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Rainfall-Runoff Event Analysis towards the Understanding of Hydrological Behaviour of a Headwater Catchment in Western Ghats, Karnataka, India – A Case Study

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Abstract This study investigates the dominant runoff generation mechanisms and flood peak controls in a small forested headwater catchment located in the Western Ghats of South India – an ecologically sensitive and data-scarce mountainous region. Using high-temporal-resolution rainfall-runoff event analysis, the research reveals that streamflow response is primarily governed by subsurface flow pathways and saturation-excess runoff, rather than Hortonian overland flow. Short lag times and low runoff coefficients across events highlight the significance of rapid interflow and shallow groundwater contributions, supporting the applicability of the Variable Source Area (VSA) concept in explaining hydrologic behaviour. Antecedent wetness conditions, quantified through antecedent precipitation and the Catchment Storage Index (CSI), were identified as stronger predictors of flood peaks and saturated area expansion than rainfall intensity or amount. The results emphasize the importance of internal storage dynamics and threshold responses in stormflow generation. The study demonstrates that reliable hydrological insights can be derived through event-based correlation analysis even with limited data availability. Findings hold important implications for flood forecasting, hydrological modelling, and infrastructure planning, and highlight the need to explicitly incorporate subsurface processes, dynamic contributing areas, and antecedent conditions into modelling frameworks for VSA-dominated catchments.

Keywords Western Ghats, Source Area Catchment, Variable Source Area Hydrology, Antecedent Wetness Condition, Flood Peak, Catchment Storage

1. Introduction

Understanding the hydrologic response of a catchment to rainfall is fundamental for elucidating runoff generation mechanisms governed by complex, dynamic, and spatially variable factors [1]. Rainfall–runoff event analysis provides a useful framework to separate the combined effects of climate, rainfall characteristics, land use, soil properties, topography, geology, and surface–subsurface interactions. These factors collectively determine the spatial and temporal variability of runoff generation within a catchment [2–4].

Two dominant mechanisms-Hortonian overland flow and saturation-excess overland flow often govern the prevailing runoff processes within a catchment [5]. While Hortonian flow occurs when rainfall intensity exceeds the soil's infiltration capacity, saturation-excess overland flow is primarily controlled by antecedent moisture conditions and the cumulative rainfall amount [6,7]. Identifying the dominant mechanism is essential for understanding how rainfall is transformed into streamflow, particularly under varying landscape and climatic settings.

Previous studies have extensively explored rainfall–runoff responses across diverse hydrological environments [8–13]. Experimental catchment studies have highlighted that pre-event soil moisture conditions can exert a stronger influence on runoff generation than rainfall intensity or volume alone [14-19]. In particular, studies have shown a nonlinear relationship between soil moisture and streamflow, with threshold behaviour often marking the onset of significant flow [16-18]. However, in catchments with highly permeable soils, a more linear relationship between pre-event soil moisture and runoff coefficients may emerge [20,21]. Another vital characteristic in event-based analysis is the time lag between rainfall peak and runoff peak, which provides insights into the flow pathways and storage mechanisms within the catchment [22]. For instance, studies on forested watersheds have found that subsurface pipe flow can accelerate the runoff response, reducing lag time and amplifying peak flows [23].

However, the relative importance of different runoff generation mechanisms continues to vary with climatic zone, catchment scale, and land cover characteristics. While numerous modelling and field-based approaches have been developed to quantify rainfall–runoff relationships, the complexity of hydrological processes and their spatial heterogeneity often limit their transferability across regions.

In this study, rainfall-runoff analysis of a second-order catchment in Western Ghats region of Karnataka, India, is presented, where Variable Source Area (VSA) hydrology is known to exist. Unlike regions where rapid surface runoff dominates flood peaks, sub-surface flow contributions play a central role in streamflow generation in the Western Ghats. These catchments often sustain flow even after prolonged rainfall, highlighting the significance of subsurface pathways.

While a few modelling studies have incorporated these hydrological processes [24], empirical event-based investigations supported by high temporal resolution data to support the dominant runoff generation mechanism remain limited in Western Ghats catchments. Moreover, robust methods for estimating design flood peaks in VSA-dominated landscapes are still lacking due to insufficient understanding of the controlling factors. To address these gaps, this study employs a correlation-based event analysis to explore runoff generation mechanisms and identify the factors influencing flood peaks. Unlike most earlier studies that relied on coarse daily datasets [25,26], the present analysis utilizes fine-scale temporal observations (15 min. interval), enabling a more realistic assessment of the rapid hydrological responses, which is the characteristic of small, forested headwater catchments. This approach offers a practical means of gaining insights into hydrological responses in data-scarce environments.

2. Study Area and Data Collected

The Western Ghats are a series of hill ranges running south to north along the Western Coast of India, almost parallel to the coast (Figure 1). They separate the South Indian plateau from the coast. The hills in the range rise to elevations up to about 3000 m, while the plateau has an average elevation of about 1000 m [27]. The Western Ghats region is bestowed with very heavy rainfall, occurring throughout the South-West monsoon season. Further, the whole region is underlain by very old igneous rocks, Granite and Gneiss being the most common. A combination of such hard rocks and heavy rainfall has rendered the region with deep soil mantles, which are host to a very rich vegetation cover. The soil thickness in the region varies from 3 to 50 meters, significantly influencing the region's hydrology [28].

Investigations presented in this paper are based on hydrometeorological observations from the Heruthihalla catchment, a second-order headwater catchment within the Kumaradhara River Basin in the Western Ghats region of Karnataka. High-resolution rainfall and runoff data were collected during the monsoon season (hydrological processes are active during the monsoon season) of the years 2021 and 2022 using an installed Automatic Weather Station (AWS) (for meteorological data collection) and an Automatic Water Level Recorder (AWLR). Stream discharge was derived from water-level measurements recorded by the AWLR, with a rectangular notch constructed below a culvert across the stream in the catchment at the outlet.

It is observed that rainfall above 5 mm led to an observable runoff, hence only such rainfall events were designated as storms in the study. However, so as to keep the events clearly distinguishable, corresponding event hydrographs with single peaks and spaced by more than two hours of rainless duration were considered for analysis. The analysis of collected data is performed using such 30 selected rainfall-runoff events.

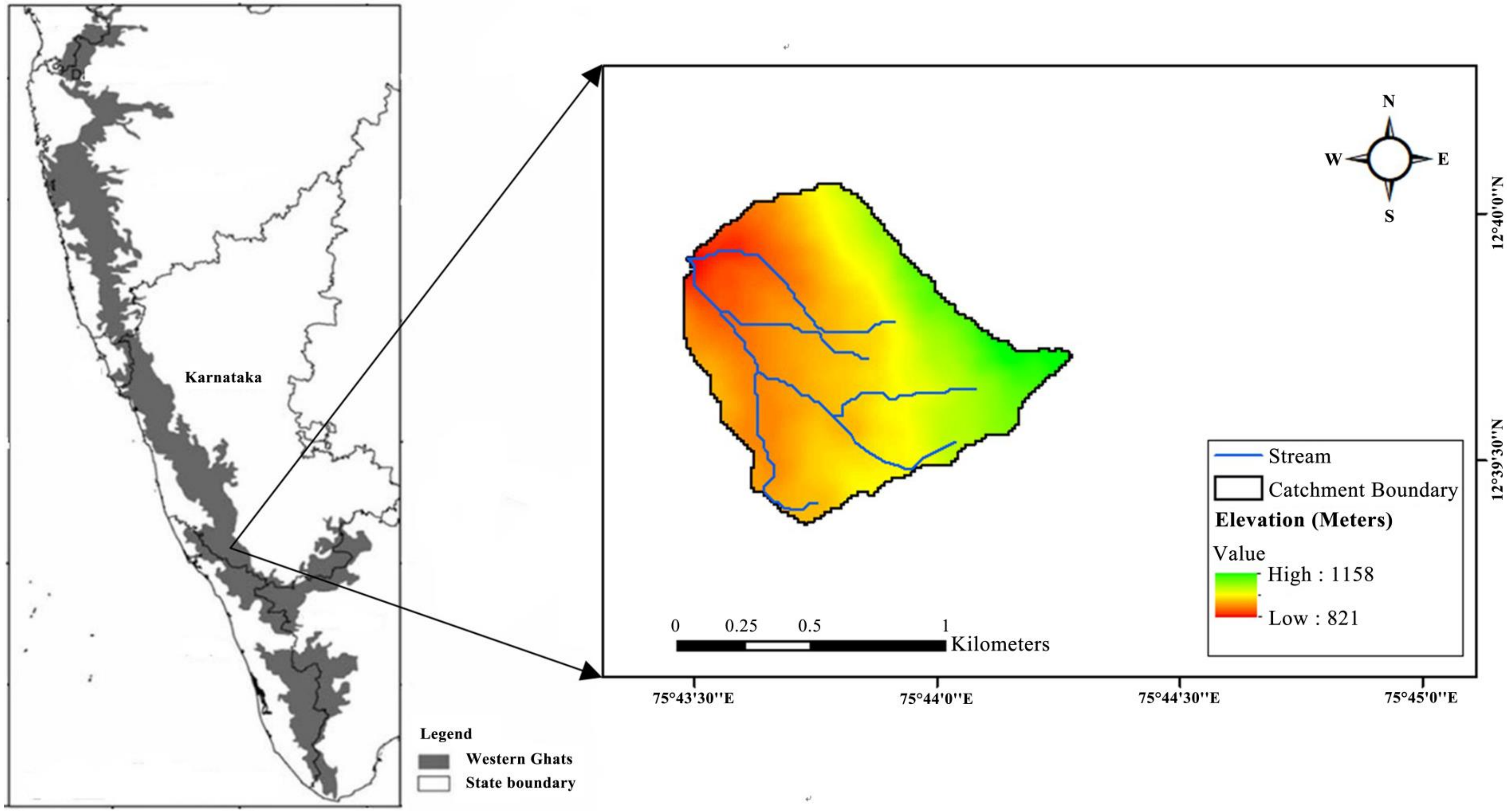

Figure 1. Stretch of Western Ghats over Karnataka (Source: MRY Putty et.al, 2000) and the location of the study area

3. Materials and Methods

The stream flow data is analysed to identify discrete discharge peaks, and the corresponding rainfall events that coincide with these flood peaks are also identified. Baseflow separation was conducted using the simple straight-line method because of its simplicity, reproducibility, and widespread use in event-based hydrological studies. The method assumes a linear baseflow variation between runoff initiation and a point on the recession limb corresponding to the catchment's time of concentration [29], making it suitable for short-duration storm events in small to medium catchments. Although it does not explicitly represent groundwater dynamics and involves subjective endpoint selection, it provides a robust estimate of direct runoff for comparative analyses. During the study period, the hydrological behaviour of the catchment was assessed by employing the event runoff coefficient, together with studying the association between the runoff and rainfall characteristics. The parameters that are derived from the records for the corresponding runoff events, such as event rainfall, antecedent wetness condition and incremental discharge, are used to comprehend the formation of flood peaks in the study area.

Antecedent precipitation and the Catchment Storage Index (CSI) are the two different metrics used as measures of antecedent wetness condition (AWC) in the study area. Antecedent precipitation is calculated by aggregating (a) the total rainfall over a period of 5 days and (b) the rainfall 24 hours before the onset of the runoff-producing storm events as represented by (1).

$$AP = \sum_{i=1}^{n} Pi \qquad (1)$$

where AP is the antecedent precipitation, Pi is the daily precipitation, and n is the number of days.

CSI is considered as that magnitude of flow in the stream which lasts consistently for a few hours prior to the flood hydrograph (Figure 2) - it can be argued that this magnitude of flow occurring during a period of insignificant rainfall is due to the amount of water stored in the catchment prior to the flood event and forms a true representation of the catchment wetness.

Table 1 provides a concise overview of the key attributes pertaining to the rainfall-runoff events that have been identified.

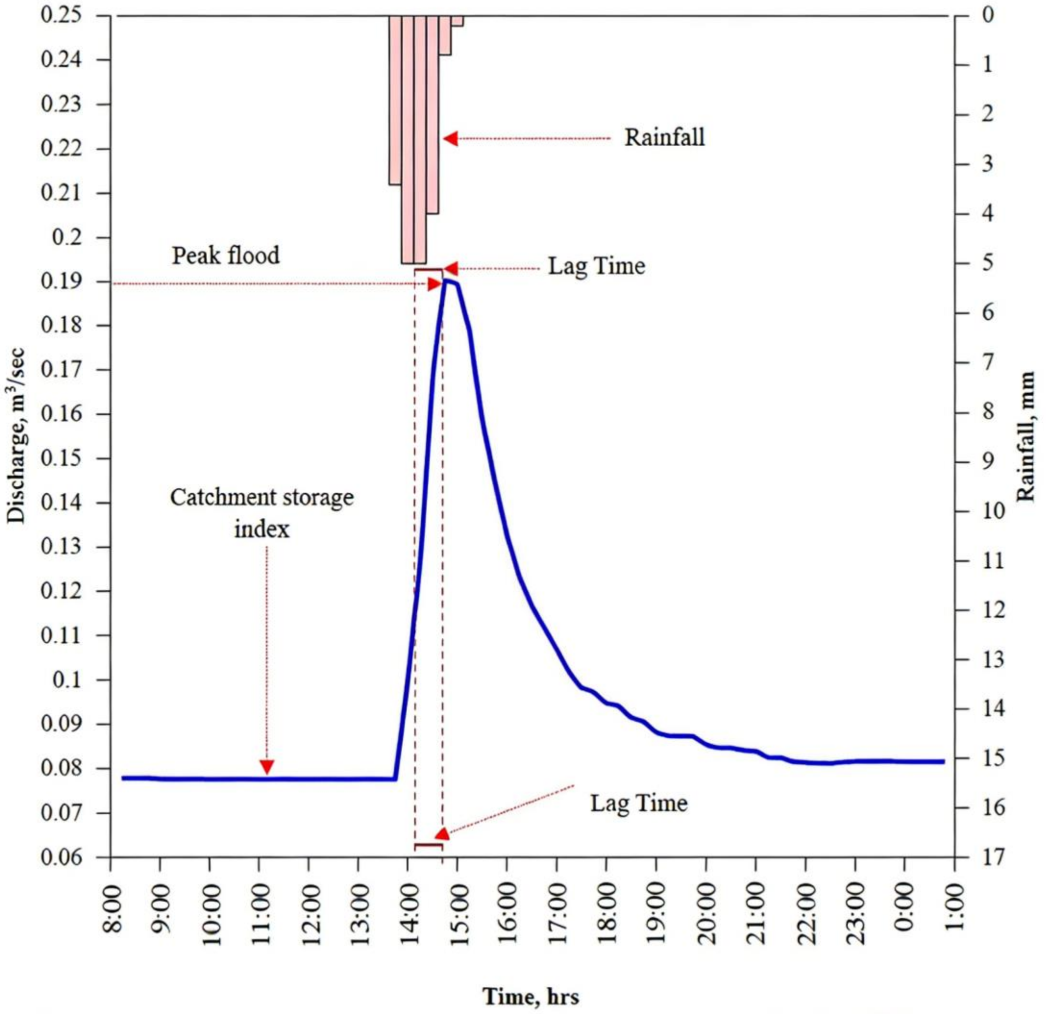

Figure 2. Graphical illustration of storm hydrograph characteristics evaluated in the study

Table 1. Basic hydrologic characteristics of analyzed rainfall-runoff events

No.	**Date**	**Rainfall characteristics**			**Runoff characteristics**					**AWC**			**MCA** (%)
		P (mm)	I (mm/hr)	H (hr)	R (mm)	QF (mm)	Q_P (m^3/sec)	Q_I (m^3/sec)	QF/P	CSI (m^3/sec)	$P_{5\ day}$ (mm)	$P_{24\ hrs}$ (mm)	
1	18-Jun-21	18.00	8.00	2.25	36.88	0.82	0.75	0.34	0.05	0.41	336.00	77.00	3.88
2	19-Jun-21	17.40	6.33	2.75	35.13	0.67	0.61	0.15	0.04	0.46	443.00	52.60	3.84
3	20-Jun-21	13.20	17.6	0.75	26.42	0.32	0.40	0.10	0.02	0.30	430.00	13.60	2.39
4	20-Jun-21	15.80	7.02	2.25	26.42	0.54	0.44	0.14	0.03	0.30	430.00	27.80	3.38
5	21-Jun-21	18.20	7.28	2.50	29.34	0.74	0.54	0.20	0.04	0.34	367.00	47.80	4.04
6	23-Jun-21	6.00	12.00	0.50	14.80	0.07	0.21	0.01	0.01	0.19	227.60	1.60	1.18
7	27-Jun-21	12.00	4.36	2.75	8.08	0.08	0.12	0.02	0.01	0.10	46.00	15.20	0.68
8	01-Jul-21	19.60	6.53	3.00	7.46	0.34	0.19	0.11	0.02	0.08	33.60	0.60	1.75
9	03-Jul-21	8.80	3.52	2.50	7.01	0.16	0.11	0.03	0.02	0.08	41.00	0.80	1.79
10	06-Jul-21	16.80	16.80	1.00	6.65	0.15	0.15	0.07	0.01	0.08	40.20	0.20	0.90
11	01-Aug-21	11.20	3.73	3.00	3.45	0.26	0.08	0.04	0.02	0.04	36.60	22.80	2.28
12	05- Aug -21	19.20	19.20	1.00	4.02	0.40	0.18	0.15	0.02	0.03	35.60	0.00	2.08
13	06- Aug -21	27.40	9.96	2.75	4.89	0.89	0.19	0.16	0.03	0.03	42.20	29.40	3.25
14	13- Aug -21	22.80	10.13	2.25	3.53	0.21	0.15	0.12	0.01	0.03	21.60	6.00	0.91
15	22- Aug -21	14.40	4.80	3.00	3.00	0.32	0.10	0.07	0.02	0.03	35.50	5.20	2.23
16	23- Aug -21	13.80	27.60	0.50	4.05	0.27	0.18	0.15	0.02	0.03	38.20	2.00	1.98
17	21-Oct-21	11.60	9.28	1.25	5.71	0.29	0.16	0.10	0.02	0.06	10.40	7.40	2.46
18	29-Oct-21	10.20	5.83	1.75	3.09	0.10	0.06	0.03	0.01	0.03	9.20	0.00	0.94
19	31-Oct-21	12.00	8.00	1.50	3.41	0.28	0.07	0.04	0.02	0.03	14.40	3.60	1.80
20	27-Jun-22	13.00	26.00	0.50	4.63	0.19	0.11	0.09	0.01	0.03	49.00	12.00	1.42
21	28-Jun-22	16.50	8.25	2.00	8.08	0.37	0.16	0.09	0.02	0.06	78.00	36.00	2.26
22	29-Jun-22	12.50	10.00	1.25	8.94	0.26	0.15	0.05	0.02	0.10	97.00	41.50	2.11
23	26-Jul-22	16.60	5.53	3.00	21.30	0.13	0.30	0.05	0.01	0.25	96.60	4.00	0.79
24	27-Jul-22	15.20	6.76	2.25	20.27	0.63	0.37	0.14	0.04	0.23	72.00	17.80	4.11
25	30-Jul-22	21.20	28.27	0.75	17.82	0.33	0.34	0.15	0.02	0.20	64.80	21.40	1.57
26	02-Aug-22	26.40	8.12	3.25	15.37	0.99	0.34	0.18	0.04	0.16	53.00	7.00	3.74
27	21-Aug-22	17.00	9.71	1.75	10.14	0.46	0.22	0.11	0.03	0.10	40.60	25.00	2.72
28	25-Aug-22	45.00	5.81	7.75	15.56	1.20	0.29	0.12	0.03	0.18	133.50	8.00	2.66
29	01-Sep-22	25.50	12.75	2.00	8.51	0.39	0.17	0.07	0.02	0.09	25.00	0.00	1.51
30	06-Sep-22	27.50	27.50	1.00	7.03	0.34	0.19	0.12	0.01	0.07	43.00	60.00	1.22

P (event rainfall), I (rainfall intensity), H (rainfall duration), R (runoff for the day), QF (Direct runoff), Q_P (peak flood), Q_I (incremental discharge), QF/P (runoff co. efficient), CSI (catchment storage index), $P_{5\ day}$ (last 5-day rainfall), P_{24hrs} (previous day rainfall), AWC (antecedent wetness condition), MCA (minimum contributing area)

The estimation of the event runoff coefficient is based on the ratio between the volume of the event's quick runoff component and the corresponding amount of rainfall. This runoff coefficient is influenced by the storage levels in the different storages, such as vegetation interception, soil moisture accumulation, and percolation into subsurface layers. Further, the response time (Table 1) in this work (also known as lag-time) refers to the period of time between the highest intensity of the storm and the peak of the corresponding event hydrograph (Figure 2). This metric serves to quantify how fast the peak discharge is attained.

4. Results and Discussion

4.1. Rainfall–Runoff Event Analysis and Identification of Runoff Generation Mechanisms

During the study period from June to October, the total recorded rainfall in the experimental catchment was 3600 mm in 2021 and 4100 mm in 2022, both within the climatologically normal range for the region (3000–6000 mm annually). These totals reflect typical monsoonal rainfall patterns of the Western Ghats and provided an appropriate temporal window to capture hydrologically significant events. Across both years, 30 distinct rainfall–runoff events were identified and analysed. Rainfall depths ranged from 6 mm to 45 mm, while average intensities (calculated by dividing the total rainfall amount during an event by the storm duration) varied between 3.5 mm/hr and 28 mm/hr. Most of the events (65%) had average intensities below 10 mm/hr, indicating that moderate-intensity rainfall dominates storm profiles in the region [24].

The hydrologic response time, defined as the lag between rainfall peak and corresponding streamflow peak, ranged from 15 to 45 minutes for most of the events, except when the catchment was relatively dry. Such short response times, even under moderate rainfall, suggest rapid mobilization of water through subsurface pathways, likely facilitated by preferential flow or pipe flow mechanisms. Large peak flows observed despite short lags in the catchment are consistent with the observations in small forested catchments where well-connected subsurface networks are present [24].

Analysis of the quick flow component, calculated using event separation techniques, revealed values ranging from 0.07 mm to 1.19 mm per event. Statistical correlations showed a stronger relationship between quick flow and total rainfall amount ($r = 0.72$) than with rainfall intensity ($r = -0.2$) (Figure 3a and Figure 3b), supporting the conceptual framework of Variable Source Area (VSA) hydrology. Further, the significant influence ($r = 0.62$) of event duration on quick flow compared to rainfall intensity shows that prolonged rainfall increases the spatial extent of saturated areas, thereby expanding runoff-contributing zones and enhancing flow volumes (Figure 3c). These results underscore the importance of rainfall amount and duration as primary drivers of runoff generation in VSA-dominated systems, consistent with previous findings in humid, forested, hilly catchments [30].

Evaluation of runoff coefficients in relation to Catchment Storage Index revealed a moderate positive correlation ($r=0.63$) (Figure 4), indicating that infiltration and subsurface storage dominate the hydrologic response. The catchment's soils are likely deep and highly permeable, capable of storing substantial volumes of infiltrated water and releasing it gradually as baseflow. Hydrographs of selected events (Figure 5) further illustrate the dominance of delayed flow, where more than 60% of total streamflow is contributed by baseflow. This sustained response, even after rainfall cessation, highlights the role of subsurface storage and interflow in shaping the hydrograph in the catchment.

4.2. Controls on Streamflow Generation

The processes governing streamflow generation in a catchment are strongly influenced by a combination of climatic and physiographic factors. Rainfall characteristics, particularly depth and intensity, determine whether runoff is to be initiated. From the event analysis, a threshold rainfall depth of approximately 5 mm was identified as the minimum required to generate measurable streamflow at the catchment outlet. This threshold reflects interception by canopy and leaf litter, infiltration into permeable soils, and other initial losses before runoff contributes to the stream. Such thresholds are typical of forested headwater systems, where a substantial fraction of rainfall is temporarily stored or delayed [30].

Rainfall intensities in the study catchment ranged between 3.5 mm/hr and 28 mm/hr, considerably lower than the saturated infiltration capacity observed in experimental plots of similar forest systems in the Western Ghats [24,28,31]. This disparity indicates that infiltration-excess overland flow (Hortonian Overland Flow, HOF) is unlikely to be a major contributor to runoff. Low runoff coefficients observed for most events (Table 1) further support the notion that rainfall largely infiltrates the soil, minimizing overland flow. High soil permeability and dense forest cover reinforce this pattern: deep, well-drained soils store substantial infiltrated water for later contributions to baseflow, while canopy and undergrowth intercept a significant fraction of rainfall.

The timing of streamflow response, expressed as lag time to peak flow, provides additional insight into the factors controlling stormflow. A mean lag time of approximately 36 minutes was observed between rainfall onset and hydrograph peak, which is 1.5 times longer than the lag time estimated using Dunne's empirical method (1987) [32], which is calibrated for infiltration-excess systems. This lag supports rapid subsurface flow via preferential pathways, such as root channels or soil pipes, commonly found in humid, undisturbed forest soils [33,34].

All these observations present a coherent picture that the dominant runoff generation process in the studied Western Ghats catchment is saturation-excess overland flow.

The relatively low runoff coefficients, high soil infiltration capacity, weak correlation between rainfall intensity and runoff, and moderate lag times suggest that the hydrologic regime is primarily governed by subsurface storage and antecedent moisture conditions, with only a minor contribution from Hortonian overland flow.

This understanding has important implications for hydrological modelling and flood forecasting in similar forested, humid catchments. It emphasizes the need for models that can capture threshold behaviour, dynamic contributing areas, and interflow pathways-parameters that are often oversimplified in conventional lumped or HOF-centric models.

4.3. Factors Influencing Flood Peaks

Building on the insights gained from stormflow generation mechanisms, it is evident that flood peaks in the studied catchment are not merely a function of rainfall intensity or amount alone, but rather the result of a complex interplay of hydrological, soil, and topographic factors. In regions like Western Ghats, where variable source area (VSA) dynamics dominate and subsurface flow pathways are prominent, flood peaks are often influenced by the duration of rainfall, antecedent moisture conditions, spatial expansion of saturated areas, and the connectivity between hillslopes and stream channels. Understanding these contributing factors is crucial not only for accurate flood prediction but also for designing effective watershed management and flood mitigation strategies tailored to such a hydrologically sensitive landscape.

As the peak flow of a rainfall-runoff event represents a critical hydrological parameter in the assessment of flood risk, hydraulic structure design, and watershed management, it is essential to understand the factors that govern its magnitude and variability. Numerous studies have emphasized the role of peak discharge in design flood estimation and flood hazard analysis, particularly in small and steep catchments where response times are short and flood events can escalate rapidly [35,36].

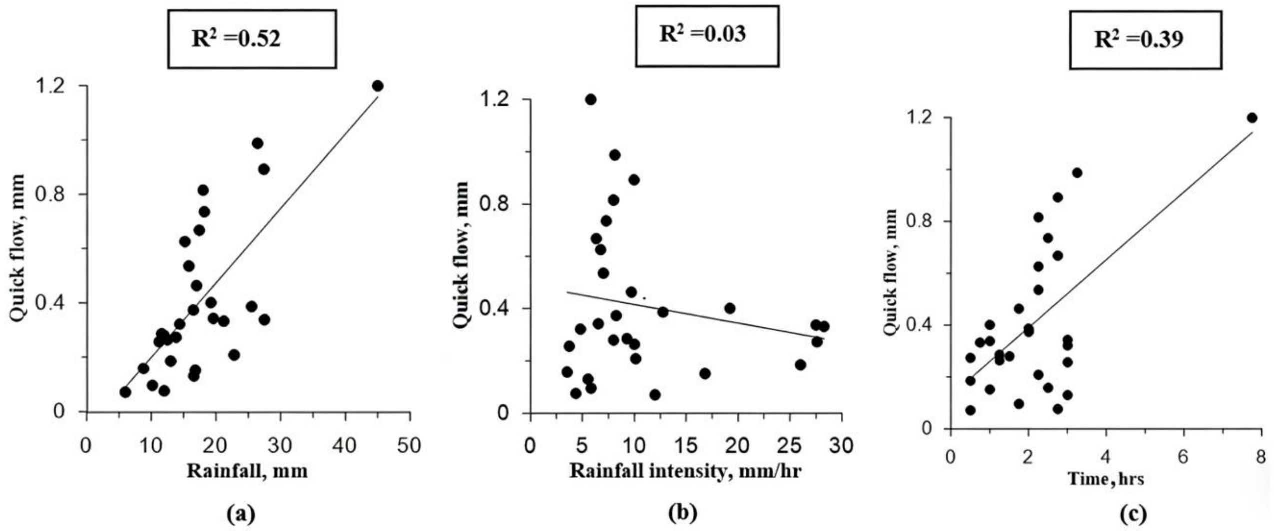

Figure 3. Scatter diagram showing the association between a) Quick flow and Rainfall amount b) Quick flow and rainfall intensity c) Quick flow and rainfall duration

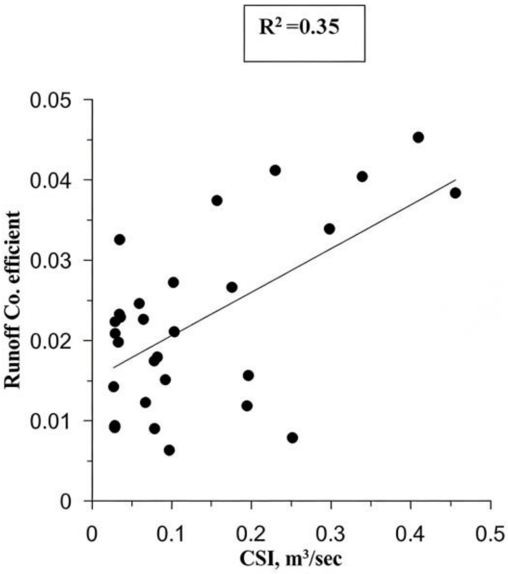

Figure 4. Scatter diagram showing the association between Runoff coefficient and Catchment storage index **(CSI)**

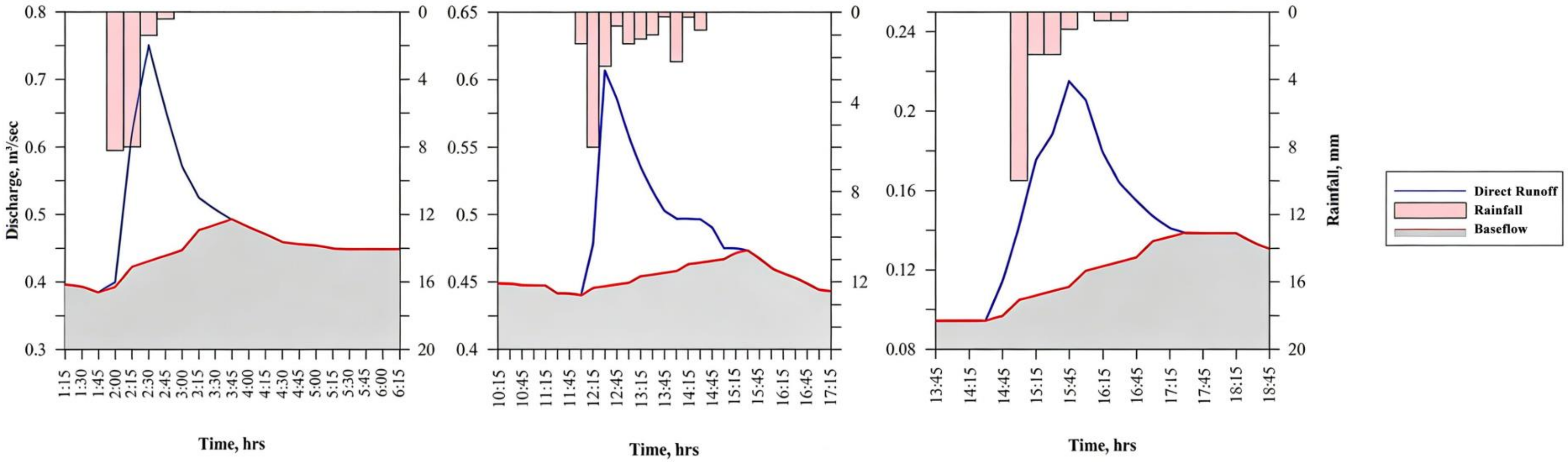

Figure 5. Hydrographs for the events: Event No. 1; 2 and; 27 respectively

In the context of the present study, this analysis becomes particularly relevant given the history of extreme hydrological events in the region, notably the flood event during the 2018 monsoon, which resulted from sustained heavy rainfall over the Western Ghats. Such events underscore the necessity of accurately characterizing the controlling factors of peak flows, especially in headwater catchments with complex runoff generation dynamics.

To this end, the study evaluated the relationship between event peak flow and a set of key rainfall and catchment characteristics, which are traditionally known or hypothesized to influence flood peaks. These include total rainfall amount, rainfall intensity, rainfall duration, antecedent wetness conditions, and lag time between rainfall and peak flow.

Relationships were explored using scatter plots, allowing visual assessment of correlation patterns and potential threshold behaviours. This graphical approach provided an intuitive means of identifying dominant influences and nonlinear trends. Each relationship is discussed in detail in the following sections, with an emphasis on how the results reflect the unique hydrologic behaviour of the forested, highly permeable catchment of the Western Ghats.

4.3.1. Effect of Event-Causing Rainfall

In order to understand the role of rainfall characteristics in controlling flood peaks, a scatter diagram was drawn to examine the relationship between peak flow and the total event-causing rainfall depth (Figure 6a). Contrary to the conventional expectation that larger rainfall events would generate proportionally higher flood peaks, the results revealed a low correlation (r=0.19) between the two variables, suggesting that total rainfall alone is not a strong predictor of peak discharge in this catchment.

This weak association raises an important consideration about the hydrological response behaviour of catchments governed by variable source area (VSA) dynamics. In such systems, peak flow is not solely the outcome of rainfall volume but may rather depend on how rainfall interacts with the antecedent moisture conditions and the already existing baseflow in the system. To further investigate this, the relationship between rainfall depth and incremental discharge, which is defined as the difference between the pre-event baseflow and the observed event peak, was examined (Figure 6b). The logic behind this approach was that peak flow may largely represent the augmentation of pre-existing streamflow conditions, rather than being a direct translation of rainfall into runoff.

However, even this refined analysis yielded a weak positive correlation (r=0.39), indicating that incremental discharge is not significantly related to rainfall depth either. This finding highlights the complexity of runoff generation mechanisms in forested, humid catchments, where a variety of interacting controls, such as antecedent soil moisture, rainfall duration, infiltration dynamics, and subsurface flow connectivity, can modulate the stream response.

The findings are consistent with previous studies in similar environments, where soil moisture thresholds, event sequencing, and temporal distribution of rainfall have been shown to exert a stronger control over stormflow generation than rainfall totals alone [37,38]. This underscores the need to incorporate pre-event hydrologic states in predictive flood models for better accuracy in peak flow estimation in such sensitive and highly dynamic hydrological systems.

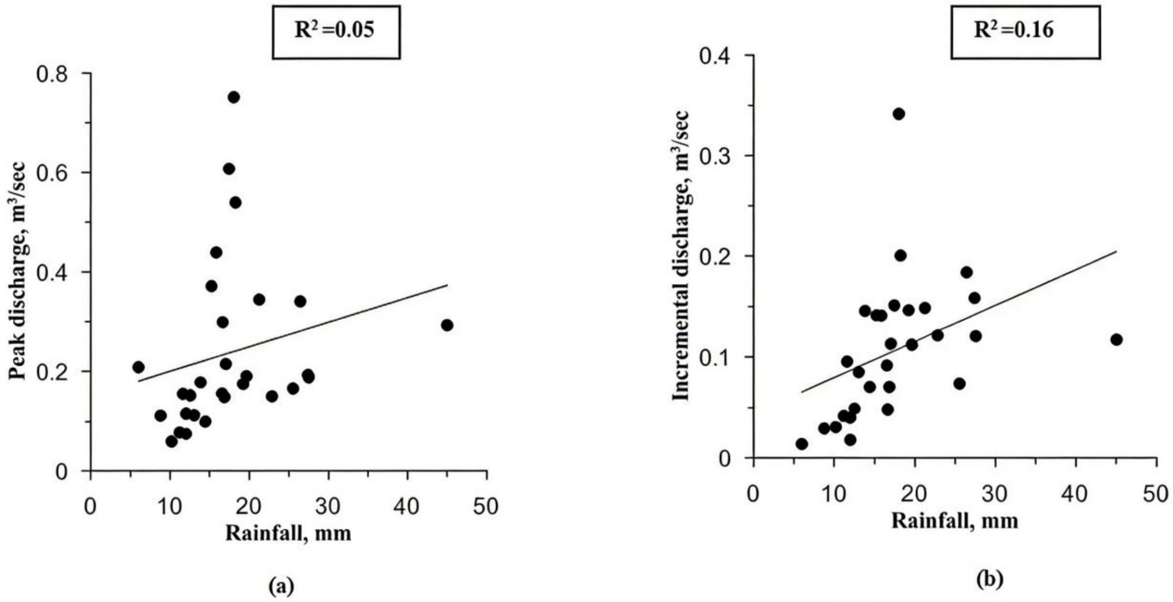

Figure 6. Scatter diagram showing the association between a) Peak discharge and event rainfall b) Incremental discharge and event rainfall

4.3.2. Effect of Antecedent Wetness Conditions on Flood Peaks

Given the weak correlation observed between event-causing rainfall and flood peaks, it became essential to examine the role of antecedent wetness conditions, which are often found to significantly influence runoff generation, especially in humid, forested catchments with dominant subsurface flow pathways. In this study, two distinct indicators were employed to assess antecedent wetness in the catchment.

1. Antecedent rainfall
2. Catchment storage index (CSI)

To quantify antecedent rainfall, cumulative rainfall over the five days preceding each selected runoff event was computed and plotted against the corresponding event peak discharge (Figure 7a). In addition, the rainfall occurring on the day immediately preceding each event was also considered as a secondary metric (Figure 7b). The comparison of these two plots revealed that the five-day cumulative rainfall shows a more consistent and stronger correlation (r=0.81) with flood peaks than the previous day's rainfall (r=0.63). This suggests that, short-term soil moisture memory and sustained wetting over multiple days play a more critical role in saturating the soil profile and enabling the expansion of runoff-contributing zones.

However, among all examined indicators, the Catchment Storage Index (CSI) emerged as the most significant (r=0.94) and reliable predictor of flood peaks (Figure 7c). CSI, which reflects the baseflow level at the beginning of each rainfall-runoff event, serves as a proxy for the overall wetness or storage state of the catchment. The observed very strong positive correlation between CSI and peak flow reinforces the idea that the catchment's antecedent storage capacity has a key control on the magnitude of stormflow.

This finding aligns well with the hydrological behaviour of the study catchment, where delayed subsurface flow contributes significantly–often over 60%–to the total streamflow, both during dry weather and active rainfall events [24]. The magnitude of flood peaks is less a function of instantaneous rainfall inputs and more a result of the cumulative wetness condition of the catchment.

Moreover, this outcome supports the conclusions drawn from other studies in VSA-dominated terrains, which have emphasized the importance of pre-event storage states and catchment memory in shaping runoff responses (e.g., [16,30]). The CSI, acting as a synthesized representation of all slow-moving subsurface processes, thus provides an integrated measure of antecedent wetness and proves to be a robust predictor for flood peak estimation in such hydrological settings.

4.4. Saturated Area Development in the Catchment

Field observations during the active monsoon months reinforce the theoretical and empirical conclusions drawn in the study. During periods of sustained rainfall, the stream channels, which are typically narrow under baseflow conditions, begin to expand laterally due to the development of saturated zones along their banks. These zones, initially restricted to riparian areas, grow in size as rainfall continues, eventually occupying significant portions of the valley floor. Once these areas become saturated, any additional rainfall falling on them directly contributes to surface runoff, thereby significantly amplifying streamflow volumes and flood peaks.

This dynamic spatial expansion of saturated areas underscores a fundamental principle of the VSA concept, wherein runoff-contributing areas are not fixed but evolve in response to antecedent wetness and rainfall characteristics.

Since the runoff response is spatially and temporally variable due to factors like antecedent wetness and rainfall intensity, estimating the Minimum Contributing Area (MCA) helps in determining how much of the landscape is actually contributing to the increased streamflow and flood peaks. However, capturing the dynamism of saturated zones was difficult in the field due to the difficulty associated with continuous field-based mapping. Hence, as a practical alternative, the Minimum Contributing Area (MCA) is estimated in this study for individual events using event hydrographs.

According to the variable source area theory, saturated zones are assumed to form primarily in the vicinity of the stream network, and all rainfall falling on these saturated areas is converted directly into runoff. Hence, the saturated contributing area or MCA is derived by dividing the direct runoff (quick flow volume) by the depth of rainfall that triggered the event.

The computed MCA values for selected events in the Heruthihalla catchment (Table 1) reveal a highly dynamic behaviour, with the maximum MCA reaching 4.11% of the catchment area during a peak event on 27 July 2022. To explore this variability, the relationship between MCA and Catchment Storage Index (CSI)-a proxy for catchment wetness-was examined (Figure 8a).

Although a general trend suggests increased MCA with higher CSI (r=0.57), the scatter in the data indicates that CSI alone does not fully account for the observed variability in saturated area extent. This necessitated further investigation into the potential influence of rainfall characteristics. Subsequent scatter plots revealed a weak positive dependence of MCA on rainfall amount ($r = 0.2$) compared to rainfall intensity, which showed a weak negative relationship ($r = -0.27$). This suggests that total rainfall volume may have a slightly greater influence on catchment wetness than short-duration rainfall intensity. Still, among all the variables considered, CSI continues to show a greater influence on MCA variability than rainfall amount, reinforcing the importance of antecedent catchment conditions in shaping runoff-contributing areas.

A summary table for the statistics of all analysed variables is given in Table 2. The analysis underscores the complex interplay between static (soil and topography) and dynamic (rainfall and storage) factors in governing the hydrological response of catchments with VSA behaviour.

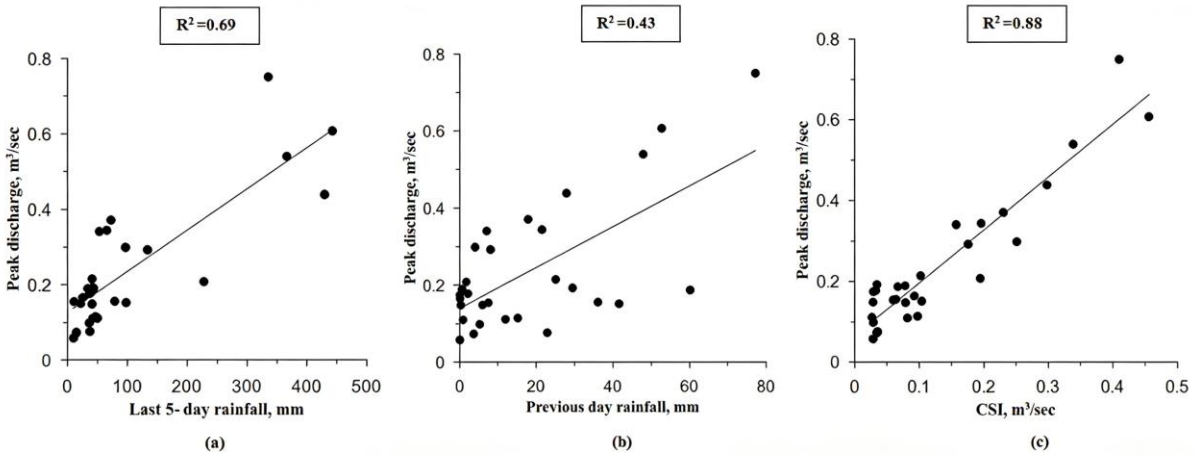

Figure 7. Scatter diagram showing the association between a) Peak discharge and last 5-day rainfall b) Peak discharge and previous day rainfall c) Peak discharge and catchment storage index (CSI)

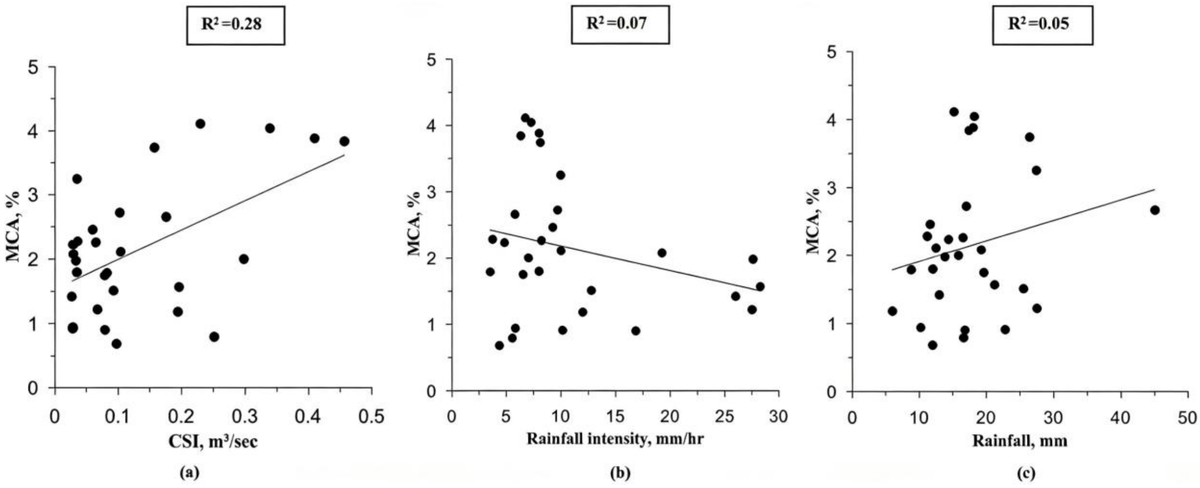

Figure 8. Scatter diagram showing the association between a) Minimum contributing area (MCA) and catchment storage index (CSI) b) Minimum contributing area (MCA) and rainfall intensity c) Minimum contributing area (MCA) and rainfall amount

Table 2. Summary of statistics for analysed variables

Variables considered	Correlation r (Pearson)	p-value	Significance
Quick flow (QF) & Event rainfall (P)	0.72	0.0000	Significant
Quick flow (QF) & Rainfall intensity (I)	-0.20	0.3050	Not significant
Quick flow (QF) & Rainfall Duration (H)	0.62	0.0002	Significant
CSI & Runoff coefficient	0.63	0.0001	Significant
Event rainfall (P) & Peak discharge (Qp)	0.19	0.2980	Not significant
Event rainfall (P) & Q_incremental (Q_I)	0.39	0.0300	Significant
Peak discharge (Qp) & $P_{5\ \text{day}}$	0.81	0.0000	Significant
Peak discharge (Qp) & $P_{24\ \text{Hours}}$	0.63	0.0002	Significant
Peak flow Peak discharge (Qp) & CSI	0.94	0.0000	Significant
MCA & CSI	0.57	0.0000	Significant
MCA & Rainfall intensity (I)	-0.27	0.1391	Not significant
MCA & Event rainfall (P)	0.20	0.2886	Not significant

5. Conclusions

This study provides critical empirical insights into the runoff generation mechanisms and flood peak controls within a small, forested headwater catchment in the Western Ghats of South India. Through high-resolution rainfall-runoff event analysis, the research confirms that streamflow response in this region is predominantly governed by subsurface processes and saturation-excess runoff, rather than Hortonian overland flow. The short lag times and low runoff coefficients observed across events highlight the role of rapid interflow and shallow groundwater contributions, underscoring the relevance of the Variable Source Area (VSA) concept in explaining the catchment's hydrologic behaviour.

Antecedent wetness conditions-quantified through antecedent precipitation and the Catchment Storage Index (CSI)-emerged as more reliable predictors of flood peaks and saturated area development than rainfall intensity or amount alone. This emphasizes the importance of internal catchment storage dynamics and moisture thresholds in shaping stormflow responses.

Furthermore, the study demonstrates that even with limited data availability, meaningful hydrological insights can be obtained using event-based correlation analyses supported by a high-temporal-resolution dataset.

The findings have significant implications for flood prediction and hydrological modelling of VSA-dominated catchments. Correlation between considered variables highlights the necessity of incorporating subsurface flow processes, dynamic contributing areas, and antecedent conditions into conceptual and physically based models to better simulate hydrologic responses in VSA-dominated landscapes.

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