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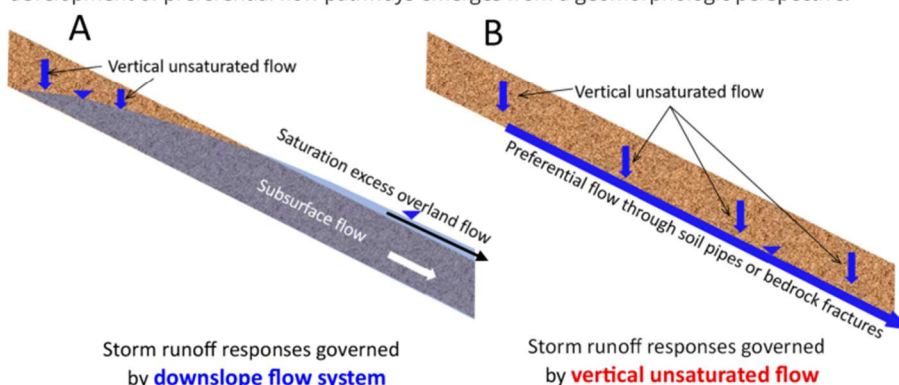
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Graphical Abstract

The old water paradox is difficult to resolve based on the traditional runoff mechanism (A). Our observations and theoretical studies revealed that rainfall-runoff responses are governed by vertical unsaturated flow augmenting shallow groundwater that is subsequently drained by rapid preferential flow (B). This mechanism explains a physical basis for runoff-storage relationship models and enables the evaluation of the sensitivity of peak runoff rates to soil properties. Discussion on the development of preferential flow pathways emerges from a geomorphologic perspective.



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Vertical Unsaturated Flow Governs Storm Runoff Responses: Observational and Theoretical Foundations

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ABSTRACT

The old water paradox is difficult to resolve based on the traditional runoff mechanism consisting of a downslope flow system that includes overland and subsurface flows. Our observations and theoretical studies revealed that rainfall-runoff responses are governed by vertical unsaturated flow augmenting shallow groundwater that is subsequently drained by rapid preferential flow. This mechanism explains the physical basis for runoff-storage relationship models and enables the evaluation of the sensitivity of peak runoff rates to soil properties and soil-layer depth. This commentary discusses the development of preferential flow pathways from a geomorphologic perspective and provides information for developing calibration-free, physically-based runoff models in which parameters can be estimated from measurable field indicators.

1 | Introduction

Although numerous hillslope observations and theoretical analyses have been conducted to elucidate where and how storm runoff responses are generated in steep mountain catchments, the answers to these questions are still elusive. The rainfall input must be rapidly transmitted to the storm runoff response. However, the mechanism that enables this rapid transmission involves problems that are complex and difficult to explain (e.g., Sidle et al. 2000; Onda et al. 2006; Ebel et al. 2007; Harman and Sivapalan 2009). Based on field hydrological observations in Japan where frequent torrential rains occur, once cumulative rainfall exceeds a threshold (usually 100–200 mm), most subsequent rainfall tends to be allocated to stormflow (Kimura 1978; Supraba and Yamada 2015). In such cases we must assume that all rainfall within the runoff contribution area, extending even near ridges, contributes to the streamflow generation including the formation of peak flow within a relatively short timeframe (Tani 1997; Tani et al. 2012). This begs the question—what runoff mechanisms would produce such runoff responses during large magnitude storms?

The following mechanisms are tentatively assessed: (a) infiltration-excess overland flow (Horton 1933); (b) a

combination of subsurface flow and saturation-excess overland flow (Ishihara and Takasao 1962; Freeze 1972) or (c) rapid preferential flow in the soil that cannot be described by Richards equation (Montgomery and Dietrich 2002). On the other hand, many studies based on water quality and tracers have clearly shown that stormflow consists largely of old water (e.g., Sklash and Farvolden 1979; Pearce et al. 1986; Onda et al. 2006; Iwasaki et al. 2015), making explanations relying primarily on overland flow as the main source (i.e., as assumed in (a) and (b)), difficult to accept. The relevance of this old water paradox has been extensively debated internationally for more than half a century as a difficult problem in hillslope hydrology (Sidle et al. 2000; Kirchner 2003; Kienzler and Naef 2008).

Recently, Kojima and Tani (2025) have suggested a runoff mechanism noted in (c), based on hillslope observations. They demonstrated that the conversion of high intensity rainfall to runoff in sufficiently wet soils is driven by vertical unsaturated flow within the soil layer. They further hypothesised that subsequent downslope drainage was likely due to high-velocity flow through preferential pathways such as fractures in the weathered bedrock. Thus, it is plausible that stormflow consists primarily of water that was stored in the soil and shallow bedrock prior to the storm.

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Based on this runoff concept, we can provide a rational explanation for several problems debated in hydrology. After a brief introduction to the observational results by Kojima and Tani (2025) in Section 2, Section 3 explains why runoff response can be simulated using simple storage-type runoff models. Section 4 elucidates what catchment properties contribute to the reduction of peak runoff rate and Section 5 infers that the development of preferential pathways would be an essential requisite for enacting the hydrogeomorphic systems in soil-mantled steep hillslopes.

2 | Runoff Mechanisms Estimated From Observations in Steep Hillslopes

A hydrological study was conducted in a 42° planar hillslope at Shigaraki Study Forest, central Japan. The site is underlain by sedimentary bedrock; pressure heads across the hillslope and spring discharge from bedrock fractures at the toe of the slope were measured (Figure 1) (Kojima and Tani 2025). Results revealed that the peak pressure head at the base of the soil layer occurred between the peaks of rainfall intensity and spring runoff when the soil was wet throughout the entire soil profile. Thus, the unsaturated hydraulic conductivity was within the range of the rainfall intensity (pressure head > −10 cm). Because rainfall intensity usually ranges from 1 to 100 mm h^{−1}, vertical flow in wet unsaturated soil exhibits extremely high celerity even at low velocities (Torres et al. 1998; McDonnell and Beven 2014).

Application of the Vadose Zone runoff model (VZ model; Tani 2023) based on the one-dimensional form of Richards equation successfully simulated observed pressure heads and runoff rates. This model calculates runoff responses to rainfall by integrating the flux discharged from the bottom of the soil via the vertical unsaturated flow within the entire contribution area. It

then makes the bold assumption that, since groundwater rapidly drains downslope through preferential pathways, changes in the shape of the hydrograph there can be ignored. The validity of this assumption was confirmed not only in Shigaraki by Kojima and Tani (2025), but also in three other steep catchments located within the humid climate circum-Pacific Tectonic belt—Tatsunokuchi-yama, Kiryu and CB1 (Tani 2023).

3 | Physical Basis for Simulating Runoff Using a Simple Storage-Type Runoff Model

A one-to-one relationship between runoff rate and storage volume has formed the basis of storage-type runoff models such as the tank model (Sugawara 1979). Despite the simple structure of these models, they are capable of simulating storm runoff responses. The relationship is generally represented by the simple fundamental equation of the storage function model frequently used in flood control plans in Japan (Kawamura et al. 2004):

$$S = kq^p \quad (1)$$

where S and q represent the catchment storage and storm runoff rate per unit catchment area, and k and p are empirical parameters. The physical basis for this equation was often thought to represent overland flow governed by Manning's equation, resulting in $p = 0.6$ (e.g., Sugiyama et al. 1997). However, since we reject the mechanism of overland flow based on the 'old water paradox' and field observations, we need to reexamine the basis for this conclusion.

Tani et al. (2020) conducted numerical experiments using Richards equation to investigate in detail the relationship between the flux discharged from the bottom of the soil via vertical unsaturated flow and the storage volume obtained by integrating the volumetric water content throughout the soil cross-section.

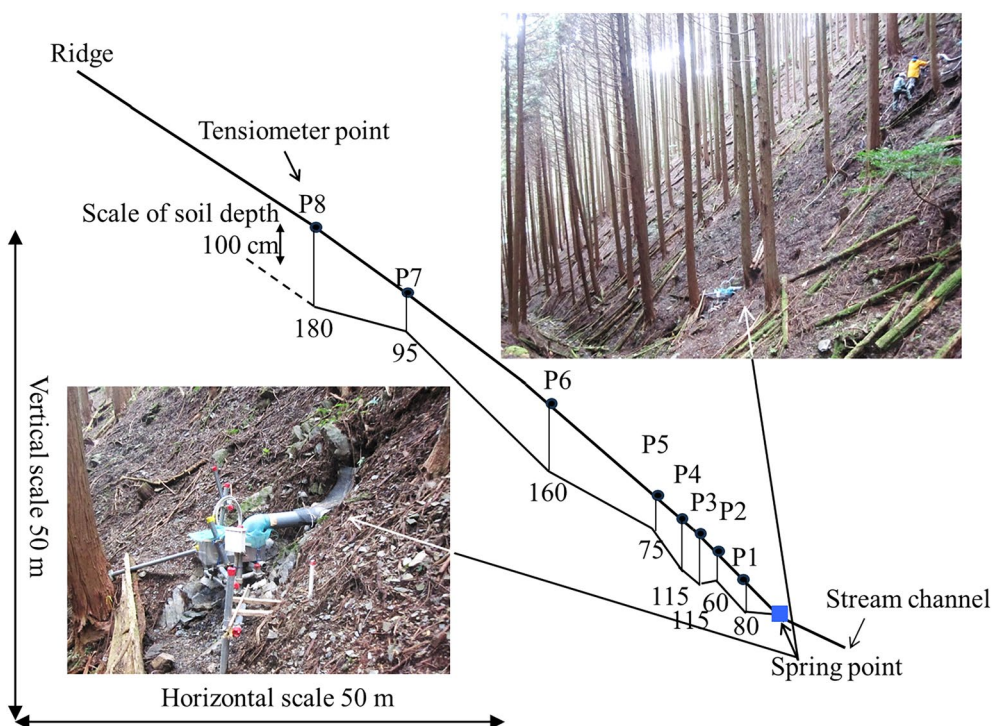


FIGURE 1 | Cross-sectional view and photographs of the study slope in Shigaraki. Modified from Kojima and Tani (2025).

The results revealed that the relationship between the two can be approximated by Equation (1), and that the value of p is roughly governed by the ratio of the thickness of the soil layer to a parameter representing the soil–water retention characteristics in Kosugi’s (1994) model based on a lognormal pore size distribution. Hence, it does not assume a constant value (e.g., 0.6). These numerical experiments suggest that the physical basis of the storage-type runoff model lies in the vertical unsaturated flow, and also provide a solution to the ‘old water paradox’.

4 | Effects of Catchment Properties on Peak Runoff Rate

The finding that vertical unsaturated flow is the primary factor controlling runoff response may shift the focus of headwater catchment research. This is because soil thickness and soil physical properties may be more sensitive than topographic factors, which have traditionally been emphasised in runoff models such as TOPMODEL (Beven and Kirkby 1979).

In the case where cumulative rainfall is sufficiently large and total storm runoff per unit catchment area is nearly equal to the total rainfall, Tani (2008) formulated the effect of runoff flattening with a lower peak runoff rate by ‘runoff buffering potential (R_{BP})’, developing a method to evaluate the sensitivity of R_{BP} to each of the various catchment properties using solutions of Richards equation. Now, R_{BP} is defined as follows:

$$R_{BP} = \left. \frac{dS}{dq} \right|_{q=r_m} \quad (2)$$

This equation implies that rainfall intensity r fluctuates around the average r_m after the soil layer in the entire catchment is sufficiently wet. Since the total of runoff rate (q) per unit area discharged from the catchment can be the same as the total of r for such wet conditions, q also fluctuates around r_m . If the water storage (S) per unit area obtained by integrating the volumetric water content in the

soil layer over the entire catchment does not change with time, R_{BP} in Equation (2) will be zero and q will be equal to r because of plug flow. Instead, when S fluctuates, the larger the magnitude of the fluctuation, the fluctuations of q will be flatter compared to the fluctuations of r , producing a lower peak.

Illustrating this with the two tanks (Figure 2), if the fluctuation of r is the same, Tank A, with a smaller bottom outlet than Tank B, exhibits a greater fluctuation of S ; consequently, the fluctuations of q will be flatter. We conclude that when the soil layer is sufficiently wet, the runoff phenomena can be approximated as quasi-steady state (Figure 2), and therefore the conversion from rainfall to runoff can be evaluated using the R_{BP} value.

Tani (2013) investigated the spatial distribution of pressure head in a sloping rectangular soil layer under steady-state conditions of constant rainfall intensity, and evaluated the sensitivity of slope angle, soil thickness, slope length and soil physical properties to R_{BP} . Two methodologies were introduced in the sensitivity analysis: parameterisation by assigning large saturated hydraulic conductivity values for the effects of preferential pathways (Tani 2008), and a nondimensionalisation form of Richards equation based on the similarity law derived from Kosugi’s (1994) model based on soil physical properties (Tani 2013).

This analysis not only demonstrates the characteristics of the solutions to Richards equation but also provides a basis for evaluating the actual impact of catchment properties on peak runoff rates because its applicability is verified by hillslope observations cited in Section 2.

5 | Evolutional Process of Preferential Pathways

We have explained that storm runoff responses are primarily governed by vertical unsaturated flow, but the existence of preferential pathways is the necessary condition. In this section, we will discuss this issue from the perspective of hydrogeomorphology.

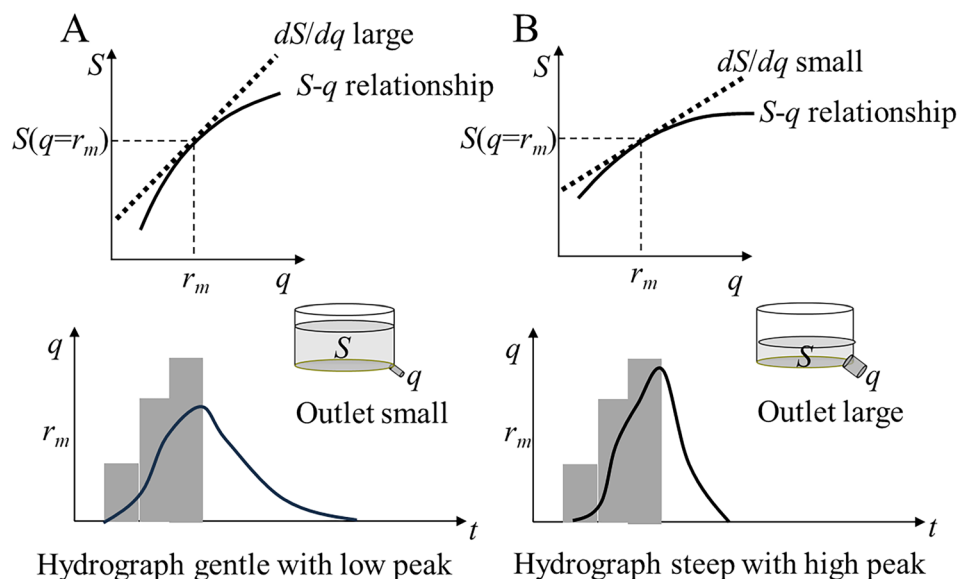


FIGURE 2 | A conceptual diagram comparing the runoff buffering potential R_{BP} of two catchments with respect to rainfall intensity fluctuating around the mean r_m using the relationship of catchment storage S to runoff rate q (Top panel) and storm hydrograph (bottom panel). Catchment A, which has a larger R_{BP} than catchment B, produces a lower peak runoff rate.

In mountainous catchments, subsurface runoff occurs in soil layers and weathered bedrock formed via long-term geomorphic development, such as mountain uplift, bedrock weathering, soil creep, surface and subsurface erosion, and slope failure (Heimsath et al. 1999; Sidle et al. 2017; Watakabe and Matsushi 2019; Ohta et al. 2022). On the other hand, hydrological processes are a major driving force for geomorphic development during large-magnitude rainfall events (Sidle and Bogaard 2016). Therefore, geomorphic and hydrological processes are closely coupled (Matsushi and Matsukura 2007), and runoff pathways are not simply random but may possess some level of organisation (Tsuboyama et al. 1994; Sidle et al. 2000; Tani 2013). This was sometimes called the 'organisational principle' (McDonnell et al. 2007). Thus, although the verification is sparse, we can surmise that the formation of preferential pathways and the resulting efficient drainage of groundwater play important roles in the long-term stability of soil on steep slopes.

In fact, the existence of preferential pathways has been confirmed on a steep hollow (CB1) in Oregon, USA, where tracer tests revealed the high permeability of fractures in the weathered bedrock (Anderson et al. 1997). Furthermore, when the soil failed on this hillslope, the pore water pressure near the bottom of the soil layer increased due to the exfiltration from the fractures (Montgomery et al. 2009). Similar preferential flow phenomena have been observed at deep-seated landslides in southern Kyushu, Japan (Sidle and Chigira 2004).

These observational results suggest that the development of drainage networks consisting of preferential pathways and the disruption of rainwater buffering and storage functions by slope failures are twofold attributes of the same hillslope geomorphological system. Groundwater recharge that accelerates rock weathering and subsurface erosion is largely transmitted by 'ordinary' rainfall. As long as the rainfall intensity remains below the threshold of the hillslope drainage capacity, the groundwater discharge must generate feedback that may enhance the drainage function. The optimised network of drainage pathways as a time-integrated result of hydrogeomorphic processes near the soil base or bedrock surface allows for the rapid runoff of old water stored in the soil and/or fractured bedrock.

In cases of 'extreme' rain events where soil water is injected into substrate beyond the drainage capacity—limited by the sectional percolating area and saturated hydraulic conductivity of the preferential pathways activated only during saturated conditions—the water forced out from the weathered bedrock returns to the downslope soil layer, triggering a shallow landslide that removes the soil overburden. This mechanism is supported by observational data indicating positive pressure build-up from deep within the local soil layer (Matsushi et al. 2006; Montgomery et al. 2009), as well as by process-based model simulations (Moon et al. 2026).

Given that the nature of this paradoxical system within soil-mantled hillslopes has yet to be fully resolved, the existence of preferential pathways to support downslope shallow groundwater drainage appears to be a necessary condition to explain the storm hydrograph response produced largely by the vertical unsaturated flow. This phenomenon is expected to be further

clarified through advances in interdisciplinary research in geomorphology and hydrology.

6 | Conclusion

In hydrology, storm runoff response mechanisms have been debated for many years, and numerous runoff models have been developed to simulate storm hydrographs. However, conventional runoff models have great difficulty in evaluating the influence of catchment properties on runoff responses. This is thought to be because these runoff models do not reflect the runoff mechanisms obtained from the field hillslope observations, as shown in Section 2. For example, lateral subsurface and/or overland flows represented by kinematic-wave type formulations (e.g., Takasao and Shiiba 1988) cannot adequately describe the rapid drainage processes of old groundwater occurring in steep hillslopes. Consequently, it was unavoidable to calibrate the parameter values of these models by working backward from observed rainfall-runoff responses to obtain good simulation results (Gao et al. 2019; Sayama et al. 2025).

Based on a series of studies by the authors, this paper has shown that the runoff mechanism during heavy rainfall events in steep forested hillslopes is mainly controlled by two processes: specifically, this involves the conversion of rainfall intensity to runoff rate due to vertical unsaturated flow in the wet soil layer, followed by rapid downslope drainage through preferential pathways. Based on the runoff mechanisms, the VZ model, based on the vertical unsaturated flow, suggested soil-layer thickness and soil physical properties are highly sensitive to storm runoff responses.

Using this mechanism as the basis for runoff models makes it possible to assess the impact of steepland catchment properties on runoff. This commentary also provides useful information for developing calibration-free, physically-based runoff models in which parameters can be estimated directly from measurable field indicators, contributing to runoff prediction even in ungauged catchments.

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The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

No data are available.

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