https://doi.org/10.5194/hess-2024-84
Preprint. Discussion started: 29 April 2024

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Exploring the interplay of new and young water fractions with hillslope topography in a subtropical headwater catchment

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Abstract. Our study explores the intricate relationships between new water (F_{new}), young water (F_{yw}), and topographic influences within small catchments, utilizing the Height Above the Nearest Drainage (HAND) as a key metric. Analysis revealed that seepage water consistently contains higher fractions of young water than stream water, despite similar contributions of new water from precipitation, highlighting differential hydrological responses. The relationship between F_{new} and F_{yw} exhibited varying slopes for seepage and stream water, suggesting distinct hydrological sources and behaviors, with seepage water reflecting a "flashy" system and stream water indicating a "damped" system. A nonlinear dynamic was observed between HAND and transit time measures, with a notable threshold at approximately 10 m of HAND, beyond which the contribution of young and new water to streamflow declines, indicating a shift in hydrological pathways. This threshold behavior emphasizes the complex influence of topography on water movement and age within catchments. This research bridges gaps in our understanding of catchment hydrology, offering insights into the spatial and temporal dynamics of water movement and the pivotal role of landscape features in shaping hydrological responses.

1 Introduction

Comprehending the interactions between new and young water in a catchment is crucial for deciphering its hydrological behaviors and the journey of solutes through catchments (Hrachowitz et al., 2016; Benettin et al., 2020). The concept of young water fraction (F_{yw}) refers to the proportion of recently fallen precipitation that contributes to the water content in various reservoirs and flows, offering a method to estimate the water's age in streams (Kirchner, 2016). Conversely, the new water fraction (F_{new}) employs a revised hydrograph separation technique, akin to longstanding methods for assessing the impact of fresh precipitation on stream flows during rain events. This method involves dynamic mixing models that adjust with each sampling, categorizing the prior sample as "old" water and the intervening precipitation as "new" water (Kirchner, 2019). By aggregating these hydrograph separations, a representative value for the new water fraction is derived, indicating the share of stream water originating from recent rainfall. Many works delve into young (typically up to 2 months old) or new water (around 2 weeks old) fractions, employing these transit time measures to illuminate the complex dynamics of water movement within a catchment.

Modeling studies have suggested that hillslope geometries (Gauvain et al., 2021) and vertical connectivity (Xiao et al., 2021) play crucial roles in influencing hillslope transit times. However, empirical research on new and young water fractions

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at the hillslope scale is sparse. To date, Zhang et al. (2023) conducted one of the few experimental studies by measuring the F_{yw} using suction lysimeters along a 20-meter section of a hillslope. Their findings indicated higher F_{yw} values at the upper slope compared to the lower slope. Nonetheless, their research was limited to the lower portion of a hillslope, leaving the water age dynamics across the entire hillslope largely unexplored in empirical studies.

Observing seepage at various heights along a hillslope offers a valuable opportunity to study water age variation without the need for disruptive instruments like suction lysimeters, allowing for direct manual collection. The concept of HAND (Height Above Nearest Drainage), introduced by Nobre et al. (2011), effectively categorizes a grid cell into distinct drainage areas based on the drainage position of each Digital Elevation Model (DEM) pixel along the ridge-valley transect. This approach focuses solely on hillslope-scale topography by eliminating broader regional topographic influences. The resulting distinct positions correlate with water table depth, enabling HAND to serve as a robust indicator for predicting plant community composition and species distribution (Schietti et al., 2014). In this system, water from higher HAND zones flows downhill to successively lower zones, with only the lowest zone directly interacting with streams. HAND's utility extends beyond hydrology; it has been applied in mapping continental-scale flood inundation (Liu et al., 2018) and is increasingly recognized as an indicator of ecosystem niches (Schietti et al., 2014). Despite these advancements, the specific influence of hillslope topography on the F_{yw} and F_{new} remains unclear, highlighting a significant gap in our understanding of hydrological processes at both hillslope and catchment scales.

This study posits that if the relationships observed at the catchment scale between topography and hydrology can be extrapolated to hillslope scale, specific null hypotheses can be tested: (1) seepage water is expected to have higher fractions of F_{yw} and F_{new} compared to stream water. (2) the F_{yw}-F_{new} relationship may be similar between seepage and stream water, indicating similar hydrological behaviors. (3) the relationship between HAND and both F_{yw} and F_{new}, anticipating a linear relationship. Through this investigation, we aim to contribute to the nuanced understanding of hillslope and headwater catchment hydrology and the factors influencing water composition and movement.

2 Materials and Methods

The Hehuan headwater catchment, situated between altitudes of 3077 and 3418 m, is a notable high-altitude region characterized by its complex and fractured geological structure. The lithology consists of dark gray or blackish, well-cleaved hard shale, slate, and phyllite. Three catchments R1, R2, and R3, spans 13, 70, and 10 ha respectively. The slopes of R1, R2, and R3 are 27.0, 26.6, and 25.4 degrees, respectively. The soil is primarily Inceptisol, with a layer of silty clay from 0 to 40 cm depth, loam from 40 to 70 cm, and sandy loam from 70 to 110 cm. The vegetation varies with altitude, with *Abies kawakamii* dominating below 3,200 m and *Yushania niitakayamensis* above 3,200 m. This area experiences a significant amount of precipitation, with an annual total of 4,923 mm, and a pan evaporation rate of 746 mm, indicative of its humid environment. The mean air temperature in this region ranges from 6 to 11°C, reflecting the cool climate conditions prevalent at such high elevations. The seasonal cycle is distinctly divided into summer and winter periods, with the former extending from May to October and the latter from November to April.

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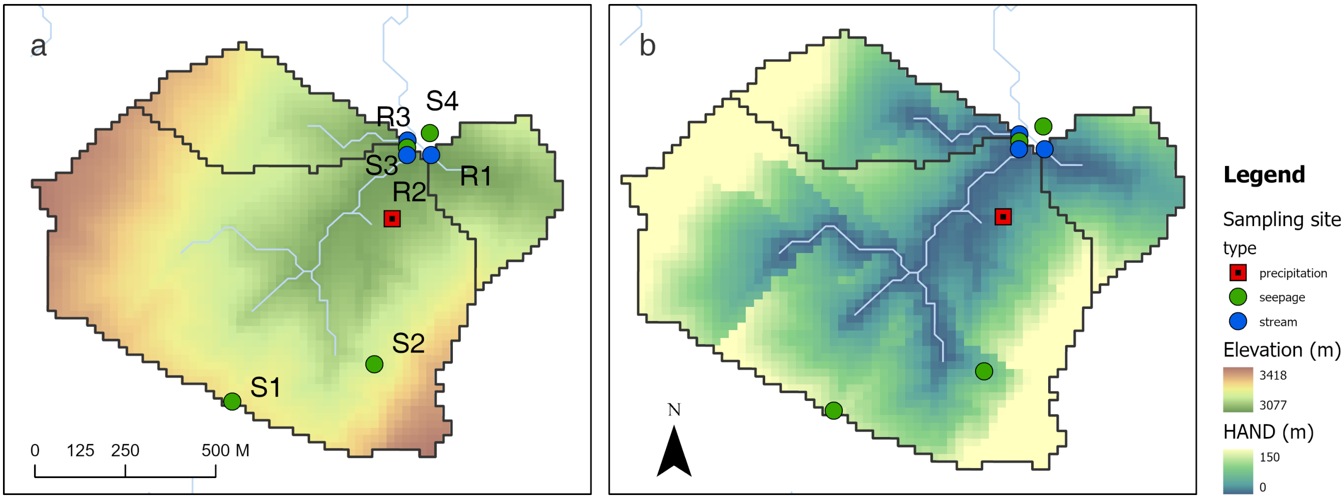

Figure 1: Sampling sties of precipitation, seepage and stream water with (a) Topography and (b) Height Above the Nearest Drainage (HAND).

Between June 24, 2014, and June 3, 2016, we conducted biweekly sampling of precipitation, seepage water, and stream water, with no snowfall recorded during this period. Samples were meticulously collected into 100 mL bottles designed to prevent evaporation and were then stored in a 4°C ice bucket until transported back to the laboratory. Each sample was transferred into a 2 mL vial for analysis using Off-Axis Integrated Cavity Output Spectroscopy (OA-ICOS). An automated sampler injected 0.2 to 1.0 μL of the liquid sample into the injector, which was maintained at a temperature of 70°C to ensure complete evaporation. The vaporized sample was then conveyed through a Teflon tube into the analysis chamber, where its isotopic composition and laser absorption were measured, following the methodology described by Lis et al. (2008). Calibration standards used included Vienna Standard Mean Ocean Water (VSMOW) with δ^2H and $\delta^{18}O$ values set at 0‰, and Standard Light Antarctic Precipitation (SLAP) with δ^2H at -428‰ and $\delta^{18}O$ at -55.5‰, achieving a precision of 0.2‰ for $\delta^{18}O$ and ≤0.8‰ for δ^2H. Our study focused on δ^2H data to more accurately calculate the fractions of young and new water.

Calculating the young water fraction (Jasechko et al., 2016) involves analyzing the seasonal cycles in precipitation and streamflow, which can be characterized by their amplitudes (A) and phases (φ). To estimate these parameters, one can employ nonlinear fitting techniques to model the seasonal variations as sine functions of time (t), represented as

$$c_P(t) = A_P\sin(2\pi ft - \phi_P) + k_P,$$
$$c_S(t) = A_S\sin(2\pi ft - \phi_S) + k_S, \quad (1)$$

where k_p and k_s are constants. Alternatively, these cycles can be dissected into cosine and sine components through multiple linear regression, yielding

$$c_P(t) = a_P\cos(2\pi ft) + b_P\sin(2\pi ft) + k_P,$$
$$c_S(t) = a_S\cos(2\pi ft) + b_S\sin(2\pi ft) + k_S, \quad (2)$$

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from these coefficients, the amplitudes and phases are derived using the relationships. These parameters are crucial for understanding the temporal dynamics of water movement within the catchment, enabling the estimation of the young water fraction by comparing the seasonal signals in precipitation and streamflow,

$$F_{yw} = A_P / A_S. \quad (3)$$

To calculate the new water fraction (Kinchner, 2019), it's essential to account for the time-varying nature of new and old water concentrations, as opposed to treating them as constants. This dynamic approach is captured by the equation

$$C_S(t) - C_S(t-1) = F_{new}(t)[C_{new}(t) - C_S(t-1)], \quad (4)$$

where $C_S(t)$ and $C_S(t-1)$ represent the streamwater concentration at the current and previous time steps, respectively, and $C_{new}(t)$ denotes the concentration of new water. The ensemble hydrograph separation method (Kirchner, 2019) leverages the similarity of this equation to the conventional linear regression model,

$$y(t) = \beta x(t) + \alpha + \varepsilon(t), y(t) = C_S(t) - C_S(t-1),$$

$$x(t) = C_{new}(t) - C_S(t-1), \quad (5)$$

where α and $\varepsilon(t)$ incorporate any bias or random errors from measurement inaccuracies and other factors. This analogy suggests that by analyzing the regression slope, one can estimate the average new water fraction $F_{new}(t)$. This approach effectively uses the streamflow concentration differences as a proxy for understanding the proportion of new water contributing to streamflow, making it a powerful tool for hydrograph separation and analysis of water sources within a catchment.

To calculate the Height Above the Nearest Drainage (HAND), we employed a DEM with a 20-m resolution. The selection of the stream threshold was meticulously aligned with the stream network delineated in remote sensing plots to ensure consistency in defining stream channels (Fan et al., 2019; McGuire et al., 2005). The flow direction and flow accumulation processes were executed using the D8 method, a widely recognized technique in hydrological modelling. This method involves dividing the area around a central cell into eight directions and determining the flow direction from each cell to its steepest downslope neighbour. This approach facilitates the accurate modelling of water movement across the terrain, which is crucial for the HAND calculation. HAND itself is derived by measuring the vertical distance from any given point in the landscape to the nearest stream channel, as defined by the flow accumulation and direction analysis.

3 Results

3.1 Young water and new water fraction

Figure 2 illustrates the seasonal oscillations of δ^2H, highlighting that the variation in seepage is generally smaller than that observed in stream water samples, with the exception of S3. S4 exhibits larger fluctuations, whereas S3 shows the smallest variation among all. Intriguingly, S4 and S3 are geographically proximate, a detail that warrants further exploration in the discussion section. In contrast, the variation in stream water remains consistently minimal across the board, suggesting a more stable isotopic composition compared to seepage water.

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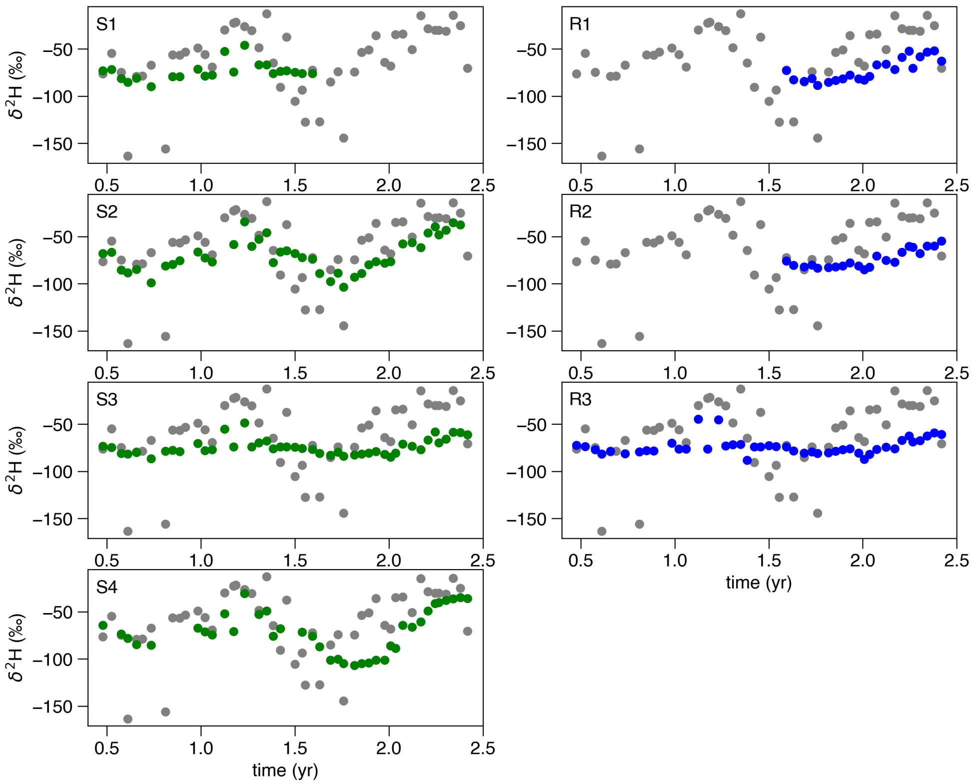

120 **Figure 2: Time series of δ²H for precipitation, stream water, and seepage water. Gray, blue and green dots represent precipitation, stream water, and seepage water, respectively.**

The δ²H seasonal variations, as detailed in Table 1, were analyzed using fitted sine-wave function parameters. It was observed that seepage typically exhibits a larger amplitude compared to stream water, indicating more pronounced seasonal shifts. However, no consistent pattern emerges from the phase terms across the samples, suggesting the complexity of underlying hydrological processes. The offset term shows greater variation in seepage water than in stream water, pointing to diverse sources or pathways of seepage water. Furthermore, both the root mean square error and the standard error of the F_{new} are higher for seepage water than for stream water, reflecting greater uncertainty in seepage measurements. Most notably, seepage water tends to have a higher F_{yw} than stream water, yet the F_{new} are comparably similar between the two, indicating different hydrological dynamics at play.

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Table 1: Summary of young water fraction and new water fraction results with sine wave fit results, their root mean square error, and standard error of new water fraction.

Site	Amplitude	Phase	Offset	RMSE	F_{yw}	F_{new}	SE_F_{new}
Precipitation							
P	37.11	0.41	-62.67	24.45			
Seepage							
S1	10.98	0.07	-74.11	4.29	0.296	0.061	0.077
S2	22.17	-0.08	-70.18	7.65	0.598	0.123	0.057
S3	8.79	-0.21	-74.70	5.44	0.237	0.039	0.036
S4	29.45	-0.41	-73.64	8.73	0.793	0.128	0.050
Stream							
R1	14.17	-0.48	-72.11	3.20	0.382	0.145	0.047
R2	11.53	-0.70	-73.39	2.78	0.311	0.073	0.032
R3	6.95	-0.20	-74.18	6.88	0.187	0.050	0.044

3.2 The relationship between F_{new} and F_{yw}

The F_{yw} increased with the F_{new} with different slopes for seepage and stream water (Fig. 3). Seepage water had more young water than stream water under the similar F_{new}. With the similar increment of 0.10 of F_{new}, the F_{yw} increased 0.18 and 0.52 for stream and seepage water, respectively. This indicates that seepage and stream water sourced from different systems. Seepage water is from the flashy system, while stream water is from the damped system.

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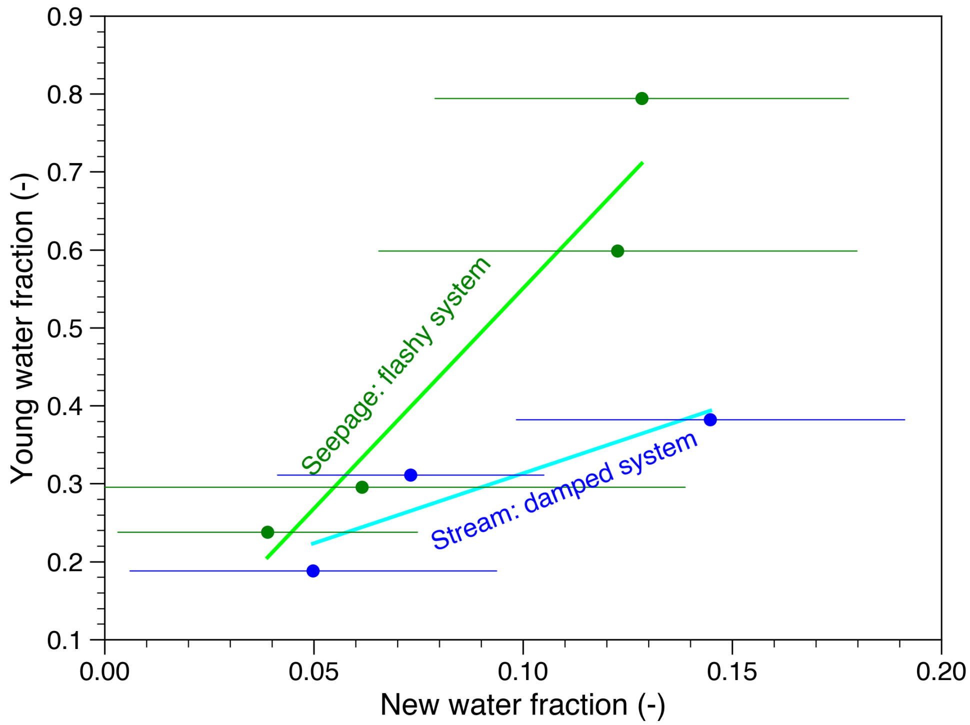

140 **Figure 3: The relationship between new water fraction and young water fraction. The error bars indicate the standard error in estimating the new water fraction. Blue and green dots represent stream water and seepage water, respectively. The blue and green lines represent the linear regression for stream water and seepage water.**

Ensemble hydrograph separation results revealed notable inconsistencies in identified transit times, age-identified water fractions, and TTDs shapes between seepage and stream water (Fig. 4). The δ^2H tracer indicated identification periods of less than 30 weeks for most seepages (except S1, which was 16 weeks) and less than 18 weeks for streams (except R3, which was 28 weeks). This observation suggests that seepage water can be identified over a longer transit time than stream water. The age-identified water fraction varied from 30% to 97% for seepages and 22% to 38% for streams. This discrepancy implies that a significantly larger portion of water can be identified for seepage than stream water. Additionally, the shape parameter (α) of TTDs ranged from 0.50 to 1.03 for seepages and from 0.45 to 0.58 for streams, indicating that seepage water exhibits a broader range of TTD compositions than stream water. In summary, seepage water is characterized by a younger age, and a higher proportion of water can be identified, whereas stream water tends to be older with a lower proportion of identified water ages.

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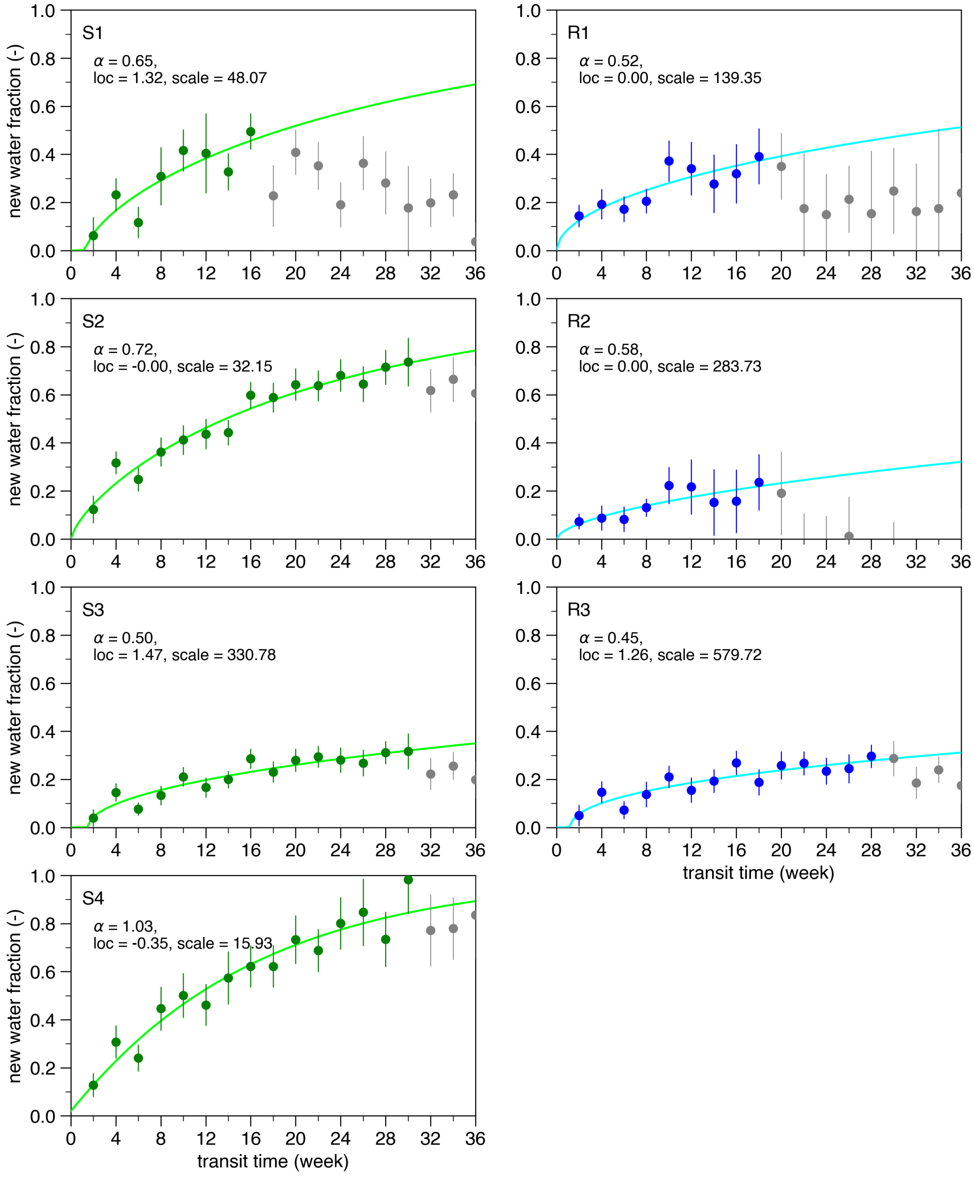

Figure 4: The new water fractions obtained for various sampling windows, with error bars representing the standard error in estimating the new water fraction. The blue and green dots signify stream water and spring water, respectively. Gray dots are excluded from the regression analysis. The blue and green lines represent the cumulative density function form of the gamma distribution for stream water and spring water.

3.3 The relationship between topography and α, F_{new}, F_{yw}

Figure 5 reveals the intricate relationship between transit time measures and topographic characteristics, demonstrating a consistent trend across various metrics: areas with more young water, more new water and a larger α value tend to exhibit similar hydrological behaviors. However, our analysis indicates that the relationship between HAND and these transit time

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measures is not straightforwardly linear. Instead, we observe a nonlinear dynamic with a discernible threshold at approximately 10 m of HAND value. Beyond this threshold, both F_{yw} and F_{new} show a decline as HAND increases, suggesting that as the elevation above the nearest drainage rises, the contribution of young and new water to the streamflow diminishes. Conversely, below this threshold, a decrease in HAND is associated with a reduction in F_{yw} and F_{new}, highlighting a complex interplay between topography and hydrological processes that warrants further investigation.

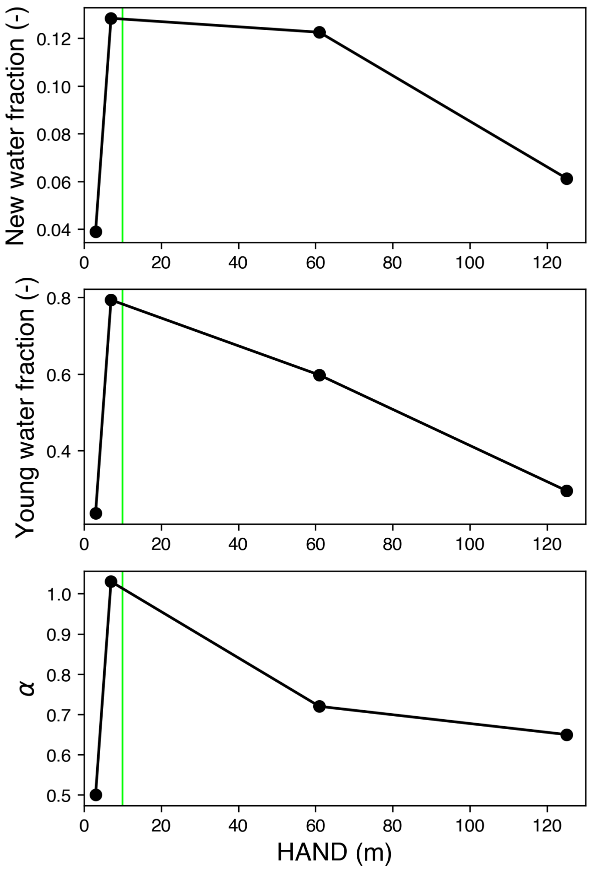

Figure 5: Scatter plots illustrating the associations between HAND and the parameters α, F_{new}, and F_{yw}. The green lines represent thresholds in HAND that delineate unique correlations with various transit time measures.

4 Discussion

We have presented findings on F_{yw} and F_{new}, along with their corresponding HAND controls. Previously, the variation in water age across different HAND elevations was not well-understood due to the absence of seepage samples from areas of low to high HAND. By studying the Hehuan catchment, we conducted a natural experiment that allowed us to explore the influence of hillslope topography on water age.

Contrary to our hypothesis 1, our data indicate that while seepage water indeed exhibits higher F_{yw} compared to stream water, F_{new} does not significantly differ between the two. Thus, we reject hypothesis 1 that seepage water consistently has higher F_{yw} and F_{new} than stream water. Furthermore, our findings do not support hypothesis 2 that seepage and stream water share similar hydrological characteristics, as evidenced by the distinct slope observed in the F_{yw}-F_{new} relationship between the two water types. Lastly, we refute hypothesis 3 that suggests a linear relationship between HAND and either F_{yw} or F_{new}. Instead, our analysis points to a threshold effect in the HAND relationship with these factors. Below, we delve into how these results align with or diverge from previous studies and contribute to our understanding of hydrological processes on hillslopes.

4.1 Seepage water have more young water but no different new water than stream water

Before delving into the differences in water age between seepage and stream water, we align the findings from our Hehuan catchment study on F_{yw} with those from previous research. The F_{yw} in Hehuan streams, which ranged from 19% to 38%, is comparable to values reported in other alpine environments. For example, in the alpine grasslands of the Qinghai-Tibet Plateau in western China, F_{yw} values ranged from 18% to 39% as reported in various studies (Song et al., 2017; Wang et al., 2023; Yang et al., 2021). In Switzerland, a F_{yw} of 34% was noted (Ceperley et al., 2020). Hehuan stream F_{yw} is in stark contrast to the significantly lower F_{yw} of 5% observed in the southeastern Peruvian Andes (Burt et al., 2023). This discrepancy could be attributed to the differences in mean catchment slopes, with Hehuan's being less steep at 26.6° compared to the Peruvian Andes' slope of 33.8°. Previous global empirical (Jasechko et al., 2016) and regional model studies (Yang et al., 2022) have shown that steeper slopes can lead to reduced F_{yw}, as steeper environments with more fractures may result in longer flow paths and a decrease in young water.

To date, literature on seepage F_{yw} is scarce. Therefore, we compared our seepage water F_{yw} findings with those from suction lysimeter studies, considering that the water sampled by lysimeters is part of the mobile water. For instance, Burt et al. (2023) reported F_{yw} values of 15% in hillslope and 6% in riparian lysimeters in the Peruvian Andes, with stream water F_{yw} at only 5%. Another study by Zhang et al. (2023) on a 20-meter experimental hillslope found lysimeter water F_{yw} to range between 70-100%. Our seepage water F_{yw} findings, which ranged from 24% to 79%, exhibited a broader range than these studies, possibly due to our larger HAND range in seepage sampling. This suggests a high degree of heterogeneity in the hillslope aquifer. Regarding F_{new}, both seepage and stream waters at our sites exhibited significantly higher values than those reported for the Peruvian Andes by Burt et al. (2023), implying that our catchment may have a gentler slope than theirs.

Returning to the comparison between the ages of seepage and stream water, the observation that seepage water generally has a higher F_{yw} compared to stream water implies shorter flow paths for seepage. In contrast, stream water is likely characterized by longer flow paths. Despite the prevalence of exfiltration-induced overland flow as a primary water source in headwater catchments, as noted by Chen et al. (2023), our findings from the Hehuan catchment suggest that stream water may have a greater contribution from groundwater. This would result in a lower F_{yw} for stream water and less variability across different catchments. The similarity in the F_{new} between seepage and stream water could be attributed to the dynamics of very new water (less than 2 weeks old). Such water likely constitutes only a minor portion of the subsurface water, with the majority undergoing vertical drainage. Consequently, this results in minimal differences in F_{new} across various landscapes

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within the catchment, as the rapid vertical movement of very new water reduces its impact on the observed differences in water age between seepage and stream water.

4.2 Different F_{new} – F_{yw} relationship between seepage and streamwater

The distinct relationship between the F_{new} and F_{yw} observed between seepage and stream water underscores fundamental differences in their flow path and sources. Our findings, as illustrated in Fig. 3, demonstrate that seepage water exhibits a steeper increase in F_{yw} with an increment in F_{new} compared to stream water. Specifically, for a similar increase in F_{new} by 0.10, F_{yw} in seepage water rose by 0.52, whereas in stream water, it increased by only 0.18. This differential response suggests that seepage water is more responsive to recent precipitation events, behaving in a manner consistent with what might be described as a “flashy” system. In contrast, stream water appears to follow a “damped” system, indicating a more buffered response to precipitation, likely due to longer transit times and more extensive mixing with older water.

The ensemble hydrograph separation results, detailed in Fig. 4, further highlight these disparities through inconsistencies in transit times, age-identified water fractions, and age distribution shapes. Seepage waters were characterized by longer identification periods and a broader range of age-identified water fractions, suggesting a more complex and varied hydrological response compared to stream waters. Moreover, the broader range of shape parameters α for seepages, compared to streams', indicates a greater diversity in the age distribution of seepage water.

4.3 HAND Threshold

The complex relationship between HAND and water transit times, as shown in Fig. 5, highlights the intricate interactions between landscape topography and hydrological mechanisms. The discovery of a critical threshold around 10 m of HAND, after which both the F_{yw} and the F start to decrease with further increases in HAND, emphasizes the subtle yet significant role of elevation relative to nearby waterways in dictating water movement and age within a watershed (illustrated in Fig. 6b). This decrease in F_{yw} and F_{new} past this threshold points to a shift in the primary hydrological processes (Fig. 6a), possibly from quicker, more direct pathways to slower, more indirect ones, as the elevation rises and the Transit Time Distribution (TTD) adopts a shorter tail (Fig. 6c). Below this threshold, a decrease in F_{yw} and F_{new} with a reduction in HAND may reflect a stronger link to older groundwater sources, characterized by quicker exchange rates and thus older water on average, with the TTD showing a longer tail (Fig. 6c). This contrasts with findings from suction lysimeter water studies (Burt et al. 2023; Zhang et al., 2023), which reported higher F_{yw} at higher elevations and lower F_{yw} lower down. We propose that their findings are limited by sampling only at lower HAND levels, preventing the observation of alternate patterns that emerge beyond the HAND threshold.

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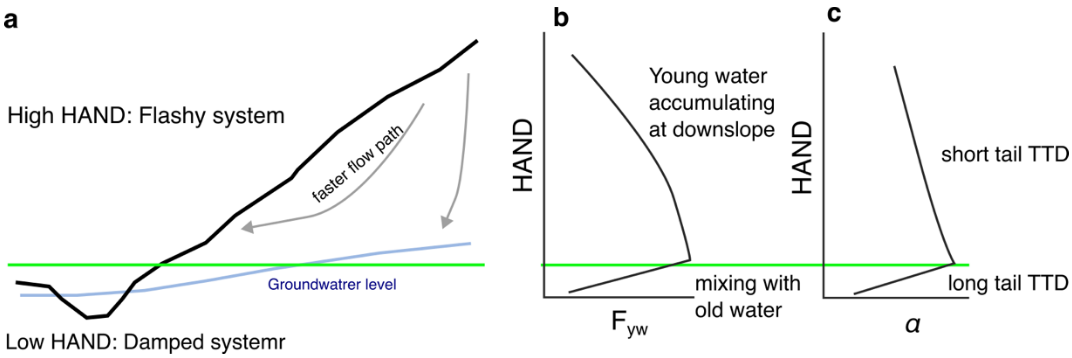

Figure 6: (a) Conceptual diagram illustrating the impact of HAND on (b) F_{yw} and (c) shape parameter α of TTD. The diagram features green lines indicating specific HAND thresholds that demarcate distinct correlation patterns.

5 Conclusions

This study deepens our understanding of the interplay between topography, specifically Height Above Nearest Drainage, and hydrological processes, revealing nuanced relationships that challenge traditional linear perspectives. Our findings suggest that the fraction of young water and new water in a catchment do not uniformly increase with proximity to streams or lower HAND values. Instead, a notable threshold exists around 10 m of HAND, beyond which the contributions of F_{yw} and F_{new} to streamflow begin to diminish, indicating a transition in hydrological processes. This threshold effect points to a complex interplay between elevation and water movement, where higher HAND values correlate with reduced young and new water fractions, likely due to slower, more diffuse hydrological pathways.

Contrary to expectations, seepage water did not consistently show higher fractions of young and new water compared to stream water, leading us to reject the hypothesis that seepage water invariably has higher F_{yw} and F_{new}. The observed relationship between F_{yw} and F_{new} differed between seepage and stream water, suggesting distinct hydrological behaviors and sources. The slope of the F_{yw}-F_{new} relationship was steeper for seepage water, indicating that it is more influenced by recent precipitation and behaves like a "flashy" system, while stream water exhibits characteristics of a "damped" system with a more buffered response to precipitation.

Our study extends the body of empirical research on hydrological dynamics at the hillslope scale, particularly in the context of young and new water fractions. By integrating the HAND metric, we have offered a fresh lens through which to examine water age variation across different topographies, enriching our understanding of catchment hydrology. These insights not only contribute to the scientific discourse on hydrological processes but also have practical implications for water resource management and conservation strategies, emphasizing the need to consider the intricate relationships between landscape features and hydrological dynamics.

Data availability. Isotope data can be obtained by requesting it from Tsung-Ten Peng.

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Preprint. Discussion started: 29 April 2024

Author contributions. Conceptualization and Methodology: TRP and JYL. Data Curation and Validation: TRP. Formal analysis: JYL. Investigation and Writing – Original Draft: JYL. Writing – Review and Editing: TRP and JYL.

Competing interests. The authors claim no potential competing interests

Acknowledgements. This research was funded by the project "Hydrogeological Survey and Compilation of Hydrogeological Map in Southern River Basin," sponsored by the Central Geological Survey, Taiwan (B10411). J.Y. Lee received support through grants from the National Science and Technology Council, Taiwan (112-2811-M-005-012).

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