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# Quantifying preferential flow occurrence in dependence of land cover on the southern slopes of Mount Kilimanjaro, Tanzania

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ABSTRACT

*Study regions:* This study examined preferential flow occurrence and patterns in eight ecosystem types on the southern slopes of Mount Kilimanjaro in Tanzania.

*Study focus:* We analyzed continuous soil moisture content measured in three soil depths and rainfall data at 1-h resolution from January 2022 to August 2023. After a separation and clustering of rainfall events we assessed the dynamics of soil moisture responses. The sequence and timing of soil moisture changes informed about the occurrence of preferential versus sequential (matrix) flow.

*New hydrological insights for the region:* The results showed that the frequency of occurrence of preferential flow events were notably high in *Erica* forest (81.6 %), montane forest (26.4 %), and *Ocotea* forest (30.1 %), highlighting rapid subsurface water movement and potential for groundwater recharge. Other land covers such as disturbed Ocotea forest, grassland and maize indicated more uniform flow dynamics, which may favor surface runoff and increased soil erosion. We found that rainfall depth, duration and intensity are important factors that influence preferential flow. Additionally, the level of initial soil moisture also played a role in preferential flow occurrence, with optimal initial soil moisture levels between 35 % and 45 %. Both, very dry and very wet soil conditions were less favorable for preferential flow occurrence. These findings have important implications for understanding subsurface water movements and managing water resources in both natural and disturbed ecosystems.

## 1. Introduction

Mount Kilimanjaro, Tanzania, is considered a 'water tower', where the lowlands are strongly dependent on (ground)water inputs from the uplands. The region features a remarkable diversity of land covers ranging from natural forests to agricultural lands (Hemp, 2006a), which significantly impacts soil hydrological processes, particularly preferential flow (PF), which refers to the rapid

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movement of water through macropores, root channels, or fractures in the soil, bypassing the general vertical flow through the soil matrix (Beven and Germann, 2013). PF is a common phenomenon in hydrology that influences soil moisture dynamics, nutrient transport, surface runoff generation, and ground water recharge (Wiekenkamp et al., 2016; Zhang et al., 2018). Understanding the PF occurrence in relation to different land covers types is essential for implementing effective water resource management and soil conservation strategies in this ecologically sensitive region.

PF occurrence is influenced by various factors including soil properties, such as texture, structure, bulk density, hydrophobicity, and organic matter content. But also processes such as soil wetting, desiccation, leaching and landscape characteristics like topography and lithology play a significant role, all of which are in turn affected by land use and land cover (Demand et al., 2019; Price, 2011). For instance, soils under natural forests typically exhibit more stable structures with higher organic matter content, which promote macropore formation and stability (Galindo et al., 2022), enhancing PF pathways (Benegas et al., 2014). Tang et al. (2020) observed substantial differences in PF occurrence depending on slope position and lithology. Overall, PF results in rapid infiltration and deep percolation of rainwater, reducing surface runoff and soil erosion (Germer et al., 2010) and promoting groundwater recharge (Cuthbert and Tindimugaya, 2011) which is vital for maintaining streamflow during dry periods. Plantations and agroforestry systems, managed land use types with structural similarities to natural forests, can help to preserve or re-establish soil structure and promote macroporosity. Consequently, PF remains relatively high in these systems compared to purely agricultural lands (Jacobs et al., 2022; Owuor et al., 2018; Zhu et al., 2019). Intensive agricultural practices, particularly those involving machinery, lead to soil compaction and the breakdown of soil aggregates. This reduces the number and connectivity of macropores, resulting in diminished PF and increased surface runoff and soil erosion, worsening water scarcity issues during dry seasons.

Temporal factors such as rainfall characteristics and initial soil moisture play a significant role in influencing the occurrence of PF. For instance, Liu and Lin (2015) highlighted the substantial impact of rainfall characteristics, including total rainfall amount and duration as well as initial soil moisture on PF occurrence. Demand et al. (2019) further emphasized the role of rainfall intensity in controlling PF occurrence. On the other hand, Wiekenkamp et al. (2016) found no clear relationship between PF frequency and initial soil water conditions. Similarly, Wang et al. (2022) reported that initial soil moisture conditions were not the key controlling factor for PF occurrence in the broadleaved and coniferous forests they investigated. These discrepancies in findings underscore the complexity of PF dynamics and suggest that the influence of temporal factors on PF occurrence may vary significantly across different environments. The mixed results from the above-mentioned studies highlight the need for further investigation in diverse climatic settings to better understand the controls of PF occurrence and dynamics. Particularly, there is a need to explore how different rainfall patterns and initial soil moisture conditions interact to influence PF in the regions that have been less investigated, such as the tropical and subtropical regions of Africa.

There is a wide range of methods for observing and quantifying PF, including image analysis methods, tracer studies, dye infiltration experiments, and soil physical methods (Allaire et al., 2009; Zhang et al., 2018). These methods provide insights into spatial and temporal dynamics of water movement through the soil, but often have some limitation. For instance, dye infiltration studies can visually demonstrate the presence and extent of PF pathways in different land cover types (Nespoulous et al., 2019; Wang et al., 2022), but can only be applied once as the soils must be excavated. Double ring infiltration measurements often require vast amounts of water (Owuor et al., 2018), and permeameter-type devices or lysimeters are expensive to install and time-consuming to maintain (Allaire et al., 2009). Furthermore, all of these methods are destructive or artificially enrich soil moisture to measure infiltration or PF potential. Tracer studies and infiltration or permeameter measurements also do not allow to infer on the relationship between rainfall intensity, duration, soil moisture content and PF as they provide a snapshot of the conditions under which the measurements were carried out. In the past decades, an indirect method to infer the existence of PF under in situ conditions based on changes in continuously measured soil moisture profiles has become popular (e.g. Demand et al., 2019; Graham and Lin, 2011; Lin and Zhou, 2008; Wiekenkamp et al., 2016). This method is based on the analysis of response patterns of soil moisture to rainfall events. A sequential response from one soil layer to the next indicates matrix-based flow conditions, while a more rapid reaction of soil moisture in lower soil depths as compared to the above soil layers indicates some sort of bypass or PF (Lin and Zhou, 2008). Continuous measurements of soil moisture over a long time allow to derive the effects of weather patterns or changes in soil structure due to land use, cover and management changes and their impact on PF occurrence.

Despite its importance, the quantification of PF remains challenging, particularly in diverse and variable environments such as those in Sub-Saharan Africa. While significant advancements have been made in understanding PF dynamics and controls in regions such as Europe (Demand et al., 2019; Wiekenkamp et al., 2016), North America (Lin and Zhou, 2008; Liu and Lin, 2015; Tang et al., 2020) and Asia (Hu et al., 2019; Wang et al., 2022). A substantial research gap exists in tropical regions, particularly in Sub-Saharan Africa where unique vegetation types, climatic conditions, and soil properties remain underexplored. The scarcity of studies in this region, especially in areas with poor infrastructure or harsh environmental conditions underscores the need for focused investigation PF processes.

This study addressed this gap by expanding research on PF to the tropical and montane ecosystems of the Sub-Saharan Africa, specifically on the southern slopes of Mount Kilimanjaro. The region encompasses a diverse range of forest types and land cover classes, from low elevation agricultural lands and grassland to montane forests, subalpine *Erica* forest and alpine *Helichrysum*. The study not only broadens the range of forest and land cover types analyzed for PF dynamics, but also provides a unique perspective on the interactions between PF occurrence and rainfall characteristics, offering valuable insights into their role in shaping subsurface hydrological processes. Most existing studies quantify PF by the analysis of soil moisture responses across only a few land cover types, limiting the generalizability of their findings to landscape scales. For example, Demand et al. (2019) examined PF in forest and grassland, emphasizing the spatial heterogeneity and temporal variation in PF processes, but restricted to just two land cover types. In contrast, our study investigates multiple land use and cover types across varying climatic settings, offering a more comprehensive understanding of PF occurrence and patterns across the landscape. By focusing on this underrepresented region, our study offers more robust and generalizable insights into PF processes and the critical role of diverse land covers in shaping hydrological dynamics in underrepresented tropical landscapes.

## 2. Methods

### 2.1. Study site

This study was conducted on the southern slopes of Mount Kilimanjaro, located in the northeastern Tanzania near the border with Kenya. The study area lies between latitudes 3°02’ to 3°25’S and longitudes 37°02’ to 37°43’E (Fig. 1). Mount Kilimanjaro, the highest mountain in Africa, stands at an elevation of 5895 m above sea level (a.s.l.). It is characterized by a unique range of ecosystems with diverse land cover types and a sharp elevation gradient. The lowland savanna plains, occurring at elevations ranging from 700 to 1100 m a.s.l., are characterized by light tree cover dominated by *Acacia*, *Grewia* and *Combretum* genera This zone is also used for agricultural production, particularly for maize, beans and sunflowers (Hemp, 2006). The submontane zone, between 700 and 1700 m a.s.l., consists of traditional home gardens, grasslands and coffee plantations. The home gardens have a multi-layered vegetation structure similar to lower montane forests, including trees, shrubs, lianas, epiphytes and herbs. Many trees are remnants of the former forest cover. Underneath the trees, bananas, coffee, taro and beans are grown, as well as other crops for food or fodder for livestock (Hemp, 2006). In contrast to the home gardens, commercial coffee plantations are managed more intensively and represent a monoculture type of agroforestry system, where coffee is grown under a sparse tree layer. The grasslands are former forest areas which were converted for grazing or mown for livestock fodder. Soils in the lowlands are predominantly Vertisols, which become very hard and crack when dry. These cracks allow for rapid initial infiltration, but infiltration rates reduce drastically once the surface soil is thoroughly wetted. This could result in flooding and surface runoff. In the lowland savannah plains, Cambisols also occur, which generally have a good water holding capacity and internal drainage due to high porosity.

The lower montane forests, ranging from 1700 to 2100 m a.s.l. and the montane zone, between 2100 and 2800 m a.s.l, experiences persistent cloud condensation, resulting in high precipitation and humidity. Lower montane forests have a different composition than

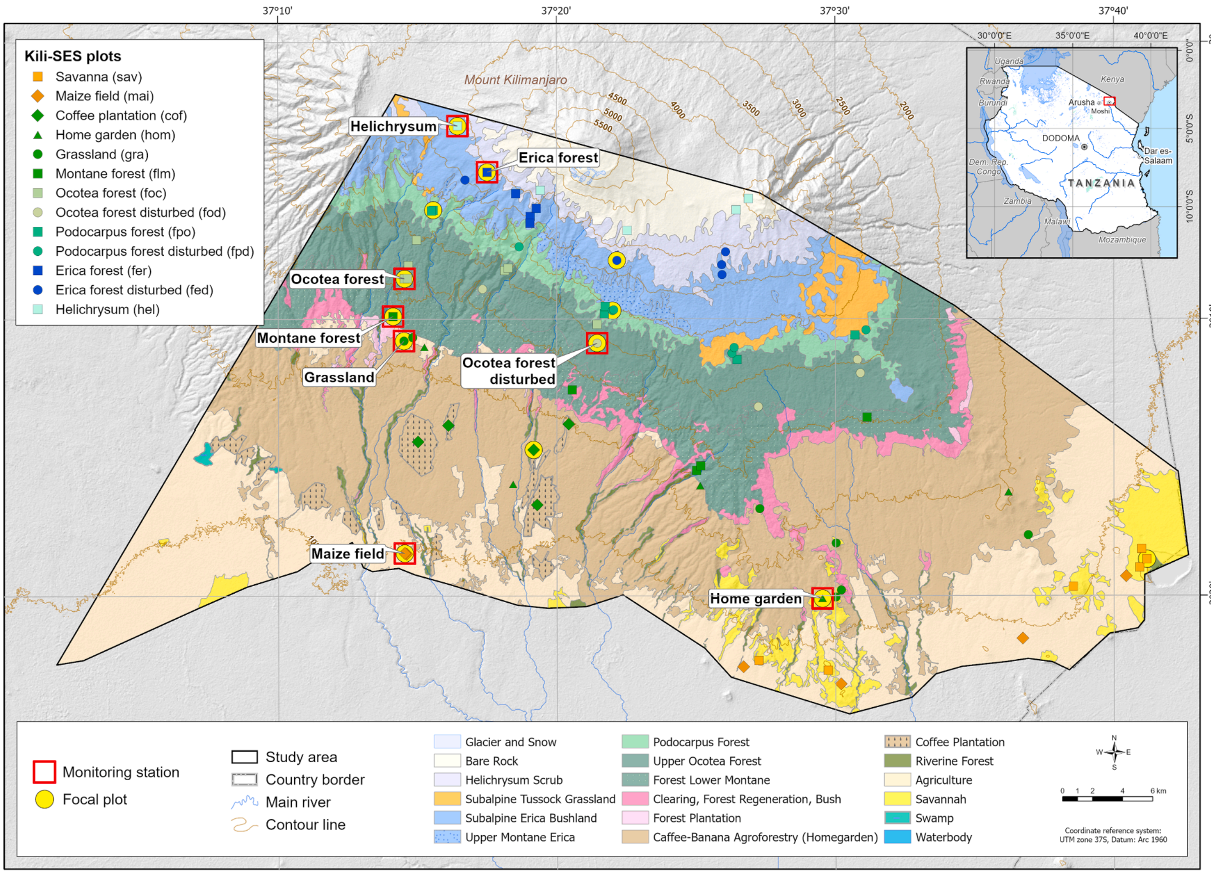


**Fig. 1.** An overview of the study area, showing the location of 64 Kili-SES plots across 13 land cover types from Hemp et al. (2017). The red rectangles represent the 8 rainfall and soil moisture monitoring stations used for this study.

the forests at higher elevations. The lower montane forest is dominated by the genera *Newtonia*, *Strombosia*, *Entandrophragma* and *Macaranga* (Rutten et al., 2015). At higher elevation, *Ocotea usambarensis* dominates, hence the naming '*Ocotea* forest'. In some areas, these forests have been disturbed through selective logging, as the tree species has a high commercial value (Rutten et al., 2015). At higher elevation, many trees are covered in epiphytes, which contribute to rainfall or fog water retention in the vegetation layer before reaching the soil. Forests in the lower montane and montane zones grow on Andosols, which are characterized by excellent drainage and high water holding capacity, because of their high porosity. Dried out Andosols, for example where the forest cover has been reduced, might have a lower water holding capacity and might be more susceptible to erosion.

The upper montane zone, from 2800 to 3200 m a.s.l., is dominated by *Podocarpus* forests. As elevation increases, the land cover changes to subalpine *Erica* forests, the highest elevation forests of Africa, and alpine *Helichrysum* vegetation at elevations between 3200 and 4000 m a.s.l., and finally the upper alpine zone, characterized by bare soil which extends to the mountain's glaciated peak (Hemp, 2006). Whereas the *Erica* forests are also characterized by Andosols, higher elevation land cover types are associated with Leptosols, which are shallow and contain little fine earth. These soils are generally free draining, but their water holding capacity is limited due to their shallowness and/or stoniness.

The area experiences a unique climate profile characterized by a bimodal rainfall pattern, with two rainy seasons. The first rainy season, known as *Vuli* occurs from October to December, followed by a brief dry spell spanning the months of January to February. Subsequently, the long rainy season, referred to as *Masika*, extends from March to May, before yielding to an extended dry period spanning June to September (Appelhans et al., 2016; Røhr and Killingtveit, 2003). The steep elevation gradient significantly influences the local climate, leading to considerable variations in mean annual rainfall amounts. These range from approximately 800 mm at the foothills, increasing with elevation to about 2700 mm within the lower montane forest zone, and subsequently decrease to around 500 mm within the upper alpine zone (Hemp, 2006). Similarly, the mean annual temperature exhibits a wide range, from 23°C at the lowland to sub-zero temperatures, dropping to −7°C at the Uhuru peak (Appelhans et al., 2016; Hemp, 2006). These climatic variations have significantly impacted and transformed the local volcanic soils, resulting in noticeable alterations and the formation of distinct soil types (Table 1).

This study is part of the German Research Foundation (DFG) funded research unit 5064 "*The role of nature for human well-being in the Kilimanjaro Social Ecological System (Kili-SES)*" and therefore, it utilizes a network of pre-established study plots. A total of 64 plots on 13 different land cover types were established along an elevational gradient from 870 to 4550 m a.s.l (Hemp et al., 2021). There are 5 plots per land cover type, except for the fire-disturbed and undisturbed *Erica* forests which have 3 and 4 plots, respectively. Coffee plantations and alpine vegetation, on the other hand, have 6 plots each. For each land cover type, one focal plot has been identified as representative of the land cover type, and most of the research is carried out on this subset of plots (Fig. 1). To be able to understand the PF dynamics across the landscape of the southern slopes of Mount Kilimanjaro, we selected 8 focal plots that represent the full climatic and vegetation gradient for the study area.

### 2.2. Field measurements

#### 2.2.1. Soil moisture measurements

Soil moisture has been monitored with an automatic soil moisture sensor network installed at eight focal plots (Table 1) starting in November 2021. At each station, three capacitance-based soil moisture sensors (TEROS 10; Meter Group, Inc. Pullman, WA, USA; with 0.001 $m^3/m^3$ resolution and ± 0.03 $m^3/m^3$ accuracy) were installed at depths of 10, 30 and 60 cm below the soil surface. The sensors measure and record volumetric water content ($m^3/m^3$) using a connected data logger (METER ZENTRA series, ZL6 basic, Meter Group, Inc. US Pullman, WA) at 1-h intervals. Before sensor installation, default factory calibration was adopted, and sensors were verified for their proper functioning and accuracy using the TEROS verification clip by checking if they were measuring within the manufacturer's expected range (0.356–0.419 $m^3/m^3$). The sensors were installed in a vertical array with the sensor body in a horizontal position from a hand-dug hole to a depth of the deepest sensor (60 cm). The sensors were installed on the sidewalls in undisturbed soil. After installation, the hole was carefully backfilled using the excavated soil to avoid dislocating the sensors. Data analysis began two months after installation in January 2022 to allow the soil to settle and recover from potential disturbance caused by the installation.

**Table 1**
Site characteristics of the analyzed monitoring stations with, mean annual rainfall (MAP) and temperature (MAT) data from three altitudinal transects within the study area covering the period 2011–2013 (Appelhans et al., 2016)[a]. Dominant soil type and soil texture at a soil depth of 0–10 cm for the eight land cover types investigated in this study (Guetlein, 2020; Gütlein et al., 2018; Kühnel et al., 2014)[b].

| Stations ID | Land cover type | Elevation (m a.s.l) | MAP[a] (mm) | MAT[a] (°C) | Soil type[b] | Soil texture[b] (%) sand/silt/clay | Available data (%) |
|---|---|---|---|---|---|---|---|
| mai0 | Maize field | 1009 | 1100 | 23 | Vertisol cambisol | 52/24/24 | 99.8 |
| hom4 | Home garden | 1275 | 1600 | 19 | Sodic vertisol | 6/37/57 | 99.4 |
| gra0 | Grassland | 1732 | 1900 | 19 | Vertisol | 20/63/17 | 95.4 |
| flm1 | Montane forest | 1920 | 2500 | 16 | Umbric andosols | 21/60/19 | 94.3 |
| foc1 | *Ocotea* forest | 2120 | 2600 | 12 | Umbric andosols | 11/51/38 | 97.6 |
| fod2 | *Ocotea* forest disturbed | 2470 | 2300 | 12 | Umbric andosols | 21/49/30 | 99.3 |
| fer0 | *Erica* forest | 3956 | 600 | 6 | Melanic andosols | 48/43/9 | 100 |
| hel1 | *Helichrysum* | 3880 | 800 | 4 | Andic leptosol | 28/58/14 | 100 |

#### 2.2.2. Rainfall measurements

Due to the high variability in rainfall distribution within the study area (Appelhans et al., 2016; Hemp, 2006; Røhr and Killingtveit, 2003), rainfall data were monitored at each soil moisture monitoring stations to account for its spatial variability and provide precise spatial matching data for the analysis of rainfall events to changes in soil moisture. A 7043-type tipping bucket rainfall gauge (Theodor Friedrichs, Germany) with a sampling area of 214 $cm^2$ and resolution of 0.2 mm per tip, was used to automatically record and store rainfall data at 10-minutes temporal resolution with an inbuilt data logger (Tinytag TGRP-1200, Gemini Data Loggers, Chichester, UK). The rain gauges were installed at a height of 1 m above the ground on a solid metal post next to the soil moisture logger systems.

### 2.3. Data pre-processing

For this study, we used soil moisture and rainfall data for the period between 1 January 2022 to 31 September 2023. To ensure that the data collection process was accurate and reliable, we inspected our monitoring stations at fortnightly intervals to detect any technical problems and maintain cleanliness, particularly for stations located in forested areas. Gaps (1 hour to 22 days) in the available data time series resulted from clogged rain gauges, soil moisture sensor's malfunction due to disconnected sensors, dead batteries, or damaged cables by rodents. The station in the montane forest had most data gaps, resulting in data being available for 94.3 % of the time (Table 1). The dataset for the stations in the *Erica* forest and *Helichrysum* was complete (100 %). A time series of each station is provided in the Supplementary Material (Figure S2).

In order to align the rainfall data with the soil moisture data and for direct comparison of the datasets, we aggregated 10-minutes rainfall data to 1-h intervals. All data were visually checked to identify suspicious or inaccurate measurements. Cross-referencing rainfall data with their corresponding soil moisture measurements helped to detect inaccurate records, for example in cases where soil moisture indicated wetter conditions than what the rainfall data suggested.

To identify data gaps arising from clogged rain gauges, we used soil moisture data to detect the potential timing of the missed rainfall event and adopted an interpolation method recommended by Røhr and Killingtveit (2003) to fill in the missing data points. The method utilizes information from neighboring stations for filling missing rainfall data using normalized parameters which are a function of elevation. Moreover, we systematically eliminated any spikes in soil moisture data, particularly those occurring within a short time frame (less than 3 h) without corresponding rainfall data. The resulting gaps from the eliminated values were filled using linear interpolations.

### 2.4. Data analysis

#### 2.4.1. Rainfall event separation

Rainfall data was separated into individual events through a python-based script developed by the authors based on established methods (Graham and Lin, 2011; Wiekenkamp et al., 2016; Demand et al., 2019; Liu et al., 2020; Hu et al., 2019 and Tang et al., 2020). The method separates rainfall events based on a combination of two thresholds: a minimum rainfall amount ($P_{\min}$) and a specific duration of time without rainfall ($t_{wr}$). A rainfall event starts when $P_{\min}$ is recorded in a fixed time window (e.g., 1-h) and ends when $t_{wr}$ has elapsed without recording any $P_{\min}$. To align with the objective of this study, we filtered rainfall events that resulted in an increase of the soil moisture content above a certain threshold $\Delta\theta$ and checked whether the soil moisture increased at one of the sensors. The soil moisture threshold $\Delta\theta$ was set to 1 vol% (Demand et al., 2019; Kang et al., 2023).

To identify the best rainfall thresholds for this study, we conducted a sensitivity analysis as recommended by Urgilés et al. (2021). We varied $P_{\min}$ in a range from 0.2 mm to 2 mm and $t_{wr}$ from 1 to 36 h and kept $\Delta\theta$ fixed at 1 vol% in line with previous studies (Demand et al., 2019; Lin and Zhou, 2008; Liu and Lin, 2015; Liu et al., 2020; Singh et al., 2021; Wiekenkamp et al., 2016). Based on the sensitivity analysis, we used thresholds of $P_{\min} \geq 1$ mm and $t_{wr} = 12$ h.

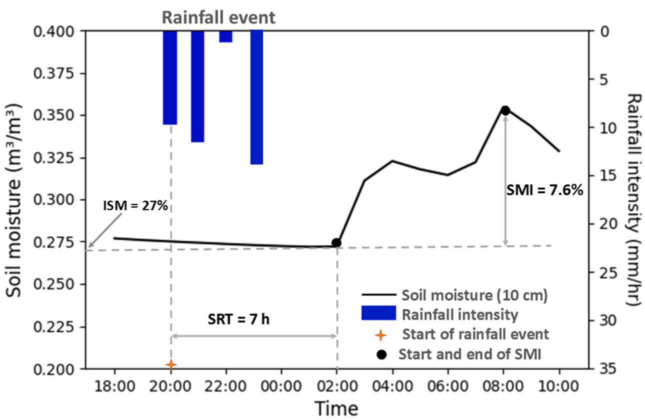


**Fig. 2.** Illustration of soil moisture metrics in responses to rainfall events determined in this study. ISM = initial soil moisture content; RST = soil moisture response time; and SMI = soil moisture increase.

After rainfall events were successfully separated, we determined specific characteristics for each individual event, including event total rainfall depth (mm), its duration (h) and mean intensity (mmh$^{-1}$). Finally, we utilized the *k*-means clustering method to categorize the events into clusters with similar rainfall characteristics. More details on the *k*-means methodology can be found in Urgilés et al. (2021).

#### 2.4.2. Soil moisture responses

We examined soil moisture responses across all sensors in the soil profile during the identified rainfall events. We identified four key soil moisture response metrics to understand the relationships between rainfall and soil moisture dynamics, (Fig. 2). The soil moisture response percentage (RSP) is the fraction of events that generates a detectable response. The initial soil moisture content (ISM) is the minimum soil moisture content 2 h before and after the start of the rainfall event. The soil moisture response time (RST) is the duration between the start of rainfall event and time when soil moisture shows a detectable response (Singh et al., 2021; Tian et al., 2019). The soil moisture increase (SMI) is the sum of soil moisture increment during a soil infiltration process (Tian et al., 2019). We used RST to estimate the occurrence of preferential flow, RSP, ISM to and SMI to explore the soil moisture dynamics, and ISM to investigate the control of PF.

The soil moisture metrics were further analyzed separately for each rainfall event cluster to understand the patterns and variations in soil moisture dynamics corresponding to different rainfall characteristics. This approach allowed us to explore how soil moisture responds within each rainfall cluster. Finally, we compared the soil moisture response metrics across land covers to gain an understanding of potential influences of land cover on soil moisture dynamics and preferential flow conditions.

#### 2.4.3. Occurrence of preferential flow

The occurrence of preferential flow was detected by analyzing the sequence of soil moisture response times when passing through the soil profile following a corresponding rainfall event, in line with previous studies (Demand et al., 2019; Graham and Lin, 2011;

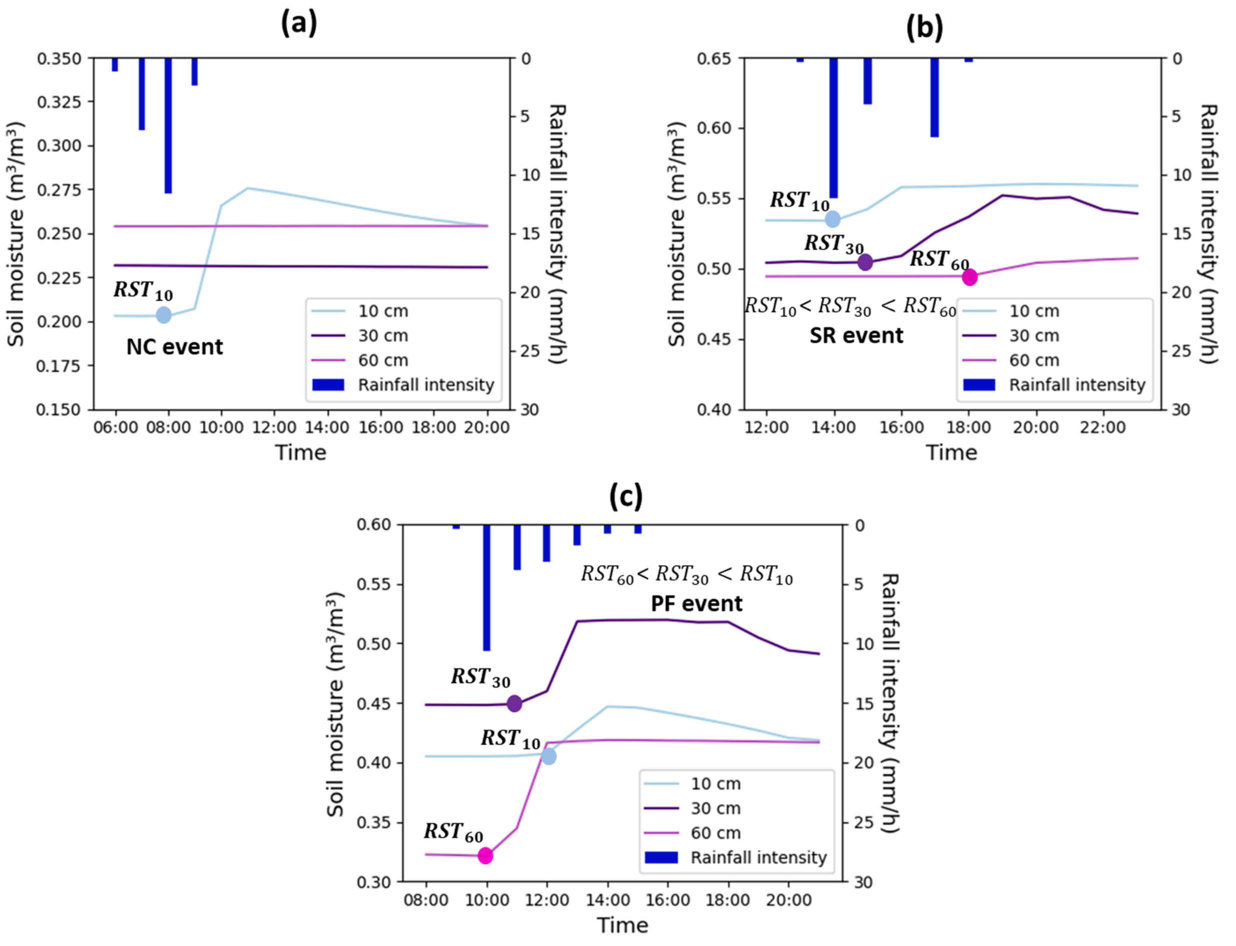


**Fig. 3.** Examples of soil moisture responses: (a) not classifiable (NC) if soil moisture response was only detected in the upper soil layer. (b) sequential response (SR) if soil moisture response was detected in the upper sensor down to the bottom sensors in sequence, (c) preferential flow (PF) if soil moisture response was detected in deeper soil layer earlier than shallow soil layer(s). RST = soil moisture response time.

Kang et al., 2023; Lin and Zhou, 2008; Liu and Lin, 2015; Tang et al., 2020; Wang et al., 2022; Wiekenkamp et al., 2016, 2020). For each rainfall event, the RST was determined and classified for each soil moisture sensor. If the soil moisture response was only detected in the upper soil layer (10 cm), we classified the response as *not classifiable* (NC) (Fig. 3a). When the soil moisture response was detected in the upper sensor down to the bottom sensors in sequence, the response was classified as *sequential response* (SR) (Fig. 3b). Any other response pattern (e.g., deeper sensor responding earlier than sensor(s) above it) was considered a *preferential flow* (PF) event (Fig. 3c). The frequency of occurrence of each flow type for each monitoring station was calculated as the ratio of number of events under each flow type to the total number of rainfall events identified.

#### 2.4.4. Land cover influence on preferential flow

As the land cover types occur along an elevational and therefore climatic gradient, different land cover types are associated with different rainfall characteristics (amount, duration and intensity). Therefore, the analysis further assessed the impact of land cover and its associated rainfall characteristics on PF by first assessing the characteristics of both rainfall events and soil moisture dynamics, and then comparing the derived rainfall characteristics, soil moisture metrics as well as PF patterns across the different land cover types.

#### 2.4.5. Statistical analysis

A normality test was first conducted to assess the distribution of data within each depth and land cover type using the Shapiro-Wilk test. If the data was found to be normally distributed ($p \geq 0.05$), a one-way analysis of variance (ANOVA) was employed to assess the statistical differences within depths and between land cover types. When a significant different ($p < 0.05$) was observed, Tukey's HSD test with significance level of 5 % was subsequently used to compare the means across soil layers and different land cover types. For non-normally distributed data ($p < 0.05$), a non-parametric Kruskal-Wallis test was performed instead of ANOVA, followed by pair-wise comparisons using Dunn's test. All analyses were performed using python-based script developed by the authors.

## 3. Results and discussion

### 3.1. Rainfall events and characteristics

We identified a total of 595 rainfall events across all sites that resulted in an increase of soil moisture content exceeding 1 vol% over the study period. The analysis of rainfall events across various land cover types revealed a distinct pattern along the elevation gradient. Fewest rainfall events, about 35 were observed at the maize field in the lowlands. The number of events gradually increased with 58, 86 and 87 events recorded in home garden, grassland, and montane forest, respectively. More rainfall events, totaling 113 events, were observed at the station located within the *Ocotea* forest. Subsequently, a decreasing trend was noted, with the *Ocotea* forest disturbed and *Erica* forest recording 67 and 103 events, respectively, while the *Helichrysum* station in the upper alpine zone registered 46 events (Table 2). The observed patterns are consistent with the documented rainfall distribution in the study area as outlined by Appelhans et al. (2016) and Røhr and Killingtveit (2003). Røhr and Killingtveit (2003) established an elevation-based rainfall function, revealing the peak rainfall occurrence at about 2200 m a.s.l. This finding closely resembles the findings of Appelhans et al. (2016) who reported a linear increase in rainfall reaching its peak at 2200 m a.s.l., followed by slightly exponential decrease with increasing elevation. Mid-elevation precipitation peaks have also been observed on other tropical mountains, depending on the prevailing air flow, vertical distribution of atmospheric moisture and atmospheric conditional instability (Anders and Nesbitt, 2015).

The analysis of rainfall events characteristics revealed significant variations in the rainfall events' total depth, duration, and intensity across different land cover types. Specifically, the events' total varied notably between land cover types (Fig. 4a), with grassland showing the highest median depth at 20.8 mm and the greatest variability. *Helichrysum* and *Erica* forest recorded a significantly lower median depth with 4.0 mm and 9.4 mm respectively, and with less variability. Rainfall duration also showed significant variation (Fig. 4b), with grassland and montane forest experiencing the longest median durations of 8.0 h, while the *Erica* forest and

**Table 2**
Distribution of rainfall events and their characteristics, including the median values for event rainfall depth (mm), duration (h) and intensity (mm $h^{-1}$) at each monitoring station and within each cluster group.

| | | Number of rainfall events | Events depth (mm) | Events duration (h) | Events intensity (mm $h^{-1}$) |
|---|---|---|---|---|---|
| STATION | Maize field | 35 | 16.0 | 5 | 3.7 |
| | Home garden | 58 | 23.7 | 6 | 3.6 |
| | Grassland | 86 | 20.8 | 8 | 3.6 |
| | Montane forest | 87 | 19.4 | 8 | 2.9 |
| | *Ocotea* forest | 113 | 17.0 | 5 | 3.3 |
| | *Ocotea* forest disturbed | 67 | 16.2 | 5 | 3.3 |
| | *Erica* forest | 103 | 9.4 | 4 | 2.6 |
| | *Helichrysum* | 46 | 11.4 | 4 | 2.5 |
| CLUSTER | I short-light | 371 | 10.0 | 4 | 2.6 |
| | II long-light | 105 | 43.8 | 19 | 2.2 |
| | III short-heavy | 84 | 22.1 | 2 | 10.5 |
| | IV long-heavy | 35 | 155.2 | 55 | 2.7 |

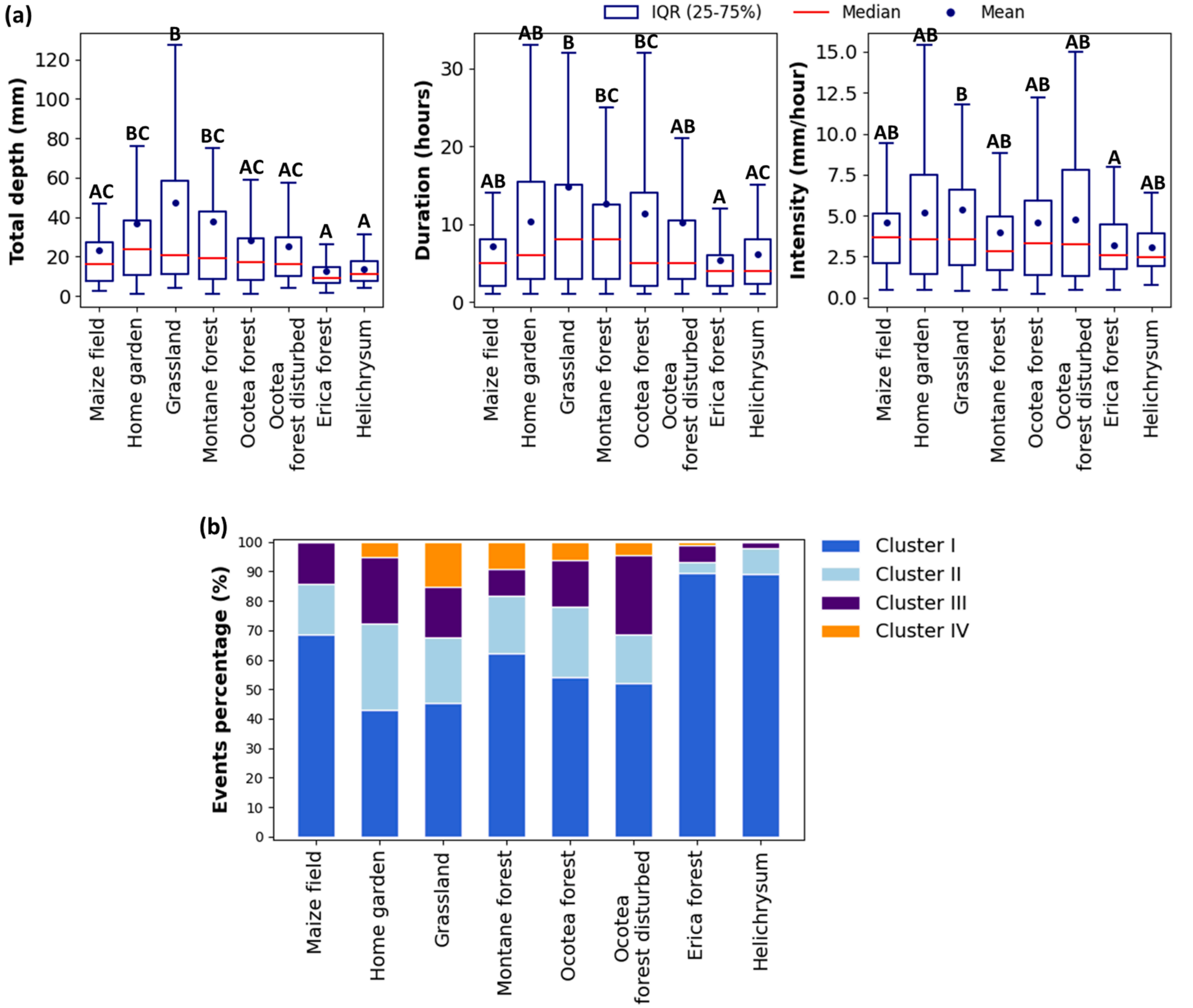


**Fig. 4.** Distribution of rainfall event characteristics: (a) total depth, (b) duration and (c) intensity., Boxes with no letter(s) in common indicate a significant difference in rainfall characteristics between land cover types (α<0.05). (d) Number of rainfall events in percentage by clusters and land cover types. Cluster I = short light; Cluster II = long light; Cluster III = short heavy; Cluster IV = long heavy; IQR = interquartile range.

*Helichrysum* both had the shortest median durations (4.0 h each). There was no significant difference observed in rainfall intensity for most land cover types, except between *Erica* forest and grassland (Fig. 4c). The significant difference in rainfall characteristics across different land cover types is likely to be related to the complex topography that, determines spatiotemporal rainfall patterns along steep elevation gradients (Roe, 2005). This complexity leads to high spatiotemporal variability, which is difficult to capture with a single rain gauge.

The rainfall events clustering indicated that rainfall in the study area was predominantly characterized by events with short duration and low intensities (cluster I) (Fig. 4d). The frequency of occurrence of these events ranged from 43.1 % in the home garden to 89.0 % in both *Helichrysum* and *Erica* forest stations. Long light rainfall events (cluster II), characterized by low-intensity rainfall occurring over a long-time interval, accounted for 3.9–29.3 % of the total events. Additionally, between 1.0 % and 26.9 % of events exhibited short periods of intense rainfall (cluster III). These rainfall events mostly occurred in the *Ocotea* forest disturbed (26.9 %), home garden (22.4 %), and grassland (17.4 %), while prolonged heavy rainfall events (cluster IV) were rarely observed. They occurred mostly in grassland (15.1 %) and ranged from 0.0 % to 9.2 % in other stations. Notably, the maize field in the lowlands and *Helichrysum* in the upland recorded zero events of this type (Fig. 4d).

### 3.2. *Soil moisture response patterns*

#### 3.2.1. *Soil moisture response percentage*

The analysis of soil moisture response to rainfall events yielded significant variations across depths and land cover types. The soil moisture response percentage (RSP), i.e., the proportion of events that produced a detectable soil moisture response, showed a decreasing trend with increasing depth. Most land cover types exhibited higher RSP values ranging between 69 % and 100 % at a shallow depth of 10 cm. In contrast, at deeper depths of 30 cm and 60 cm, the RSP values ranged between 51 % and 96 %, and between 29 % and 83 %, respectively, for all land cover types. The only exceptions were observed in the *Erica* forest and *Ocotea* forest, which displayed a higher RSP (83 %) at 60 cm depth and 93 % at 30 cm depth compared to 10 cm depth (69 % in *Erica* and 89 % in *Ocotea*), respectively (Table 3). This suggests the occurrence of rapid infiltration, bypassing the shallow soil layer along cracks or tree roots and only resulting in increases in soil moisture in deeper soil layers. Another explanation might be the saturation of the top soil, inhibiting a further increase in soil moisture content and change in RSP during rainfall events. The latter is particularly likely in the *Ocotea* forest, where soil moisture content was generally high in the topsoil (Fig. 5). The general results of this study align with findings from Singh et al. (2021), where they noted that the soil moisture response percentage was higher at shallow soil depths (10–30 cm) and decreased response was observed at deeper depths for most land cover types they examined. Also Tian et al., (2019) reported the highest frequency of soil wetting events at upper soil layers, decreasing with depth across different land cover types.

### 3.2.2. Initial soil moisture

Generally, initial soil moisture (ISM) varied significantly across the different land cover types and soil layers (Fig. 5). Deeper soil layers had significantly higher values of initial soil moisture (ISM) compared to shallow soil layers for most land cover types, except for *Ocotea* and *Erica* forest, where higher ISM values were observed in the shallower (10 cm) and medium (30 cm) depths, respectively (Fig. 5). Ocotea forest and Ocotea forest disturbed both showed high ISM values across all depths. However, the *Ocotea* disturbed forest showed significantly lower ISM compared to natural *Ocotea* forest, indicating potential impacts of disturbance on soil moisture dynamics. Similar differences in soil moisture between secondary and mature forests were observed on the south-western slopes of Mt. Kilimanjaro, which was attributed to differences in soil texture and its influence on soil water storage (Schrumpf et al., 2011). Lower water holding capacity in Andosols is often attributed to reduced soil organic carbon content, but both land cover types had similar soil organic carbon content according to Cornejo et al. (2023). Also, the disturbed *Ocotea* forest has a higher stem density and leaf area index (Cornejo et al., 2023), which could lead to higher interception and less water reaching the soil, as was observed for secondary forests (Schrumpf et al., 2011).

The median ISM levels at different soil depths on the southern slopes of Mount Kilimanjaro aligned with the rainfall pattern. Stations at lower altitudes (maize field) had lower values of median ISM of 26.7 % at 10 cm depth, which increased to a median of 33.6 % at 60 cm depth in the home garden and gradually increasing with elevation and reaching peak at the *Ocotea* forest station. Beyond this point, ISM declined as the altitude increased, with *Helichrysum* showing the lowest ISM at 10 cm depth (Fig. 5). The observation of high ISM in the natural forests and relatively low in the disturbed forest and agriculture land covers (grassland, home garden, and maize field) are similar to the findings of Owuor et al. (2018) who reported high water content in native forests compared to large scale commercial plantations and small-scale agricultural lands. The pattern also coincides with changes in soil organic carbon content, which can improve the water holding capacity of soils, along the elevation gradient, where highest concentrations were found around 3000 m a.s.l. (Zech et al., 2014).

### 3.2.3. Soil moisture response time

The soil moisture response time (RST) ranged from 0 to 27 h (Fig. 6). In most land cover types, there was a significant increasing trend in RST with depth indicating that it took longer for the soil moisture to respond at deeper depths. These findings align with a previous study (Tian et al., (2019), which also observed that the soil moisture response time increased with depth for variousl land cover types, except for high coverage grassland, where the increase was statistically insignificant. These differences could be due to variations in root systems, vegetation structure and climatic conditions between the land cover types. In the *Erica* forest, there was no significant difference in RST across depths (Fig. 6), implying a relatively uniform response irrespective of depth under this land cover. This is reflected in the significantly shorter RST at 30 and 60 cm depth compared to other land cover types and also aligns with the previous observation of higher RSP in deeper soil layers in the *Erica* forest, related to flow bypassing the topsoil. This finding is similar with the observation made by Singh et al. (2021), who found a non-linear increase in initial soil response time for some specific land covers, indicating the presence of PF pathways. Li et al. (2015), reported that soil moisture content at deeper soil layers of forested land responded to rainfall events before the upper soil layers except for the 10 cm depth, and the phenomenon was used as evidence to determine the occurrence of PF in the soil.

The RST also showed greater variability with increasing depth (Fig. 6), indicating a more varied response in deeper soil layers for most land covers. The median RST was relatively shorter (between 2 and 3 h) at shallower depths for all land cover types, and longer (5–12 h) at deeper depths (60 cm), except for the Erica forest. There was no significant difference ($p > 0.05$) in RST at 10 cm between land covers (Fig. 6), suggesting that the upper soil layer's response to rainfall events is relatively the same across different land cover

**Table 3**
Response percentage (%, RSP) at each soil layer and land cover.

| Soil layer depth | Maize field | Home garden | Grassland | Montane forest | *Ocotea* forest | *Ocotea* forest disturbed | *Erica* forest | *Helichrysum* |
|---|---|---|---|---|---|---|---|---|
| **10 cm** | 100 | 98 | 100 | 92 | 89 | 100 | 69 | 100 |
| **30 cm** | 51 | 72 | 87 | 91 | 93 | 90 | 75 | 96 |
| **60 cm** | 29 | 50 | 66 | 51 | 45 | 60 | 83 | 59 |

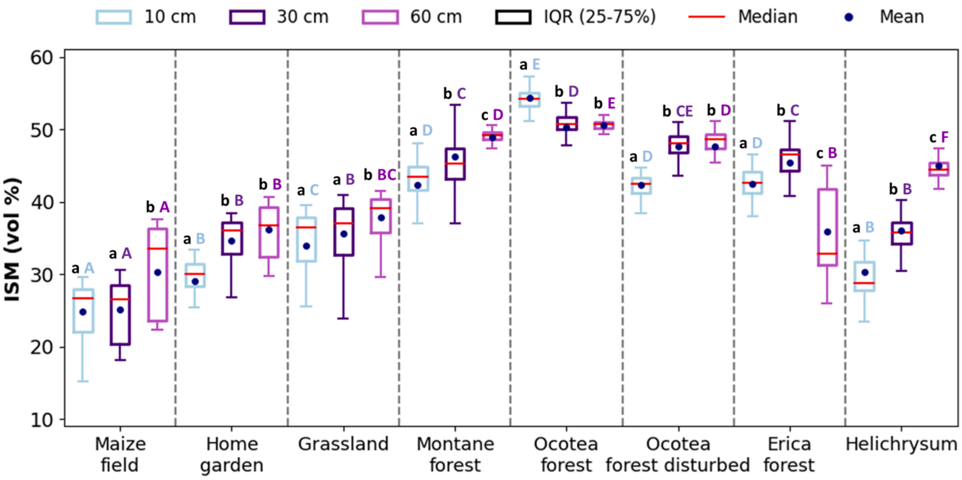


**Fig. 5.** Profile distribution of initial soil moisture (ISM) for soil layers at 10, 30 and 60 cm for specific land cover types. Boxes with no letter(s) in common indicate a significant difference. Lowercase letters indicate significant differences between depth levels within each land cover type, while uppercase letters indicate significant differences between land cover types (α<0.05). IQR = interquartile range.

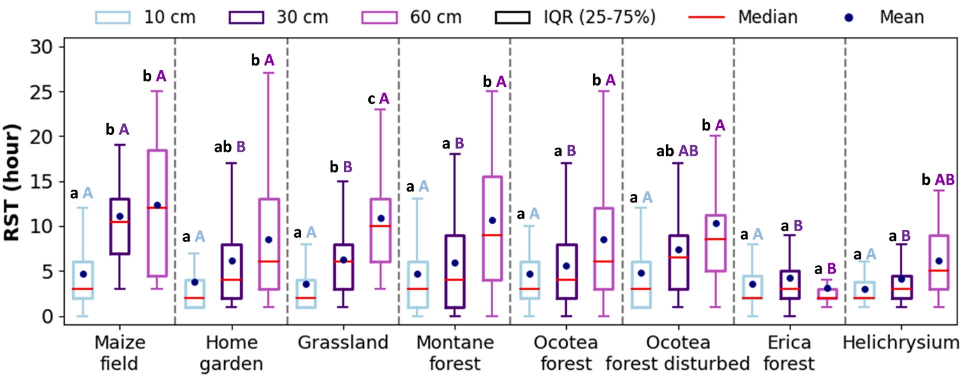


**Fig. 6.** Profile distribution of soil moisture response time (RST) for soil layers at 10, 30 and 60 cm for specific land cover types. Boxes with no letter (s) in common indicate a significant difference. Lowercase letters indicate significant differences between depth levels within each land cover type, while uppercase letters indicate significant differences between land cover types (α<0.05). IQR = interquartile range.

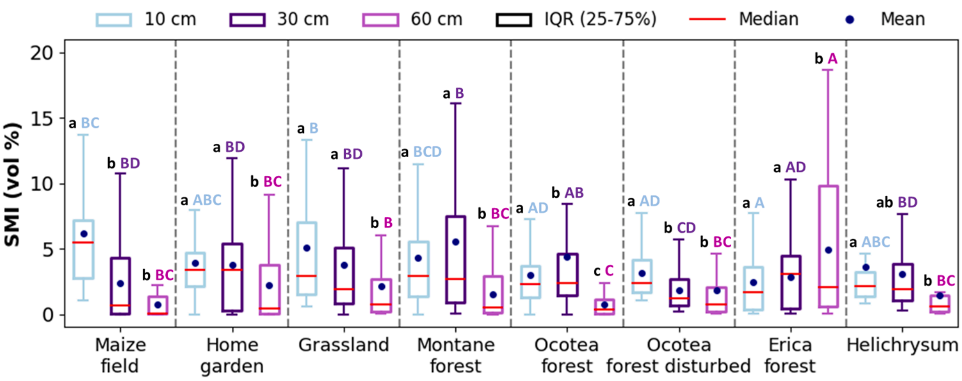


**Fig. 7.** Profile distribution of soil moisture increase (SMI) for soil layers at 10, 30 and 60 cm for specific land cover types. Boxes with no letter(s) in common indicate a significant difference. Lowercase letters indicate significant differences between depth levels within each land cover type, while uppercase letters indicate significant differences between land cover types (α<0.05). IQR = interquartile range.

types at shallow depths. However, a significant difference ($p < 0.05$) in RST was observed at 30 cm depth between the maize field and other land cover types (Fig. 6). Longer RST in maize fields could be related to the higher bulk density of these soils (Cornejo et al., 2023a) and therefore most likely lower infiltration rates Also reduced infiltration rates in dry Vertisols could contribute to higher RST in the lowland land cover types.

#### 3.2.4. Soil moisture increase

Similar to other observations (Tian et al., (2019), the SMI during infiltration events decreased significantly with depth and differed significantly among most land cover types (Fig. 7). The median SMIs were highest (5.5 vol%) at 10 cm depth and lowest (0.03 vol%) at 60 cm depth, both observed within the maize field. Generally, deeper soil layers had relatively lower and less variable SMI for most land cover types, with notable exceptions in the *Erica* forest. In the lower montane forest, high variability (between 0.1 % and 18.6 %) was observed at 30 cm depth (Fig. 7), although the median SMI was slightly lower than at 10 cm depth. A lower SMI in deeper soil layers could be expected, given that the rainfall first replenishes the upper soil layer and less water is available to infiltrate in deeper soil layers during the rainfall event. The median SMI in the *Erica* forest was high (3.0 %) at medium soil depths (30 cm) and slightly lower at 60 cm depth but with high variability (between 0.1 % and 18.6 %). These observations were closely linked to the other soil moisture response parameters, which indicated rapid wetting of deeper soil layers in the *Erica* forest. Soils in the *Erica* forest zone have a lower clay content than soils in the other forested land cover types, which could, together with macropores from tree roots and cracks, contribute to the rapid infiltration rates (Fig. 7).Tian et al. (2019)

### 3.3. Preferential flow occurrence

The frequency of occurrence of each flow type (NC, SR, PF), exhibited considerable variation across different land cover types over the monitoring period. Out of 595 analyzed rainfall events, between 1 and 17 events per station were classified as NC flow events. The maize field demonstrated a higher proportion of NC flow events (48.6 %) (Fig. 8), signifying that a nearly half of the rainfall events in this land cover resulted in water infiltration limited to the upper soil layer (10 cm).

Notably, this high occurrence of NC events is particularly interesting given that the maize field is characterized by sandy clay loam soils, which typically have a moderate infiltration capacity. However, factors beyond soil texture alone are influencing hydrological responses. High NC events in maize fields may also be related to soil compaction in response to agricultural managements practices, as indicated by the high bulk density in this land cover type (Cornejo et al., 2023b). Soil compaction can significantly reduce pore spaces and hinder water infiltration, leading to increased surface runoff and limited downward movement of water. According to Truong et al. (2022), human activities often lead to compaction that disrupts natural soil structure, thereby impeding water movement through the soil profile. For example, a study conducted in the Bitale catchment indicated that changes in land cover due to human activities resulted in alterations in hydrological processes leading to increased surface runoff and decreased soil water content (Kuma et al., 2023). Similarly, Engida et al. reported that land use changes in the Baro basin resulted in increased surface runoff and decreased groundwater flow, emphasizing the impact of anthropogenic activities on hydrology. The studies support the notation that agricultural practices, such as those observed in maize fields may lead to increased occurrence of NC flow events due to limited infiltration capacity

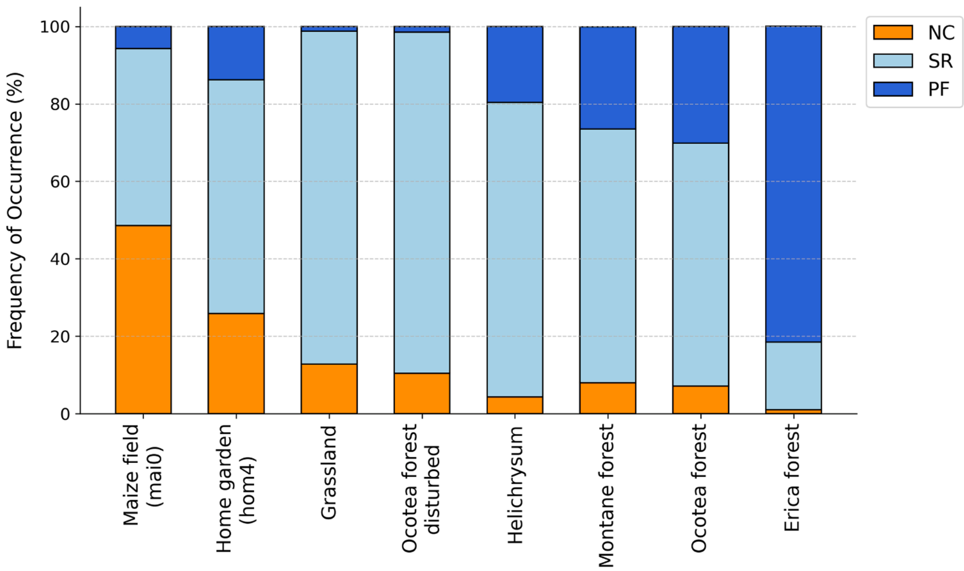


**Fig. 8.** Percentage distribution of the frequency of occurrence of flow types: not classifiable (NC), sequential response (SR), and preferential flow (PF) for specific land cover types. The percentages are calculated based on total rainfall events recorded at each monitoring station over a monitoring period (January 2022 to August 2023).

and increased surface runoff generation (Getu Engida et al., 2021; Kuma et al., 2023)

In contrast, NC events only occurred sporadically in forested land cover types, such as in the montane forest (8.0 %), *Ocotea* forest (7.1 %) and *Ocotea* forest disturbed (10.4 %). Lower montane forests are characterized by silt loam soils that promote stable hydrological responses due to their balanced drainage and retention capabilities. The *Ocotea* forest, with silty clay loam soils, also supports effective water movements through its structure. These observations are supported by others (Mutayoba et al., (2018), indicating that natural forest ecosystems enhance water retention and promote flow dynamics due to their dense root systems and organic matter content. The *Erica* forest and *Helichrysum* land cover observed the least occurrence of NC events with 1.0 % and 4.3 %, respectively. This highlights how specific combinations of vegetation soil types can favour water infiltration, as both land uses have loamy and silty-loamy soils that facilitate good drainage and moisture retention.

SR events were observed to be the most dominant flow type in the majority of the land cover types, with a particularly high frequency of occurrence in the *Ocotea* forest disturbed (88 %), grassland (86 %), and *Helichrysum* (76 %) (Fig. 8). Montane forest, *Ocotea* forest, and home gardens also showed frequent occurrences of SR events, with 65.5 %, 62.8 %, and 60 % respectively, highlighting the relative stable flow dynamics within these land cover types. On the other hand, *Erica* forest showed a low occurrence of SR events (17.5 %), which aligns with the observed rapid increases in soil moisture and rapid response of soil moisture content in deeper soil layers to rainfall events based on soil moisture response patterns. SR is beneficial for reducing surface runoff, thus minimizing soil erosion as water infiltrates more uniformly, improving the soil water retention and enhancing plant water availability which is important for plant health.

The occurrence of PF events was notably high in specific land cover types, suggesting that specific combinations of vegetation and soil types promote rapid subsurface water movement within selected land cover types in the study area. In particular, the *Erica* forest demonstrated an exceptionally high frequency of PF events (81.6 %) (Fig. 8). Also, the Montane and *Ocotea* forests recorded a notable occurrence of PF events of 26.4 % and 30.1 %, respectively. The rapid water movement through the soil through PF is likely facilitated by soil macropores and root channels, indicating a high potential for groundwater recharge in these land cover types as water quickly percolates through the soil to reach the aquifer. However, this rapid water movement can also result in reduced water retention in the upper soil layers, potentially reducing plant water availability, especially for shallow-rooted plants, while deep-rooted plants can still access shallow groundwater efficiently, mitigating potential plant water stress.

The station at the *Helichrysum* land cover showed a moderate PF frequency at 19.6 %, reflecting balance between structured and unstructured flow pathways in this unique high-altitude land cover. In contrast, grassland and *Ocotea* forest disturbed showed very low occurrence of PF events at 1.2 % and 1.5 % respectively, suggesting that uniform infiltration process was dominant in these land cover types. Maize fields and home garden showed relatively few PF events at 5.7 % and 13.8, respectively, which could be caused by

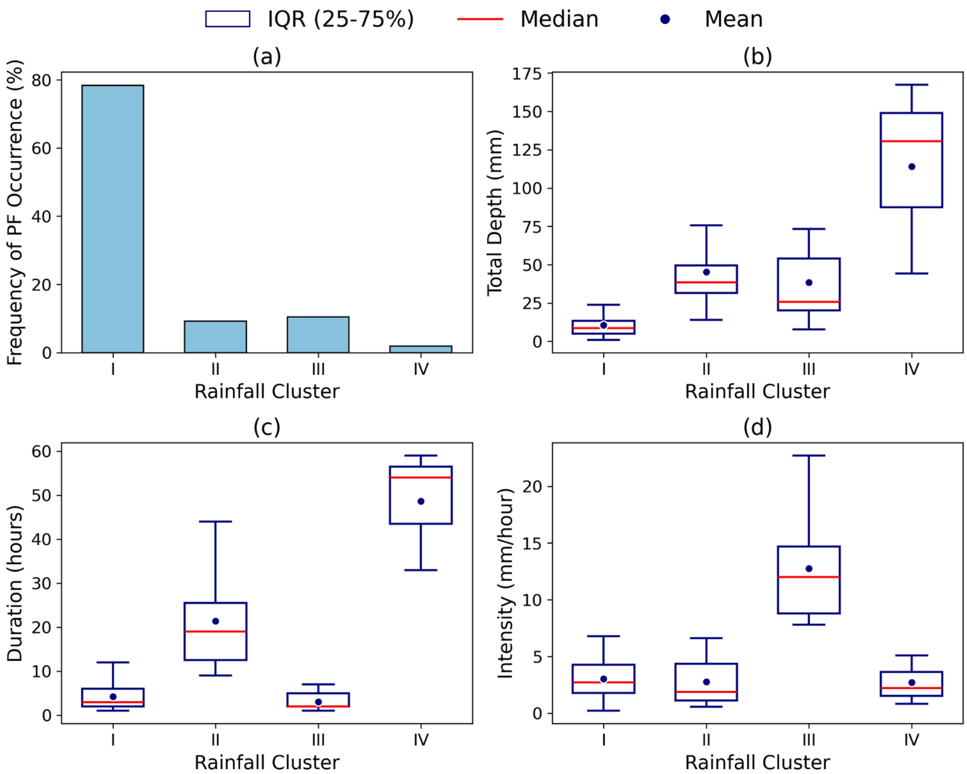


**Fig. 9.** Distribution of (a) frequency of preferential flow (PF) occurrence and rainfall characteristics (b) Total depth (c) duration (d) intensity for rainfall clusters for preferential flow events.

agricultural practices that modify soil structure by reducing the preferential flow pathways. The impact of agricultural practices on soil structures is well-documented (Mutayoba et al., (2018). Mutayoba et al. noted that tillage can disrupt natural pore structures, leading to reduced PF pathways. Our findings are supported by previous studies. For instance, Zhu et al. (2019) reported that agroforestry systems improved the soil infiltrability and PF, which promoted groundwater recharge. Despite following a different approach to quantify PF, Sánchez-Murillo, Birkel (2016) reported that groundwater recharge across Caribbean slopes was controlled by the presence of rapid PF flow paths. Furthermore, Bargués-Tobella et al., (2020) experimented on the influence of tree cover on groundwater recharge, and found that tree cover enhanced microporosity and PF which promoted deep soil water movement and groundwater recharge. The potential for groundwater recharge in forest areas especially in the *Erica* forest is important for water supply in the ecosystems and communities in the lowlands, emphasizing the importance of preserving these natural forests.

### *3.4. Influence of rainfall characteristics on preferential flow*

The distribution of the frequency of PF occurrence varied significantly across different rainfall clusters, resulting in distinct patterns. Fig. 9a shows this variation, highlighting that PF occurrences are predominantly associated with rainfall under cluster I, which accounts for 78.4 % of PF events. Cluster I is characterized by low total rainfall with short duration and light to moderate intensity (Fig. 9b-d), which apparently creates conditions that favor the occurrence of PF. Such rainfall events reduce the chance of saturation excess (large amount of rainfall) or infiltration excess (high intensity rainfall) overland flow, which would inhibit PF. At the same time, it is important to note that cluster I rainfall is the most common in the study area and could therefore account for the highest proportion of PF events. In contrast, other rainfall clusters exhibited significantly lower frequencies of PF occurrence compared to cluster I. Longer rainfall events with the same intensity (cluster II) did not necessarily lead to the same level of PF occurrence. Cluster III, which includes events with short duration and heavy intensity rainfall (Fig. 9c, d), accounts for only 10.5 % of PF events. Possibly, infiltration capacity is reached here, leading to the generation of infiltration excess (Hortonian) overland flow. Cluster IV events might create conditions which are less favorable for PF development, as the soils may become saturated more gradually and hence allow more SR rather than the PF observed with cluster I. In addition, such rainfall events could result in saturation excess overland flow with saturated pores and even macropores. These findings contrast the results of previous studies, such as those by Demand et al. (2019) and Graham and Lin (2011), where heavier intensities of rainfall events were found to have a higher likelihood of PF occurrence. It might well be that there is a threshold range of minimum and maximum rainfall intensities that promote PF in our study area, as low intensity rainfall might not be sufficient to switch on PF flow paths, whereas high intensity rainfall results more likely in surface runoff. The latter could be particularly relevant in the maize field and *Helichrysum*, where infiltration rates might be limiting. There might also be an interaction between rainfall intensity and antecedent wetness conditions or ISM (Nanda and Safeeq, 2023), which is not apparent from the current dataset. Longer observation periods and the inclusion of other monitoring sites of different land cover types will allow to elucidate the diverse interwoven processes involved in the development of PF.

### *3.5. Influence of initial soil moisture on preferential flow*

The influence of ISM on preferential flow was assessed by grouping the ISM into seven classes (Fig. 10). PF is very rare at very low ISM levels, with occurrences of $<$ 2.0 % for ISM level $<$ 30 % (Fig. 10). The findings of limited PF under low ISM conditions from this study suggest a reduced deep percolation and groundwater recharge, but may also imply high surface runoff and increased risk for soil erosion due to less infiltration pathways. Low ISM mostly occurs in maize fields, and at 10 cm depth in home gardens and *Helichrysum*,

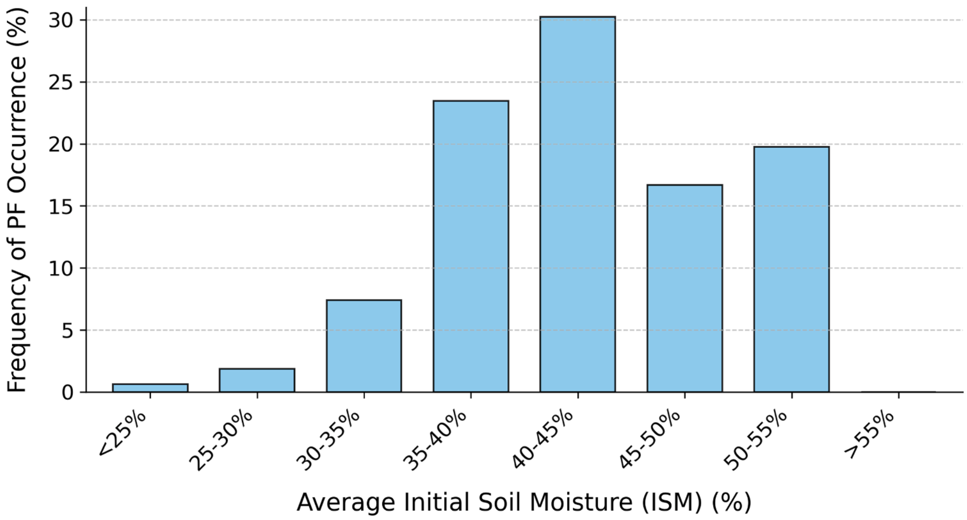


**Fig. 10.** The frequency distribution of preferential flow (PF) occurrence for different average initial soil moisture groups.

where PF occurrence is not very frequent in general, which could further explain the low PF occurrence. At low soil moisture content, there might be reduced connectivity between macropores, inhibiting PF (Graham and Lin, 2011). As ISM increases to moderate levels (between 30 % and 35 %), the occurrence of PF increases to 7.4 % (Fig. 10). The highest occurrence of PF was observed in classes of 35–40 % and 40–45 % soil moisture with frequencies of 23.5 % and 30.2 %, respectively. With an even higher ISM of 45–50 %, PF declines again to 16.7 % and is only slightly higher at 50 % ISM with 19.8 %. Based on these results, the peak in frequency of PF occurrence at 40–45 % ISM suggests an optimal moisture range where soil macropores are sufficiently wetted to promote rapid water infiltration. Higher ISM might be close to saturation, at which further rainfall leads to NC events through saturation excess overland flow. High PF occurrence at high ISM might therefore be very unlikely.

These results align with the findings by Hu et al. (2019), who found that higher ISM levels were associated with an increased PF occurrence. Also, Xu et al. (2024) observed higher PF occurrence at sites that generally had a higher soil moisture content, but did not find a relationship between PF occurrence and ISM. In contrast, Demand et al. (2019) observed that low initial soil moisture increased the occurrence of PF in forests and grasslands, whereas Wang et al. (2022), Tang et al. (2020), and Wiekenkamp et al. (2016) found no or only minimal relationships between initial soil moisture and the occurrence of PF suggesting that ISM was not a controlling factor for PF occurrence. The discrepancy of these results with ours highlights the variability and complexity of PF processes and suggests that the influence of ISM on PF occurrence may depend on a specific site condition and factors. For example, the relatively high silt content in the soils on the southern slopes of Mt. Kilimanjaro (Cornejo et al., 2023) could reduce the importance of ISM in generation of PF (Grant et al., 2019). More studies on PF generation, particularly in tropical landscapes, are required to better understand the underlying process.

## 4. Conclusions

The occurrence of PF was estimated through the analysis of the order of soil moisture changes and response time in different soil depths in eight different land cover types of the southern slopes of Mount Kilimanjaro in Tanzania. A total of 595 rainfall events were identified from January, 2022 to August, 2023. The results of PF revealed significant variation of each flow type (not classifiable, sequential flow or preferential flow), across different land cover types. Due to the highest occurrence of rainfall events at mid elevations – in the lower montane and montane zones at 1700 to 2800 m a.s.l. – as well as soil moisture characteristics that facilitate preferential flow, these zones have the highest potential to contribute to the recharge of groundwater. In contrast, the maize field in the lowlands exhibited the highest occurrence of NC flow events. Low initial soil moisture content and soil compaction reduce infiltration and preferential flow, thus limiting groundwater recharge and increasing surface runoff and soil erosion. SR flow events were more dominant in the *Ocotea* forest disturbed, grassland and *Helichrysum*, enhancing soil stability and plant water availability within these land cover types. High occurrence of PF events in *Erica* forest, montane forest and *Ocotea* forest, related to favorable soils with high drainage capacity, macropores and higher initial soil moisture content, indicate rapid subsurface water movement, supporting groundwater recharge but potentially reducing water available to plants at upper soil layer. In contrast, very high initial soil moisture content led to lower occurrence of PF, potentially due to saturation of the soil. We found that rainfall depth, duration and intensity are important factors that drive the occurrence of PF, as mostly low to medium-intensity events of short amount and duration led to PF. These findings show that the conservation of high-elevation land cover types with suitable precipitation, vegetation and soil characteristics for PF occurrence are crucial for groundwater recharge and, therefore, to ensure the water supply in the drier lowlands, where rainfall more likely leads to replenishment of plant available water or even surface runoff. While this study provides valuable insights into the role of rainfall characteristics and initial soil moisture in PF dynamics, the overlapping influences of these factors, along with land cover specific attributes, add uncertainty to the results. Future studies incorporating multiple plots and replicates for each land cover type and a more detailed analysis of soil-vegetation-climate interactions are necessary to improve our understanding of the mechanisms driving PF occurrence. These steps would strengthen the ability to generalize findings across diverse ecosystems and enhance the usefulness of the results for different water resource management. This is particularly relevant for so-called 'water tower system' where the lowlands are strongly dependent on (ground)water inputs from the uplands.

## CRediT authorship contribution statement

**Breuer Lutz:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Windhorst David:** Software. **Munishi Subira Eva:** Writing – review & editing, Supervision. **Jacobs Suzanne:** Writing – review & editing, Supervision. **Codalli Fabia:** Writing – review & editing, Data curation. **Shagega Frank Paul:** Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2025.102215.

## Data availability

Data will be made available on request.

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