment content, and root biomass were explored as potential controlling factors (Liu and Lin, 2015; Wiekenkamp et al., 2016; Guo and Lin, 2018). Statistical t-tests were used to compare factors and to generate hypotheses about their potential significance in generating PF. Factors for PF-producing events vs. SR-producing events were tested to indicate whether there were any significant differences ($P < 0.05$). When a t-test is significant, the factor analyzed is considered to influence PF processes (Liu and Lin, 2015). We further merged values of different slope positions into a group to explore differences at the hillslope scale.

3 Results

3.1 Soil properties of studied hillslopes

Many of the soil properties between the upper and deeper layers were significantly different ($P < 0.01$) in both forests. Results of basic soil properties indicated that the upper soil had higher SOM (mean value of 52.81 g/kg and 52.19 g/kg in the coniferous forest and broadleaf forest, respectively), lower bulk density (mean value of 0.89 g/cm^3 and 0.92 g/cm^3 in the coniferous forest and broadleaf forest, respectively) and more roots biomass (110.33 g and 215.33 g in the coniferous forest and broadleaf forest, respectively) in both forests. Moreover, the soil at the down slope position had the highest SOM content in both forests. K_s at upper soil layer was usually higher than that of the deeper soil layer, and K_s at upper soil layer showed considerable change even at nearby sites.

3.2 Preferential flow pathways revealed by dye tracing experiments

Dye photographs clearly showed important effect of roots and rock fragments on PF pathways (Fig. 6). For the horizontal dye patterns in the coniferous forest (Fig. 7), a sharp decrease of dye coverage was observed at 20 cm depth, where the existence of rock fragments drove water to flow through the soil-rock interface and bypassed soil matrix (Fig. 6c). Meanwhile, the surging increment of the dye coverage at 85 cm depth was likely due to small-sized rock fragments, where the dye solution flowed along lacunar pores and stained the surrounding soil matrix and rocks, leading to a larger stained area. In the broadleaf forest, a sharp increase of dye coverage was observed at 20 cm, where roots network drove water flow laterally and stained surrounding soils along the water flow pathways (Fig. 7), and then the dye coverage fluctuated at the depth between 20 and 50 cm, where the complex soil-root-rock structure change was observed during soil profile excavation. Below 50 cm depth, dye coverage decreased with the increase of soil depth.

For the vertical dye photographs, a similar decreasing trend of dye coverage from far to near the center of the dye ring was observed. In addition, soils in the broadleaf forest showed a higher dye coverage, and this indicated a more extensive lateral movement of the dye tracer than in the coniferous forest. Results also demonstrated that the broadleaf forest had faster water velocity and further flow distance compared with that in the coniferous forest (Fig. 8), because the topography of dye tracing experiment sites in two forests was similar.The maximum depth of stain (MDS) was 115 cm in the coniferous forest and 95 cm in the broadleaf forest. Soil profile excavation showed that the larger MDS in the coniferous forest was mainly controlled and regulated by large rocks at the deep soil layer where solution water flowed through the soil-rock interface to deep soil layer.

3.3 Individual throughfall events and general soil moisture conditions

Throughfall was characterized by long duration and low intensity in both forests. A total number of 70 and 45 throughfall events were delineated with an average duration of 27 and 21 hours, average throughfall intensity of 0.53 and 0.55 mm/h, mean total event precipitation amount 17.14 and 12.70 mm in the coniferous forest and broadleaf forest. Moreover, 44.3% and 46.7% of throughfall events had total event precipitation amount less than 5 mm in the coniferous forest and the broadleaf forest, respectively. There was no difference in the throughfall characteristics ($P > 0.1$) between the forest types. Soil water potential at 10 cm showed the largest variation compared to other depths during monitoring period in both forests. Soil water potential at 100 cm in the broadleaf forest experienced more intense variation compared with that in the coniferous forest, this indicated that intense interaction with throughfall in the broadleaf forest may be the result of frequent PF occurrence. It should be noted that the soil water potential in the studied period was in high water potential status regardless of forest types and depths (Fig. 9).

3.4 Preferential flow frequency and controlling factors

There were a total of 128 (including 17 sequential PF events) and 91 (including 11 sequential PF events) events identified as PF, accounting for 67.8% and 71.7% of total response events in the coniferous and broadleaf forests, respectively, indicating that PF occurrence was common in our study. The minimum PF frequency was found at the upslope sites (with 60.0% in the coniferous forest and 65.9% in the broadleaf forest), and the maximum PF frequency was found at the downslope site in both forests (with 74.6% in the coniferous forest and 79.1% in the broadleaf forest). Both forests showed an increasing trend of PF frequency from up to down slope sites (Fig. 10). Total throughfall amount and maximum throughfall intensity were identified as controlling factors on PF occurrence at the down slope sites in both forests. A higher throughfall amount (21.87 mm for PF vs. 8.60 mm for SR in the coniferous forest; 15.65 mm for PF vs. 3.73 mm for SR in the broadleaf forest) and higher maximum throughfall intensity (4.63 mm/h for PF vs. 2.54 mm/h for SR in the coniferous forest; 4.46 mm/h for PF vs. 2.38 mm/h for SR in the broadleaf forest) were observed. Throughfall duration in PF-producing events at the down slope site in the coniferous forest was much longer than that of SR events. Any initial soil water condition was not recognized as a controlling factor in both forests.

The response times of PF and SR events to throughfall events at different soil depths and forest types were compared (Fig. 11). There was no significant difference ($P > 0.05$) in response time at 10 and 50 cm between the coniferous and broadleaf forest. A significant difference ($P < 0.05$) in response time at 100 cm was observed with the mean value of 517 mins in the coniferous forest and 365 mins in the broadleaf forest. Mean PF frequency was 38.10% at the upper layer and 34.30% at the deeper layer in the coniferous forest, and 34.53% at the upper layer and 48.20% at the deeper layer in the broadleaf forest. There was an increasing trend of PF frequency of the deeper soil layer from up to down slope sites in both forests (Fig. 12). Temporally varying factors (throughfall characteristics and initial soil water conditions) were not identified as controlling factors of PF generation between soil layers, with the exception of initial SWP 50 cm at hillslope scale (Table 3).

4. Discussion

4.1 Spatial controlling factors of PF occurrence

The average PF frequency in the upper layer (10-50 cm) of the coniferous forest was 38.10%. This is comparable to results from the Wüstebach catchment dominated by Norway spruce (*Picea abies (L.))* and Sitka spruce (*Picea sitchensis*), where PF frequency ranged from 7% to 51%, and the maximum depth of sensor installation is 40 cm (Wiekenkamp et al., 2016). The average PF frequency in the broadleaf forest was 34.53%, which is similar to results observed at the deciduous Shale Hills forest in Pennsylvania, USA (ranging from 16% to 47%), where the deepest sensors are installed at a depth of 50 cm (Liu and Lin, 2015). In the upper soil layer (10-50 cm), the root network (see Fig. S1) and hydrophobicity caused by the SOM usually leads to high PF occurrence and subsurface flow in forest soils (Bogner et al., 2010; Alaoui et al., 2011; Gerke et al., 2015). A dense root network supplies abundant soil-root interphase and decaying root channels to favor PF occurrence (Gerke et al., 2015). Higher SOM at the upper soil layer results in a stronger hydrophobicity effect, and the formation of organic coating on soil aggregate makes soil hard to wet and forces water to converge into PF pathways (Nimmo, 2012; Gerke et al., 2015). The low clay content (< 4%) in this study, which was below the threshold of 8% for initiating and persisting macropore structures in soils (Koestel et al., 2012) for both studied forests, indicated that roots network constituted the main flow pathways (Bogner et al., 2010; Demand et al., 2019). Abrupt change of soil K_s in a short distance was observed in our study at the upper soil layer, which is also in favor of PF in soils (Kishel and Gerla, 2002). Further, smaller-sized rock fragments at the upper layer might not strongly affect water flow since these rocks and surrounding soils were completely stained (Hartmann et al., 2020). Significant difference in root biomass between forest types resulted in a slight discrepancy in PF frequency at the upper soil layer, and this indicated that PF occurrence is probably related to fine roots (Luo et al., 2019).

Within the deeper soil layer (50-100 cm), mean PF frequency was 35.43% in the coniferous forest, 48.20% in the broadleaf forest. Rock fragment content in the deeper layer showed no difference between forest types, whereas less soil porosity in the broadleaf forest had higher PF occurrence, this may be explained by the fact that PF in stony soils uses only a small fraction of porosity (Clothier et al., 2008; Jarvis et al., 2016). Another explanation may be the appearance of large rocks in both forest sites, which was not included in this study due to limited sampling scale and later elucidated by dye tracing experiments. Large rocks in the broadleaf forest experienced more severe weathering than the coniferous forest owing to a better thermal conditions resulting from its lower elevation, and more soil-rock interphase contributed to funnel flow (Cerdà, 2001; Sohrt et al., 2014; Hartmann et al., 2020). Overall, rock fragments are not a negligible component for PF occurrence, and appearance of rock fragments in deeper soils leads to continuous macropores and cracks (Zhang et al., 2016; Li et al., 2019).

Topographic effects on PF occurrence were evident in this study. An increasing trend of PF frequency from up to down slope sites was observed, similar to observations in other studies (P.Öhrström, 2002; Holden, 2009; Guo and Lin, 2018). The higher hydrophobicity caused by higher SOM, gentler slope and increased contributing area at down slope sites enhanced PF occurrence for both forest types (Hardie et al., 2011; Benegas et al., 2014; Guo and Lin, 2018). Topography seemed not to have an effect on the PF frequency at the upper soil layer in both forests (Fig. 12), the reason lies in the high heterogeneity of the upper soil layer. Moreover, the higher PF frequency in the deeper soil layer in the broadleaf forest may be attributed to more fragmented rocks, which leads to more lacunar pores when compared with the coniferous forest.

4.2 Temporal controlling factors of PF occurrence

Throughfall characteristics, especially its intensity, were believed to be the key factors controlling the PF occurrence (Green and Erskine, 2011; Liu and Lin, 2015; Hopkins et al., 2016; Demand et al., 2019; Tian et al., 2019), and we also found a positive relationship between throughfall intensity and PF frequency (Fig. S2). Total throughfall amount and maximum throughfall intensity were identified as controlling factors on PF ($P < 0.05$) at the down slope sites in both forests (Graham and Lin, 2011; Liu and Lin, 2015). A possible explanation for the observed phenomena may be the combined effect of topography and throughfall, because throughfall with long duration and low intensity tends to moisten soil more uniformly, and this was the prerequisite of subsurface connectivity. Besides, gentler slope favors the formation of the transient water table at surface or layers with contrasting hydraulic conductivity and forces water flow into PF pathways at the down slope sites (Guo and Lin, 2018).

Initial soil water condition was not identified as a controlling factor in both forests, and this is consistent with Nimmo (2012), who argued that local saturation of soil was more likely to occur PF regardless of initial soil water condition. Similarly, Wiekenkamp et al. (2016) found no clear relationship between the PF frequency and initial soil water condition when rainfall amount was less than 25 mm, and Tang et al. (2020) found a significant difference in initial soil water condition at only one of three studied sites. Another explanation is that soil moisture showed slight fluctuation owing to plentiful and concentrated throughfall during the study period and was far from the threshold of influencing PF occurrence (Figure S3).

4.3 Integrating multiple methods for PF investigation

Soil moisture monitoring network has created new opportunities for detecting and quantifying PF with high spatial and temporal resolution. The method has the advantage of being noninvasive or minimally invasive compared with the traditional methods (e.g., Dye tracing), and is a real-time reflection of soil moisture to dynamic throughfall input.

And this has the potential to bridge the gaps between scales and to predict PF patterns in soils (Jarvis et al., 2016; Guo and Lin, 2018). Meanwhile, validation of PF information revealed by soil moisture monitoring network and possible PF flow pathways are essential for better understanding of PF.

Dye tracing experiments can supply two-dimensional images of spatial variations in water flow patterns at the pedon scale (Weiler and Flühler, 2004; Jarvis, 2007; Hartmann et al., 2020). Visualization of flow pathways is based on images information interpreted by photographing excavated soil profiles, and detailed soil profile information (e.g., soil structure, distributions of roots and rocks) can be observed and obtained at the same time to connect PF pathways with soil properties or soil structure (Holden, 2009; Gerke et al., 2015; Guo and Lin, 2018). Nevertheless, the dye tracing experiment obtained limited information about the real-time processes and its temporal dynamics, which can be compensated for with information gained by a soil moisture monitoring network. Thus, the combination of the two methods enables exploring the theoretical mechanisms of PF (Jarvis et al., 2016; Guo and Lin, 2018). For example, soil moisture monitoring revealed higher PF occurrence in the deeper soil layer at down slope position in the coniferous forest, while soil properties showed no dramatic difference among slope positions. Dye tracing experiment at down slope position revealed that the large rocks dispersed water flow through lacunar to deeper soil. The agreement between results derived from the soil moisture monitoring network and dye tracing method confirmed the effect of rock fragments on PF occurrence. Without the dye tracing experiment, soil moisture monitoring network cannot reveal the possible flow pathways and dye tracing experiments cannot link the lacunar (soil-rock interface) with PF frequency. Therefore, combining soil moisture monitoring network and dye tracing experiments enhances more reliable interpretation.

5. Conclusions

The hydrological process of PF is challenging to study, given the need to characterize vast heterogeneities in hydraulic properties of subsurface flow environments and changing environmental conditions over time. Our study integrated a soil moisture monitoring network and dye tracing experiments, providing an unprecedented view of PF pathways and frequency. Results showed that the root network and rock fragments are of importance in PF occurrence in forested hillslopes of the east Tibetan plateau. The frequency of PF was high in both the coniferous forest and broadleaf forest. In the upper soil layer, macropores created by the roots network are primary PF pathways and led to a high frequency of PF. PF frequency at deeper soil was mainly attributed to rock fragments through lacunar macropores (soil-rock interface). Further, PF tends to occur at down slope sites in both forest types, and this was attributed to gentler slope and larger contributing area of down slope sites. Total throughfall amount and maximum throughfall intensity were identified as key controlling factors on PF occurrence at the down slope sites in both forests. Initial soil moisture did not regulate PF occurrence in both studied forests. These results revealed potential subsurface flow through roots network in shallow soil, and rapid water flux through lunars in thick saprolite on forested hillslopes.

The integration of dye tracing experiments (which provides information on PF pathways)_and a high-frequency soil moisture monitoring network (which provides temporal dynamics and spatial variation of PF) is a promising way forward in the investigation of PF and its controlling factors under field conditions. Future directions toward the operational prediction of PF in forested landscapes might focus on the assimilation, synthesis, and integration of high-resolution data on climatic forcings (e.g., of precipitation and throughfall) and subsurface architecture and properties (e.g., of the distribution of pore spaces and characteristics of the porous media). This information, in turn, would be used in concert with a high-frequency soil moisture monitoring network to capture the dynamic field conditions (Guo and Lin, 2018). The time is ripe for such high-resolution studies at hillslope and watershed scales, given advances in characterizing surficial topography (Brubaker et al. 2013), scaling micro-CT analyses to field settings, and in geophysical characterization of deep critical zone structure using novel approaches (e.g., Flinchum et al. 2018, Oakley et al. 2021).

Conflicts of interest

The authors declare that they have no conflicts of interest.

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