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Hydrological Dynamics Of The Kale River Basin: Linking Rainfall, Land Use Runoff, And Channel Discharge

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Abstract: The Kale River Basin in the Eastern Himalayas presents a dynamic hydrological system shaped by intense monsoonal rainfall, diverse land use patterns, and complex topography. This study investigates the interrelationship between rainfall, land use, surface runoff, and channel discharge over three hydrological years (2020–2023) using field-based experiments, remote sensing, and geospatial analysis. Results indicate a strong correlation between rainfall variability and both surface runoff and river discharge, with barren and agricultural lands showing the highest runoff sensitivity. Forested areas, while contributing significantly to total runoff, showed a moderate response, indicating their role in buffering hydrological extremes. Surface runoff and channel discharge accounted for an average of 78.2% and 70.6% of the total water volume, respectively, highlighting rapid conversion of rainfall into flow with limited groundwater recharge. The increasing discharge trend corresponds with rising rainfall and changing land use, highlighting the integrated watershed management. This study emphasizes the need for sustainable land-use practices, forest conservation, and enhanced water retention strategies to mitigate flood risks and ensure long-term hydrological resilience in the ecologically fragile Eastern Himalayan region.

Keywords: Kale River Basin, hydrological dynamics, surface runoff, channel discharge, rainfall variability, landuse, Eastern Himalayas, watershed management, LULC, sustainable water resources.

I. INTRODUCTION:

Hydrological processes are fundamental for evaluating watershed dynamics, forecasting flood hazards, and maintaining sustainable water management. The interplay among precipitation, land use, and stream flow represents a critical factor in catchment systems. Rainfall acts as the principal driver of the hydrological cycle, shaping surface runoff and groundwater replenishment (Dingman, 2015). Yet, the conversion of rainfall into runoff and eventual stream flow is heavily influenced by land use characteristics. Differences in vegetation, urban development, and agricultural activities substantially modify infiltration capacity, evapotranspiration rates, and water routing mechanisms (Bruijnzeel, 2004; Bonell & Bruijnzeel, 2005). Land use alterations, including deforestation, urban expansion, and rotational farming, can amplify surface runoff, diminish infiltration, and intensify peak flows during storms (Fohrer et al., 2005). Such modifications also reshape the timing and spatial patterns of runoff entering river networks. Urban impervious surfaces, for instance, prevent water absorption, accelerating runoff generation and increasing volumes that often exceed channel capacities (Sharma et al., 2016). The relationship between rainfall-runoff processes and channel discharge becomes increasingly complex in heterogeneous landscapes, particularly in tropical and mountainous regions where land use practices are dynamic. In such settings, the hydrological response of a watershed reflects not just the intensity and duration of rainfall but also the geomorphology, soil type, and anthropogenic alterations of land cover (Zhou et al., 2013). In the Eastern Himalaya hydrological behavior of river basins is governed by intricate interactions between rainfall intensity, land use patterns, and catchment characteristics. (Singh et al., 2011; Valdiya, 1980).The Kale River Basin, located in the Ziro Valley of Arunachal Pradesh, represents traditional agricultural systems, dense forest cover, and high intensity monsoonal rainfall creates a dynamic and highly variable hydrological environment. Rainfall in Ziro Valley is characterized by pronounced seasonality, with more than 75% of annual precipitation occurring during the monsoon months from May to September (IMD, 2020). This seasonal influx leads to change in surface runoff, particularly in different land use types. Changes in rainfall intensity and duration directly affect infiltration capacity, soil saturation thresholds, and overland flow, resulting in variability in channel discharge (Goswami et al., 2009). Moreover, the orographic influence of the surrounding Ziro valley increases convective precipitation events, contributing to both intra-annual and inter-annual hydrological fluctuations (Nandy et al., 2006).

Land use and land cover (LULC) play a central role in mediating runoff generation and sediment transport in mountain basins. In the Kale River Basin, traditional wet rice cultivation (paddy fields), forest conservation practices, and areas under shifting cultivation contribute variably to hydrological output. Forest areas tend to reduce peak runoff and enhance infiltration, while agricultural lands, particularly paddy fields, amplify surface runoff during intense rainfall events due to reduced infiltration and anthropogenic modification of natural slopes (Tiwari et al., 2016). Shifting cultivation, although declining, still contributes to temporary land cover disturbances, exacerbating soil erosion and modifying runoff coefficients (Ramakrishnan, 1992).

II. STUDY AREA:

The Kale River Basin is located in the Ziro Valley, Eastern Himalayas Arunachal Pradesh (fig.No1) It covers an area of 204.06 km², extending between 27°25'52" to 27°38'37" N latitude and 93°45'30" to 93°55'50" E longitude it is the only major river traversing the Ziro Valley, flowing southward for about 36 kilometers before its confluence with the Pange River near Yachuli. The river originates from the confluence of three fifth-order streams—Sekhe Kale Channel, Neilang Nalah (to the north), and Chiya Channel (to the northeast)—near Tajang Village, forming a sixth-order river. Additional tributaries feeding the Kale River include Sul, Pail, Niyalisi, Niuth, and Sikhe, which contribute to its perennial nature. Geologically, the basin lies in the core zone of the Bomdila Anticline and primarily exposes the Khetabari Formation of the Lesser Himalayas (Gopendra Kumar, 1997). This formation, is visible around Khetabari village along the Kimin–Ziro road, comprises granite, gneiss, schist, phyllite, and quartzite. Overlying the Khetabari Formation is the Tenga Formation, while Quaternary deposits including boulders, pebbles, sand, and clay are also observed. Intrusions of granite and gneiss are widespread, especially in the Pakro Yazali region, resulting in the presence of extensive enclaves of the older Khetabari rocks. The upper part of the basin (Ziro Valley) has a relatively flat topography, whereas the southern regions are rugged and steep, with elevations ranging from 700 to 2700m. The Apatani tribe primarily inhabits the upper valley, practicing sedentary paddy cum fish cultivation, while the Nyishi tribe occupies the lower stretches and engages in shifting cultivation (Jhum) and dry farming (Joshi & Riba, 2008). The land use/land cover (LULC) within the basin exhibits considerable diversity. The Ziro Valley is dominated by irrigated paddy fields integrated with fish culture, while the southern parts exhibit traditional Jhum cultivation, dry farming, and patches of degraded forest. Natural vegetation comprises bamboo groves, pine forests, dense mixed jungle, degraded scrubland, and barren rocky terrain. This combination of complex geology, variable topography, distinct land use practices, and seasonally intense rainfall contributes to the highly dynamic hydrological behavior of the Kale River Basin.

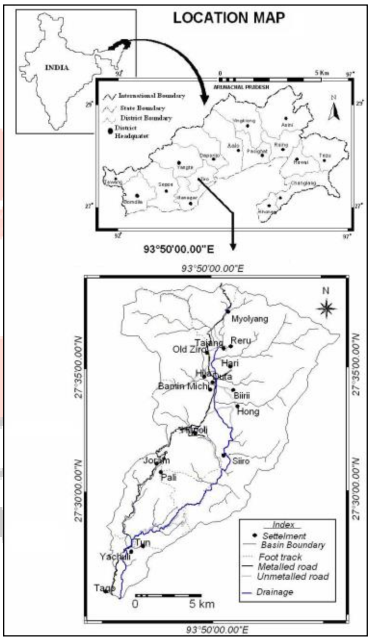


Fig1: Base Map

III. Materials and Method

The present study was conducted in a watershed located in the Eastern Outer Himalayas of Arunachal Pradesh, characterized by a mixed pattern of sedentary and shifting cultivation. The objective was to assess the hydrological dynamics across different land use categories using a combination of remote sensing, field-based hydrological experiments, and geospatial analysis.

III.I. Land Use Classification:

The study area was classified into three major land use/land cover (LULC) categories i.e Agriculture, Barren, and Forest to analyze and compare the runoff behavior under varying surface conditions and vegetation cover (P. Carol, 1993). This classification was based on multi-spectral LISS-III 8-bit satellite data, which was processed using digital image classification techniques. Ground truth verification was conducted through field visits to ensure the accuracy of LULC interpretation **(Fig. 3).**

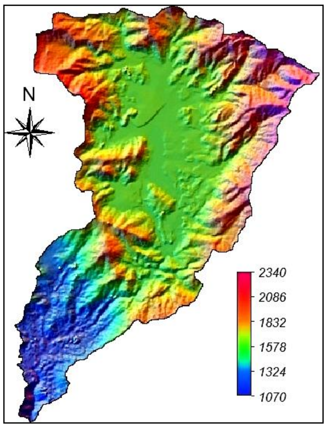


Fig 2: DEM (3D Display)

III.III. Plot Design for Runoff Estimation:

To quantify runoff and overland flow, a plot-based experimental design was adopted (Jose et al., 1995). For each of the three land use categories, three erosion plots measuring 3 meters by 5 meters were established on varying slope gradients to capture the influence of topography on runoff dynamics. Each plot was equipped with a collection system, where overland flow was directed through pipes into calibrated containers for monthly measurement and analysis (Joshi et al., 2007). This experimental setup allowed comparative analysis of monthly runoff volumes across land use types and slope categories, providing insight into the impact of land use and slope on hydrological response.

III.IV DEM Generation and Hydrological Analysis:

A high-resolution Digital Elevation Model (DEM) of the study area was created using interpolated contour lines and spot heights extracted from Survey of India (SOI) Topographic Maps (Fig. 2). DEM optimization and artifact removal were carried out using the ITC methodology proposed by Hengl et al. (2003). The filtered DEM, with a spatial resolution of 10 meters, was used for the extraction of morphological and hydrological parameters, such as slope, flow direction, flow accumulation, and watershed boundary delineation.

The integrated use of satellite imagery, field instrumentation, and DEM-based terrain analysis ensured a comprehensive understanding of runoff generation and discharge behavior within different land use settings in the Kale River Basin.

III.V. Total water volume available in the water shed:

The data in Table No. 1 highlights inter-annual variability in rainfall and the resulting total and available water volumes within the Kale River watershed over three hydrological years (2020–2023). Rainfall increased steadily from 217.96 cm in 2020–2021 to 327.71 cm in 2022–2023, marking a 50.3% rise over this period. This increase is directly reflected in the corresponding rise in total water volume, from 444.84 million cubic meters in 2020–2021 to 668.84 million cubic meters in 2022–2023. The average daily available water volume across the three years is 1,519,190.70 cubic meters, while the average per second availability stands at 17.58 cubic meters, indicating a consistently high runoff and stream flow potential.

Table No. 1: Total water volume available in the water shed

Observation period	Rainfall (cm)	Total water volume cubic meter	Water volume available in cubic meter			
			Day	Hour	Minute	Second
2020-2021	217.96	444843563.49	1218749.49	50781.23	846.35	14.11
2021-2022	269.39	549825398.66	1506370.96	62765.46	1046.09	17.43
2022-2023	327.71	668844855.79	1832451.66	76352.15	1272.54	21.21
Average	271.69	554504605.98	1519190.70	63299.61	1054.99	17.58

This pattern suggests that the watershed not only receives substantial rainfall but also exhibits an efficient conversion of rainfall into surface water availability, likely due to the steep gradients and the absence of significant water retention infrastructure.

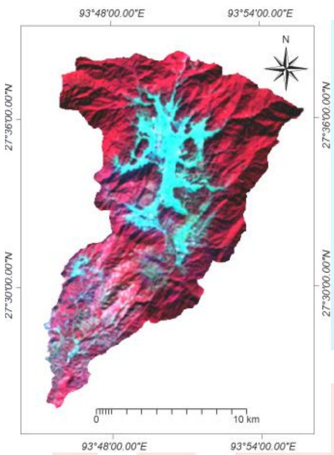
The year 2022–2023 stands out with the highest rainfall and corresponding water yield, the average rainfall across the study period is 271.69 cm, which sustains a significant volume of water for both ecological and human use.

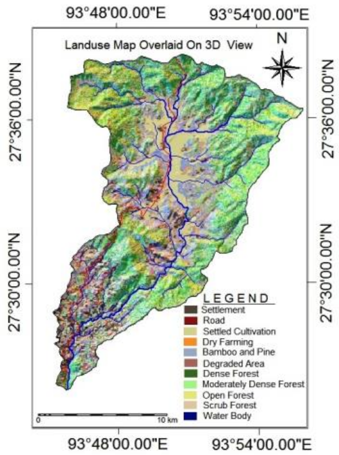
IV. CHANNEL DISCHARGE:

The channel discharge data for the Kale River Basin across the three-year observation period (2020–2023) demonstrates a clear upward trend in total discharge volumes and daily average flow rates (Table No. 2). In 2020–2021, the total channel discharge recorded over 204 observation days was 1868.97 cubic meters per second (cumec), converting to an average daily discharge of 9.16 cumec. This value increased to 2145.05 cumec in 2021–2022, with a corresponding daily average of 10.51 cumec. The most significant rise occurred in 2022–2023, where the total discharge surged to 3747.18 cumec, marks higher daily average of 18.37 cumec. The three-year average discharge stood at 2587.07 cumec, with a mean daily value of 12.68 cumec. This progressive increase in both total and average discharge values suggests a strong hydrological response to rising rainfall trends, consistent with the observed increase in precipitation across the basin.

Table No. 2 Kale River Basin: Total CHANNEL Discharge

Observation period	Total Discharge (daily year wise observations) Cumec	Average per observation value Cumec for 204 days
2020-2021	1868.97	09.16
2021-2022	2145.05	10.51
2022-2023	3747.18	18.37
Average	2587.07	12.68





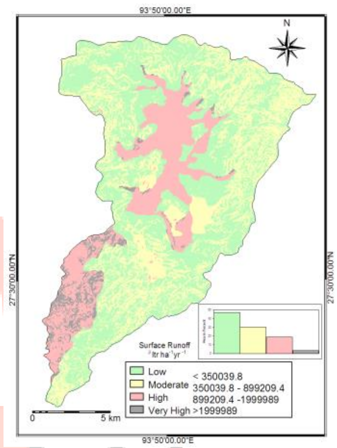


Fig 3: Satellite picture of the study area Fig 4: Land use Map Fig 5: surface runoff intensity

The increase in average daily discharge between 2020–2021 and 2022–2023 indicates a sharp intensification of surface runoff and stream flow, likely influenced by a combination of higher rainfall intensity, land use dynamics, and possibly reduced infiltration due to land cover alterations.

V. TOTAL WATER VOLUME AVAILABLE IN WATERSHED AS SURFACE RUNOFF:

The data presented in Table No. 3 illustrates the total surface runoff volumes generated from different land use types agriculture, barren land, and forest within the Kale River watershed over a three-year period (2020–2023). The values indicate distinct inter-annual and land use-based variations in runoff contribution, which are influenced by rainfall patterns, land cover characteristics, and topography.

In 2020–2021, total surface runoff amounted to 415.58 million liters, with the forested areas contributing the largest share at approximately 286.52 million liters. Agricultural lands and barren areas contributed 107.85 million liters and 21.21 million liters, respectively. This high runoff from forest land, particularly in the initial year, may be attributed to saturated soil conditions, steep terrain, and potential degradation of forest cover that reduced infiltration capacity.

The corresponding time-based runoff values for this year reached 1,138,578.93 liters per day, 47,440.79 liters per hour, 790.68 liters per minute, and 13.18 liters per second.

In 2021–2022, total runoff dropped significantly to 341.84 million liters, reflecting a reduction in total rainfall and possible improvements in ground absorption or land use management. Forest areas still contributed the highest volume (198.12 million liters), followed by agricultural plots (118.89 million liters), and barren areas (24.82 million liters).

TABLE NO. 3 TOTAL WATER VOLUMES AVAILABLE AS SURFACE RUNOFF IN THE WATER SHED

Year	Surface flow from different land use plots in $l^3 yr^{-1}$			Total cubic liter	Surface Runoff based on Time in cubic liter			
	Agriculture	Barren	Forest		Day	hour	min	sec
2020-2021	107854045.62	21208650.45	286518614.91	415581310.99	1138578.93	47440.79	790.68	13.18
2021-2022	118894564.14	24821183.79	198120283.33	341836031.27	936537.07	39022.38	650.37	10.84
2022-2023	163531394.54	31908592.93	332953543.30	528393530.77	1447653.51	60318.90	1005.31	16.76
Average	130093334.77	25979475.73	272530813.85	428603624.34	1174256.51	48927.35	815.46	13.59

The average runoff per time unit also declined, with 936,537.07 liters per day and 10.84 liters per second, signifying lower hydrological pressure on the watershed. By 2022–2023, there was a sharp increase in total surface runoff to 528.39 million liters, consistent with a spike in annual rainfall. Forest areas has the highest contribution (332.95 million liters), with notable increases from both agriculture (163.53 million liters) and barren land (31.91 million liters). The time-based metrics surged to 1,447,653.51 liters per day and 16.76 liters per second, indicating a marked intensification of surface hydrology.On average across the three years, forests consistently contributed the most runoff (272.53 million liters), highlighting the dominant role in controlling basin-wide hydrological outputs despite their typical classification as infiltration-favoring land cover. Agricultural lands followed with an average of 130.09 million liters, while barren lands, although minimal in area, yielded 25.98 million liters on average, likely due to poor infiltration and lack of vegetative cover.

This pattern highlights the complex interactions between land use, rainfall, and runoff generation in the Kale Basin. Forest areas, especially when degraded or located on steep slopes, can produce significant runoff volumes. Similarly, increasing runoff from agricultural land may reflect intensive land use practices, compaction, or lack of vegetative buffers. Barren lands, though smaller in total volume, pose disproportionate risks for soil erosion and sediment load due to their low absorption capacity.

Overall, the data emphasize the need for watershed-specific land management strategies. Enhancing forest health, promoting conservation agriculture, and stabilizing barren patches with vegetation could help mitigate excessive runoff and its associated impacts, such as soil erosion, flooding, and downstream sedimentation in the ecologically sensitive Eastern Himalayan landscape.

VI. COMPARATIVE ANALYSIS OF THE OF WATER VOLUME IN THE WATERSHED:

The comparative table No. 4 of water volume available in the Kale River Basin as surface runoff and channel discharge offers a clear picture of the hydrological balance and the efficiency of the watershed in translating available rainfall into observable water flow. Over the three-year period (2020–2023), the total water volume available in the watershed steadily increased from 14.10 cumec in 2020–2021 to 21.21 cumec in 2022–2023, reflecting increasing annual rainfall and possibly more intense precipitation events.

Surface runoff derived from different land use categories in the watershed showed a varied response. In 2020–2021, surface runoff was 13.18 cumec, accounting for 93.43% of the total available water—indicating a high proportion of rainfall being converted to overland flow. This high percentage suggests a relatively low infiltration capacity during that year, possibly due to already saturated soils, intense rainfall events, or degraded land cover conditions, particularly in forest and agricultural plots.

In contrast, 2021–2022 saw a marked decline in surface runoff to 10.83 cumec, constituting only 62.13% of the total water available. This indicates improved infiltration or reduced precipitation intensity, leading to greater water retention in the soil profile or subsurface flow. It might also reflect more stable vegetation cover or seasonal distribution of rainfall that allowed more water to be absorbed.

By 2022–2023, runoff increased again to 16.75 cumec—about 78.98% of the total available water—highlighting a rebound in surface flow corresponding to the year's highest rainfall. This pattern reflects a strong correlation between rainfall intensity and surface runoff generation, particularly in terrains with significant slope gradients and mixed land use practices like shifting cultivation and paddy-fish farming In terms of channel discharge, which represents the portion of rainfall effectively routed through streams and rivers, the average discharge per observation shows a clear upward trend—from 9.16 cumec in 2020–2021 to 18.36 cumec in 2022–2023. The percentage of available water emerging as channel discharge was

64.91% in 2020–2021, declined slightly to 60.25% in 2021–2022, and rose sharply to 86.54% in 2022–2023. This increasing efficiency in discharge generation may result from reduced interception, faster overland transport, or geomorphological channel adjustments responding to higher rainfall events.

TABLE NO.4 COMPARATIVE OF WATER VOLUME AVAILABLE IN THE WATER SHED SURFACE RUNOFF AND CHANNEL DISCHARGE

Year	available water in cumec	water from the different land use of the basin Cumec	% of water from the available water in the basin/sec as surface runoff and channel discharge	Average channel discharge per observation value Cumec	% of water from the available water in the basin as channel discharge
2020-2021	14.10	13.18	93.43	9.16	64.91
2021-2022	17.44	10.83	62.13	10.51	60.25
2022-2023	21.21	16.75	78.98	18.36	86.54
Average	16.13	12.47	78.20	11.63	70.59

On average across the three years, 78.20% of the total water available in the basin became surface runoff, while 70.59% was discharged through river channels. These values indicate that a significant portion of the rainfall is being rapidly converted into runoff and streamflow, leaving limited room for groundwater recharge or deep percolation. This trend could raise concerns about long-term water sustainability, soil erosion, and watershed health if not managed through integrated water and land use planning.

In summary, the comparative data reflect dynamic interrelations between climate, land use, and watershed hydrology in the Kale River Basin. The high percentage of runoff and channel discharge points to a responsive but potentially fragile hydrological system, requiring strategic interventions to enhance water retention, reduce erosion, and support sustainable agricultural and ecological practices in this Eastern Himalayan setting.

VII. Correlation Analysis of variable with rainfall:

Agriculture Surface Flow: Very strong positive correlation between rainfall and agriculture surface flow indicates that increases in rainfall is closely associated with increases in surface runoff from agricultural lands. This is likely due to the nature of agricultural practices, which often involve soil tillage and reduced vegetation cover, leading to decreased infiltration and increased runoff. As rainfall intensifies, the compacted and exposed soils in agricultural areas are less able to absorb water, resulting in higher surface flow.

TABLE NO.5 Correlation with Rainfall (r)

Variable	Correlation with Rainfall (r)
Agriculture Surface Flow	+0.997 (very strong)
Barren Surface Flow	+0.999 (very strong)
Forest Surface Flow	+0.505 (moderate)
Total Channel Discharge	+0.992 (very strong)

VII.I Barren Surface Flow: A perfect positive correlation exists between rainfall and surface flow from barren lands. Barren areas, lacking vegetation, have minimal interception and infiltration capacities. Consequently, rainfall directly contributes to surface runoff in these regions. The absence of plant roots and organic matter means that water is less likely to be absorbed into the soil, leading to immediate and significant surface flow during rainfall events.

VII.II Forest Surface Flow: The moderate positive correlation between rainfall and forest surface flow suggests that forests play a role in modulating runoff. Forested areas typically have dense vegetation, leaf litter, and permeable soils, which enhance water infiltration and reduce surface runoff. While increased rainfall does lead to some increase in surface flow, the forest's ability to absorb and store water mitigates the extent of runoff compared to agricultural or barren lands.

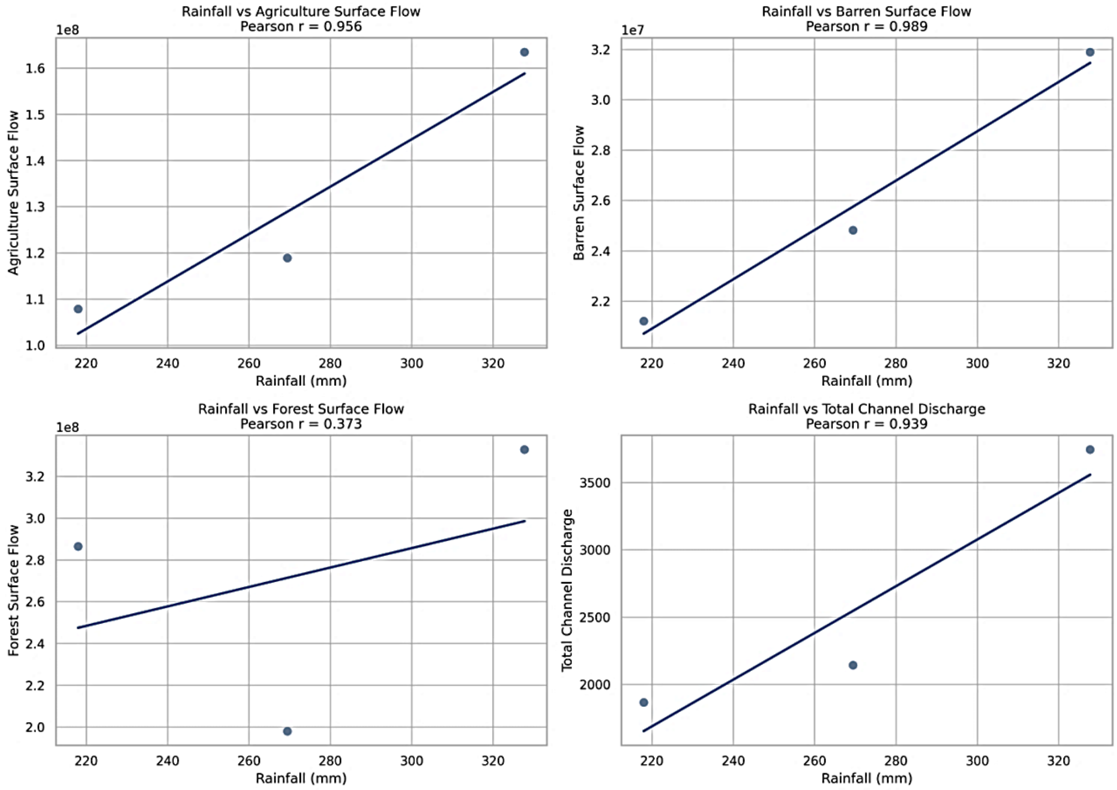


Fig 5: Correlation with Rainfall (r)

VI.II Total Channel Discharge: Very strong positive correlation between rainfall and total channel discharge indicates that overall water flow in channels is highly responsive to rainfall variations. This encompasses the cumulative effect of runoff from all land-use types. As rainfall increases, the combined surface flows from agricultural, barren, and forested areas contribute to higher channel discharge. The strong correlation underscores the significance of rainfall as a primary driver of channel flow volumes.

Overall, the correlation analysis reveals that rainfall has a significant impact on surface flow and channel discharge across different land-use types. Barren and agricultural lands show the highest runoff. Forests area, demonstrate a buffering capacity that moderates surface flow. Understanding these dynamics is crucial for effective land and water resource management, especially in the context of flood control and sustainable land use planning.

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